PUSHING the HORIZON

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Seventy-Five Years of High Stakes Science and Technology at the Naval Research Laboratory

IVAN AMATO

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In 1915, with Europe in flames, Americans looked anxiously over their shoulders, wondering whether they, too, would be pulled into the "Great War" raging across an ever-narrower Atlantic Ocean. Conversations that year between Thomas Alva Edison and Secretary of the Navy Josephus Daniels set in motion the forces that led to the establishment of an inventions factory modeled on those laboratories newly established within the most progressive part of American industry. Within a generation, the new Naval Research Laboratory (NRL) would produce the first operational American radar and sonar and accomplish path-breaking fundamental research on the transmission of high-frequency radio waves and the nature of the ionosphere.

Science writer Ivan Amato explores the origin, development, and accomplishments of NRL over the last 75 years. He analyzes the personalities, institutional culture, and influences of what has become one of the preeminent research laboratories within the United States. Tracing the Laboratory from its small and often inauspicious origins to today's large, multidisciplinary research center, Amato sets in context many of the important research events and fronts of modern military science and technology.

The author explores the role of the Laboratory within the Navy and U.S. science during the 1920s, Great Depression, and the "physicists' war" of 1941 to 1945. Amato subsequently looks at NRL during the Cold War and the birth of the space age, of which it was such a key player. He then presents overviews of contemporary research programs that will shape the substance of military capabilities well into the next century. Amato examines research fields ranging from oceanography to plasma physics to space technology in order to demonstrate how advanced science and technology have developed synergistically within the dual context of a military-sponsored, civilian-administered R&D laboratory.

– David van Keuren, NRL Historian

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ACKNOWLEDGMENTS

At the end of 1996, the Naval Research Laboratory's committee organizing the Laboratory's 75th anniversary celebration hired me to write a narrative of NRL's story. At the time, I knew just a little about the Laboratory. As a science writer, I had written a few articles—maybe three or four—about NRL research. So when I accepted the job, I had no real sense of what NRL was, which is to say I had no idea what I was getting myself into. All I knew was that I had taken on the charge of writing a full-length book in about fourteen months.

Those months have passed . . . and here's the book. The experience has been humbling. I leave this project knowing that NRL is a magnificent research institution. I leave knowing that its lineage of researchers has contributed significantly and consistently to the evolution of technological landscapes in both military and civilian venues. I leave the project with a better understanding of how institutions work—how personalities, passion for truth, the drive to develop technology, personal ambition, world events, domestic politics, social trends, fluctuating budgets, and many other factors sum into the winding course that institutions take as time unfolds. And I leave this project knowing that the book I offer here is really just a front door into what has been, and remains today, a vast enterprise of discovery and invention. NRL is far more than any book could ever convey.

It is with this attitude that I ask readers to approach this book. For each topic I cover, there are scores, even hundreds of others that also

could have been included. For each person named, there are many, many others that also might have been. Indeed, the full story of NRL cannot be chronicled between a single set of book covers; maybe not even multiple sets of covers as in an encyclopedia. There simply are too many chapters. In time, more of these chapters will come out in the pages of annual *NRL Reviews*, NRL reports, PhD dissertations, reviews by NRL long-timers, papers by NRL historians, and elsewhere. Perhaps another writer in 25 years will find this book useful in the preparation of a book for NRL's centennial.

This book is the product of a collective effort, so there are many people I would like to thank. First of all, I thank John Wegand, who contacted me initially on behalf of NRL to see if I might be interested in this project. I thank David Venezky, David van Keuren, Kathleen Parrish, Dean Bundy, Tim Coffey, and whomever else decided to actually offer me the opportunity and challenge to write this book. Thanks to Peter Imhof and Bridget Gutierrez in the Technical Information Division for putting up with my erratic needs. I thank the staff in TID's Publications Branch whose professional skills are also embodied in this book and whose office-camaraderie I greatly appreciated.

There is no way I could have written a book of this length and breadth in so short a period of time had David van Keuren, NRL's historian, not been selfless with his time and in helping me in many aspects of the research that went into this book. I cannot thank him enough. I also thank previous NRL historians David Allison, Walter Pitts, Bruce Hevley, and Herbert Gimpel, and such sometime-historians as A. Hoyt Taylor and Louis Gebhard for the various papers, oral histories, dissertations, memoirs, and other history-rich documents they have produced. In addition, I thank the several dozen NRL staff who reminisced for me about their experiences at the Laboratory. A list of their names appears in the reference section at the end of the book.

For reading and commenting on several drafts of the entire manuscript, I would like to thank David van Keuren (again), Jack Brown, David Venezky, Tim Coffey, and my father Solomon Amato. I am ad-

ditionally indebted to Captain Bruce Buckley for his thoughtful and useful review of the entire manuscript in the eleventh hour.

For looking over limited portions of the text, I owe thanks to Joel Schnur, Tom Giallorenzi, Joseph Bucaro, Donald Gubser, Burton Hurdle, Herbert Gursky, Homer Carhart, Guenter Brueckner, Louis Pecora, Randall Shumaker, Lee Hammarstrom, Jerome Karle, Isabella Karle, John Montgomery, Bill Howell, Chris Herndon, Gary Prinz, and David Nagel. In this regard, I would like to especially thank Bhakta Rath, whose diplomatic skills proved invaluable at a late stage of the project. Despite all of this assistance in my quest to minimize errors, I assume full responsibility for any errors that do make it into print.

It is one thing to write a book and it is quite another to take a ream of paper and a stack of photographs and turn these into a handsome volume. For that transition, I thank Saul Oresky whose expert and tireless copyediting (he copyedited this page, too) and insightful reading helped in the 11th hour to improve the book. I thank Kathleen Parrish for her many roles in overseeing NRL's editorial services in the making of this book. I also thank Jan Morrow for designing the book. After all, a book is not just a collection of words; it also is an object that, like all constructed objects, benefit from the skill and aesthetic eye of thoughtful designers.

Almost finally, I want to thank all of my teachers in life. Among them are my parents. And finally, I want to thank my family—my wife Mary and my two little boys Simon and Max—for the foundation of love and home life without which luxurious intellectual pursuits like the one this book represents to me would not have been possible.

Chapter 1

The Navy's Invention Factory

On the eastern bank of the Potomac River, just after the river's waters have left the heart of Washington on their southward journey to the Chesapeake Bay, resides a 130-acre campus with over 100 buildings of all shapes and sizes. Guards screen every person or vehicle entering the compound. Some of the buildings have no windows. Many are equipped with radar dishes and antennae of many varieties.

Travelers flying through the Ronald Reagan National Airport, which is just across the Potomac, can look down from their planes and catch glimpses of the industrial-looking site. Most don't notice it. If the campus even flashes onto their retinas, practically all let it pass like a stretch of anonymous landscape along an interstate highway. Attentive flyers, however, might notice some large blue lettering above the windows of the building from which juts a weathered old pier that once hosted the traffic of oceanographic research vessels. The letters spell out "Naval Research Laboratory."

To unwittingly fly or drive by the Naval Research Laboratory is akin to going right by a Bell Laboratories, a NASA, a Microsoft Corporation, or the headquarters of some other world-changing organization without recognizing the place for how it has contributed to the technological character of modern times. Despite its lack of name recognition, NRL, the Navy's own corporate laboratory, has become a

world-changing place during its first 75 years. This book tells some of NRL's story, at least that part that isn't still secret.

The history of an institution like the Naval Research Laboratory resembles a family history that unfolds in time, taking this turn and that depending on the strengths and weaknesses each new generation brings with it or inherits or on the traits it develops in response to its internal and external pressures.

When NRL opened for business in 1923, it was a cluster of five buildings surrounded by farmland. It was a place of clean air and dirt roads. It was then bucolic enough of a setting that "Bellevue" (literally "beautiful view" in French), the name given to the property by an earlier owner, intended no irony.

The 20th Century has taken its toll. The sounds of nature have given way to the roar of National Airport's every-two-minute airline traffic and of military aircraft from nearby Andrews Air Force Base and the din of car traffic from nearby Interstate 295. Often, and especially when the wind comes from the South, a sickly stench from the neighboring and sprawling Blue Plains sewage treatment plant infiltrates the air to become an unwelcome olfactory banner for NRL. There can be no argument that the name "Bellevue" has become in time a brazen misnomer.

From its initial humble role on this changing stage of Bellevue, however, the Naval Research Laboratory has evolved into a massive and major actor in the world's ongoing love/hate affair with science and technology. In scientific and technological contexts, NRL itself has been the origin of plenty of "beautiful views," these in the form of new insights about oceans, skies, and stars, and new technologies based on those insights.

What started 75 years ago as a 27½ acre, five-building main campus has expanded to encompass 130 acres and 102 main buildings, as well as 14 other smaller research sites outside of Washington, DC. These include a satellite-tracking station in Pomonkey, Maryland; a fire research vessel in Mobile, Alabama; a center of mostly oceano-

graphic research at NRL's second largest facility located on the grounds of Stennis Space Center in Bay St. Louis, Mississippi; and a meteorological modeling and prediction laboratory in Monterey, California. More important than this physical expansion has been NRL's ascent to join those world-class institutions whose footprints mark much of the technoscape that characterizes modern times.

The external appearance of NRL bespeaks of arcane science and technology. Building 43, the building with the big blue lettering on it and the seat of the Laboratory's top administration is capped by a striking 50-foot radar dish pointing heavenward. In the 1950s, that dish became part of the first communications circuit to use the moon to reflect signals. Many more dishes and antennae of all shapes and sizes adorn scores of roofs at the Laboratory making for a strange, metallic skyline.

Some of NRL's buildings are gargantuan and windowless, the kind of structures on which rumors are built and within which scientists and engineers usher astounding concepts for military technologies into hardware. It seems that half of the buildings on campus have their own, ice-caked refrigerated tank of liquid nitrogen, a household fluid for a place like this. Some of the newer buildings could be on any modern college campus except that they are identified coldly by numbers rather than by the names of the institution's overachievers or major benefactors.

On top of one of these in the northwest corner of the campus (the one bordering Bolling Air Force Base) are four large white communications radomes perched there like enormous golf balls soon to be launched across the Potomac by a giant golfer. Pretty much all that can be said about this building is that the business that goes on there is secret.

South and a bit east of the big golf balls is a stretch of rattier looking buildings, some with dented corrugated metal siding and big, insulated pipes running in and out of them helter skelter. Some of these have little red warning lights by the doors that blink to warn those

outside that powerful lasers for fusion research, nuclear weapons research, and materials science are running.

The only portion of NRL that looks like someone planned it out ahead of time is the central mall that grew from those first five buildings. A series of gardens, parking lots, and sparsely but tastefully landscaped open areas leads from the main entrance to Building 43 and its oversized radar dish. At the mall's entrance is a bigger-than-life bust of Thomas Alva Edison, whose 1915 vision of military research and the future of warfare inspired the creation of NRL.

Flanking the mall on both sides are buildings hosting a number of NRL's cast of research groups: the Radar Division, the Naval Center for Space Technology (NCST), the Acoustics Division, the Materials Science and Technology Division, the Center for Biomolecular Science and Engineering, and the Marine Physics Branch (of the Marine Geosciences Division). The rest of the buildings further to the right and left look as though they were intermittently dropped from a great height and allowed to land where there happened to be space. The result is a strange brew of geometry, architectural styles, old and new construction, decay and growth. It's the kind of crazy quilt landscape that reflects an institution's sometimes less-than-optimal solutions to evolving problems and needs.

The types of buildings and the equipment inside of them say much about what can go on at an institution. What does in fact go on, however, is determined by the people in those buildings. NRL today employs more than 3,000 individuals, about 2,950 more than it did in 1923. About 1,700 of them conduct research and more than half of these investigators have PhDs.

Among the research staff are chemists, physicists, engineers, mathematicians, computer scientists, astronomers, astrophysicists, optical scientists, electronic warfare specialists, satellite engineers, ocean scientists, meteorologists, earth scientists, systems engineers, acoustics experts, molecular biologists, and a huge range of other technical types. With a spectrum of expertise like that, the NRL staff can mix and match

amongst themselves so as to assemble the skills and intellectual stuff that it takes to keep the Navy on the myriad forefronts of military technology.

The rest of NRL's staff makes sure the research can go on by wrestling with mountains of paperwork (mostly budgetary and accounting), preparing food, mending pipes, planting flowers, acquiring and managing books and journals, plowing snow, maintaining security, operating and troubleshooting computer systems, cajoling sponsors, minding military protocol, and publicizing results; in short, by doing all the tasks required to keep NRL breathing every day.

NRL started out 75 years ago as a far more specialized place than it is now. It essentially was a small radio engineering laboratory—along with an important cadre of underwater sound experts—at a time when radio technology was growing from its birth in the late 19th Century into a seminal 20th Century technology. Rather than developing broadcast radio to reach most of the people most of the time as was the case in the civil sector, the Navy provided an entirely different context. The Navy hoped that radio technology would provide a new communications system that would link distantly separated parties on widely separated ships, shore installations, and aircraft.

The technical issues involved in such a system pushed the existing envelope of radio technology to the point that the NRL engineers were driven to investigate scientific issues—such as the role of the electrically charged upper atmosphere (which became known as the ionosphere) in the propagation of radio waves—as a necessary step in meeting the Navy's needs. In other words, the call for leading-edge technology by necessity inspired scientific curiosity. In turn, investigations into how the state of the ionosphere and other environmental conditions affect radio communications opened pathways to the development of more technology.

This powerful bootstrapping dynamic of a technological need driving both engineering and basic science research, whose results

then lead to new technological visions that, in turn, drive more scientific research, is the soul of NRL. At NRL, science and technology have never stopped raising the bar for each other. The most world-changing first fruit of this mutual bootstrapping during NRL's early years was the discovery of the scientific and engineering principles from which the U.S. Navy's first generation of radar equipment was designed and built. Military historians often say that nuclear bombs merely ended World War II while radar was the technology that won it.

As much as NRL's pre-WWII staff was prepared and motivated to push into new scientific territory, the Laboratory's primary sources of funding until the end of the war ensured that NRL's original engineering mindset would remain dominant. Most of the research money came from specific Navy Bureaus, most notably the Bureau of Engineering, whose commanders had specific problems they wanted solved. Those Navy officers who knew anything about NRL perceived it as a place where they could go for help in solving their particular technical problems. They were not interested in throwing their Bureau's money at researchers trying to ask and answer basic questions about how the world works.

As it was for mostly everything else at the time, World War II was a turning point for NRL. The war reinforced the Laboratory's problem-solving, engineering culture. It was a time when research and development simply had to yield real equipment that real soldiers, sailors, and airmen could use ASAP. It was engineering on tight deadlines whose results literally meant life or death. To carry out this work, NRL's ranks swelled fivefold from several hundred before the war to more than 2000 afterward. It was a frenetic period marked by the unmatched passion, unity, and sense of mission that swept America during World War II.

During that expansion, the growing NRL research community pooled its collective and ever more varying expertise to equip U.S. fighters with the best, newest, and most capable equipment. Radar

sets were designed, built, and shipped on short order, sometimes within days. Newly invented chemical brews for repelling sharks, marking sailors lost at sea, and neutralizing chemical warfare agents went out by the thousands. Like Edison's famous labs in Menlo Park and West Orange, New Jersey, the Naval Research Laboratory had become an invention factory run by brilliant scientists and engineers working with well-equipped crews of superlative machinists and craftsmen who could flesh out the most sophisticated and complex blueprints.

At the same time, World War II became a showcase for the way a close marriage of engineering bravado with leading-edge basic science can change all of the rules. Most emblematic of what could come of such a union was the Manhattan Project and its terrifying nuclear weapons. Radar (a simultaneous invention in several places around the world), synthetic rubber to replace embargoed sources of natural rubber, antibiotics, and the proximity fuse (which made anti-aircraft ordnance and field artillery more lethal by triggering detonations when the weapons got to an optimum distance from targets) were some of the other more consequential offspring from this marriage. The massive organizations of civilian scientists that formed to expedite these crash R&D efforts ended up setting a national trajectory for science and technology that only in the past few years has come into question.

As the end of war approached, there was no question in the minds of NRL's ranking researchers and decision makers that a culture of curiosity-driven science, one emulating the academic model of scientific research, had to become a partner with the problem-solving engineering culture that had taken root from the beginning and was strengthened during wartime. World War II was the most scientific war ever. It forcefully showed that today's science was the seed corn of tomorrow's technological harvest. What's more, the war experience proved how short the transition from science to technology can be.

The adoption of this more speculative research culture at NRL became possible, in good part, because of the post-war creation of the

Office of Naval Research (ONR), which was chartered to foster the long view of naval technology built on basic science. NRL became ONR's science-oriented in-house laboratory. Today, ONR, which distributes roughly $860 million[1] to research groups at universities and industries, still typically supplies close to thirty percent of NRL's research funding, which has amounted to over $800 million in recent years. The shift to ONR meant that NRL no longer would rest within an administrative parent like a Navy bureau whose focus on solving near-term problems would curtail NRL's potential to push scientific as well as engineering frontiers. The door had opened to NRL's becoming the Navy's corporate laboratory in the way Bell Laboratories (now Lucent Technologies) was the corporate laboratory for AT&T.

The beginnings of yet another research culture arrived at about the same time that ONR came into existence. In a 14-year sequence that began with the capture of German V-2 rockets at the end of the War and ended in 1958 with the creation of the National Aeronautic and Space Administration (NASA), NRL became one of the nation's hotbeds of both rocket engineering and rocket-borne science. These efforts were in the young tradition of the Manhattan Project in that they required large teams working on many pieces that had to be integrated into large systems. Even after most of NRL's homegrown rocket scientists and engineers became a major foundation pillar of NASA in 1958, the culture of satellite engineering remained at NRL and then grew into a third major research and development culture—the others being basic science, and a more ground-based arena of applied science and engineering. Much of what this third culture at NRL has done remains secret since its major clients and supporters were the likes of the National Reconnaissance Office (NRO).

In addition to these three prominent intermingling research cultures at NRL, other cultural factors have also helped determine NRL's unique research venue. Perhaps most prominent among them is the balance between unclassified research and classified work. On NRL's research staff are those who would prefer to stay as far away from classified research as they can. They essentially are university profes-

sors at a military laboratory. To many of them, doing science in secret is anathema to the free and open communication by which the scientific tradition normally operates. Of course this does not stop the "academic" types at NRL from finding applications of their work within classified projects, especially if hard-to-find funding can be had.

Others at NRL have lived their research lives entirely within the classified arena. Ask one of these researchers what they do and you stand a good chance of eliciting the most hackneyed joke amongst the classified research tribe: "I could tell you, but then I would have to kill you." Of course, with a little care and with assistance from NRL editors and security experts, many of NRL's classified projects do yield unclassified publications. It's often simply a matter of removing keywords from manuscripts or leaving out actual values of measurements. That is how many researchers at NRL successfully straddle the classified and unclassified research worlds.

Another important determinant of NRL's multifaceted research culture is the way the research gets chosen and funded. Since ONR funds only a portion of the annual research budget, the rest of the budget must come from other sponsors, who may choose to fund work at NRL or instead choose to put their money into other government, industry, or academic labs. These sponsors include other units in the Navy and elsewhere in the military establishment; units of the nation's intelligence network including the National Security Agency (NSA) and NRO; and civil organizations such as NASA, the Federal Aviation Administration (FAA), and the Department of Transportation (DoT). Since the 1980s, NRL researchers have been working more and more with private firms on a cost-shared basis under Cooperative Research and Development Agreements, or CRADAs. So the sponsor roster is long and diverse and getting more so. This multi-sponsor arrangement means that NRL scientists usually have to compete with other suitors for support. For better or worse, the system tends to turn NRL researchers into entrepreneurs of sorts.

NRL's blend of research cultures and resources has yielded important results, earning the Laboratory a place in the big leagues of

institutions that have influenced the technoscape. Consider this small selection of NRL trophies:

♦ Just as the Laboratory was opening its doors in 1923, Harvey C. Hayes, NRL's top scientist in underwater sound, was witnessing heartening results from a new apparatus he had designed that used the speed of sound in water to rapidly determine ocean depth. Using the apparatus (then called the Sonic Depth Finder and now known as a fathometer) aboard the destroyer USS *Stewart*, Hayes and his crew began surveying enormous swaths of the ocean floor with unprecedented accuracy and speed. This was the beginning of NRL's unending project to understand the ocean environment.

♦ In the 1930s, NRL scientists and engineers developed the United States' first generation of radar technologies at a critical time when a half-dozen other countries were independently and secretly doing the same thing.

♦ As World War II intensified in the early 1940s, NRL initiated a top secret program with the prescient goal of developing nuclear propulsion for submarines. As a result, NRL became the first U.S. government laboratory to separate uranium isotopes, a first step to producing and harnessing nuclear chain reactions. The isotope separation process, called thermal liquid diffusion, was developed initially on the NRL campus by physicist Philip Abelson. In 1944, his process, which by then had been scaled up to a large pilot plant operation at the Philadelphia Navy Yard, became a crucial component of the technical infrastructure behind the world's first nuclear bombs when it was put into operation at a then secret isotope separation plant in Oak Ridge, Tennessee. The uranium that emerged from this process became important feedstock for a final enrichment process that led to the explosive heart of the bomb that was dropped on Hiroshima.

♦ Just after the war, others at NRL began sending a range of atmosphere-measuring instruments to unprecedented altitudes using captured German V-2 rockets. As a result, NRL researchers simultaneously developed expertise in the fledgling fields of rocket engineering and rocket-borne science. Not only would this nascent research

community succeed in launching one of the world's first artificial satellites in 1958, but it also helped launch the National Aeronautics and Space Administration later that same year by providing the new NASA with its first 157 uniquely trained and experienced scientists and engineers. In other words, NRL provided a cornerstone upon which the ongoing Space Age has been built.

♦ One of the most far-reaching offshoots of NRL's foray into space was its extensive role in the conception and realization of the satellite-based Global Positioning System (GPS). The GPS grew from several seeds, including the series of Timation satellites in the 1960s and 1970s, that NRL developed to bolster the navigational capabilities of the country's nuclear-missile carrying, nuclear-propelled submarine force. The GPS evolved quickly into an exceptionally valuable resource for a whole range of military and civilian uses, only some of which were envisioned by the system's originators.

♦ As laser technology matured after its invention in 1960, NRL became a center of high-power laser research, thereby joining the community of researchers questing for controlled nuclear fusion using lasers. The work was funded by the Navy and the Department of Energy (DoE). Although the center of gravity of this work (as measured by dollars) would move to the Lawrence Livermore National Laboratory (LLNL) by the mid-1970s, NRL never stopped developing a base of expertise in high energy lasers, laser interactions with matter, and laser fusion. That expertise has proven crucial both scientifically and for guiding the big decisions that go with any national, multi-billion technology goal such as the quest for laser fusion. Today, laser fusion research continues at NRL with a DoE-funded hangar-sized krypton-fluoride laser system that can direct massive amounts of energy onto tiny material samples. The aim is to clarify the basic mechanisms by which energy concentrates or disperses within targets, which is a fundamental component of the overall challenge.

♦ In 1985, two researchers, one of whom remains at NRL after more than 50 years of service, were awarded science's most coveted and respected award—a Nobel Prize—for their work that rendered X-

ray diffraction a far more versatile and powerful tool for revealing the crystal structures of molecules and materials.

♦ In 1994, a team of satellite engineers at NRL's Naval Center for Space Technology oversaw the design and construction of the Clementine spacecraft, which mapped the Moon with unprecedented detail while proving the capability of new, lightweight sensors and other technologies for the Ballistic Missile Defense Organization (BMDO). Completed within a remarkably short time of 22 months from the time of the project's conception and at a bargain price of $70 million, the Clementine project embodied the "smaller, better, cheaper," mantra that NASA officials have said their agency would adopt following an era of ever bigger and more expensive projects. The Clementine mission became an instant classic in the space community for its innovative convergence of engineering, design, and execution.

These are among NRL's prouder (unclassified) institutional moments, like the births, marriages, and deaths in human biographies. The following narrative will show how the pathways to NRL's high points are punctuated by many fascinating and consequential twists and turns. Moreover, they will show that the Laboratory's peaks of performance and achievement could have emerged only from underlying scientific and technical strata that are sturdy, dependable, and sometimes striking in their own right.

It all began in 1915 with a global tragedy.

Chapter 2

The Laboratory That Almost Wasn't

It was an ocean away, but the spreading European war began coming home to the United States with lethal force in the early Spring of 1915. On March 28, as part of an intensifying campaign of intimidation by German submarines against merchant and passenger shipping in the war zone around England, the British passenger steamer *Falaba* was torpedoed and sunk. Among the dead was Leon C. Thrasher, an American citizen. On April 28, the *Cushing*, an American vessel, was attacked by a German airplane. Three days later, a German submarine torpedoed the American vessel *Gulflight*, causing the deaths of two more U.S. citizens.[1]

Then, on May 7, 1915, the commander of a German submarine gave orders to torpedo the British ocean liner *Lusitania*, which was carrying more than 1200 passengers. As the ship steamed by the southeast coast of Ireland on its way from Liverpool to New York, a torpedo struck the ship on the starboard side and exploded. Within 20 minutes, the 32,000 ton vessel sank. Of the 1,198 passengers who lost their lives, 128 were U.S. citizens.[2]

The sinking of the *Lusitania* was traumatic to the collective American psyche. Large-scale death dealt from underwater ships of a foreign navy was a particularly cold, technological form of warfare born of applied science and technology. The submarine menace bolstered the resolve of the "preparedness lobby," whose members in Congress and the Navy had been criticizing the Secretary of the Navy, Josephus

Daniels, and the administration of President Woodrow Wilson for failing to build up the nation's arsenals at a time when American interests clearly were threatened.[3]

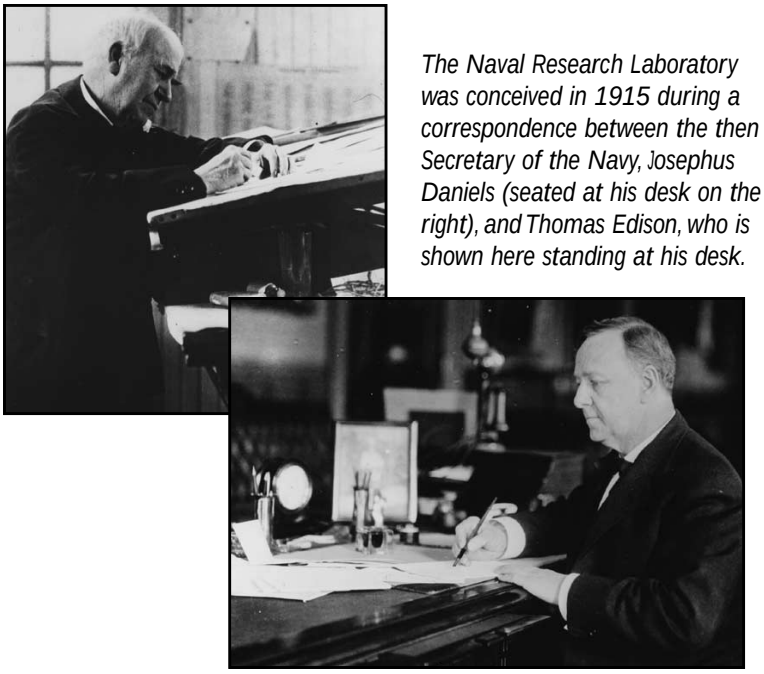
Within a week of the *Lusitania* tragedy, President Wilson began sending stern warnings to the Imperial German Government that its hostile actions had raised the ire of the then neutral United States. "The Imperial German Government will not expect the Government of the United States to omit any word or any act necessary to the performance of its sacred duty of maintaining the rights of the United States and its citizens and of safeguarding their free exercise and enjoyment," stated an official letter to the German Ambassador.[4]

It was at the end of this ominous month of growing global tension that an article appeared in the *New York Times Sunday Magazine* that would lead to the creation of a military research establishment in Washington, DC that would change the world. While the byline identified reporter Edward Marshall as the author, the article was an almost unbroken quote by Thomas Alva Edison, the 68-year-old American icon of inventive genius whose light bulbs, phonographs, and movies had been transforming daily life, about how America should respond to the European War.

When the article appeared, the part that resonated the most in Secretary Daniels came toward the end:

> *"I believe that . . . the Government should maintain a great research laboratory jointly under military and naval and civilian control. In this could be developed the continually increasing possibilities of great guns, the minutiae of new explosives, all the technique of military and naval progression without any vast expense . . . When the time came, if it ever did, we could take advantage of the knowledge gained through research work, and quickly manufacture in large quantities the very latest and most effective instruments of warfare."*[5]

For Daniels, these highly visible words by one of the most famous and respected men in the world breathed life into the long-bandied opinion amongst Navy brass that such a lab made good sense.



The Naval Research Laboratory was conceived in 1915 during a correspondence between the then Secretary of the Navy, Josephus Daniels (seated at his desk on the right), and Thomas Edison, who is shown here standing at his desk.

Edison's words also provided Daniels with a potential means to quiet his political critics. When the article appeared, the Wilson administration, Daniels included, was under increasing criticism for failing to prepare for what to many was the inevitable participation of the United States in the war that had been raging in Europe for nine months. At the start of 1915, the Wilson administration not only had been holding to a policy of neutrality, but it had even amplified its apparent disinterest in war preparation with a concomitant intention to decrease military expenditures. Even after the *Lusitania* went down, Wilson's initial intention was to remain neutral while slowly building up the U.S. military force over many years.[6]

So when Secretary Daniels read the words of Thomas Edison several weeks after the sinking of the *Lusitania*, he perceived a means for navigating a politically narrow strait between Wilson's slow-go approach to military preparedness, on the one side, and the preparedness lobby's ever louder calls for a much faster buildup and mobilization, on the other.

Edison's characterization of the war as "a matter of machines rather than men" in the *New York Times* article was the key to a potential compromise, Daniels surmised. According to the great inventor, the foundation of success in modern warfare was not massive military expenditure and immediate mobilization of large standing military forces. Success would come instead through the unparalleled ability to quickly develop and manufacture the best and latest military technology via the kind of inventive insight and research that had become the *modus operandi* at a growing roster of science-based industrial laboratories. Researchers and engineers at General Electric, Corning Glass Works, Westinghouse, E.I. duPont de Nemours, and, of course, Edison's own invention factory in Menlo Park, New Jersey, all were applying science in pursuit of new and better things. "Better living through chemistry" was how DuPont would later describe its essence. As Daniels saw it, a military version in the form of a naval research laboratory would yield military brawn through the exercise of brains focused on inventions of military consequence.

On July 7, Daniels sent a letter to Edison asking for his help. Echoing the great inventor's own ideas described in the *New York Times* article, Daniels wrote:

> *"One of the imperative needs of the Navy, in my judgment, is machinery and facilities for utilizing the natural inventive genius of Americans to meet the new conditions of warfare as shown abroad, and it is my intention . . . to establish, at the earliest possible moment, a department of invention and development, to which all ideas and suggestions, either from the service or from civilian inventors, can be referred for determination as to whether they contain practical suggestions for us to take up and perfect."*[7]

Daniels, a former newspaper editor well-versed in the power of the media, laid bare in his letter the crucial public relations role Edison could play:

> *"Such a department will, of course, have to be eventually supported by Congress with sufficient appropriations made for its*

> *proper development . . . To get this support, Congress must be made to feel that the idea is supported by the people, and I feel that our chances of getting the public interested and back of this project will be enormously increased if we can have, at the start, some man whose inventive genius is recognized by the whole world to assist us in consultation from time to time on matters of sufficient importance to bring to his attention. You are recognized by all of us as the one man above all others who can turn dreams into realities and who has at his command, in addition to his own wonderful mind, the finest facilities in the world for such work."*[8]

Having become a *de facto* catalyst for this high profile courtship, the *New York Times* was happy to print a front page story on July 13 about the first outcome. The headline read "Edison Will Head Navy Test Board." Daniels, who was interested in appeasing the preparedness lobby, could have written the sub-headline of the article, "Best Engineering Genius of the Nation to Act with Naval Officers in Strengthening Sea Power."[9] The crux of the article was that Edison had agreed to help organize what became known as the Naval Consulting Board (NCB), whose charge would be to identify and shepherd state-of-the-art military inventions that would prepare the United States for what-

The Naval Consulting Board as well as some Navy Department officials surround Thomas Edison and Josephus Daniels, who are seated behind the desk.

ever military challenges might spring up. On July 16, the *New York Times* quoted Daniels saying he hoped to have "a great naval laboratory in Washington."[10]

Of the board's two-dozen initial members, 22 were selected from 11 national science and engineering societies. For the most part, they were luminaries in the realm of science and technology. From the American Chemical Society, for example, came Leo H. Baekeland, already famous and on his way to great wealth for his invention several years earlier of Bakelite, the first fully synthetic plastic material that would show up in everything from telephones to washing machine agitators to brush handles. Willis R. Whitney, another illustrious member of the board, was director of the General Electric Company's corporate research laboratory, a pioneer facility founded in 1900 that became a model for company after company. Running the Naval Consulting Board as its chairman was Edison. His assistant, Miller Reese Hutchinson, who later claimed to have orchestrated the entire creation of the Naval Consulting Board including the arrangement of the Edison interview with Edward Marshall, was appointed to the board as a special delegate.[11]

Edison broached the idea of a naval laboratory during the very first meeting of the board on October 7, 1915. The following March, a five-member delegation of the board, including Edison, briefed the Committee on Naval Affairs in the United States House of Representatives. During his remarks, Edison surprised other members of the board's delegation when he described a grandiose and hardly realistic vision of a lab capable of fantastic feats of engineering and manufacturing, such as building a new submarine in 15 days. More cautious members of the delegation felt compelled to delicately assure the committee that the lab they were proposing would operate at a less reckless pace. Even during this pitch to the very governing body that would recommend for or against federal funding for such a laboratory, internal differences on the board were evident.

The Congressmen apparently were neither alarmed by Edison's hyperbole nor by the failure of the delegation to clearly and uniformly

define the purpose of the "Experimental and Research Laboratory," as the proposed facility first became known. On August 29, 1916, following the recommendation by the Committee on Naval Affairs, Congress appropriated $1,000,000 for the ill-defined facility.

What would become the Naval Research Laboratory, or NRL, now existed on paper. The act of Congress appropriating the Laboratory's initial funding for fiscal year 1917 included the following description of the Laboratory's mission:

> *EXPERIMENTAL AND RESEARCH LABORATORY: For laboratory and research work on the subject of gun erosion, torpedo motive power, the gyroscope, submarine guns, protection against submarine, torpedo and mine attack, improvement of submarine attachments, improvement and development in submarine engines, storage batteries and propulsion, aeroplanes and aircraft, improvement in radio installations, and such other necessary work for the benefit of Government service, including the construction, equipment, and operation of a laboratory, the employment of scientific civilian assistants as may become necessary, to be expended upon the direction of the Secretary of the Navy (limit of cost not to exceed $1,500,000), $1,000,000.*[12]

The amount of funding, which did reach the legally defined limit of $1,500,000 in a supplemental appropriation in March, 1917, fell significantly short of the $5,000,000 startup cost and $2,500,000 annual operating cost that the Naval Consulting Board had estimated would be needed.

Inadequate funding, however, was the smaller of the obstacles that would end up delaying the birth of the Laboratory. Two different clashes—one on the scale of individual human beings, the other on a planetary scale—would bring the paper lab close to a stillbirth ending.

The local clash focused on the function and location of the new lab. Of the 61 locations submitted by board members and others, including Congressmen looking to pump up the prestige and visibility of their districts, three became serious contenders: Annapolis, Maryland; Washington, DC; and Sandy Hook, New Jersey.

Annapolis quickly became the majority choice. It was close to Washington, DC. It was already the home of the Naval Academy. And it was situated on an accessible yet protected harbor in the Chesapeake Bay. What's more, it already hosted an Engineering Experiment Laboratory that was suitable for relatively efficient and inexpensive expansion into the more versatile Navy laboratory.

Edison, however, vehemently argued that Sandy Hook was the wisest site. It was close to New York, from which all types of supplies and skilled labor could be had, he argued. It, too, was accessible to Navy vessels. But the real meat of the rift was the link between the location and the way the new lab would be run. Sandy Hook was just 40 miles south of Edison's West Orange laboratory. He believed the proximity would enable him personally to do what was necessary for the naval lab to succeed, an outcome he was sure public opinion placed on his shoulders. At Sandy Hook, Edison could more readily wield control over the lab without interference from Naval officers and government officials whom he would never trust to run a useful research laboratory.

The "laboratory always in my mind has been for only one purpose, to work under civilian conditions away from naval and government conditions," he told the board at a November 1916 meeting. It was to be a civilian laboratory that has "nothing to do with the Navy except that if any naval officer has an idea, he can go there and have it made."[13]

Part of Edison's strong disdain for, and opposition to, direct naval participation in the lab likely derived from a well-publicized inquiry earlier in the year that blamed a new type of storage battery for submarines being developed by Edison's company for a deadly hydrogen explosion on a submarine as it sat moored in New York harbor. Despite the eminent inventor's vehement protest, the inquiry squarely blamed the Edison battery, while Edison pegged the blame on operating procedures on the submarine. The Navy's Bureau of Engineering adopted the inquiry's assignment of blame.[14]

The location debate culminated in a December 1916 meeting of the board. The majority opinion in favor of the Annapolis site won out over Edison's lone demand that Sandy Hook be the place. The board's recommendation put Secretary Daniels in a difficult position. Had the lone dissenter been anyone but the iconic Edison, Daniels may have been able to simply let democratic process play out. At the same time, there was no way he could accede to the Edison plan, which amounted to using Navy money to build a laboratory in which the Navy would essentially be subordinate to civilians. Daniels chose a third option: inaction. His hope was that Edison still might be swayed.

But the world did not stop turning as the Edison vs the board match came to this stalemate. In 1916, German submarines had sunk nearly twice as much tonnage of British merchant ships than in 1915. The maritime carnage continued to escalate in 1917 to a point where the Germans appeared within reach of their stated goal to break the island nation of Great Britain economically. That is when the U.S. entered the war.

Submarines were emerging as perhaps the pivotal technology in the war, but other products of military science and technology were wreaking new and awful kinds of death that would forever change the relationship of war and technology. For one thing, ever-improving mass manufacturing practices were churning out unprecedented amounts of war materiel, arms, and munitions. More ominous was the German introduction on April 22, 1915 of the first large-scale use of chemical warfare agents. From cylinders, they released 168 tons of ground-hugging, yellow-green chlorine gas into the trenches on the Western Front in Ypres, France. The Allies suffered 5,000 casualties.[15] It now had become a chemist's war, too. There would be no turning back—warfare and science had become inextricably connected.

Meanwhile, Edison remained unmoved in his opinion that Sandy Hook was the appropriate location for the unborn Navy laboratory and no forward action was taken to make the laboratory real. As his-

torian David Allison put it, "the same stubbornness that had characterized the inventor's search for a practical light bulb, which the world of science had called impossible, now determined his stand on the research laboratory."[16]

In lieu of the new corporate Navy laboratory where researchers should already have been at work on research crucial to the Navy, the Navy expanded efforts at its Radio Research Laboratory, then housed at the National Bureau of Standards (NBS) on Connecticut Avenue in Washington, DC, and at the Aircraft Radio Laboratory at the Anacostia Naval Air Station. Some antisubmarine work was underway at the Engineering Experiment Station in Annapolis, but the Navy set up new groups in this field at Nahant, Massachusetts and at New London, Connecticut.

In an attempt to end the delay in the opening of the Navy's corporate laboratory, Frank J. Sprague, a member of the board who had graduated from the Naval Academy and became well-known for developing electric trolley trains in the U.S. and other countries, including Germany, wrote to Edison:

> *"This is a frank attempt to compose the present unfortunate conditions of affairs and save the Naval Consulting Board and possibly the Secretary of the Navy, from very unpleasant criticism. A year and a half has passed since Congress appropriated a million dollars for the creation and operation of 'An Experimental and Research Laboratory.' At the time of this appropriation a large part of the world was at war, but despite the fact that for nearly ten months we have ourselves been involved in this vast conflict, the end of which no one can foresee, the naval laboratory remains a dream. No site has been selected, no detailed plans determined, no constructive steps whatever taken. And why? Because of differences of viewpoint which have thus far prevented that unanimity of decision which the Secretary of the Navy has so strongly urged as a basis for his official action."*[17]

In this letter, dated January 30, 1918, Sprague gave Edison an ultimatum. Either join in a compromise in which the Laboratory is built

at a Washington, DC site known as the Bellevue Magazine, or disband the board entirely. The latter choice undoubtedly would lead to humiliating Congressional inquiries and the in utero death of a lab that everyone involved still wanted to be born.

Everyone except for Edison, that is. His response to Sprague's entreaty was to stop participating in the planning of the Laboratory. Distasteful as the jilting might have been, it also meant that the great inventor was no longer blocking the way. Board members quickly recommended the Bellevue site to the Navy Department and they drew up plans for the Laboratory's physical plant. By mid-year, the plans had been approved and were in the hands of Secretary Daniels and the heads of the Navy's materiel bureaus, such as the Bureau of Steam Engineering and the Bureau of Ordnance, for whom the Laboratory was intended to serve. Daniels remained troubled by Edison's estrangement, however. Without Edison's imprimatur, Daniels still refused to sign off on the project.

By the end of World War I on November 11, 1918, the Laboratory remained trapped in blueprints. By now, the board, which still felt the Laboratory ought to be built, felt impotent to take the matter any further. If the Laboratory was ever going to become a real place, the momentum would have to come from elsewhere.

Almost a year later, on October 1, 1919, that momentum arrived. At the urging of the recently promoted Rear Admiral William Strother Smith, who had been the Navy's liaison to the Navy Consulting Board throughout World War I, the chiefs of the material bureaus (Bureaus of Steam Engineering, Construction and Repair, Ordnance and Yards, and Docks) sent Secretary Daniels a memorandum recommending the "construction of the Naval Experimental and Research Laboratory . . . after the general lines of the report of the Naval Consulting Board."[18]

Now coming from his own Navy brass, Daniels finally acknowledged the recommendation and authorized construction of the Laboratory at the Bellevue site. A construction contract was granted a year

later and ground finally was broken on December 6, 1920. By mid-1923, the Laboratory's original cluster of five buildings along the Potomac River just across from Alexandria would be ready for its tenants.

The site was in a section in the southeast sector of the capitol city just south of where the Anacostia River flows into the Potomac River. Although a new pier had to be built to accommodate Navy vessels, it was a convenient location for the new lab. For one thing, the U.S. Navy had purchased a portion of these grounds in 1873 in order to relocate an explosives-laden Naval magazine at the U.S. Navy Yard that had been on the other side of the Anacostia River. That move occurred after the city's Board of Health deemed the original location of the magazine too close to the White House for comfort.[19]

Just before work on the grounds began, Daniels made one last-ditch attempt to secure the support from Edison that had proven as elusive as it was desired. In the letter, Daniels said he was going to push for civilian direction (in cooperation with Naval officers) of the Laboratory and he wanted Edison to outline the "plans and direction" of this arrangement. The 73-year-old inventor answered by formally resigning from the Naval Consulting Board.

As it turned out, Edison's fear that the Laboratory would be run by Naval officers was borne out. Part of the transition of the Wilson

Secretary Daniels breaks ground for Building 1 in 1920.

administration to the administration of the new president, Herbert Hoover, was the replacement of Daniels with the new Secretary of the Navy, Edwin Denby. In a prescient letter to Denby dated March 17, 1921, the chairman of the Naval Consulting Board, William Saunders, recommended that Naval officers ought to be the executives who carry out Navy Department policy at the Laboratory, but that technically trained civilians unencumbered by Navy traditions ought to be in charge of the experimental work. "It is the hope of a large majority of this Board that you will decide to place a civilian director in charge of the laboratory," wrote Saunders.[20] Nevertheless, six months later, Denby appointed Rear Admiral William Strother Smith as the Laboratory's first director in recognition of his important role in the Laboratory's gestation. But Smith retired two days later, and his successor, Captain E.L. Bennett, was named to the post several months later. (A listing of all of the military directors and commanding officers for NRL's first 75 years appears in Appendix A.)

Meanwhile, the Laboratory buildings were also slowly emerging from farmland on the Bellevue site in 1922. However, a potential show-stopper loomed. Congress had not appropriated a single dollar for running the Laboratory in 1923 when it looked like the new facility would actually be ready for business. With neither a war, nor Daniels, nor Edison, to champion the Laboratory's cause, legislators in Congress were unmoved by the pleas for a piddling $100,000 of operating funds for fiscal year 1923 by Captain E.L. Bennett, who already had succeeded Admiral Smith as the unbudgeted Laboratory's director.

Although Congress did finally come through with that small sum in 1924, the money didn't even cover overhead and staff salaries. So if any of the Navy bureaus wanted the Laboratory to look into some problem, they'd have to pay for the work from their own budgets. Only the Bureau of Engineering opened its purse and embraced the Laboratory as an opportunity. At the urging of officers under him, the Bureau's chief, Admiral J.K. Robinson, authorized his Bureau's own

research in radio and sound, which focused on submarine detection (and that had been dispersed across many facilities and the Navy Yard), to be centralized at the new Bellevue laboratory.

Even before the Laboratory's commissioning, Admiral Smith received a request by the Bureau of Engineering to set up shop in the top floor of the new building designated for research. He then paid a visit to Commander Stanford C. Hooper, head of the Bureau's Radio Division and the man who initiated the Bureau's connection with the Laboratory. "[Admiral Smith] told me that not a single desk of any Bureau had requested any space or help there at the Naval Research Laboratory except my division," Hooper later recalled. "So he said, 'You can have the whole place. You just tell me what you want to do down there and send down your men and the money and I will have it done just the way you say and your men will be directly under your division."[21]

The Laboratory finally was no longer merely ideas in peoples' minds or drawings on paper. Its first buildings were nearly completed. It had a director. And there were two dozen researchers at the Naval Radio Research Laboratory at the National Bureau of Standards, the Aircraft Radio Laboratory at the Naval Station in Anacostia, and at the Annapolis Experiment Station in Maryland (where sound researchers working on submarine detection previously in New London had been transferred) waiting to move in.

The NRL that awaited its christening on the hot sunny morning of July 2, 1923 was composed of a cluster of white, painted buildings of industrial appearance on 27½ acres of weedy, construction-marred grounds. Building 1 served a hodgepodge of functions. It had the only research facilities while also housing administrative offices, a human-operated telephone switchboard, and the library. The Machine Shop and Foundry were equipped with a state-of-the-art complement of heavy and industrial machinery: lathes, milling machines, drills, borers, grinders, metal punches, band saws, jigs saws, metal melting furnaces, forges, and strap hammers. A railroad track owned by the B&O

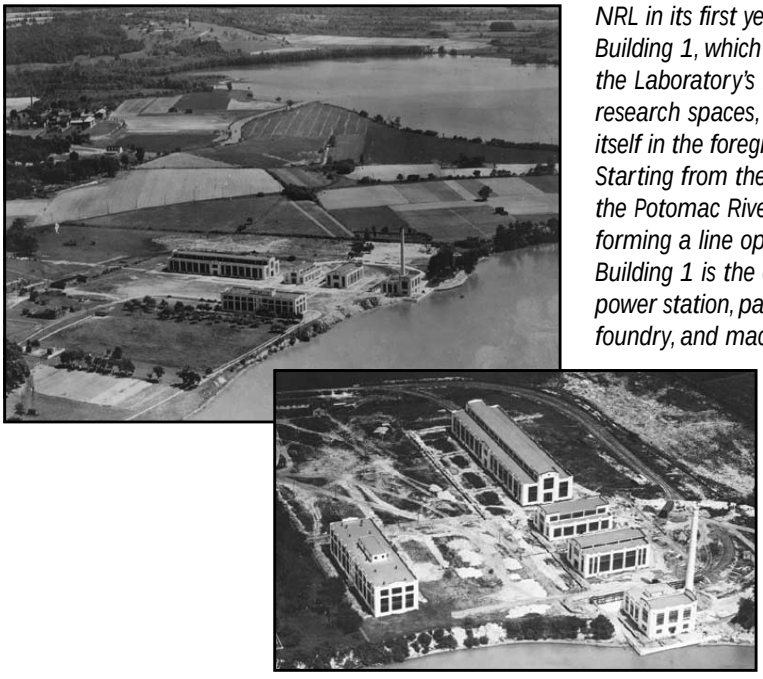
Railroad company ran directly into the largest machine bay so that especially heavy equipment could be unloaded by crane directly from the cars.

Forming a line with the shop buildings toward the river was a power station with a tall smokestack. Its location along the edge of Potomac River made boat delivery of coal a relatively easy affair.

Just south and east of the grounds were cornfields, overgrown riverbanks, a home for the aged and infirm, a burial ground for hundreds of Washington, DC's indigent dead,[19] and farmland destined to become the Blue Plains Sewage Treatment plant.

Peering upriver from the Laboratory's power station, the eye would have been drawn to the audacious Washington Monument. The stark obelisk's skyward attitude aptly symbolized both the Capitol's growing geopolitical importance and also the literally extra-global reach the Laboratory itself would earn in both military and civilian arenas.

The primary official speaker at the ceremony was the Assistant Secretary of the Navy, Theodore Roosevelt, Jr., son of former Presi-



NRL in its first year, 1923. Building 1, which housed the Laboratory's first research spaces, stands by itself in the foreground. Starting from the bank of the Potomac River and forming a line opposite Building 1 is the coal-fired power station, pattern shop, foundry, and machine shop.

dent Teddy and cousin of the future president Franklin D. Roosevelt. He stood on the front steps of a brand new three-story building that his Navy's Bureau of Docks and Yards had built. Having had averted several near abortions during its troubled seven-year gestation since its conception in 1915, the Laboratory finally had made it to an actual birthday.

Theodore, Jr.'s address was not recorded, but historian David K. Allison surmises the young Roosevelt likely reiterated a sentiment he had conveyed earlier to the House Subcommittee on Appropriations. "I feel very strongly that the Navy must not be allowed to petrify," Roosevelt told the Subcommittee the previous year. "We will petrify unless we are constantly reaching out for new and better things. The research laboratory is in direct line with this thought."[22]

On the day of the commissioning, the Assistant Secretary was almost certainly unaware that one of those "new and better things" had already dawned. Two of the Naval Research Laboratory's first hires in the Radio Division, A. (Albert) Hoyt Taylor and Leo C. Young, had registered, even before the Laboratory's doors officially opened, an historic observation of radio waves reflecting from the wooden steamer *Dorchester* that happened to be passing by on the Potomac. It was one of the first glimpses of what was to become known as radar. Taylor's and Young's observation presaged NRL's role in effecting dramatic changes not only in the U.S. Navy but in the entire technological landscape.

Listening to Theodore Roosevelt, Jr., at the commissioning ceremony were Navy officers, members of the laboratory's first few dozen employees, and their guests. Also attending were several members of the Naval Consulting Board. Notably absent was Thomas Edison. If he were there, he probably would have had a smirk on his face. As he saw it, the Laboratory was not the way he thought it ought to be and so was destined to become a cash- sapping government facility where used-up Navy officers would go and from which nothing useful would emerge.[23]

Not a single reporter from Washington, DC ventured to the other side of the Anacostia and Potomac Rivers to attend the ceremony, although the July 1 *Washington Star* did mention the Laboratory's imminent opening.

"For the rest, the opening of the new venture passed almost unnoticed," wrote A. Hoyt Taylor as he recalled the first 25 years of NRL many years later. He had by then become world famous for his role in the invention of radar.[24]

Chapter 3

First Steps

NRL's original physical endowment indeed was humble. Its starting complement of about 20 researchers and technicians, all of them men, brought their own research equipment with them, some of it even arriving by barge. The hangar-like shop building might have been nearly empty at first had the Navy not received 34 train cars of surplus machinery and equipment from the Army. Another 25 train cars worth of scrap materials—cables, antenna wire, hunks of brass and copper, meters, and countless components from old or not-yet-built radio and sound equipment—that would affectionately become known as "the dump" arrived at the Laboratory along with the two submarine detection researchers who came from the Naval Experiment Station in New London to comprise NRL's entire original Sound Division.

Albert Hoyt Taylor, the only card-carrying physicist on the Radio Division's original staff of 18 and who was destined to achieve the kind of institutional stature that gets campus streets named after you, rated "the dump" as a godsend during the Laboratory's "lean and hungry days of the middle and late 'twenties," as Taylor described them later in a memoir. Wrote Taylor: "The Foundry was able to make use of a great many of the metal parts [from the dump], recasting them into devices designed by the Laboratory engineers . . . It was no uncommon sight to see two or three engineers poking around through this pile looking for some usable item."[1]

Albert Hoyt Taylor, senior radio scientist at the Laboratory until his retirement after World War II

These were years when direct Congressional appropriations for NRL inched slowly upward from zero dollars in 1923 to $200,400 in 1929. Total funding, with the majority coming from the Navy's Bureau of Engineering and Bureau of Ships, rose from about $296,000 to a high of $569,000 in 1928.[2] The original vision of the Naval Consulting Board called for an operating budget of nearly five times that peak value. Frugality, therefore, was more of a necessity than a virtue.

Money was just one of the early worries. The electrical distribution system was far from complete when the Laboratory opened. Power to run the research equipment in Building 1 was run from the master switch box through temporary wires running along walls and floors. Night-time work was done under a maddening flickering light since the homemade system for converting the 25-cycle-per-second electrical supply from the Potomac Power Company into a conventional 60-cycle-per-second supply (a frequency high enough that human eyes do not discern its ebbs and flows through lights) was shut off every day at 4:30 PM. For years, there was no heat in the winter for the offices on the top floor of Building 1.

Balancing such shortfalls in the physical plant at the Bellevue site was the abundance of talent amongst NRL's first scientists, engineers,

machinists, draftsmen, toolmakers, laborers, and administrators. Collectively they brought with them the kind of laboratory experience, engineering skill, and machining and manufacturing know-how needed to devise and build state-of-the-art equipment, mostly in the category of radio communication gear. One particularly valuable ingredient of NRL's brew of human capability was the kind of raw scientific acumen that sees seeds of important discoveries or technologies in otherwise unassuming movements of dials, in static on speakers, in stacks of silent data, or even in previously trodden technical territories deemed unpromising by less imaginative scientific prospectors.

The predominance of radio research during NRL's debut years was partly due to the Bureau of Engineering's initiative to consolidate its handful of physically separated radio research efforts. It also was a reflection of the technological and cultural ascendance of radio during the first decades of the 20th Century.

The "dump," a heap of military surplus, junked electrical equipment, wire, and scads of other items, was a prized resource for the Laboratory's early, extremely money-conscious researchers.

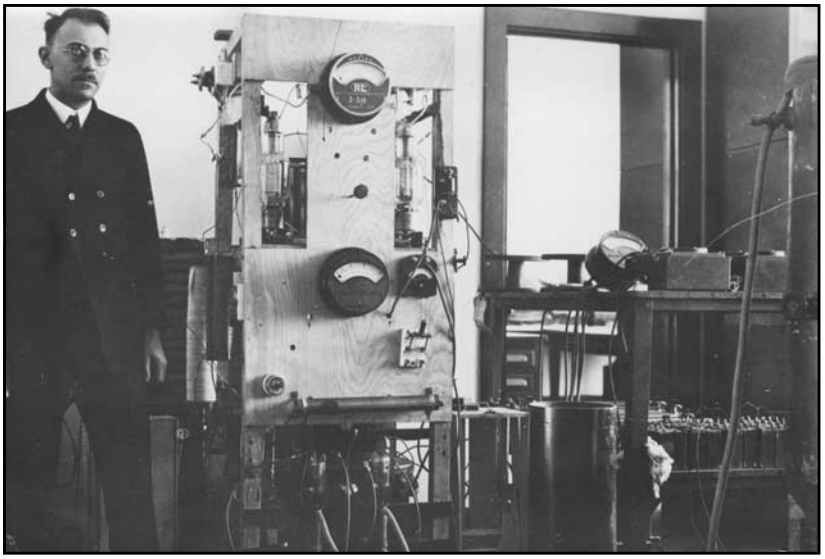
The technology of wireless transmission of electromagnetic signals, which became known as radio, began to take form in the 1880s when the German physicist Heinrich Hertz first demonstrated the practical ability to send long distance signals virtually instantaneously between two locations without the use of wires physically connecting the locations. Like many physicists of his day, Hertz was inspired by the work of the Englishman James Clerk Maxwell, who in the 1860s and 1870s laid out the general principles—whose mathematical manifestations have gone down in history as "Maxwell's equations"—by which electricity and magnetism combine as the fountain of electromagnetic phenomena. Within this wide-ranging category of nature are such things as the way electrical currents and magnetism can give rise to each other and the manner by which radiation such as light and radio waves travel, propagate, reflect, and otherwise find their way from an origin to a destination.

Until Hertz's demonstration of wireless transmission of signals, the most advanced communication was wire-carried telegraphy, which already by the time of Hertz's demonstration included transoceanic cables. (Before radio was known as radio, it was called "wireless telegraphy.") There was no practical way to link ships at sea to telegraphic systems, however. So before wireless communication, ship-to-ship and ship-to-shore naval communication had always been limited to a visual range within which lights, hand signals, or flags could be used. When a ship left its station, it could be a long time before word passed between the two.

The potential tactical power of wireless communications was not lost on the world's navies. In the final months of the 19th Century, the U.S. Navy had demonstrated its first wireless communication using equipment built by the Italian radio pioneer Guglielmo Marconi. A year later, Marconi would dazzle the world by achieving the first transatlantic radio communication. By 1915, the year NRL was conceived, radio transmitting and receiving equipment was proliferating on Naval vessels and on much newer types of airborne vehicles, including

aircraft and dirigibles. All of this radio equipment remained in early stages of development and was beset with limitations in range, quality of reception, and user-friendliness.[3]

It would have been nice if the Navy could have ridden the radio wave that was sweeping the land. When NRL opened its doors, public interest and commercial investment in radio broadcasting was in a rapid ascent. In these early days of radio, commercial development sensibly focused on the vast market for home radios. For one thing, the Navy had specialized communication needs including compact and mobile transmitters suited for a fleet of far-flung seagoing ships and submarines and aircraft whose constraints were even more pronounced. And given the Navy's role in the world, Navy brass wanted radio systems capable of providing private, rather than public, communication whose whole point was to reach whoever wanted to listen. The specialized needs meant that any development costs borne by industry to develop Navy equipment would likely gather far less return on the investment than would be possible in civilian-based



Louis Gebhard was one of NRL's early radio engineers. To his left is one of the Navy's first high-power, high-frequency radio sets that Gebhard designed for the dirigible Shenandoah.

markets. Moreover, the Navy was downsizing and so it represented a much smaller and less promising market.

The "consolidation of the Navy's research and development activities at NRL in 1923 made the Laboratory the Navy's sole in-house organization with full responsibility for advancing the Navy's radio capability, with little outside assistance," according to Louis Gebhard, one of the original radio engineers at NRL who also would achieve the status of an eminent elder.[4] Even before NRL opened, he had worked with Taylor at the Great Lakes Naval Radio Station when they were both serving there in the Navy Reserve. Taylor, a Chicago-born physics professor before WWI, joined the Naval Reserve in 1917 and by 1923 had risen to become the Navy's leading radio scientist. The two of them, Gebhard and Taylor, remain forever connected at NRL at the intersection of two campus roads named after them.

Besides Taylor, who was the sole physicist, head of the Radio Division, and an "ideas man," according to Gebhard,[5] most of the original employees in the division were people more inclined to put ideas into hardware; that is to say, they were engineers. Those pushing the frontiers of radio technology resembled today's computer aficionados. Many of the radio men at NRL had grown up fiddling with wire induction coils (that could drive speakers), quartz crystals for selecting frequencies, batteries, electron tubes (to amplify tiny signals from the crystals), antennae; in other words, the guts of radios.

In these first decades of the 20th Century, the anatomy of technology was more self revealing. Knobs turned, metal touched metal, dials swung from number to number, parts moved. The ways things worked were more obvious than in present day technologies in which so much action takes place as invisible electronic flows coursing through microscopic components packed inside thumbnail-sized chips. It was with their tools in hand and radio parts all asunder that many in the Radio Division had developed an intuitive relationship with the unseen electromagnetic waves that are the essence of radio.

When work was starting at the Laboratory, Taylor made a fateful decision about the direction the Radio Division would take. That move

would end up helping to pull the Laboratory out of the tenuous '20s when funding remained minimal and survival was not even guaranteed. "Probably the most important service of the Radio Division in the early days was the 'selling' of the high-frequency programs to the Navy, and, indirectly, to the radio communication industry," Taylor later assessed. The real buy-in from the Navy's Communication Service was won when Leo Young, who previously with Taylor had observed the radio reflections off of the *Dorchester*, showed that a 50-watt high-frequency transmitter (the power of a single light bulb) could outperform a gargantuan 250,000-watt long-wave transmitter at Annapolis in the task of communicating with Navy facilities in the Canal Zone.[6]

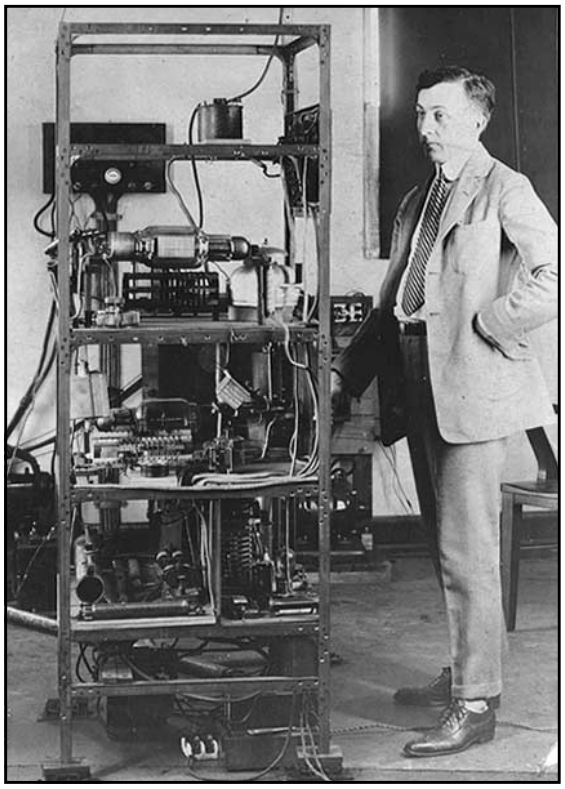
Taylor's initial decision to focus on high-frequency technology at first seems arcane. Radio pioneers like Marconi who were aiming for long distance transmission found that electromagnetic radiation of low frequencies was more practical than high-frequency radiation for broadcasting radio signals. Lower frequencies were easier to produce to begin with and also to amplify on the receiving end. Taylor opted to buck the trend. He directed his men toward higher frequencies. The move won him early skeptics amongst his funders at the Bureau of Engineering who knew how erratic both transmission and reception were at these frequencies; the quality of radio communications actually depended on what time of day or year it was. On the other hand, the energy carried by higher frequency radiation seemed to dissipate faster, so it held promise for more secure ship-to-ship communication that unwanted listeners further off would not be able to receive.

Part of this trend-bucking decision, however, was made for Taylor, not by him. Despite Navy objections, the commercial radio broadcast industry had won control of the lower frequencies between 550 kHz (kilohertz: thousand cycles per second) and 1.5 MHz (million cycles per second).

Still, part of Taylor's decision was a leap of faith into unfamiliar frequencies. "Although, we did not see the tremendous possibilities

[beyond expected gains in areas such as ship-to-ship communications] for the use of high frequencies in the field of naval communications, we did see that they would certainly be extremely valuable, provided we could sufficiently stabilize transmitters and receivers to make use of such frequencies practical under naval conditions," Taylor later recalled.[7]

Taylor's penchant for the higher frequencies had additional roots in an earlier time in 1922 just months before NRL officially opened up. At the time, he was at the Aircraft Radio Laboratory at the Naval Air Station in Anacostia, just upstream from the construction going on at the Bellevue site that was to become NRL. There he worked closely with Young, then a 31-year-old radio engineer raised in Ohio.



Leo Young stands by a high-frequency transmitter whose novel crystal frequency control system enabled communication between Australia and Washington, DC.

Like Gebhard, Young joined the Naval Reserve and ended up working with Taylor at the Great Lakes Naval Radio Station before coming to NRL. To enter radio territory of ever higher frequencies, Taylor and Young tweaked circuits, amplifier tubes, and anything else that might seem to help. All kinds of technical difficulties arose in going to higher frequencies, not the least of which was amplifying the comparatively weaker high-frequency sig-

nals with enough fidelity so that they could reproduce the intended transmitted signal.

Making the task seem doable to Young was a new device, which became known as a superheterodyne. Young had read about it in a technical paper published in 1921. After reading the paper, Young, who had been building his own radio sets since 1905 when he was 14 years old, made a copy of the device. In a receiver, a superheterodyne could convert hard-to-amplify high-frequency signals to lower frequencies, which were much easier to amplify. The "device gave us a wonderful tool for developing receivers for the higher [frequency] band," Taylor recalled.[8]

The radio men were now set to bushwhack into new radio territory. When still at the Naval Air Station, Taylor and Young field-tested a high-frequency (60 MHz) transmitter and a portable receiver they had built as part of their general search for new frequencies, or channels, that would be of use to the Navy. They noticed something that would prove to be spectacularly important.

The first clues came from experiments in which the two radio scientists took the receiver for a car ride around the station. Not only could objects between them and the transmitter block transmission completely, but buildings reflected the radio waves. The reflected signals would fade in and out as the antenna accepted the invisible series of electromagnetic peaks and valleys of the reflected radio waves. Still, with all of those buildings of different sizes and shapes, there were a lot of reflections at a lot of different angles and it was difficult to see what was going on.

To get a cleaner picture of the signal pattern, Taylor and Young drove their receiver to nearby Haines Point, a tongue of land (now known as West Potomac Park) at the confluence of the Potomac and Anacostia Rivers. With only a half-mile of water between them and the transmitter, they figured there would be little to interfere with their radio waves. When they put the receiver onto the sea wall away from trees and other potential direct obstructions, they indeed re-

ceived good solid signals. Then they noticed something odd. "We began to get quite a characteristic fading in and out—a slow fading in and out of the signal," Young later recalled. "It didn't take long to determine that that was due to a ship coming up and around Alexandria."[9] Radio signals from the transmitter across the river were bouncing off the wooden steamship *Dorchester* and into the receiver at Haines Point.

This "detection of moving objects by radio," as the men first described the general technique destined to become radar. It was an idea that several independent groups around the world were independently happening onto. Their respective work subsequently would undergo intense, parallel development in secret to become a military technology that was pivotal to the outcome of World War II.

The idea of using radio for more than just communication was in the air in the early 1920s. Just a month before the Haines Point experiment, for one, Marconi reported he had observed the reflection of "electric waves" from metallic objects and that such reflections might become the basis of detecting and tracking ships.[10] He later would become involved in radar development in Italy.

Within days of their own observations, Taylor shot a letter off to the Bureau of Engineering asking for further financial support. He believed the radio technique could be developed so that Navy ships at sea could use it for detecting enemy vessels. "Possibly an arrangement could be worked out whereby destroyers located on a line a number of miles apart could be immediately aware of the passage of the enemy between any two destroyers in the line, irrespective of fog, darkness or smoke screen," Taylor suggested to the bureau in his letter.[11] The bureau did not bite.

Taylor and Young shelved the radio detection project. Several months later, they packed their gear and moved to their new professional home at the Naval Research Laboratory where Taylor became chief radio scientist of the Radio Division. Young and Gebhard became top assistants.

The Radio Division's primary role in life throughout the 1920s amounted to doing whatever design and development work was necessary to get high-frequency radio equipment into the Fleet. This meant the staff had to work in several areas: antenna development, frequency control tactics, electron tube technology, and new power generation techniques. As the division worked these problems out and built prototypes, specifications for production models went out to private companies like the Radio Corporation of America (RCA) and Westinghouse Electric and Manufacturing Co. The military-industrial complex is not new.

This task was squarely within the realm of engineering, but the task of bringing high-frequency systems into dependable operational condition also ushered the Radio Division into basic science. It was a case in which a specific task of technology development drove the researchers to ask scientific questions whose answers might lead to new technology whose behavior, in turn, might lead to new scientific questions. That mutual bootstrapping of science and technology would become an NRL trademark.

To harness high frequencies for radio technology the Navy could depend on, there were basic mysteries about the behavior of radio waves that researchers had to solve. For one thing, they needed to better understand the environmental factors that, for better or worse, affect high-frequency radio waves as they propagate from the transmitters to receivers. They needed to understand the limits and characteristics of the waves' propagation at different times of the day and year, and at different frequencies.

These basic questions brought the Radio Division face-to-face with the upper reaches of the atmosphere, which theorists for 20 years had been suggesting could become electrically charged and thereby function like a mirror for radio waves.

The idea of an upper-atmosphere radio mirror made general sense of some remarkable observations and feats. For one thing, Marconi had sent radio signals clear across the Atlantic in 1901, which meant

radio waves somehow were bending around the curvature of the Earth instead of reaching the horizon and then ”falling off the Earth” by continuing forward at a tangent toward space. Over the next two decades, theorists worked on explanations for this Earth-hugging property of radio waves. By 1924, the British scientist Sir Joseph Larmor had developed a mathematical model of radio wave reflection in which free electrons in the upper atmosphere comprised a “conducting layer” that worked like a radio mirror. This conducting layer become known as the ionosphere.

Meanwhile, Taylor and his NRL colleagues had been making some remarkable observations of long distance transmission of high-frequency radio waves. With help from a network of globally scattered radio amateurs who could report back to NRL by postcard, the NRL scientists found that a signal could reach a distant receiver while skipping past receivers in between. “Skip distances” is what Taylor called the gaps of radio silence. Larmor's theory was relevant, but it could only explain reflection of lower frequency radio signals.

In an exercise of pure physics, Taylor teamed with Edward O. Hulburt, who had just arrived at NRL from Johns Hopkins University to head the Laboratory's first new division, the Heat and Light Division. The two aimed to develop a more generalized mathematical account of the ionosphere that would explain propagation of both low- and high-frequency radio waves. Hulburt later credited this work with putting NRL on the scientific map because its significance went beyond technical details of military communication and into the realm of basic science. Much later, a panel of the American Physical Society would rate this work as one of the 100 most important applied research papers of the century.[12]

Even before Taylor and Hulburt published their theoretical work on ionospheric reflection in 1926, Young and Gebhard had been drawn into the ionosphere research community by Gregory Breit and Merle A. Tuve, who were major players in the field at the nearby Carnegie Institution of Washington. By using the atomic lattice of a

quartz crystal to stabilize otherwise unsteady oscillations within the radio transmitter circuitry, Young and Gebhard had built a state-of-the-art transmitter whose high-frequency emissions were uniquely unwavering. For Breit and Tuve, that constancy was the key to confidently measuring the height of the ionosphere. They had access to other transmitters, but the emission frequency of these fluctuated. For them, transmitters flawed by these fluctuations were akin to using a ruler with drifting length markings. With Young and Gebhard's stable high-frequency transmitter, the Carnegie duo was able to determine that the ionospheric height varied both during the day and the time of year within a range of 55 to 130 miles.

Give scientists an inch and they want a mile, of course. To look at the upper atmosphere with radio waves was to know there was something in nature that was very interesting but still out of direct reach. The radio measurements, after all, remained an indirect means of probing the ionosphere. When word about William Goddard's pioneering experiments with rockets started circulating in the late 1920s, the upper atmosphere seemed to get closer to forward-looking researchers. In the Spring of 1927, Breit and Tuve along with Hulburt of NRL, started to drum up support in the Navy, Army, and elsewhere for the possible development of rockets that could reach the upper atmosphere. They reasoned that the military might fund development on the gamble that ordnance-tipped rockets could conceivably supplant the need for big and tremendously expensive long-range guns. And if that were so, the rocket-based means of delivering ordnance to an enemy could also serve as the means to bring the tools of scientists higher in the sky than they ever had been before.[13]

Though it would take almost another 20 years before rocket-based atmospheric research got off the ground, the interest of Hulburt presaged what for NRL would literally become a cosmic journey that would only begin with the upper atmosphere and go upward and outward from there. What started as an engineering task to develop new communications tools for the Navy forced NRL radio scientists

to look upward at an atmosphere whose properties were hardly known. The mysteries of the atmosphere happened to entangle with the radio waves the Navy researchers were learning to exploit. This entanglement, in turn, would help turn NRL into one of the most important pioneer outposts of the Space Age.

As the Radio Division looked beyond its vacuum tubes, circuitry, and antennae toward the upper atmosphere, NRL's other original division, the much smaller Sound Division, was directing its attention downward toward the vast oceanic arena of "the hidden enemy"—submarines. The division initially consisted of two men: Harvey Hayes and O.E. Dudley. Hayes had been working on submarine detection and other sound-based tools such as the Sonic Depth Finder with a group of scientists at the Navy Engineering and Experiment Station in Annapolis. After he and Dudley established the Sound Division beachhead at NRL, the group grew slowly, one man at a time, until it leveled off at about a half-dozen researchers. Their primary aim in life was to develop more capable means of detecting and tracking submarines.

Harvey Hayes was head of the Sound Division when the Laboratory opened and would oversee the development of much of the basic sonar technology that was state of the art throughout World War II.

The terror and carnage wrought by submarines during World War I was part of the reason NRL was conceived in the first place. Technology for detecting submerged submarines was extremely limited. It consisted mostly of sailors listening to the audible sounds of the sea picked up by stethoscope-like underwater microphones called hydro-

phones. At best, a listener could tell the direction from which a submarine sound was coming, but not the sub's distance. A hydrophone-equipped submarine resting silently, and therefore invisibly, on the bottom actually would be in a better position to detect a sub-searching surface ship than the other way around.[14]

Moreover, if the surface ship was moving faster than about 6 knots (merely a jogging pace for a weekend runner), its own cruising noise would feed into the hydrophones and drown out any submarine sounds. As a result, listening only made sense in slow-moving ships whose sluggish pace rendered them more vulnerable to torpedo attack. Though Hayes and others developed various hydrophones while working for the Navy in New London, Connecticut, late in the Great War, hostilities ended with essentially no reliable means of detecting the thoroughly demonstrated military menace that submarines presented.

After the submarine detection work was relocated to Annapolis, Maryland, Hayes came to the conclusion that devices listening passively to underwater sound in the audible range would never completely solve the problem of submarine detection. When he, Dudley, and a few truckloads of equipment arrived at NRL in April, 1923, they brought with them this challenge: to develop a sound system that the Navy could use for determining a submarine's bearing and distance from echoes of inaudible, high-frequency (ultrasonic) signals deliberately piped into the sea. In short, they were out to invent an active listening system that later would became known as sonar, a hybrid of three words: sounding, navigation, and ranging.

A technical key to this challenge had already been supplied by several French researchers. In the 1880s, Pierre (who would marry Marie Sklodowska 15 years later) and Jacques Curie reported observing a curious property in quartz crystals. They found that mechanical stresses, such as pressure waves associated with sound transmission, applied to the crystals resulted in a voltage generated across the crystal, a phenomenon that became known as piezoelectricity. That means

a piezoelectric crystal can detect sound. It can "listen." When impinging upon a piezoelectric crystal like quartz, a rapid series of fluctuating pressures moving through air or water (which is one way of describing sound) generates a corresponding train of subtle mechanical stresses and, thereby, a corresponding sequence of fluctuating voltages that can drive an oscilloscope, audio speaker, or a gauge's needle indicator.

A piezoelectric crystal also can "talk." Apply a fluctuating voltage across the faces of the crystal and it will oscillate mechanically. This, in turn, generates sound in the medium hosting the crystal. To generate ultrasonic sound with a piezoelectric crystal, all the NRL scientists needed to do was drive the crystal with an electric circuit that oscillates at the desired frequency.

There was precedent for this task. During World War I, the French physicist Paul Langevin and coworkers sandwiched thin piezoelectric quartz crystals between steel plates to build high-frequency transmitters. Although, these never saw war duty, commercial vessels began to use them for rough depth soundings in the early 1920s when Hayes was still in Annapolis.[15] When the Sound Division began work with quartz-based devices, no one knew what frequencies would work best in the ocean or how to get enough power out of the ultrasonic sound projectors to detect submarines at sufficient distances.

Just as in the Radio Division, technology and science quickly fed on one another in the Sound Division. To determine optimal frequencies for detecting submarines, the division conducted many field tests covering a large range of ultrasonic frequencies from those just above the audible level (20,000 Hz) up to about 100,000 kHz. Many of these tests were carried out in the Chesapeake Bay from a Navy coal barge. The barge had been converted for sound research by the addition of an oblong well in the middle into which sound projectors and microphones could be placed.

By 1928, the division was ready to test a couple of the quartz-crystal units in a more realistic naval setting. Hayes and three col-

leagues went down to Key West, Florida, where they installed the units on two submarines. At times, the equipment on one submarine obtained echoes suggesting the location of the other submarine. More often, however, the researchers were humbled by the curveballs nature threw them.

The ocean may appear to be a vast body of water without physical boundaries, but it is far from that within the context of sound transmission. Hayes and his colleagues learned just how confounding oceanic venues can be. The ocean is riddled with different territories marked by different temperatures. The horizontal or vertical boundaries separating these territories can act like mirrors to sound. Ultrasonic sound impinging at the boundaries of these strata bends to different degrees or scatters into a useless haze or even to silence. Hayes and his team could see from their many tests that pushing acoustic technologies for detecting objects in the oceans would require more than making piezoelectric transducers. It also would require thoroughly knowing the environment. Interpreting underwater sound would require basic underwater acoustic research and oceanography. In submarine detection, therefore, the medium had become an inextricable part of the message.

Even before this realization of the need to push forward the basic scientific understanding of the naval environment , another technical issue springing from ultrasonic detection launched what would become a pursuit of ubiquitous importance to the evolving NRL. The issue at hand was a search for new, better, and more capable materials. The Sound Division knew that if piezoelectric crystals were going to become the basis of underwater detection for the world's military and civilian fleets, then the demand for good quality quartz crystal was going to skyrocket. The only known supplies of such crystals were in Brazil and Madagascar, faraway places that could easily become cut off in the event of war. So critical was the crystal supply issue that the Laboratory's military director himself, Captain Edgar G. Oberlin, traveled throughout the country in search of a source of quartz crystal

that could supply the one-inch square slices then needed for the transducers.

It fell onto the shoulders of Elias Klein, a new hire to the Sound Division in 1927, to solve the quartz supply problem. Born in Poland in 1888, Klein earned a PhD in physics from Yale University in 1921 and taught in the Physics Department of Lehigh University in Bethlehem, Pennsylvania before Hayes hired him into the Sound Division. Klein's task: to develop a synthetic piezoelectric crystal superior to any others.[16]

Other scientists previously had found that a more complicated crystal known as Rochelle salt had a far more powerful piezoelectric property than quartz. It was one of the crystals that the Curie brothers had used in their original work on the piezoelectric phenomenon. After the Great War, Rochelle salt was becoming the stuff of phonograph pickups, microphones, loudspeakers, and other gadgets requiring electromechanical material. That included underwater sound equipment. It turned out Rochelle crystals were better at detecting underwater sound than quartz crystals even when the latter were ten times larger. What's more, the synthetic crystals were sensitive enough to distinguish sounds of a submarine propeller from those of a searching ship. They were also good at generating underwater sound—those famous "pings"—which meant they could work in active, echo-ranging tasks as well as in passive listening devices.

Rochelle salt had its downsides, however. For one thing, it dissolves in water. That's no small problem when underwater technology is at issue. For them to be useful, Klein had to find some way of encasing the material without simultaneously preventing sound from coming into or out from the crystal. He was convinced that some kind of rubber material could be found or made that would serve both as a sound window and as a protective housing for the crystal transducers. He, in turn, convinced the B.F. Goodrich Company to take on the problem. They responded with a new kind of rubber, rho-c.[17]

Piezoelectric transducers using quartz and Rochelle salt became the heart of an early generation of Naval underwater detection systems. In 1928, the NRL extensively tested their so-called XL equipment, which consisted of slabs of quartz crystal cemented between steel plates. They found it could detect submarines by actively sending out and listening for echoes only at distances of about three-quarters of a mile. Over the next few years, the group developed the Rochelle-salt-based JK equipment with a roughly three mile detection range based on passive detection of propeller noise.

Hayes summed up the Naval meaning of these two systems. "The combination of XL and JK, perfected by 1932, represented a distinct advance in antisubmarine equipment, since the JK could be used during search operations to discover and bring a target within range of the XL, which then took over and directed the attack."[18]

These early systems enabled Naval personnel to get a feel for the type of equipment that would remain central to Naval operations ever since. However, the gadgets that came out of this work did not remain state-of-the-art for long. For one thing, by the mid-1930s, Hayes' team was able to combine the functions of the XL and JK systems into a single more capable system known as the QB. Improved versions of the QB "played a stellar role in the Battle of the Atlantic," Hayes would recall after World War II had ended.

Even as the piezoelectric-based technology was emerging, a completely different class of transducer materials came to the Sound Division's attention. At Harvard University, G.W. Pierce had shown that some materials will mechanically deform in the presence of a magnetic field. By controlling the magnetic field, therefore, these so-called magnetostrictive materials could be made to oscillate as an ultrasonic speaker. Conversely, these materials respond to incoming sounds by generating an oscillating magnetic field, that could be converted into an electrical signal. Like piezoelectric materials, magnetostrictive materials can talk and listen. These materials, rather than piezoelectric quartz or Rochelle salt, became the heart of early standard

detection systems for destroyers made by the Submarine Signal Company.[19]

This work by the Sound Division on transducer materials, the electronic components that drove them, and the conversion and interpretation of raw signals into interpretable information became the basis for most of the sonar equipment that would end up in critical service during World War II. "Intensive work was carried on during the war which resulted in numerous improvements, but no fundamentally new sonar systems actually got into antisubmarine operation," wrote Taylor.[20]

NRL's first two divisions, Radio and Sound, were born with an established constituency in the Bureau of Engineering and with a clear sense of what they needed to achieve—wireless communication equipment and better tools for detecting submarines. In expediting these technology development tasks, researchers in these divisions sometimes found they had to delve into basic science as well. Because the ionosphere is a major player in any high-frequency radio equipment intended for long range communication, the Radio Division had to study the upper atmosphere if it wanted to give the Navy reliable high-frequency communication equipment. Likewise, researchers in the Sound Division had to ask questions about the relationship between ocean water and sound propagation.

In 1924, the Laboratory added its first new division. Unlike Sound and Radio, the new Heat and Light Division was born with basic science in mind. It had no natural link to any particular bureau of the Navy, so its funding at first came entirely from the meager Congressional appropriation supporting the Laboratory's operation. In 1924, that amounted to $100,000 for the entire Laboratory. But this independence also meant the new division would have more freedom in selecting the problems it would pursue. In its first years, the division consisted of Edward O. Hulburt and three assistants.[21]

Hulburt was born in South Dakota in 1890 but moved to Baltimore after his father got a job as a mathematician at Johns Hopkins

Edward O. Hulburt, shown here in a 1947 photograph, joined the Laboratory in 1924 to head the then newly formed Heat and Light Division. Two years later he would coauthor a paper with A.H. Taylor that helped push radio technology while simultaneously revealing fundamental properties of the ionosphere.

University. By 1915, he had earned all of his college degrees at Hopkins. His doctoral work was in optical physics, a field for which the university was then world renowned. During WWI he worked at the Army's Signal Corps Radio Laboratory in Paris. There, he and his coworkers would build various radio sets in an old house in the Latin Quarter and then immediately bring them to the troops on the front lines. If the equipment worked well enough, they would send specifications to manufacturers to have thousands of sets made. With that background, Hulburt was a kindred soul of those in the build-test-and-ship mode in the Radio Division.[22]

Like many subsequent NRL hires, Hulbert got his job after NRL staff sent letters to contacts in industry and academe in search of top-notch candidates. A professor at Hopkins recommended Hulburt. He got the job and became the first at NRL to be turned loose unencumbered by any mandate to pursue specific problems of interest to some bureau. Given the breadth of Naval operations, however, Hulburt would have been hard-pressed to find an area in physics that was not somehow relevant to the Navy.

One of the first major projects Hulburt set his new division onto was measuring the atmospheric transmission and absorption of all optical wavelengths of the electromagnetic spectrum ranging from the invisible infrared through all of the visible colors and into the

ultraviolet range. Moreover, Hulburt and his colleagues made these measurements at different times of the day and under various meteorological conditions.[23] There simply was no other way of getting a database on the most general behavior of light in the atmosphere. This work eventually would feed into all kinds of Naval applications areas, ranging from the colors and shapes of signal flags, to Naval camouflage, to detector technology, to the choice of blue lights for nighttime at-sea operation.

Taylor's work on long-range transmission of shorter radio waves also caught Hulbert's eclectic attention. Hulburt later recalled Taylor's method: "Taylor and other amateurs were discovering skip distances just by calling in the dark and seeing who answered. He'd say, 'stand by boys, I'm working tomorrow night on three meter [radio] waves. What do you hear? Send me postcards.'"[24]

Taylor was a radio man and Hulburt was an optics man. So to Hulburt, radio waves were merely much longer versions of the optical wavelengths of the electromagnetic spectrum that he had come to know intimately during his graduate school days. The same rules of reflection that apply to optical wavelengths ought to apply to radio waves, he reasoned. From the skip distance data that Taylor and others at NRL had been accumulating for several radio wavelengths, Hulburt and Taylor were able to infer much about the upper atmosphere and thereby to account for the otherwise cacophonous data on radio propagation.

What they knew from the network of amateurs was that the average skip distances for radio wavelengths of 16, 21, 32, and 40 meters were 1300, 700, 400, and 175 miles, respectively.[25] The longer the wavelength, the shorter the skip distance.

Building on earlier theoretical work by others, they assumed that the atmosphere contained free electrons whose population could vary. The general picture they derived was of an ionosphere composed largely of free electrons whose population and thickness at different parts of the world depended on the amount of solar energy reaching

it. The amount of solar energy varied over the course of a day and night, over seasons, and even over cycles of many years. So the ionosphere over anyone's head was constantly changing. It was as though the radio mirror were constantly being raised or lowered. Part of the challenge with high-frequency communications, therefore, was to have to shift frequencies to accommodate these ionospheric vicissitudes.

From this work, Hulburt and Taylor were able to predict the behavior of different wavelengths and they could explain the fading of radio signals to interference. They published their work in 1926 in the journal *Physical Review*.[26] Besides helping the Navy guide its use of high-frequency radio communication lines, this work was put to quick use during the 1929 flight over the South Pole by Admiral Richard E. Byrd. For several legs of his 1440 kilometer flight, Admiral Byrd used a high-frequency aircraft radio system built specially for the mission by the Radio Division and he used three operating frequencies chosen in accordance with the newfound knowledge about the ionosphere.

In the 1920s, the NRL team was one of several around the world that were simultaneously unveiling the personality of the ionosphere. For their part, Hulburt's and Taylor's 1926 paper stands as one of the seminal publications in the field. In providing a more thorough theory of the ionosphere, it was a contribution squarely within the arena of basic science. In providing a means for the Navy to determine how to use high-frequency radio communication more effectively, it was a practical contribution to the Navy's operational capabilities. It was the perfect mix of basic science and military technology in one.

Heat and Light, the name of Hulburt's division, covers a lot of ground. It stands to reason that the division quickly got its hands into widely divergent projects. One research program begun in 1925 falls under the category of engineering research. The idea was to build models of ship components and other Naval structures out of transparent plastic and then to apply known mechanical stresses to these models. These stresses affect measurable properties (such as the po-

larization) of light passing through such models, a phenomenon known as photoelasticity. From these photoelastic measurements, the division researchers could determine the concomitant internal strains throughout the plastic model. And since the results from the model depended on the structure and not on the model's material, this photoelastic method provided a convenient way of experimentally determining internal strain levels within even huge iron or steel ship components in which direct measurements were not possible. This work later transferred to the Navy's David Taylor Model Basin, an older Navy laboratory devoted to ship engineering studies and located just north of Washington, DC.[27]

One particularly consequential new hire into the division in 1928 was Ross Gunn. The range of his initial work included the engineering and design of new portable electric field meters and amplifier systems for infrared detection equipment as well as scientific investigations of magnetic and electrical phenomena of the Sun and Earth, which also figure greatly into radio communication.[28] In 1939, 11 years after his arrival at NRL, Gunn would usher NRL into what became a crucial and lasting role in the establishment of the Nuclear Age (see Chapter 6).

The scope of NRL again expanded in the later 1920s and early 1930s as several more institutional saplings were planted. Some of these, most notably the Division of Physical Metallurgy and the Division of Chemistry, would grow into enormous research trees with branches spanning the scientific and technological landscape. Others, like the Ordnance Section, which was funded by the Navy's Bureau of Ordnance to look into tightly specified engineering problems, would see the light of day for awhile and then recede, be absorbed by other divisions, or disappear entirely. Even in the Laboratory's early years, the organizational chart would undergo frequent changes reflecting the various internal and external forces governing the perception of the Laboratory's place in the Navy.

One of the more robust new saplings was planted on September 1, 1927, when the Division of Physical Metallurgy joined the Radio,

Sound, and Heat and Light Divisions. The Navy is metal from stem to stern, from port to starboard, from wing tip to wing tip, from breech to barrel. Ore becomes metal becomes slabs and rods and sheets. These have to be bolted and welded and connected into ships and guns and shells and helmets and armor and thousands of other Naval accouterments that have to serve reliably in bitter dry cold places or in moist, tropical settings, all the while in near or direct contact with the salty and notoriously corrosive medium known as ocean water. Moreover, many of these metal objects need to withstand metal-on-metal rubbing, constant vibration, and intermittent shocks of massive force without rattling apart into uselessness.

To look at a rocky mountain of ore and then at the massive ships that come of it is to realize that practical experience by metal workers over the past few millennia has achieved much. But getting metal to perform in ever more capable ways so that it makes a difference in the outcome of a 20th Century military war meant getting down to the physics of metal. The Division of Physical Metallurgy was established to do just that.

The division started with six full-time staff. Leading them was Robert F. Mehl, who had been a research fellow at Harvard University. As Mehl later recalled, Harvey Hayes of the Sound Division and a Harvard man himself, asked a friend on the Harvard staff if he knew of anyone who might want to come to NRL to head one of two new divisions slated to begin operations. Mehl's name came up. When Commander Oberlin, NRL's assistant director, met with Mehl at NRL soon thereafter, he hired the young scientist on the spot.[29] There was no need for a personnel office while an Old Boy network like this was in operation.

In keeping with a trend set by the other divisions, the earliest projects in Mehl's humble fiefdom at NRL were split between basic science and applied work. The Bureau of Engineering, then the largest source of funds within the Navy for the Laboratory, was the division's main customer. One of its early requests was for the new division to look into new alloys for antennae wires on ships. On this task, the

new division worked with the Radio Division in testing a large series of alloys. It was a humble foreshadowing of the way NRL could put together different types of expertise to solve problems for which less well-rounded approaches would fall short or fail.

The division also took on a set of more fundamental studies into the internal structures (phases) in metal that determine important material properties such as hardness, malleability, toughness, brittleness, and weldability. More specifically, Mehl focused this more scientific work of the division on the then-unknown mechanisms by which phases change in metals and alloys. Phases are domains within materials characterized by either a specific chemical composition or by specific crystalline or noncrystalline arrangements of those chemical compositions. Knowledge of these phases and the mechanisms by which they form becomes the basis for more intelligent decisions about what alloys to use for specific purposes, how to prepare and process them, and how the properties of these alloys might change over time under specific operational conditions in the Fleet. The papers that came out of these studies contributed to a young but growing body of worldwide knowledge that at the time was unlocking the internal mysteries of what made metal stay good and what made it go bad.

Some of the work straddled the categories of basic science and engineering. Very soon after Mehl arrived, it occurred to him that the Navy in particular could use ways of inspecting their metal castings for ship construction without having to literally cut into and destroy samples. This type of inspection goes by the name nondestructive testing. “The Navy also had a problem of cracks in loaded 16-inch shells in which I tried to keep my interest quite academic,” Mehl later recalled.[30] At the time, industry was just developing electrical, magnetic, and sound-based methods for probing the interiors of metal. The idea was to infer the quality of the structure inside a piece of metal from the measurable changes in the electrical, magnetic, or sonic signals emerging from a sample.

Mehl and division colleague C.S. Barret, who had expertise in using X-rays for determining the crystalline phases in metal samples,

decided to see if they could use a radioactive substance like radium (which was then a hot anti-cancer tool in the medical community) to reveal flaws in both cast and welded steel. The idea was that gamma rays from the radium would stream through the steel onto a photographic emulsion. This would produce a shadowgraph revealing the steel's inner anatomy, warts and all. And the warts were what was most important to find. Mehl later described the early foray into this project:

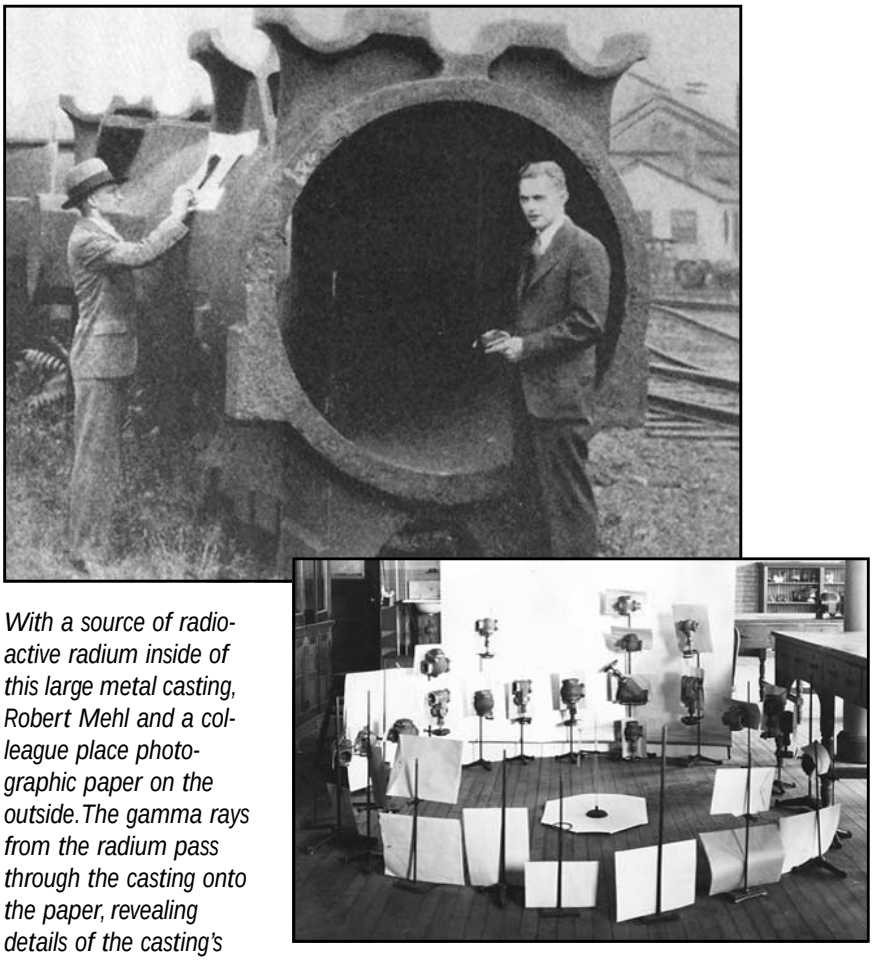
> *"We did our first experimental work in the basement of the Howard Kelly Hospital in Baltimore, a hospital which then owned the largest stock of radium in the world, some five grams. We used this in the form of small capsules of radium emanation. The work turned out to be quite successful; excellent radiographs were made of a number of objects, including a piece of 12-inch steel."*[31]

The NRL team wrote up their findings and sent the report to the Bureau of Engineering at a time when, in Mehl's words, "the Navy was experiencing very serious trouble with the stern post castings on a number of new . . . heavy cruisers, particularly the *Chester* and *Augusta*."[32] It was not lost on the department that the new method might help solve the problem. Mehl recalls what happened:

> *"Accordingly, Barret and I procured radium from the Howard Kelly Hospital and went to the Norfolk Navy Yard where the* Chester *was in dry dock. The stern post casting was a shell casting (a hollow cylinder) about 1¼-inch thick, sitting, of course, on the stern of this cruiser, above the rudder. The* Chester *had been out to sea, and in its trials, the stern post casting had cracked and had then been welded at the Brooklyn Navy Yard, but much doubt was left in the minds of the department as to its serviceability, indeed, as to whether it could go to sea again with this repaired casting in place."* [33]

The two scientists took dozens of radiographs, which indeed were revealing. Recalled Mehl: "They show the castings to have been very badly made, to have been full of blow holes and shrinkage casts and showed also that the welding which had been done was quite inadequate to remove the faulty metal."[34]

The aftermath of this was astounding to the 30-year-old scientist. After briefing a large collection of admirals and captains about the radiography results, he was asked if the 120,000 ton *Chester* ought to be put to sea. Though feeling under-ranked to say so one way or the other, he said no. Later, during a sea trial, the sternpost of the Chester broke again and it had to be towed back to port. In the end, all ten cruisers of this class ship were modified to preempt the sternpost prob-



With a source of radioactive radium inside of this large metal casting, Robert Mehl and a colleague place photographic paper on the outside. The gamma rays from the radium pass through the casting onto the paper, revealing details of the casting's interior quality and defects. The bottom photo shows how the investigators were able to use the technique of gamma-ray radiography to examine many objects—in this case, large plumbing fixtures—simultaneously.

lem. "I think this work on the *Chester* was the thing which established gamma-ray radiography in this country," Mehl later assessed.[35]

The Bureau of Engineering subsequently requested that the Physical Metallurgy Division take a more systematic look into steel casting. Enough money came in to hire more people and to equip the Laboratory's already impressive foundry with expensive new casting and metal working equipment including a state-of-the-art electric steel melting furnace (in which alloys with fewer property-degrading contaminants could be made). Some of the work done by division scientists in this period included determining the rate at which molten steel freezes during castings and assessing the strength of steel at high temperatures. All of this work was published in the open literature. In Mehl's assessment, this body of work helped these men and NRL earn respect and visibility within the nation's steel industry.[36]

Mehl himself remained at NRL for only four years. In 1931, he left to take a position first, at the American Rolling Mill Company and, subsequently, at the Carnegie Institute of Technology in Pittsburgh, where he would emerge as one of the giant figures in a field that in the 1950s and 1960s would become known as Materials Science.

In the same fit of programmatic expansion that brought a Division of Physical Metallurgy to NRL came the Chemistry Division. Like fraternal twins, the two new divisions would grow up in the same house but follow utterly individual and multiply-branching evolutionary paths that would help render NRL one of the most broad-based research institutions in the country.

The Chemistry Division owes its initial momentum to Commander Oberlin's success at getting the Bureau of Ordnance to think of the Laboratory as a place to do business the way the Bureau of Engineering already had. By the spring of 1927, the Bureau of Ordnance had assigned NRL two torpedo-propulsion problems that became the maiden topics for the new division. These were, in the words of Taylor, a "trial balloon."[37]

The Chemistry Division began as a heterogeneous mixture of two small programs already underway at NRL along with several new hires. Among the latter was Dr. Francis Russell Bichowsky, who left a faculty position at Johns Hopkins University to head the new division. One component of the division came from a three-man Ballistics Section (later the Ordnance Division), which the Bureau of Ordnance had moved from the National Bureau of Standards to NRL a month after NRL opened. For the most part, this section acted as a job shop for the Bureau of Ordnance. Its projects included the development of a high-speed camera for photographing projectiles in flight, the measurement of pressures in the main gun batteries of battleships, and work on torpedo-ranging apparatus in collaboration with the Sound Division.[38] A second component that became part of the Chemistry Division was a one-man analytical laboratory run by Milton Harman.[39]

The crux of the torpedo propulsion issue at the time was to find some way of replacing the compressed air that had been used in World War I torpedoes with something else that would enable the torpedoes to travel farther, faster, and without a visible surface track. One technique, which a researcher at the Westinghouse Corporation had been looking into near the end of World War I for the Bureau of Ordnance, was to rely on a heat-generating chemical reaction that would convert water into steam for propulsion. The other tack the division looked into was to build on an idea of several officers at the Newport Torpedo factory to replace compressed air, which is nearly 80% nitrogen, with compressed air enriched with oxygen, or even with pure compressed oxygen.[40] The thought here was that the same volume of oxygen-enriched compressed gas would propel a torpedo much faster, farther, or both.

The previous attempt at Westinghouse to build an exothermic torpedo involved the mixing of two hazardous materials—fuels including aluminum or alcohol and a substance that would supply the oxygen needed for combustion—that were hard to handle and prone to spontaneous explosions. The oxidizer in this case was solid so-

dium chlorate. Bichowsky thought it better to try two liquid components—alcohol for the fuel and the oxygen-jammed perchloric acid to supply the oxygen.

As in child rearing, the solution often becomes the problem. The heat generated by this alcohol-acid reaction was intense enough that it required the development of a new "pot," or combustion chamber, which a colleague was able to do on fairly short order. Once the new chamber was in hand, the pure oxygen torpedo became a straightforward engineering problem. By 1930, the oxygen torpedo already had entered a test phase. It demonstrated again how NRL's diversity of expertise could mix and match to solve new and difficult problems.

By that time, early rocket researchers had shown that the combustion of alcohol with the oxygen-rich vapors of perchloric acid—a cranky and explosion prone reaction—could generate tremendous thrust. "Furthermore," Bichowsky noted, "the use of organic perchlorates [more energy-packed chemical variations of perchloric acid] seemed to offer the possibilities of developing explosives of unheard power."[41] With such tantalizing potential, Bichowsky was able to hire additional chemists, including Dr. Parry Borgstrom who would come to head the division.

One of the new hires who would work on this problem was Walter Rosett. He had a penchant for taking on some of the odder and smaller-scale problems that would filter into the division. These included the development of secret inks and fluorescent materials for ultraviolet signaling. He also ended up stuck with the perilous job of preparing ethyl perchlorate, a material that looked promising for producing explosives of unprecedented power. Bichowsky recalled what happened:

"This material was known to be explosive. Every preceding worker with it had been hurt by its explosion, but we felt that by keeping it under water we would be the exception . . . We made about 5 cc [a thimbleful] without trouble and were engaged in measuring its properties. I had 1 cc and Walter had the remaining, when, suddenly, the 4 cc in Rosett's hand blew up, and followed a few seconds later by the

explosion of the 1 cc in my hand. Rosett's hands were blown to pieces. He lost a thumb and two fingers on one hand and three fingers and a part of the fourth on the other hand. I had had time to lower my hand and the explosion lacerated a palm of the right hand and one leg."[42]

Bichowsky was not so easily dissuaded from promising leads. Although the explosions led to an official banning of work on organic explosives, Bichowsky recruited another chemist and together they secretly repeated the experiments. They learned that by replacing the pure water that Bichowsky and Rosett had tried with a slightly alkaline solution, they could handle the perchlorate relatively easily and safely.[43]

As a balance to all of the applied research, Bichowsky at least aimed to have about one third of his division's work devoted to basic science. He suspected that was the way to create an environment where young, top-notch scientists might want to come to work, especially at a time their skills were in demand. One early attempt to work on basic issues was an investigation into the mechanisms of chemical reactions occurring inside vacuum tubes. Though basic on the surface, there was a potential technological spin-off in the form of new types of more energy-efficient tubes for electronic devices.

Before they could build much momentum in that project, however, a more imminent concern diverted their attention. The submarines of this era carried banks of over 100 battery cells, each one containing a reservoir of sulfuric acid. These batteries intermittently caused explosions for unknown reasons, sometimes with tragic results.

Bichowsky recalls finding clues to battery explosions while crawling on hands and knees with E.G. Lunn, a colleague in the division, in the "smelly hole of a disreputable pig boat," by which he meant a submarine. They found that the ventilating ducts were covered with a spray of sulfuric acid. The slower the ventilation, the more acid there was. On the bottom of the ducts, there was evidence of many minor fires. They later showed these were produced by small sparks gener-

ated when the motion of the ship broke the conducting film of acid. And with plenty of hydrogen generated from the action of acid on metal, the elements for fires were well in hand.

This conclusion led to the need to determine the rate of battery ventilation. Bichowsky described what Lunn came up with:

" . . . the technique was to get a good [cigar] smoker and have him, on the signal, puff in a small puff of smoke into the entrance of the glass tube [associated with each battery cell]. Dr. Lunn, with a stop watch, would measure the time taken for the smoke to travel down the tube and, thus, the rate of battery ventilation . . . Eventually, Dr. Lunn had to invent a chemical cigar smoking machine to furnish the necessary puffs."[44] He later took on the natural sequel, which was to find a way to reduce the acid spray from the batteries. Part of the solution was to supply each cell with its own ventilation rather than the common ventilation pathway that proved hazardous. Part was to redesign the batteries.[45]

Like the torpedo work, this project was very much in the realm of applied science. Aside from a few small forays into more basic issues such as chemical reactions in a vacuum, however, the division's initial work focused almost completely on short-term problems that their sponsors in several Navy bureaus needed solved. Besides the several submarine-related projects, the division's repertoire diversified into such areas as the search for anti-fouling paints, better dielectric materials for making high-frequency radio components, illuminated gun sights, and ways of recovering water from the exhaust of the engines of dirigibles (lighter than air vehicles) to compensate for weight lost to the burning of fuel.

As the Laboratory's technical scope diversified and expanded throughout the 1920s, increasing amounts of money from the Bureau of Engineering were funneled into the fledgling NRL. Since the Laboratory's administrative location was within the office of the Secretary of the Navy, it was one step removed from direct bureau oversight, however. It stood to reason that a new round of questions about

the Laboratory's appropriate place in the Navy was bound to arise. The crash of the stock market in 1929 and the general money consciousness this would produce in every sector of the economy helped fuel a major soul search at NRL in the early 1930s.

Chapter 4

An Orphan Proves Itself

For all of Thomas Edison's opposition and bellyaching after the Laboratory's overlong gestation during the Great War and the early 1920s, the Laboratory actually opened its doors much as the great inventor had envisioned it should. Save for a few PhD scientists, the technical staff was populated by engineers who did not mind getting dirt under their fingernails. Most of the work was aimed at inventing new gadgets, rather than adding to what Edison believed was an already enormous heap of untapped basic scientific understanding.[1] Moreover, the Naval Consulting Board saw to it that the Laboratory had a state-of-the-art shop with a staff that could make just about anything. Although NRL had not become a place where a submarine could get built from scratch in 15 days, as Edison had once told Congress the Laboratory ought to be able to do, it had begun life as a small-scale invention factory not so unlike Edison's own in New Jersey.

One of Edison's main fears did appear to come true, however. Rather than civilians, Naval officers were at the top of Laboratory management. Realistically, it could never have been otherwise. It was the Navy after all that was footing the bill for the Laboratory. And the whole point of its existence was to keep the Navy at the forefront of military technology. Captain E.L. Bennet was the first official director. But NRL was only one of his many responsibilities and his

office was at the Navy Department, not the Bellevue site. It was Captain Oberlin, by title the Laboratory's first assistant director, who was the hands-on manager of NRL. He made most of the decisions for NRL during his tenure, which lasted until 1931.

Captain Oberlin was keenly aware of the naturally conflicting relationship his new laboratory would have within the context of the U.S. Navy. For one thing, NRL would have to answer to its financial supporters at the Navy materiel bureaus and in Congress. Yet Oberlin zealously believed the Laboratory needed to defend its autonomy from any specific bureau. Otherwise, he feared, it would become just another Navy engineering facility instead of the unique broad-based research Mecca its conceivers had wanted.

Captain Edgar G. Oberlin was the Laboratory's first assistant director and its sixth director proper. Early in 1930, he went head to head against powerful Navy officers in the Bureau of Engineering who wanted to wrest control of the young Laboratory.

The Laboratory's initial administrative placement under the Secretary of the Navy, rather than under any particular bureau, helped to enforce a degree of autonomy. Most of the money for doing research in the early years of the Laboratory, however, did come from the Bureau of Engineering, which had specific communications and submarine detection problems it wanted the Laboratory to solve.

In spite of these realities, Captain Oberlin championed the cause of expanding the Laboratory's technical base into areas of more basic science for which funds might not be so readily available. The Heat and Light Division came to be in 1924 only after Captain Bennet reluctantly approved its creation on faith that the Radio Division's Taylor, Hayes of the Sound Division, and Captain Oberlin knew what they were doing in proposing it.[2] The new division had no automatic constituency in the Navy. The main argument for its creation was that NRL ought to be able to do any kind of research work so long as it held some promise to be useful to the Navy. A Navy relies on heat and light so a Division of Heat and Light was not so outlandish.

Like the Heat and Light Division, the Division of Physical Metallurgy began without bureau support but then quickly proved its worth with such successes as the gamma radiography revelations of the Navy's metal casting problems. The start of the Chemistry Division more resembled the Radio and Sound Divisions in the sense that it had Bureau support from the start. In the Chemistry Division's case, however, the Bureau of Ordnance played the role of sponsor rather than the Bureau of Engineering. Although still in its infancy at the end of the 1920s, the Laboratory had achieved a solid footing.

At the end of 1929, when the stock market crashed and the country began falling into the Great Depression, the Laboratory, which by then had a total budget of $559,655,[3] actually was not hit so hard. As Taylor recalled it years later, the Depression had little immediate effect on the Laboratory. Two scientists were dismissed for an initial total savings in salary of $12,000 per year. Later during the Depression years, every civilian employee in the Government took a temporary pay cut.[4]

The Depression did, of course, raise fiscal consciousness everywhere, including in the Navy's Bureau of Engineering, which perennially had been supplying more than half of NRL's total budget. Money for less-than-imminent Navy concerns like, say, leading-edge basic research, was becoming even more scarce.[5]

One reflection of the scarcity of money became apparent in 1930 in the aftermath of a momentous discovery on June 4 by Lawrence Hyland and Leo Young in the Radio Division. The discovery nearly died on the vine for lack of financial support.

Years later, Young recalled the moment:

> *"We were conducting experiments relative to guiding planes into a field using high-frequency beams . . . We were flying a plane determining just what effects were in the air when the plane was trying to follow these beams and what not."*
>
> *"In making some field measurements on this set-up, Mr. L.A. Hyland had field strength [measuring] equipment out at what is now the lower end of Bolling field, just north of the Laboratory. And of course, as soon as planes began flying around, he noticed the meter bobbing all up and down . . . [He] determined that he was getting some kind of effect from planes that flew through those beams. When he came in he immediately brought it to our attention, and of course, we immediately realized that we were getting the same effect from planes that we had from a ship back in 1922."*[6]

What Hyland had observed in his receiver was an intermingling of two signals. One came directly from the transmitter and normally would have produced a continuous signal. Instead, a secondary beam reflecting from the plane was interfering with the primary signal, creating an interference pattern. As the plane moved, and with it the origin of the reflected beam, so did the ebbs and flows in signal strength characteristic of an interference pattern. When that little dial bobbed down, the signal was waning; and when it swung back up, the signal was waxing. Although it wasn't the first time anyone had detected a moving object using radio signals, this was a historic moment for the

Naval Research Laboratory. It marked the beginning of its effort to produce the U.S. Navy's first generation of radar technology.

Hyland had found that radio could be used to detect airplanes. Since airplanes were becoming a serious component of warfare, his observation presaged the U.S. development of radar with more force than Taylor's and Young's radio detection of a wooden ship on the Potomac from Haines Point eight years earlier just before they moved to NRL.

Throughout the summer and early fall, Hyland, Young, and Taylor performed more experiments. They varied the antennae shape. They used different frequencies. They even drove a receiver around in a car so as to simulate the motion of a ship as it might try to detect a plane in the air. By early November, Taylor was ready to inform the Bureau of Engineering of the development. In his 11-page letter he wrote:

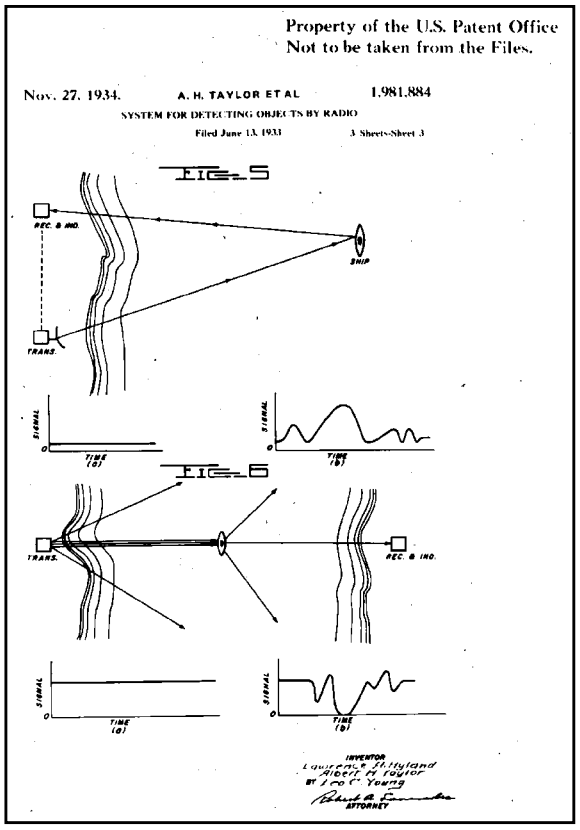
> *"The Laboratory has at present two definite objectives in this work: the first is to detect the presence of moving objects in the air or on water, possibly later even on the ground, at such distances that their detection by other well-known methods is difficult or impossible. It may be noted that the personnel piloting any moving object would probably not know that any observations were being taken upon them. Second, to develop . . . a method of measuring the velocity of moving objects at great heights or at considerable distance, or on the surface of the water . . . It is not desired in this report to give the Bureau the impression that the work is anything like in a finished state but it does appear to this Laboratory to be far enough advanced to warrant much further and intensive investigation over a considerable period of time."*[7]

The bureau was not immediately moved by Taylor's letter to send NRL more support to pursue the technology. In January, 1931, Commander E.D. Almy, who then was NRL's acting director, bolstered Taylor's pitch with a letter to the bureau. He wrote:

> *"The Director considers [this] subject matter of the utmost importance and of great promise in the detection of surface ships and aircraft. No estimate of its limitations and practical value can be made until it has been developed. However, it appears to have*

> *great promise and its use [appears to be] applicable and valuable in air defense, in defense areas for both surface and aircraft and for the fleet in scouting the line."*[8]

The letter apparently carried some weight. Just days after receiving the letter, the bureau assigned the Laboratory a problem designated as W5-2, which it emphasized as confidential. The now historic problem specified that the Laboratory "investigate use of radio to detect the presence of enemy vessels and aircraft."[9] The written acknowledgment by the bureau that it was interested in detection of objects by radio was welcome. The bureau's assignment of problem W5-2 amounted to an unfunded mandate, however. The bureau still did not allocate additional money, which meant any radio detection studies would have to compete with existing radio projects of higher priority to which men and money already were committed.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Not to be taken from the Files.

Nov. 27, 1934. A. H. TAYLOR ET AL 1,981,884

SYSTEM FOR DETECTING OBJECTS BY RADIO

Filed June 13, 1933 3 Sheets-Sheet 3

FIG. 5

REC. & IND.

SHIP

TRANS.

SIGNAL

TIME (t)

FIG. 6

TRANS.

REC. & IND.

INVENTOR
Lawrence A. Hyland
Albert H. Taylor
BY Leo C. Young

ATTORNEY

A page from patent 1,981,884 for a "System for Detecting Objects by Radio," whose later incarnations would be known as radar.

Later in the year, Captain Oberlin took over the full-fledged directorship of the Laboratory. In that capacity, he wrote a desperate letter to the Secretary of the Navy on November 2, 1931. In it, he lamented the practice of the bureaus, whose funds were already overly subscribed, to sidestep real support of longer-term research in order to expedite short-term projects that promised economic return. Aside from a few written words, Oberlin noted in the letter that no money came from the bureaus to pursue the promising lead of detecting airplanes by radio. "On the other hand," Oberlin continued by way of example, "recent discoveries which affect radio transmission were immediately taken up by the bureau as they showed a means of meeting a long-recognized need and perhaps of effecting considerable economies. The last example further supports the contention that the bureau's immediate financial interests are the controlling factor in their use of funds available."[10]

If that were the case, and Oberlin feared it was, then there would be no place for long-term research. And without long-term research, the Navy would have no role in advanced science or even more speculative engineering. Yet that was just the kind of role the NRL leadership thought its Laboratory ought to have in the world. Patient, adequate support for research was required to transform discoveries like Hyland's bobbing radio receiver dial into valuable new tools for the Navy.

The future of NRL's soul was not merely an abstract concern for Captain Oberlin at the time he wrote his letter to the Secretary of the Navy. By secretly arranging to shift NRL from its administrative location within the office of the Secretary of the Navy to reside instead within the Bureau of Engineering, the Bureau's top officers had been orchestrating a veritable *coup d'état* to win control of the Laboratory.

That the bureau meant business was made painfully obvious to Oberlin on one Saturday morning in the fall of 1931. As he recounted in a letter to an officer friend written soon after, a low-ranking officer from the Bureau of Engineering dropped into his office without warning. The officer had orders to take over the Laboratory! Oberlin soon

learned that Admiral Samuel Cooper, head of the Bureau of Engineering, had been in secret correspondence with the Secretary of the Navy, Claude Swanson, about the fate of the Laboratory for some time. Just days before Oberlin saw the take-over order, this correspondence resulted in the official transfer of control to the Bureau of Engineering.

The first item of "Navy General Order 223" of November 3, 1931, which was signed by the Secretary, read, "The administration of the Naval Research Laboratory is hereby placed under the cognizance of the Bureau of Engineering."[11] The transfer of NRL to the bureau was a done deal, yet Oberlin, the Laboratory's director, never had a say in the discussion leading to the decision.

The conspiracy of the men behind the transfer became painfully clear to Oberlin once he got hold of the relevant memoranda and letters. The conspiracy had began to reach its crescendo on October 10, 1931, when Stanford C. Hooper, the Director of Naval Communications within the Bureau of Engineering and a long time critic of NRL as too research-oriented, wrote a memorandum to his superior, Admiral Samuel M. Robinson, head of the bureau. "In confirmation with our discussion yesterday on the subject of Bellevue [NRL]," Hooper wrote to Robinson, "my feeling is that if the Laboratory is to be retained by the Navy it must be administered directly under a Bureau, otherwise the cost of the Laboratory will continue to mount out of all bounds, and the Laboratory [will] become so headstrong that little good for the Navy will come out of it."[12]

After portraying NRL as an inferior impostor to the nation's great research laboratories where he believed the most advanced Navy research ought to take place, Hooper continued his diatribe with a cynical edge: "Frankly, I have never been able to get the results desired from Bellevue, and we never will get these results because we cannot possibly spend enough money there, so, insofar as research is concerned, I would favor abolishing the laboratory . . . " All that should remain, he continued, are maybe a half-dozen "research technicists [sic]" whose role would be to keep the bureau abreast of work going on at commercial laboratories.

Robinson concurred with Hooper. More than that, he packaged Hooper's memorandum with a like-minded memorandum of his own dated October 14, procured the signatures of approval of the chiefs of the Bureaus of Ordnance, Construction and Repairs, and Aeronautics, and sent the documents to the Chief of Naval Operations. Robinson called for a draconian reduction in NRL staff, a shift of the Laboratory's mission to the testing of equipment developed by commercial firms, and placement of the diminished facility directly under the Bureau of Engineering.[13] The next morning, the Secretary of the Navy approved the memorandum.

A week later, by which time the bureau had sent its Saturday messenger to NRL, Oberlin desperately began countering the events that had transpired behind his back. To his mind, the stakes could not have been higher for the Navy and he was willing to put his career on the line to steer NRL out of the lethal danger that others had exposed it to. In an October 22 memorandum to the Chief of Naval Operations, he wrote that "it would be far preferable to close down the Laboratory entirely as a research activity than transfer it as such to any bureau."[14]

Eleven days later, on November 2, Oberlin sent a 13-page memorandum to the Secretary of the Navy in which he identified the battle over NRL's place in the Navy with the bigger and more important issue of the Navy's general policy on research. "I am convinced that placing the Laboratory under any bureau will totally defeat the purpose for which the Laboratory was authorized and intended,"[15] he wrote. For one thing, the Laboratory would no longer be able to consider the Navy as a whole but rather it inevitably would become an organ of the single bureau. For another thing, engineering work to solve immediate problems would supplant any long-term research to prepare the Navy for future challenges.

Therein lies the crux of the issue. On page 10 of his memorandum, Oberlin wrote:

> *" . . . a research laboratory does not exist for solving immediate and pressing needs for materiel development, although under certain circumstances it might render assistance along those lines.*

> *Whether the Navy is warranted in expending funds for general research is a question on the answer to which the future of the Naval Research Laboratory should depend."*

At the end of the lengthy memorandum, Oberlin drew a line in the sand:

> *"I stand ready to stake my professional reputation and future naval career upon the prediction that full investigation and unbiased judgment by a qualified body:-*
>
> *(a) will find that the decision arrived at and policies adopted when the Laboratory was first established remain correct;*
>
> *(b) will pronounce the Naval Research Laboratory a vital part of the Naval Establishment;*
>
> *(c) will decide that naval research is an economical and essential assurance of national defense; and*
>
> *(d) will be convinced that placing the Laboratory under any bureau will stifle if not entirely eliminate research and will narrow the work to that bureau's needs rather than render it of value to the Navy as a whole, thus effectively nullifying the purpose for which the Laboratory was established."*

In a prescient closing, Oberlin wrote that "the principles involved are of too great naval importance to warrant the least consideration of any personal or selfish interests."

The issue ascended to the Navy's highest advisory body, the General Board, which subsequently made a thorough inquiry into the questions of the proper function and administrative location of NRL. The opinion, which they issued on February 9, 1932, vindicated Oberlin. It endorsed his belief that the Navy needed a laboratory like NRL whose mission was long-term research. Moreover, the Board recommended that NRL remain in a more central location of Naval administration, specifically suggesting the Office of the Chief of Naval Operations.

It looked like Oberlin's gambit would work. A few weeks later, however, a ruling came through from the same Secretary of the Navy that had approved Robinson's original memorandum suggesting NRL's administrative transfer. NRL would remain under the cognizance of the Bureau of Engineering. Strike two for Oberlin.

The determined Oberlin made one more attempt to reverse the decision, this time trying to go over the head of the entire Navy by appealing to the Subcommittee of Naval Appropriations of the House of Representatives Appropriations Committee. He succeeded in getting the topic of NRL onto the agenda of the subcommittee's upcoming hearings, partly due to support from Miller Reese Hutchison. Hutchison, Edison's long-time assistant, remained a member of the extant though inactive Naval Consulting Board from which NRL sprang, and he was a friend of one of the Congressmen on the subcommittee.[16]

Before the hearings began, however, Oberlin's maverick campaign caught up with him. His superiors and enemies were able to relieve him of his NRL directorship and place him into a veritable holding pen as "the Technical Aide to the Secretary of the Navy," a position that was little more than a title.

The aftermath of the subcommittee hearings on NRL followed a path similar to that followed after the General Board of the Navy gave their assessment of the situation. Like the General Board, the subcommittee identified the Laboratory as a place of long-term research centered on basic science and not on engineering and testing. A strong endorsement of Oberlin's view came from subcommittee member Representative William Oliver. In a rebuttal to Admiral Robinson's argument for transferring control of NRL to his bureau, Oliver said,

> *"So long as you lend undue emphasis to the testing side, or, as you call it, the experimental side of the work there, you will soon lose sight of that which is equally, yes, far more important, perhaps, the scientific and research study of great underlying problems, that not only will cause you to advance, but will invite*

> *others from the outside to come in and willingly lend their aid and assistance to you in advancing."*[17]

Moreover, the subcommittee agreed that NRL ought not to be under the wing of the Bureau of Engineering.

Despite all of this, Secretary Adams was unmoved. NRL remained under the Bureau of Engineering.

Captain Oberlin's half-year long battle against the Naval establishment to keep NRL out of the hands of the Bureau of Engineering resulted first in his dismissal as NRL's director and thereafter to his retirement on July 15, 1932. His cause was not entirely lost, however. The philosophical endorsement for the Navy's need of long-term, basic scientific research from both the governing board of the Navy and the U.S. House of Representatives Subcommittee of Naval Appropriations had lasting effects. Without these high level reiterations of Oberlin's passionate vision of what NRL ought to become, the Laboratory might well have evolved into just another engineering laboratory as other officers in the Naval hierarchy would have had it.

Ironically, NRL's transfer to the Bureau of Engineering might have been what saved the Laboratory from capsizing during the financial and administrative whitewaters of the early and mid-1930s. As A. Hoyt Taylor assessed the situation in hindsight, " . . . it is doubtful whether our research would have been so plentifully supplied with operating funds had we remained under the Secretary during the financial depression." What's more, the strong administration of the bureau helped to stabilize the Laboratory during a rapid succession of five different military directors during the three years following Oberlin's departure in 1931.[18]

The Laboratory still had quite a way to go before becoming a full-fledged member of the Naval community. That the Laboratory was strongly in need even of name recognition, let alone recognition for the work of its staff, becomes clear in an oft-told and probably apocryphal account in which a Naval officer yachting by the Laboratory nearly swatted NRL from the Earth as though it were a fly that had alighted on his arm.[19]

The Laboratory staff on April 4, 1935. Just shy of 100, the entire staff fit easily into a single portrait.

In Taylor's version of the story, it happened this way: "A certain high-ranking official was taking a weekend trip down the Potomac in the Secretary's yacht. On passing the grounds of the Naval Research Laboratory, he pointed to the white buildings on his left and asked what that place was. Finally, somebody said it was the Naval Research Laboratory. 'Well,' said the official, 'What do they do there?' It appeared that no member of the party knew what the Laboratory was doing and so the official made a memorandum then and there, noting that in the interest of economy the activity might as well be abolished. Several official moves in that direction had already been made when we heard of it."[20]

Nevertheless, the Laboratory did not go down like some hapless fly. On the contrary, the technical brew of the Laboratory was beginning to reach a critical mass. Unplanned and unexpected confluences of human insight and state-of-the-art equipment began to yield results that would help to change not only the nature of warfare but also the human relationship to sky and ocean.

The Laboratory's humble complement of a half-dozen divisions, each with its own staff and range of expertise, began to mix and match. New divisions budded from existing ones. From the Chemistry Divi-

sion, for example, came the Thermodynamics Division, which inherited and expanded its parent division's original problem of converting heat from chemical reactions into propulsive power for torpedoes. Only three years later, this new division would merge with the Physical Metallurgy Division to become the multisyllabic Thermodynamics and Physical Metallurgy Division. The Mechanics and Electricity Division was an outright newcomer that later would be recast as the Mechanics Division. Divisions could come and go on short order, too. The short-lived Aeronautics Division, after failing to attract support from the Navy's Aeronautics Bureau, was resorbed into the Radio Division from which it had temporarily sprung.

To those involved in the bickering and maneuvering of 1931 and 1932 at the highest levels of the Navy and beyond, it was the very soul of NRL that was at stake. The actual changes in the Laboratory and its research agenda were small and temporary. To curtail speculative research and instead stress the short-term needs of the Navy in the financially strapped times of the Depression, for example, the bureau increased the number of testing problems for the Radio and Sound Divisions from 10 in 1930 to 68 in 1934. The bureau also split the Radio Division into a 20-man engineering division and a smaller, 9-man research division. The split proved too artificial and counterproductive, and the two were reunited within a year.

By 1935, the political and economic context that had so harassed Captain Oberlin began to disappear. As the economy began recovering from the Depression during the long administration of Franklin Delano Roosevelt, money for long-term research began to dribble in. Congress even appropriated an extra $100,000 to the Laboratory.

At about the same time, Oberlin's nemesis tag team at the Bureau of Engineering, Captain Hooper and Admiral Robinson, both left the Bureau of Engineering. Taking Robinson's place as the Navy's "Engineer-in-chief" was Rear Admiral Harold G. Bowen, who was personally interested enough in NRL to place it directly under his authority in the bureau instead of under the bureau's Radio Division where it

had been during Robinson's reign. Unlike Robinson, Bowen was a great supporter of basic research. And now he had NRL as a research instrument of his own.

Under the banner of Bowen's Bureau of Engineering during the 1930s, NRL researchers began to score the kinds of successes that would end debates about whether the Laboratory should exist or not. These came largely from the creative genius of engineers and inventors rather than from basic scientific discovery. The most emblematic success during this period was the development of radar whose name is credited to Captain Sam Tucker of the Bureau of Ships. He contracted "**ra**dio **d**etection and **r**anging" into "radar."[21]

NRL was one of a handful of places around the world that simultaneously and secretly had been learning to take radio waves beyond their conventional role as carriers of communication into such new arenas as detecting navigational obstacles or attacking aircraft. The spectacular results at NRL would help earn the Laboratory the right to become a place where engineering research focused on harnessing known principles in the quest for better military technology would form a unique, creative synergy with basic research aimed at scientific discovery.

The radar project became a top priority at the Laboratory in 1934.[22] This was not so much because anybody really knew what was the technological potential of radio-based detection of ships and planes. But a technology that enables you to detect things that you otherwise could not see is impressive, the kind of thing that could impress people who control money. Members of the Naval Appropriations Subcommittee were slated to visit the Laboratory. The ability to demonstrate a new detection tool like radar, which then was still known as radio detection, could only help the Laboratory's cause.

At this point, the radio detection group in the Radio Division was basing its work on Hyland's original observation in 1930 of radio reflections by an airplane. Radio signals reflecting from an object like an airplane interfere with a stronger set of signals arriving at the same

receiver more directly from the transmitter. Someone monitoring a distant receiver could detect an object reflecting radio waves by the presence of characteristic variations, or beats, in the incoming signal. That is what Hyland saw when the needle of his receiver bobbed back and forth. If there is no object present that can reflect the signal, there will be no interference pattern to make the receiver signal bob back and forth. One key technical detail of this type of radio detection is that a high frequency transmitter must emit radio waves continuously like a singer who holds a note forever without stopping to take breaths.

The demonstration with the continuous waves apparently contributed to a good time for the visiting subcommittee members. That definitely contributed to their approval of an extra $100,000 in the Laboratory's direct appropriations. But there were worrisome technical drawbacks in the continuous wave approach. One of the major problems was that in order to get discernible signals, the transmitter and receiver had to be farther away from one another than a ship is long. Said differently, the system couldn't fit on a ship.

In an intuitive leap, Young came up with a dramatically different approach that he thought just might work. The path from his conception to the Navy's first working model of a radar set illustrates what can happen when a critical mass of diverse expertise and equipment is assembled in close proximity, as it was at NRL.

Young was familiar with using radio pulses as a probe because that is how Merle and Tuve of the Carnegie Institute did their measurement of the ionosphere in the 1920s using the crystal-stabilized transmitter he and Louis Gebhard had built. But since the ionosphere was so much larger than objects like airplanes, and since the wavelengths necessary for getting echoes from planes were so much shorter for probing the ionosphere, Young reasoned in 1930 that pulses would not work for detecting planes. He opted instead to pursue the continuous wave approach.

Young changed his mind three years later. For one thing, the continuous wave work simply was not lending itself to shipboard equip-

ment. Another reason for the shift derived from his work on a purely technical bug that plagued shipboard radio operators using high-frequency transmitters. A radio operator sending code signals inadvertently generated troublesome bits of radio noise on a wide range of frequencies. These so-called "key clicks" hampered any shipboard reception that might be going on simultaneously at a nearby receiver. To a Navy in wartime, the key click problem could be disastrous. When Young analyzed these clicks, he realized they had about the same power as the continuous waves that already had proven successful for detecting airplanes. So pulses, the right kind of pulses, could work.

Meanwhile, another part of Young's conception for a new approach to radar had been a mainstay of work in the Sound Division. There, Harvey Hayes and his associates already had developed a technique in which an echo from an underwater pulse of high-frequency sound would show up as a blip on a circle sweeping out on an oscilloscope. In a way, sonar is an underwater, sound-based precursor of radar! Since the circle swept around with clocklike precision, and since sound travels in media like water at known speeds, the position of the blip along the circle was sufficient for determining the distance of the object from which the sound pulse bounced. It was clear to Young and the rest of the radar group that the same concept would apply to reflecting radio signals.

With the problem pretty well-defined, it fell onto the shoulders of Robert Page, who had been drawn into the radar group to help with the 1934 demonstration, to engineer Young's ideas into reality.

Page, son of a sometime lay minister, had joined NRL in 1927, just two weeks after receiving a bachelors degree in physics. The seventh of nine children, he had grown up on a farm in Minnesota and got his first experience in the world of electricity during high school when he earned money by helping his electrician brother wire houses.[23]

He originally planned to become a minister himself and enrolled in the church-supported Hamline University in St. Paul. Once there, however, science became his mission. His physics professor, who was

Robert Morris Page was central in the invention and design of the Navy's first radar systems that were completed prior to the U.S. entry into World War II. In 1948, he would become the Laboratory's first civilian director of research.

a friend of Taylor's, recognized Page's talent and encouraged him to pursue a career in science. When Taylor offered the young man a job, he took it.

Page arrived at the Laboratory with no experience in radio engineering. It did not matter. He soon developed a conspicuous aptitude for coming up with practical solutions for those in the division he was assigned to assist. Although he was driven by the joy of innovation itself, he also became strongly motivated by NRL's policy at the time of allowing inventors on its staff to own full commercial rights to patents from their work.

"I became imbued with the idea that I was going to be inventor, that I was going to invent things and that I was going to have patents on them and that the commercial rights were going to be worth something," Page recalled thinking during even his earliest days at NRL. His prediction was a good one. By the time he left NRL in 1966, he had 65 patents to his name.[24]

In 1934, when Page joined Young and several others on the radar project, his mission was to put his inventive juices to work on the technical challenges involved in making pulse radar a reality. By the end of the year, he had pretty much solved the transmitter side of the problem. He had rigged up vacuum tubes with circuitry of his own design to generate trains of electrical pulses. He designed more circuitry that fed the shorter signals of this train into a transmitter that he had drastically modified specifically for the short pulses it would have to amplify and then broadcast. By December, he had built a transmitter that could emit pulses lasting a mere 10 millionths of a second (microseconds), wait for the next 90 microseconds or so, and then emit another 10 microsecond pulse, rest again for 90 microseconds, and so on.[25]

It would take him almost all of the following year to tackle the receiver, which had to distinctly display a transmitted radio pulse and the echo from an object despite the fact that both of these fast-as-light signals would reach the receiver virtually simultaneously. To do this he had to build complex, multistage amplifiers, which required new developments in circuit design that had only months earlier been published in a French periodical. He had to prevent any feedback or instabilities that would degrade the receiver's ability to discern the hardly separated pulses coming from the transmitter from those reflecting from objects. This required him to include components to filter out unwanted frequencies and to shield other parts of the system from troublesome electrical fields. To get the receiver to work, he even had to modify the latest generation of vacuum tubes that RCA had just introduced.

Page, as well as other talented engineers such as Art Varela, who would design sets to work at higher frequencies, made all of this progress despite the absence of financial support earmarked for the project. Page and colleagues worked on the radar project when they weren't working on other more conventional radio problems that were directly supported as part of some specified problem assigned by the

bureau. Taylor, who undoubtedly recalled his and Young's squelched radio detection discovery in 1922, even camouflaged some of the work by making it look as though it were part of another funded communications problem. He later admitted that the practice probably was illegal.[26] Meanwhile, Page made sure to file patents, some of which stand amongst the earliest radar-based patents in the world.

In early 1935, as Page began chipping away at the obstacles to building a workable receiver, Taylor became even more fervent a champion of radio detection. After Taylor secured nods from Captain Greenlee, then the Laboratory's director, and from Admiral Robinson, the same bureau chief that Oberlin had fought so hard against, he and Hayes from the Sound Division went uptown to Capitol Hill and made a pitch to James Scrughum, the most influential member of the Naval Appropriations Subcommittee, which had visited the Laboratory in 1934. Taylor recalled the events:

> *"We put up a strong plea for a substantial addition to the small direct, appropriation which the Naval Research Laboratory usually received from Congress, this increment to be earmarked for long time investigations, particularly in the field of microwaves and supersonics [an early term relevant to sonar development]. Mr. Scrughum listened in silence, asked a few questions, but promised us nothing. We left his office feeling very much discouraged, but on the following Monday morning, he telephoned to state that the Committee had agreed to give us an extra $100,000.00 to be spent on this work."*[27]

At that time, Taylor recalled, this "looked like ten million dollars." The money went into hiring new personnel, purchasing equipment, as well as a handful of research projects. The radar project shifted into double-time. Taylor assigned another man, Robert Guthrie, to work under Page, and the two men then worked nearly full-time on the radio detection equipment. With money now specifically slated for the project, Taylor stepped up his own pressure to get results. Perhaps the hottest prod for Page and Guthrie, however, was news that in the summer of 1935, the French liner *Normandie* had been equipped

with a radio-based device for detecting icebergs. Radio was a worldwide phenomenon, a worldwide technology, and people beyond NRL had noticed intriguing reflections of radio signals for years. The *Normandie* report only confirmed that the arena of radio detection had become a technology horse race.

In the spring of 1936, after having worked a number of major and minor modifications into the system roughed out two years earlier, Page, Guthrie, and the other engineers were ready to begin testing. To save the expense of having to build a large new antenna, they had designed and built their test equipment so they could use a large "curtain array" antenna already at the Laboratory. This was a conspicuous transmitting structure that stretched, web-like, between a pair of 200-foot towers. The receiver was in the penthouse of a nearby building and attached to a less assuming antenna on the roof with a "giant killer" cable whose extra thickness ensured that weak signals coursing into it would not be lost to resistance.

When they flicked on the equipment on April 28th, they watched the trace on the oscilloscope race horizontally. Then they saw frenetic vertical blips leaping up from the traces that renewed themselves on the left when they came to an end on the right. These blips were due to planes a few miles away that were reflecting radio signals emitted from the curtain array. The first day, they could detect planes that were 2½ miles away. The next day, when they used more power, that distance doubled. As the tests continued, hints of the power and versatility of this technology emerged. During one set of tests in the summer of 1936, a pilot had gotten lost in thick weather about 25 miles away. Taylor recalls what happened next:

> *"We told him to fly five minutes in an easterly course. He did so but we saw no pip on the scope . . . We told him to fly ten minutes in a westerly direction. Soon the pip appeared, whereupon we told him he was on the beam. He came home safely. Probably this was the first instance of a plane being brought home by radar in thick weather."*[28]

Proving the principle in laboratory tests is one thing, but getting the Navy to buy into new technology is another thing entirely. The pace toward operational radar for the Fleet quickened yet more after June 10th when a pair of high-level officers of the bureau's Radio and Sound Divisions witnessed a perfect test of Page and Guthrie's equipment. They became immediate champions of the technology. Two days later, their boss, Admiral Bowen, chief of the Bureau of Engineering, wrote a letter to NRL. In it, he requested the Laboratory give the "highest possible priority" to the development of shipboard equipment.[29] Moreover, Bowen wrote,

> *"It is requested, upon receipt of this letter, that the subject problem be placed in a secret status, that all personnel now cognizant of the problem be cautioned against disclosing it to others, and that the number of persons to be informed of further developments in connection therewith be limited to an irreducible minimum."*[30]

Even before the first shipboard tests were conducted, Captain Cooley, who took over the Laboratory's directorship in 1935 soon after Bowen took over the Bureau of Engineering, was able to use the testing equipment to lure the topmost layer of the Navy hierarchy, including the Secretary of the Navy, to the Laboratory. Even before it had yielded anything for the operational Fleet, the radio detection team was helping the Laboratory with its name recognition problem. It still was up to Page and his expanding team of researchers to follow through on Bowen's request for practical shipboard equipment. For one thing, no ship commander was going to put a couple of 200-foot towers on his vessel.

Page knew that scaling the antennae down meant using shorter wavelengths, and that meant both redesigning a lot of circuitry and somehow getting hold of more capable components. What's more, if Taylor had it his way, the next design prototype also would feature something that Page initially considered to be impossible: a single antenna that would both transmit *and* receive. With this, Taylor wished

to minimize the size and complexity of any proposed addition to an ship's already-encumbered structure.

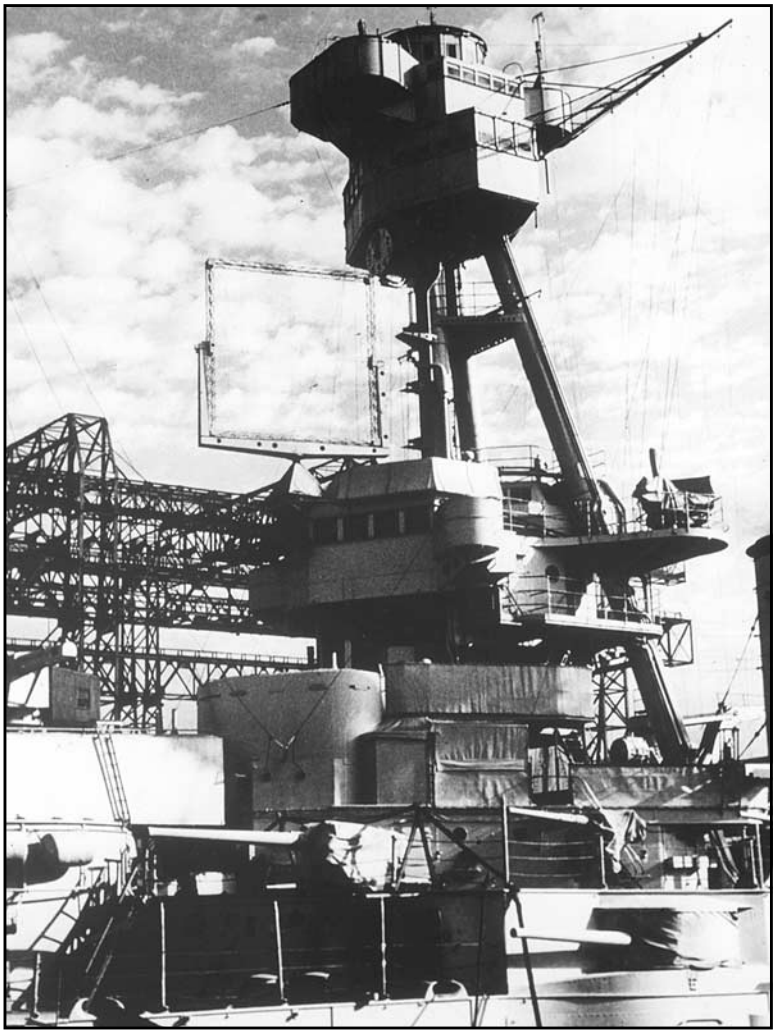
Page's initial thought was that Taylor's idea was utterly impossible to realize. But when he got beyond his own skepticism and summoned his innovative talents, he came up with an electronic switch that would make a one-antenna system possible. Called a duplexer, the mechanism protected the delicate receiver circuitry and components from the strong transmitter pulses on their way to the antennae and then shunted the weak radio echoes picked up by the same antennae back to the receiver.

With the duplexer in hand, Taylor was anxious to get the equipment in the field for tests. By April 1937, the radar team had installed the latest version of their 200 MHz radar detection equipment aboard the destroyer USS *Leary*, which had been docked at the nearby Washington Navy Yard. These tests successfully detected planes at distances of up to 17 miles. Although it showed that radio detection of unseen airplanes was possible from a ship, the result was disappointing since tests at the Laboratory by then had detected aircraft up to 40 miles away. Page knew what they needed: more power feeding into the transmitter.

By the end of the year, pressure was coming in for the Laboratory to complete its work for the 200 MHz radar equipment. Commander Wilber J. Ruble, head of the bureau's Radio Division, was even asking the Laboratory to set down production specifications so that manufacturers could begin supplying the Fleet with the new tool. By the end of the year, after more design and engineering iterations, the first production prototype of a 200 MHz radio detection system was in hand. At 17-ft square, the antenna was still so big and cumbersome that only the larger ships of the Fleet could accommodate it, and then only if their commanders were willing to take it on.

The guinea pig ship turned out to be the USS *New York*. This was the flagship of Admiral A.W. Johnson, commander of the Atlantic Fleet who already had seen NRL's radar. In keeping with Bowen's se-

crecy order, the sailors of the *New York* were kept in the dark about the strange new equipment and oversized antennae, which they mocked as the "flying mattress."[31] The NRL radar developers installed this prototype radar set, called the XAF, early in 1939 so that it would be ready to sail to the Caribbean for exercises slated to take place through March.



The "flying mattress," visible two-thirds of the way up the tower of the USS New York*, was the antenna for the XAF, the first production model of NRL's 200 MHz radar.*

Unknown to Page and his associates, their equipment was actually about to go head-to-head against another radio detection prototype, the CXZ, built by RCA's Production Department under a secret request by the Bureau of Engineering in 1937. Five years earlier, researchers at the company had begun looking into a new generation of radio communication using microwaves, which are shorter and of yet higher frequency than NRL had been using. By 1937, the RCA team had realized the lessons they were learning from this work could serve for non-communications applications like detecting navigational obstacles as the French had done. They even had happened onto the same pulse method that Young came up with. In 1937, during which the Bureau of Engineering had disclosed the NRL results in keeping with the practice of relying on outside contracts for production, an experimental radar based on microwave pulses was on the company roof in Camden, New Jersey. And it was detecting echoes from Philadelphia's skyscrapers a few miles away over the Delaware River. For the at-sea expedition and competition with the NRL engineers, the RCA engineers had installed a 400 MHz radio detection set aboard the USS *Texas*.

As it turned out during the expedition, the XAF outperformed the CXZ in every respect. The XAF could detect ships at 10 miles, at least 2.5 miles farther than the CXZ. The XAF detected planes up to 48 miles away; the CXZ would go blind to planes farther than 5 miles out. The XAF could detect buoys, the flight of 14-inch shells as well as their splashes 8 miles away. Page even recalls watching the system he helped shepherd into existence as it detected large birds. Moreover, the XAF worked nearly continuously under all weather conditions and was not bothered by the shock of gunfire. The CXZ, on the other hand, couldn't take the heavy gunfire nor did it stand up well to the moisture of the oceanic environment.

The feat that clinched a place for radio detection in the U.S. Navy occurred in the dark on January 16. A number of vessels that had been sent over the horizon had orders to turn around at a designated

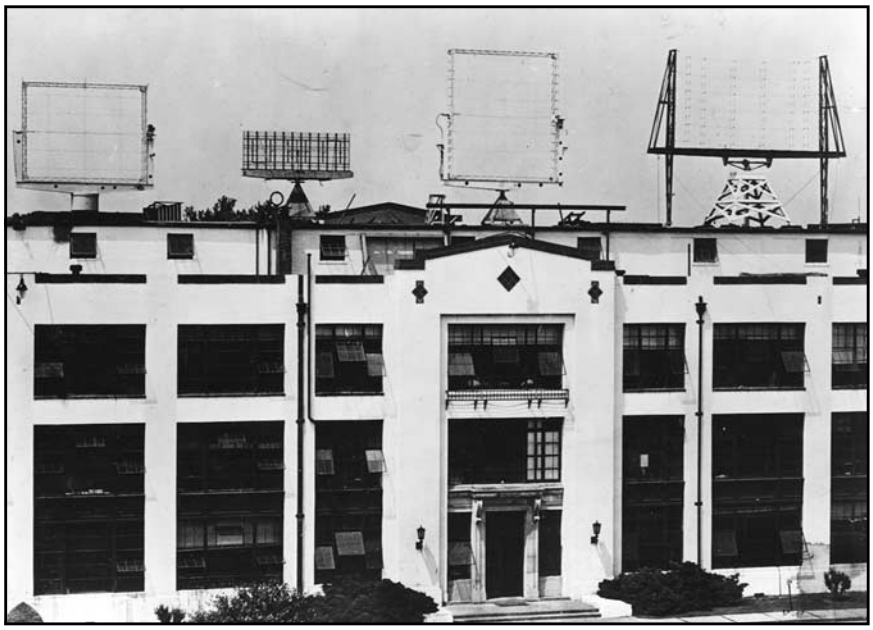
time unknown to Page and to come toward the USS *New York*. The Admiral of the Fleet, A. W. Johnson, asked Page to see if he could use the XAF to detect the ships during their return. The Admiral then went to the movies. Page recalls what happened after that:

> *"When the movies were over, he came up. He started watching the scope—he watched it and watched it—and he knew it was time for the attack, and he didn't see anything. Finally, he gave up and said he had gotten tired of watching the scope. He turned to leave. [When] he got to the doorway, he stopped for some reason and turned around and came back to look once more before he went down. Within a couple of rotations of the antenna, as we swept past, he saw the destroyer. He saw it, and like a kid he jumped, 'There she is!'*[32]

Page recalls that the destroyer was nearly 6 miles away when the Admiral saw its echo on the scope. After the NRL team gave him the destroyer's bearing, the Admiral ordered the *New York's* searchlights to be trained on that bearing. "We didn't see a thing," Page recalled. "It was slightly hazy and we got the reflection off the haze and the lights and couldn't see very far. [But] the next day, the officers from the destroyer [and] the destroyer skipper came aboard. [The skipper] was just a little bit shaken. He said 'what'd you have on that ship last night? When you turned on your searchlights, you illuminated my lead destroyer."[33]

In subsequent nighttime tests, even when approaching destroyers had been forewarned of the new detection tool, they still could not avoid detection. "That really impressed the officer," Page recalls. "From then on they were sold on the stuff and they would give us anything we wanted."[34]

The official response to this demonstration could not have been more gratifying to the NRL team. The Captain of the *New York* officially recommended immediate installation on those vessels that could accommodate it. More glowing, however, was the assessment from Admiral Johnson, Commander of the Atlantic Squadron. In his report to the Bureau of Engineering in April, 1939, he wrote " . . . the



This summer of 1940 picture shows Building 12 with its rooftop contingent of experimental and production model radar antennae.

equipment is one of the most important military developments since the advent of radio itself. Its value as a defensive instrument of war and as an instrument for avoidance of collisions at sea justifies the Navy's unlimited development of the equipment . . . "[35]

In May of 1940, RCA, which had outbid Western Electric Company for the contract to produce the Navy's first shipboard radar sets, began delivering the first of six units, that had been specified to be exact copies of the XAF. The next 14 units, which were slightly modified and designated as CXAM-1, came a little later. But by the time of the Japanese surprise attack on Pearl Harbor on December 7, 1941, most of these units were installed and operational aboard 20 of the U.S. Navy's heavy cruisers, carriers, battleships, and seaplane tenders. In official reports at the end of WWII, this type of radar would get credit for contributing to major Naval victories in battles at the Coral Sea, Midway, and Guadalcanal.[36] Most subsequent historical accounts of the development of radar in the U.S. during World War II would

highlight the Radiation Laboratory, or Rad Lab, which the U.S. established during World War II as a national center for radar development at the Massachusetts Institute of Technology. As a result of this slant, NRL's earlier pioneering work in Naval radar has appeared diminished.

Nonetheless, with radar, NRL had given the Navy something entirely new—the ability to see the enemy in the dark and through clouds and in many other ways not yet discovered. That group of radio men at NRL who first developed radar for the Navy in the United States had counterparts in the United States, England, Japan, Germany, and elsewhere where researchers were exploiting the same physical principles and natural laws to develop a smorgasbord of first-generation radar equipment. There may even have been a greater sense of urgency in Europe where Hitler and his Nazi party were rallying in ever-increasing belligerence. A mere half-year after Page and Guthrie returned from the Caribbean in 1939 with the pleasant knowledge that their dogged radio detection work was on its way to becoming what historian David Allison has called a "new eye for the Navy," the Nazis marched into Poland. The second Great War in Europe had begun and radar would be in it for the duration, and way beyond. NRL's radio men and their colleagues had no idea how much their lives and the Laboratory were about to change.

Chapter 5

An Adolescent NRL at the Crossroads of History

For NRL, the prewar years were lean. They were also promising. Even though the Bureau of Engineering steered research at NRL toward short-term problem-solving and engineering just as Captain Oberlin had feared, the bureau also had proven to be a responsible and stable guardian for the Laboratory. The Laboratory's budget had risen from about a half-million dollars in 1935 to well over $800,000 by 1939 when administrative control of NRL again shifted, this time from the Bureau of Engineering to the office of the Secretary of the Navy.

Over that same period of time, the size of the Laboratory's staff approached about 300. The technical diversity of this laboratory also expanded to cover ever more of the scientific spectrum. The number of divisions had grown to seven—Radio, Sound, Physical Optics (formerly Heat and Light), Mechanics, Metallurgy, Chemistry, and Interior Communications, whose staff focused on the problems of integrating the growing panoply of on-ship communications equipment into the infrastructure of Naval vessels.

There was another sign that the very existence of the Laboratory no longer would be a serious question: construction picked up after the dearth of building during the Depression years. You usually don't build a house unless you expect to move in and live there for awhile. The first chemical laboratory went up by 1938 and already had been expanded by 1941. By then, the Radio Materiel School, at which thou-

sands of uniformed Navy men learned how to use all of that new radio equipment going into the Fleet, also had a new building as well as barracks to house the students. A year later, the Radar Division, a spin-off from the Radio Division, also got a badly needed new facility.

What remained in question about NRL, however, was just what kind of laboratory it was supposed to be. During the 1930s, Captain Oberlin's prediction that NRL would become just another Navy engineering laboratory if it fell under bureau control came at least partially true. Work at NRL was dominated by short-term studies in response to problems specified by the Bureau of Engineering and other Navy bureaus. That left little time, and even less money, for scientific research.

The example of radar, on the other hand, demonstrated that NRL nonetheless had evolved into a valuable institution that can produce militarily significant surprises. NRL had become a place where the ability to harness known principles in the quest for better military technology, which is otherwise known as engineering, would form a creative synergy with more fundamental research aimed at scientific discovery. In that sense, it was on a track akin to the one that would make Bell Laboratory's Murray Hill research center in New Jersey and DuPont's Purity Hall in Wilmington, Delaware famous bastions of science-to-technology innovation.

The development of high-frequency radar technology in the Radio Division during the 1930s was and will always be a standout in the institutional life of NRL. It has become to NRL what the transistor became for Bell Labs and what nylon became for E.I. Du Pont de Nemours where that landmark polymer became a technological newborn during the same prewar years as the birth of radar. In all of these cases, work toward improvements, spinoffs, and variations on the original themes never stopped.

Even throughout World War II, the Radio Division was the largest, best supported, and one of the two oldest divisions at NRL. NRL was never solely a radio laboratory, however. Just as the radar project

had begun its ascent in 1934 to become the Laboratory's highest profile yet most secret activity, for example, Harvey Hayes and his cadre in the Sound Division were christening their QB underwater detection system based on new Rochelle salt crystal transducers. With the QB system and its improvements, a trained operator could determine the bearings of a submarine more than 6 miles away even while his own boat was cruising at nine knots.

As it turned out, the Navy Department did not initially accept the NRL underwater detection gear for production. Taylor later speculated that had these systems been installed in the Fleet prior to 1935, "the battle of the Atlantic might have been won sooner and with fewer casualties."[1]

Despite the Navy's slow acceptance of the equipment, the Sound Division continued improving on the QB system during the rise of Fascism in Europe in the mid- and late 1930s. One improvement was the "Uni-Control System," which helped operators keep amplifiers in the transmitters and receivers tuned to a common ultrasound frequency. "This allowed the use of a narrow sound beam for directing an attack and a wider low-frequency beam for underwater search," wrote Taylor.[2]

Another improvement completed by the end of 1940 was the "dome shield," a thin, smoothly contoured housing of reinforced steel on the underside of the ship's bow. This housing protected the transducers and yet allowed the passage of sound energy so that both echo-ranging and searching could take place even when the ship was moving up to 15 knots. Yet a third improvement in sonar systems came not from hardware but from a better understanding of how oceanic temperature affects the transmission of sound. Ever more detailed and sophisticated environmental knowledge of this sort was the route to extracting more tactically significant information from the same signals.

Several other efforts of the Sound Division got into the Fleet more readily. One was an improved depth finder, or fathometer, for ship navigation. Like its sonar cousins, the sound transducers of these depth

finders incorporated the kinds of sensitive Rochelle-salt crystals that Elias Klein had helped develop. Nearly every Navy ship carried these devices during World War II, Taylor later wrote.[3]

On another front, the Sound Division solved the so-called "singing propeller" problem. The heart of the problem was a maddening, high-pitch whine of mysterious origins that made life miserable and nights sleepless for crews under certain cruising conditions. NRL's acoustics experts were able to pin the problem on the shape of a ships' propellers. They suggested that machining the propellers to have slightly different shapes whose resonant frequencies were outside of the audio range would end the sonic torture. It worked.[4]

By the time the United States entered World War II in December 1941 following the Japanese invasion of Pearl Harbor, NRL had become a substantial place where talents and tools could be mixed and matched to solve real Navy problems or to open pathways toward new and potentially valuable technologies. For challenges such as developing better armor plate, or lightweight and portable aircraft power supplies for radio sets, staff from different divisions were beginning to cross pollinate.

Part of this synergy came from the Chemistry Division.[5] A present-day motto amongst chemists is that "chemistry is the central science." What they mean is that chemistry has a place in just about any scientific question you might ask, whether it be on the propagation of electrochemical impulses down the spinal cord, the chemical synthesis of pain killers, the corrosion of automobile chassis, or the composition of galactic clouds.

The NRL chemists proved they could become part of the solution to technical headaches in the Radio Division. As Taylor's radio men kept pushing toward higher frequencies, they were running into problems with dielectric materials—electrically insulating substances used in many electronic components such as capacitors and component housings. The existing dielectric materials tended to allow electrical current to leak as the oscillating radio waves coursing through them increased in frequency. That leakage had all kinds of negative reper-

cussions when it came to building reliable and practical communications and other radio-based equipment. As members of the professional chemistry community, the NRL chemists not only knew what they were doing in their own labs, but what their colleagues were doing elsewhere. When the Naugatuck Chemical Company had come up with a new type of plastic material that the company itself deemed too costly for practical use, NRL chemists got hold of some and found its dielectric properties to be superior to anything the Radio Division had in hand. This led to a collaboration with company chemists that yielded a new plastic–"Victron." This new material was not a long-term answer to the electrical leakage problem, however; it melted too readily and was too weak for war service. But it did serve as a stopgap material that allowed the Radio Division to continue pushing into new territories of high frequency.[6] In that sense, this humble and readily forgotten episode represents how NRL slowly became the forward-looking place that Edison and Daniels had envisioned in 1915.

The Radio Division was only one place NRL chemists were helping out. In the prewar years of the 1930s, the Navy was discovering how central chemistry was to its own operation. From the corrosion of metal by salt water to the combustion of fuel and from the transformation of molten metal into reliable ship parts to the protection of troops against chemical warfare agents, chemistry was there.

Between 1935 and the beginning of the war, the staff of the Chemistry Division had expanded from 10 to 25. Two of the Division's five sections (later called branches, which even later subsumed sections of their own), the Electrochemistry Section and the Physical and Organic Section, continued work on some of the division's original problems in torpedo propulsion and submarine storage batteries. More and more, however, new problems were making it onto the agenda.

Consider the Corrosion Section, which formed in 1938 when the Chemistry Division had reached the 10 year mark. Inhibiting rust, the age-old naval bugaboo, was high on the section's to-do list, but its purview was far bigger. The section embarked on the still active quest of developing better anti-fouling paint that could dissuade organisms

like barnacles from mooring themselves on ships' hulls, aircraft pontoons, and other surfaces. Unwanted colonization of such organisms mar hydrodynamic contours, thereby slowing ships down. Slower ships eat more fuel and are sunk more readily. It is conceivable that barnacles could lose a battle for you. Anti-fouling paint was, therefore, not a mere convenience for the Navy.

Another problem the scientists in the Corrosion Section also addressed was that of corroding fuel tanks. Their solution was to search for non-corrosive additives to fuel and lubricating oil. The section also developed a de-icing fluid, water-repellent coatings for aircraft windshields, and defogging agents for optical surfaces that the Army and Navy both put to use.

The Chemistry Division's most ominous-sounding section, whose wartime activities would entangle NRL a half-century later in emotional litigation that went to the very heart of the morality of research during times of national emergency, was the Chemical Protection Section (see next chapter). Prior to NRL's foray in 1940 into the arena of chemical warfare, which had so traumatized the world psyche during World War I, the Army's Chemical Warfare Service had a veritable monopoly on research in offensive and defensive chemical warfare. In 1940, however, NRL got into this business because there was great concern that chemical warfare agents would become part of the carnage of World War II. The Laboratory received some initial mentoring from researchers at the Army's Edgewood Arsenal, about an hour's drive north in Maryland. During the war, the Chemical Protection Section would grow more than any other in the Chemistry Division. It would include the construction of the short-lived Building 44, complete with a gas chamber that could accommodate human test subjects, on the grounds of the Blue Plains sewage plant next door to NRL.

While the Chemistry Division was diversifying and expanding into new buildings, the Heat and Light Division was making do with a small staff headed by Edward O. Hulburt. Until 1941, the division

remained minuscule, averaging about seven men. The division maintained its general studies into ways the atmosphere and the sea affect the passage of visible, infrared, and other ranges of light. Developing such items as better smoke screens or search lights depended on knowledge of this general sort. The division, whose name later was changed to the Physical Optics Division, also developed anti-reflective coatings to reduce glare, thereby increasing the efficiency of optical devices such as submarine periscopes. Another problem on the division's agenda was the Fleet's protocol during blackouts to remain concealed from the enemy. The entire on-board lighting system for blackout situations was changed from blue light to red light after Hulburt's team discovered that blue light was far more noticeable to enemy aircraft than any other visible color of light.

In these years, camouflage remained largely in the realm of optics and that meant Hulburt would be involved. He hired his next door neighbor, Washington, DC, artist Charles Bittinger, to help out in this regard. With Bittinger's assistance, the division determined the optimum colors and patterns for all kinds of Naval vessels. Hulburt compiled these results in the "Handbook of Camouflage," which became the Navy's bible of camouflage during the war.[7]

As aircraft became more militarily important, so too did aircraft camouflage. The closer a plane could get to its target without being noticed, the more likely it was that the plane could hurt the enemy and get away unscathed. This was a time when radar, which would not be tricked by painted camouflage, had yet to make its operational debut. In the mid-1930s, the Navy's Bureau of Aeronautics was interested in using camouflage to decrease the distance at which a plane might approach enemy locations before first being noticed. They asked Hulburt to look into the question: could artificial lights mounted on an airplane cloak the aircraft by making its surface as bright as the surrounding daytime sky?

The result of this inquiry showed how a laboratory with a critical mass of expertise can help steer military decision makers away from

dead ends. The answer Hulburt's team came up following test flights with planes from the Anacostia Naval Air Station was "no." For one thing, so much light was required to sufficiently illuminate the entire underside of the plane that the weight of the batteries to run the lights would be impractical. Worse, Hulburt realized, to maintain concealment, the pattern of light and color would have to be readjusted for every turn, bank or other maneuver a pilot might make. The idea was just too complicated and impractical. In dropping the illumination-based camouflage idea, the Bureau of Aeronautics heeded Hulburt's conclusion that a quest for "electric camouflage" carried with it "almost insurmountable difficulties."[8]

Like the Chemistry Division, which was created at the same time in 1928, the Physical Metallurgy Division increased from a staff of 11 in 1935 to 40 in 1941. Steel, the stuff of hulls and a thousand lesser necessities of the Fleet, was its primary concern. And the improvement of steel casting remained its core activity. Taylor captured the comprehensiveness of this involvement:

> *"By trials and nondestructive examination [like gamma-ray radiography pioneered by Robert Mehl, the Division's first superintendent], the methods used in all of the stages in the molding, casting, and testing of steel were improved. The best degree of fluidity for pouring, the cooling-solidification rate which would result in the least number of flaws, the best molding sand to use, and the additives which would produce the highest quality of steel for armor, ship frames, and fittings were determined."*[9]

In addition to its core strength in developing better steel casting methods and means for analyzing solid metal pieces for flaws, the division also began to study the materials and methods of welding. This became an important topic in the late 1930s, when the Navy decided to do away with the traditional method of building ships by riveting steel plates together. Electric welding became the joining method of choice. But with that shift in manufacturing practice came a lot of scientific ignorance about the metallurgical details of welding

processes. If Naval defense was going to depend on welded hulls from now on, the Physical Metallurgy Division was going to do what it could to demystify what makes those all-important metal seams stay good or go bad.

By 1941, the Mechanics Division had been renamed the Mechanics and Electricity Division. Its staff of 13 was spread thinly over six widely ranging sections, all under the supervision of Ross Gunn, whose second role as Technical Aide to the Laboratory's commander would help him become a pioneer in nuclear technology. One of the division's sections, Thermodynamics, had originally been established for the torpedo propulsion problem and then operated for several years under the banner of the Physical Metallurgy Division. This kind of pinball migration of research units between organizational units of the Laboratory became commonplace and remains so to this day.

Other sections under Gunn's wing included Ballistics, Electricity and Magnetism, Mechanics, Engineering Development and Instruments, and Physical Testing. The researchers in these sections pursued a dizzying variety of projects. As the Ballistics Section noisily looked into the penetrating power of projectiles and the resistance of armor, the Thermodynamics Section was developing a radical new way of converting fuel directly into electricity. Meanwhile, others in the division were devising instruments to instantaneously determine horsepower from measurements on a ship's propeller shaft as their colleagues were looking into electrically and magnetically based methods of ship and submarine detection.[10]

Whatever the division's staff accomplished during the prewar years, however, would be overshadowed in hindsight by a top secret program that presaged critical components of the not-yet-imagined Manhattan Project to create nuclear weapons. In 1939, within weeks of the world's first announcement by German scientists that they had split atoms, Gunn initiated a secret project in the Mechanics and Electricity Division. The aim was to devise a means of separating the more fissile (capable of splitting) uranium isotope, U^{235}, from the less fis-

sile isotope, U^{238}. By this act, Gunn helped earn NRL the distinction of becoming the first government agency to do research on atomic energy. The project would began as a preliminary investigation into the possibility of using energy liberated from splitting uranium atoms as a means of generating heat to drive turbines for Naval propulsion. In that regard, it was a parochial effort for the Navy itself. But it would end up involving a future luminary in the field of nuclear physics, killing two people in an unfortunate accident at the Philadelphia Navy Yard, and then becoming an important component of the Manhattan Project and the development of the first atomic weapons. Gunn's project would become one of NRL's most world-changing accomplishments (see next chapter).

Just as this historically consequential project was getting underway in one section of one NRL division, the entire Laboratory once again was experiencing an administrative sea change. This time it was returning from the Bureau of Engineering to the more central site of the office of the Secretary of the Navy. Ironically, the man who was responsible for this change was the new Secretary of the Navy, none other than Thomas Edison's son Charles.

Secretary Edison based this administrative shift on what he had perceived as the now-proven predictions by Captain Oberlin that NRL, if placed under the Bureau of Engineering, would become primarily a testing and engineering laboratory. This was not so much a criticism of the bureau as a natural consequence of the mission of the bureau and the role its own labs would have in fulfilling that mission. Despite intermittent patches of basic research, the vast majority of work that had been done at NRL, in fact, fell under the categories of engineering and testing. That is just what Oberlin feared would happen and why he had fought so hard against shifting NRL into the Bureau of Engineering earlier in the decade.

In 1939, as part of a much larger Naval reorganization that consolidated the shipbuildings bureaus (Bureaus of Engineering and Construction and Repair), Edison returned NRL to the more central supervision of the Secretary's Office: "I feel the laboratory must at-

tach greater emphasis to research, and for this reason I have placed the Anacostia Laboratory [NRL] directly under the Office of the Secretary of the Navy and proposed to provide a central organization to coordinate and emphasize all naval research and development," Edison told a committee of the House of Representatives in 1940. "We will utilize the facilities and the staff at Anacostia and gradually extend the scope and activities of this organization."[11]

The organization Edison spoke of here was established in late 1939 and became known as the Navy Department Research Council. It presaged the 1946 creation of the Office of Naval Research (ONR), which plays this coordinating role today for Naval research in general. NRL's ascending place in the Navy's overall research agenda was evidenced by the designation of NRL's Director as the chairman of the council, which included representatives from the Navy's materiel bureaus (Aeronautics, Ordnance, Construction and Repair, and Engineering).

Secretary Edison articulated the changing status of NRL in a directive to his Chief of Naval Operation: "The primary duty of the Laboratory divisions—will be fundamental research designed for the benefit of naval science and national defense and such collected benefits to private industry as may develop therefrom."[12]

With research leadership at NRL already in the hands of talented civilian scientists like Taylor, Hayes, Hulburt, and Gunn—all of them PhD physicists from respected universities—there was no doubt the Laboratory had the scientific stuff for doing more fundamental research. But to make that so in actuality also required buy-in along the chain of military command from the commander of NRL on up. In addition, a good portion of the money required to run the Laboratory had to come from sources that were not only friendly to basic research, but were also patient when it came to demonstrable payoff for the Navy. Under the bureau, money was there, but not when it came to longer term, more speculative scientific research.

In Secretary Charles Edison, who was born and bred in one of the most technical environments of his time, science in the Navy had a very powerful friend. And that bode well for NRL.

The Laboratory's prospects were further strengthened by the ascendancy of Admiral Harold G. Bowen (see Chapter 4), the brusque science-loving officer who had replaced Admiral Robinson as head of the Bureau of Engineering, and who took over the NRL directorship in October 1939.

When he took the helm at the age of 56, Bowen already had given the Navy 38 years, beginning when he became a student at the Naval Academy in 1901. In 1914, he earned a master's degree in mechanical engineering from the Naval Postgraduate School. In 1931, he became Assistant Chief of the Bureau of Engineering, and four years later he became the bureau's chief. In that position, he made friends and enemies in his hard-fought campaigns to modernize the Navy with such changes as high-pressure, high-temperature steam for propulsion, high-speed turbines, and alternating current.[13] When he took over NRL, he already knew that radar had the potential of being the most important electronic innovation since radio. His ambition was to upgrade Naval research and development as no one had before.

It would have seemed in late 1939 that NRL finally had the ticket to become the Navy's visionary "corporate" laboratory whose outlook spanned out to and beyond the horizon. The contemporaneous outbreak of war in Europe, however, would postpone NRL's ability to fully redeem that ticket. Although direct U.S. involvement in World War II was still two years away, the country needed its military forces to be prepared for anything. The Nazis already had taken and occupied Poland earlier in the year. In 1940, they marched on Holland and then on France, which was a mere British Channel away from England. Basic research would have its place at NRL, but the times were calling far more for NRL's demonstrated genius at engineering.

Chapter 6

NRL Goes to War

Just as the sinking of the *Lusitania* on May 7, 1915 had thrust World War I onto the United States with acute drama, a singular tragic drama on December 7, 1941 pushed the United States into the throes of World War II. On that day, the attack on Pearl Harbor killed nearly 2,400 sailors, Marines, and army soldiers and civilians, sunk or damaged 21 ships, and damaged or destroyed more than 300 aircraft. The next day, the United States declared war on Japan and the entire country began mobilizing as it never had before. A. Hoyt Taylor later recalled what the U.S. entry into World War II meant to the Naval Research Laboratory: "The activity had to change, almost overnight, from a fairly modest, almost academic-type laboratory into one of the greatest research institutions in the world."[1]

The buildup was phenomenal. From 1941 to the end of the war in 1945, NRL personnel increased by more than 400%, from 396 to 2,069. That was not the half of it, however. Attendance at the Radio Materiel School, which had shared the NRL campus since 1924, swelled as the need for persons trained in radio communications grew along with the Navy's surface Fleet and airborne units. By 1945, the school grew to accommodate nearly 2,400 enlisted men as well as 200 officers, all sleeping and studying in a quickly built compound of temporary barracks, classrooms, and even a chapel. "So much construction is in progress on the Station that NRL is beginning to look

like a modern boom-town," read an article in a July 1944 issue of the *NRL Pilot*, the Laboratory's newsletter at the time.[2]

It took a lot more money to run the burgeoning Laboratory during the four frenetic war years. The Laboratory's budget mushroomed accordingly from $1.7 million to $13.7 million, a trend that would not reverse after the war. The annual load of problems the Navy's bureaus were assigning to NRL divisions rose from about 200 to nearly 900 during the war.[3]

Before the war, the uniformed presence at NRL was minor. After the attack on Pearl Harbor, civilian clothes began giving way to military uniforms as though it were an expression of high fashion. In 1941, there were 20 Naval officers working at NRL; by 1945, there were 1,018. Most of the increase was due to a defensible scam. Cognizant of the crucial behind-the-scenes role a place like NRL might end up playing in a technologically sophisticated war, the Navy Department had worked out a compromise with the local draft board in which the Laboratory's civilian scientists could be inducted into the Navy but then assigned to work at the Lab. That prevented the likely alternative of having a lot of badly needed research and engineering talent getting drafted by normal routes and then sent anywhere in the world they might be needed.

In this agreement with the draft board, those at NRL who could have earned officer ranks received Naval commissions at grades that reflected their ranks within the Laboratory's professional hierarchy. Those who couldn't meet the physical requirements of officerdom became petty officers. At times, this led to ironic arrangements in which senior scientists were militarily outranked by their professional subordinates.

These were not the only additional uniforms that began showing up for work at the Laboratory. Some 167 women, who had joined the Navy to assist the war effort in noncombatant jobs, also came to NRL. They were known as WAVES (Women Accepted for Volunteer Emergency Service) and took on much of the additional clerical work that

The Laboratory as it appeared in late 1944

increased markedly along with the quickening of the Laboratory's pace. The WAVES also imported more romance than the Laboratory had ever known. Every week, the *NRL Pilot* announced with the requisite corniness of the times of some "hand holding" going on along the river or, more seriously, another marriage of a WAVE and an NRL researcher or shop worker.

The roster of contract employees, who could be hired far more quickly and efficiently than by relying on cumbersome protocol established by the Civil Service, also rose to a high of 750 during the war years. Once here, these researchers and engineers often slid into permanent slots at NRL.

With all of these additional people coming to work at the Bellevue site, there were more mouths to feed, more rooms to illuminate and heat, more toilets to flush, more work to be done, more paper to push, more phone lines to operate. Buildings were going up almost overnight. Cars were in parking lots, day and night. Draftsmen (and

draftswomen) hunched over tables at all hours drawing up plans for hundreds of wartime gadgets. The shop was in a constant frenzy, loud with model building and prototype construction so that the companies contracted to build production models would know precisely what the Navy wanted them to make. More trucks were delivering more supplies and hauling away more garbage. With all of this hiring and procurement, there was more governmental red tape to navigate. More fingers were dialing more phone calls and keeping the increasing roster of switchboard operators very busy. To use a jazz colloquialism, "this joint was jumping."

To accelerate the transition of equipment designed at the Laboratory to operational status in the Fleet, several special liaison groups sprang up. These groups linked NRL researchers and the industrial contractors they worked closely with to produce equipment, on the one side, with Navy personnel who would use the equipment, on the other side.

One of these groups was the Airborne Coordinating Group (ACG), whose airborne electronics specialists would number 140 by 1943. Their job was to troubleshoot breakdowns and failures in all airborne electronic devices, come up with corrective measures, and perform maintenance. Radios, homing beacons, radar searching and jamming equipment, identification equipment, and other more specialized gadgets were popping up all over the inside and outside of planes. The men of the ACG carried out about 1,000 field missions around the globe. A shipboard version of the ACG, the Electronic Field Service Group of 325 officers, enlisted men, and civilians, did the similar tasks for shipboard electronics, which involved a far more extensive inventory.

A third special group, created in 1942, the Combined Research Group (CRG), was tasked with coordinating work on an electronic device known as IFF (Identification: Friend or Foe). "The CRG had its start to unify the many beacon systems in use during WWII to direct bombers to their targets," recalls Henry M. Suski, then a project engi-

neer with the CRG.[4] The group's major goal, however, was to develop a device that would enable the new radar systems entering service during the war to distinguish between friends and foes. With so much shooting taking place beyond ranges where visual verification was possible, new techniques of determining who it was you were shooting at took on critical importance. This was especially critical in a conflict like World War II, where multinational forces with a wide variety of equipment joined forces against the enemy.

NRL's Radio Division went part of the way toward the goal of a multinational IFF system in 1942 by providing IFF equipment—designated as Mark III—that was adopted by both the United States and United Kingdom. "The system was installed on practically every aircraft and ship of the U.S. forces," Louis Gebhard of the Radio Division later stated. "It was used extensively, particularly during operation in the Pacific."[5]

There were a number of technical problems involved with the Mark III, not the least of which was the amount of time it took to make an identification. The CRG was formed to solve these problems. The group's membership combined researchers from the U.S. Army, U.S. Navy, the National Defense Research Committee's Radiation Laboratory at MIT, the British Admiralty, Canada, and others, all under contract from the United States' National Defense Research Committee. As it turned out, the CRG made considerable progress toward what became known as the Mark-V IFF, but the new system was just undergoing evaluation for Fleet use when the war ended.[6]

In addition to the explosive growth at the main campus along the Potomac River, the Laboratory's first major field station, the Chesapeake Bay Annex (now called the Chesapeake Bay Detachment), was undergoing its own fantastic growth spurt on the western shore of the Chesapeake Bay. Just before the war, Taylor, Young, and Gehbard had identified and procured a site about 40 miles from the Laboratory along cliffs overlooking the Chesapeake Bay. Its location made it an ideal place to field-test experimental communications and radio de-

tection equipment, new antennae, and other large and small gadgets. Radio and radar engineers could perform these tests under more realistic and revealing conditions because Navy vessels of any shape and size could approach the annex in an open body of water. From 1941 to 1945, the newly acquired CBA grew to over 100 personnel and to more than a dozen large buildings, including a barracks and mess hall.

Staff of the Radio Division were not the only ones commuting to the CBA. Researchers from the Optics and Sound Divisions also were putting the facilities to use. And beyond NRL staff, engineers from commercial contractors such as General Electric, RCA, and Bell Labs took up barrack space at the annex so that they could field-test the latest prototypes of the electronic gear their companies were building under contract to the Navy's bureaus or the National Defense Research Committee.

The wartime NRL was an adolescent laboratory in a raging growth spurt on its way to adulthood. Such transitions inevitably bring growth pains and the Laboratory was growing faster than could be easily managed. The number of research divisions grew to ten. The Laboratory's functions and needs were becoming more varied and complex at a time when the war was greatly amplifying the normal challenge of procuring skilled workers, researchers, and the research materials needed to do top quality work. This was a time, after all, when rubber was scarce enough to ration, and nylon, which DuPont had just commercially introduced during the war, had been pulled from the general market to make its limited supply available for making parachutes, tire cords, and other militarily important equipment.

The old, homey style of recruitment by which Laboratory superintendents would write letters and make phone calls to solicit recommendations from their trusted friends in the science world gave way to brand new Laboratory bureaucracies dedicated to personnel issues. Hiring became more of a crapshoot than the sure thing it once had been. The population of lawyers, a sure indicator of an organization's

loss of innocence, grew. As the Laboratory's staff invented more and more gadgetry at an ever-accelerating wartime pace, the Laboratory installed a Patents Section (later generalized to become the Legal Department), which by the end of the war employed 16 attorneys.

Changes in the Laboratory's drafting service also reflected the wartime bustle. The drafting staff had always resided in the Radio Division, but when their skills became more generally required throughout the Laboratory, this technical drawing staff budded off into its own Design and Drafting Section in 1943. The section got so busy during the war that it advertised in the *NRL Pilot* for "girls interested in drafting." Had it not been wartime, even humble opportunities like this in a male-dominated technical setting most likely would not have been available for women.

Despite the nearly unmanageable growth and the concomitant arrival of more bureacracy, the Laboratory was fully swept up with the nation's gung-ho, single-minded war effort. The *NRL Pilot's* often printed axiom was: "The difficult we will do at once—the impossible may take a little longer." To cope with tire shortages, the *Pilot's* editors implored employees to use car pools. Buying War Bonds and donating blood for use overseas near the battlefronts were other ubiquitous mandates drilled into the newsletter's readers.

Each *NRL Pilot* served as both a pep talk and a paternal lecture. In the first issue of 1944, the *Pilot* touted Mildred K. Ruth for the important work she was doing in testing light bulbs for their ability to withstand shock and vibration. "If the lights go out on a ship, many lives are likely to be lost," an article read. "[Mildred Ruth] has the satisfaction of knowing that she is contributing an important bit to the war effort."

The *Pilot* also intermittently brought the war down to the most personal level. One article in the final issue of 1943 included the following short item: "NRL extends sympathy to Albert E. Meininger, who received word last month that his son was reported missing in action following an air attack over New Britain Island. Mr. Meininger

thinks his son might be a prisoner of the Japs, as his plane was seen to crash in the harbor at Rabaul." Another *Pilot* article reported that 36-year-old Kermit Robey, a former NRL machine shop worker, was killed in action. Every issue of the *Pilot* also recorded the minutiae of normal life: softball scores, birth announcements, rumors of romances, weddings, and corny poems.

Meanwhile, World War II was having a profound effect on the Laboratory's overall character. The immediacy of war superseded any plans Admiral Bowen and Charles Edison might have had for long-term and more fundamental research. With a war upon whose outcome the fate of the world literally rested, there were more urgent matters that NRL researchers needed to address. In fact, much of NRL's work during the war involved the Navy's version of consumer-testing to make sure that equipment imminently slated for use in the Fleet actually could assimilate into their intended settings and work reliably once they were there. There also was a constant stream of top priority calls to solve emergency situations that cropped up as the U.S. Navy went into all kinds of new environments with a combination of new equipment and machines, freshly trained sailors, and new technologies.

On the administrative level, the Laboratory already had ricocheted from the dominion of the Secretary of the Navy back to being an arm of a Navy bureau. The shift occurred in July 1941 as the war in Europe was intensifying but before the U.S. entered the conflict. This time, NRL fell under the Bureau of Ships, which then Secretary of the Navy Edison had created in 1940 by merging the former Bureau of Engineering and the Bureau of Construction and Repair. Given the times, the administrative shift was just as well. As Taylor later put it: "the matter of administration made very little difference to us during the war, for by far the greatest percentage of our work was done for the Bureau of Ships anyway."[7] The shift brought with it the advantage of placing NRL administratively closer to those who would know technical details about the Fleet's wartime needs.

To recount the stories of even 1 percent of NRL's wartime projects would turn this book into a sizable compendium that would read like a catalog. The following handful of the more dramatic or consequential episodes played out on NRL stages is intended only to serve up a taste of wartime NRL.

Electronic Warfare—The Solution Becomes the Problem

More influential than the administrative shifts within the Navy on overall NRL's activities was the creation in June, 1940 of the NDRC, a high-powered advisory and funding body that became part of the more encompassing Office of Scientific Research and Development (OSRD). The NDRC was made up of the country's most respected scientific leaders. Its role was to coordinate war-related research across the nation's full complement of technical assets in academia, industry, and government. The world in which NRL could view the Navy as where the buck stopped became a world where the Navy and NRL became players on a much larger team.

Among the most fateful and historically significant decisions of the NDRC to affect NRL was to shift the center of military radar research to a newly organized facility, the Radiation Laboratory (known also as the Rad Lab), at the Massachusetts Institute of Technology (MIT). This all-out, top-priority, top-secret research and development facility produced results that rank along with nuclear weapons, synthetic rubber (to substitute for embargoed supplies of natural rubber), and the proximity fuze as among the most important technological developments of World War II.

The formation of the Radiation Laboratory and the character of radar research in the United States changed dramatically following the1940 Tizard mission, during which a cadre of British scientists led by Sir Henry Tizard visited the United States, including NRL, as part of an effort to coordinate war-related research amongst the Allies. Prior to the Tizard mission, NRL's radio detection work focused on high-frequency systems for ships. The British were more immediately vul-

nerable, especially at night, to German attack by way of bombers, and later by way of unmanned V-2 "buzz" bombs flying in from air bases located in occupied France. Understandably, their research effort centered on airborne radar.

Since planes are smaller than ships, however, the British were more pressed to develop compact radar systems than was the United States. A key difference between high-frequency and microwave-based systems (whose wavelengths are shorter) is that the latter enables engineers to design more compact systems using smaller antennae that are more suited for aircraft. Another reason the British were technically ahead in this microwave regime of radar technology, which others including NRL at least had dabbled in for several years, was the invention of a gadget—the multicavity magnetron—by a physicist at the University of Birmingham.

Unlike the electronic tubes available in the United States, the multicavity magnetron could electronically oscillate at the higher microwave frequencies with great enough power to generate strong radar pulses and detectable echoes from distant-enough targets. Besides enabling the use of much smaller antennae, the multicavity magnetron's microwave frequencies could be used to generate more powerful and sharply directed radar pulses. In turn, this helped clear the way for specialized and more capable radar equipment for fire-control on shipborne guns, nighttime operation of fighter planes, and antisubmarine warfare (ASW) by helping ASW attack planes locate their hard-to-find targets. Another advantage of microwave radars was that, for a substantial time, the Germans and Japanese were unaware of the progress of the British in this regime and neglected to deploy detectors to warn themselves when illuminated at microwave frequencies.[8]

The multicavity magnetron and microwave radar became the *raison d'être* for the Rad Lab. NRL used the multicavity magnetron to design its own airborne radar equipment, designated the ASB system. In time, 25,000 ASB sets were produced and installed in Naval air squadrons. The radar experts on the Tizard mission did not return to Britain empty-

handed. One of the more important technical leads they took back to their laboratories was the duplexer that Robert Page of NRL's Radio Division had developed in the late 1930s. The duplexer and its ingenious electronic switching mechanism enabled a single antennae to serve as both the transmitter and receiver for a radar system (see Chapter 4).

Prior to NRL's disclosure of the duplexer, British radar designers—the most advanced in the world—had been relegated to using two antennae, a cumbersome and performance-eroding arrangement for fighter planes. When Winston Churchill, Britain's Prime Minister during WWII, gave his famous speech in which he said, "Never have so many owed so much to so few," the radar men honestly could include themselves amongst the "few."

Yet NRL's place in the history of radar would never fully recover from the creation of the Rad Lab and the emergence of microwave radar over high-frequency radar as the pinnacle of World War II radar technology. The Rad Lab, a temporary wartime entity, would go down in history as the womb of radar in the United States even though it had nothing to do with the earliest developments at NRL and by Army researchers. A recently published 600-page history of radar by Robert Buderi, *The Invention that Changed the World*, chronicles the Rad Lab's story in great detail while hardly mentioning the role of NRL's Radio Division.

The staff of the Radio Division, which by the end of the war had grown to over 1,000, did in fact make critical lifesaving contributions during the war. The high-frequency shipborne systems for search and detection that NRL demonstrated in the late 1930s and the new airborne ASB radar that emerged following the Tizard mission's disclosure of the multicavity magnetron became crucial instruments of war that played significantly in the outcomes of many missions and battles.

The NRL radio men also helped prove to Naval officers that radar was good for more than just providing early warning of enemy ships and planes. Soon after the U.S. entry into the war, they demonstrated

that novel radar-based fire control systems to direct heavy gunfire could improve upon the age-old optical fire-control methods. Recalls Taylor: "In the beginning, the 'line' officers of the Navy were very skeptical about radar fire-control, but after the second battle of Savo Island (1942), when radar saved an American task force, the Fleet became completely sold on its use."[9]

Radar was so new in World War II that every aspect of the technology was ripe for improvement. The earliest radar operators were challenged to make sense of scratchy lines shooting nervously upward from a glowing horizontal point sweeping across a fluorescent screen. A sweeping line hardly corresponds to the three-dimensional volume around a ship and plane, making this early type of display difficult to read and interpret. NRL researchers worked quickly in the early part of the war to improve the display of radar information by developing the PPI, or Plan Position Indicator. The device displayed radar echoes so that the farther they were from the receiver, the farther from the display's center the echo appeared on the screen. Moreover, the angle of the displayed echoes corresponded more closely with the detected objects actual bearing. With the PPI, operators could more readily detect and track many enemy threats simultaneously. Many versions of these displays were produced by the thousands and ended up in the Fleet during the war. (They are still widely in use today in ship, aircraft, and air traffic control displays.)

The increased electronification of warfare during World War II brought an unprecedented weight down upon the shoulders of scientists and engineers. As soon as Allied or Axis fighters flicked on the switch of some new piece of communications or radar technology, radio and electronics experts on the other side took off on a research and development sprint to come up with measures to counter the new technology. Each additional day a new Nazi or Japanese radar system could detect Allied bombers without being countered in some way translated into additional deaths of comrades and uncompleted missions. What's more, once one side introduced some new counter-

measure, scientists and engineers on the other side went into another reactionary research and development frenzy to come up with counter-countermeasures. From the beginning, NRL was in the heat of this deadly game of electronic cloak-and-dagger.

Hints of this kind of electronic warfare showed up early in the history of radio. Indeed, radio was still called wireless telegraphy when its vulnerable underbelly showed itself. Soon after the turn of the century, Naval radio operators discovered that radio communication was susceptible to both accidental and deliberate disruption. The former might be called interference; the latter became known as jamming.

A receiver tuned to a particular frequency will pick up any radio signals from any sufficiently strong source so long as the signals match the frequency to which the receiver is tuned. To jam radio communication at 50 kHz, therefore, all you have to do is build a transmitter that emits static at 50 kHz. To counter the jamming at 50 kHz, you need a radio system that can switch frequencies. To counter a radio system that can use multiple frequencies, you need a jammer that can switch to those same frequencies. This is just one reason why so much of the NRL's radio developers' effort went into building different kinds of radios that could operate at different ranges of frequencies.

Soon after NRL opened its doors, members of NRL's Radio Division set out to modernize another early tactic of radio warfare—direction finding (DF). As its name implies, a direction finder helps to locate a radio transmitter. With DF equipment, an enemy's radio transmitter becomes a beacon revealing its location. Howard Lorenzen, a radio engineer newly hired at NRL in 1940 and later head of the newly formed Countermeasures Branch and then the more comprehensive Electronic Warfare Division, later explained why DF already had become an important part of antisubmarine warfare during World War I:

> *"In successful submarine operations, the submariner needs to tell his operational commander where he is located and receive the benefit of any changes in orders or guidance or intelligence on the enemy's disposition. The conventional submarine's range is lim-*

> *ited by the amount of fuel it can carry, and periodically it must be refueled and replenished. To effect a rendezvous with a tanker or support ship he must be able to tell them where and when to meet him."*[10]

Even during World War I, the United States put DF equipment to good use on ships and shore stations to help locate enemy submarines operating in the Atlantic.

By the time the United States entered World War II, NRL radio engineers and technicians had developed more accurate DF equipment. Rupert Huskins supervised installation of this equipment in a network of shore stations covering Atlantic Ocean areas. His colleague, Sterling Thrift, worked with industry in the vast effort to fit ships with DF equipment. Several French refugee researchers who escaped from France after it fell to the Nazis contributed greatly to NRL's DF work from their new research venue at the Federal Telecommunications Laboratory at Amagansett, Long Island.[11]

The resulting network of shore-based and shipborne direction finders enabled the Navy to steer convoys away from enemy submarines lurking either by themselves in shipping lanes or in "wolf packs." The DF equipment also helped U.S., British, and Canadian carriers and destroyers locate and then sink the submarines. What's more, when Japanese airmen began using ultrahigh frequency (UHF) and very high frequency (VHF) radars to search for American submarines in the Pacific, an engineering team at NRL quickly developed and installed equipment, including direction finders, that alerted the submariners whenever enemy radar pulses were reaching them.

The advent of radar equipment in World War II catalyzed a never-ending round of countermeasures work. No sooner did radar make its way into military operations than did radar engineers begin coming up with means to detect and locate, jam, deceive, and otherwise counter enemy radar systems.[12] Thus began the behind-the-scenes, high drama of electronic countermeasures and electronic warfare that continues under great secrecy to this day in NRL's Building 210 and other places around the world.

Just four days after the Pearl Harbor attack, Admiral Julius Furer, a major player in coordinating research and development, convened a high level meeting with representatives of the Office of Scientific Research and Development, the Rad Lab, and the Navy. The goal of the meeting was to figure out how the United States was going to create an adequate infrastructure for the sophisticated countermeasures R&D that war planners sensed the United States was going to need. Less than two weeks later, official machinery had been set in motion to create an obscurely named Radiation Research Laboratory (RRL) at Harvard. Essentially adjacent to the Rad Lab at MIT, it would become a national center of a massive countermeasures R&D effort in the middle of the relentless and deadly cat-and-mouse game with the enemy's radio and electronics researchers. Once again, NRL became a participant in something too big for any one facility to handle.[13]

Early warning airborne receivers, for example, could tell pilots when their planes were being illuminated by an enemy radar. Once the frequency of an interrogating radar was known, frequency-matched transmissions from radar jammers could be high-beamed at the enemy radar system to blind it to specific targets. That, of course, only prodded clever radar engineers and electronics experts to develop equipment for switching frequencies whenever jamming became a problem. That only provoked similarly clever development of jammers that could continuously sweep frequencies and then lock onto any found. Depending on the relative strengths and speed of the equipment and their operators, such a jammer could essentially blind an enemy radar or at least keep it on the run, making it tougher to get a good fix on targets.

Howard Lorenzen got a taste for what his world was going to be like immediately after being assigned to the coyly named Special Developments Section of the Radio Division. He later recalled what happened:

> "*One of my first projects was to build a 400 MHz receiver for a new radar system that was being developed for the Navy within the Laboratory. I was working on the second floor of the building*

> *where the Radar Division had [its] radar systems installed in the penthouse. Shortly after I finished wiring up the receiver and had it on the bench for alignment, one of the radar engineers came in and asked if we had any oscillators running at 400 MHz. I answered that I was working on a 400 MHz receiver. He asked me to turn it off. He came back in a few minutes and said, 'Leave that darned thing off, you are jamming our radar in the penthouse and we can't see anything on the scope.' That was my first experience with jamming, though it was purely unintentional."*[14]

Soon after the United States entered the war, Lorenzen and his colleagues were beguiled by a group of visiting British researchers who told of their harrowing jousts with the German electronics warriors. Among the most alarming developments was the German introduction of guided weaponry into warfare. Using radio signals as invisible guides, the Germans could steer manned bombers, and later unmanned flying bombs, into strategic British target areas. The Special Developments Section at NRL learned how their cohorts in England had developed the means to essentially bend the German's guidance beams so as to steer the death-dealing bombs into unoccupied countryside.

In 1943, United States forces first came under attack with this new form of warfare when the Germans launched several crude, guided bombs against U.S. ships operating in the Mediterranean. After one of these bombs, a Henschel 293, missed and sank in shallow water, the Navy retrieved it with the hope that its scientists could develop a means to counter it. Among those drawn into this top priority project, which mandated round-the-clock work until the job got done, was Lorenzen's group. Lorenzen recalled the experience:

> *"This bomb, the HS-293, was really a small guided aircraft controlled by radio signals. The U.S. Navy felt this was a prime threat to operations in the Mediterranean. To provide the Navy with a counter for this bomb, a special project was set up at NRL and equipment was produced on a 'crash basis' for two destroyer escort ships, the USS DAVIES and JONES."*[15]

Lorenzen and his closest coworkers at NRL developed receivers for intercepting the enemy's radio guidance signals as well as equipment to record and analyze those signals. With this information, another group in the Special Projects Section, including Carl Miller, built jammers that could confuse the glide bombs. Miller later told a chronicler of wartime countermeasures work what that job was like:

> *"Building a transmitter to cover the required band was a bear. That is one of the most difficult frequency spreads to cover. In the end, we managed it by dividing the coverage into a couple of bands. We built a series of experimental jammers that solved the problems in different ways. We never had any time to test the jammers, however, because as each hand-built set was completed, somebody from the Fleet would come and grab it from the laboratory. It would be hastily installed into one of the warships, and off it would go to sea. We made about five of the jammers during the summer and early fall of 1943."*[16]

In a particularly harrowing part of this effort to counter the guided bombs, Navy engineers went aboard ships that were newly equipped with NRL-made signal analyzers. The ships then sailed into waters known to be vulnerable to the new weapons. Taylor recounted what came of this:

> *"Acting as bait for a large number of German bombs was a nerve-racking experience but the operation paid off by the acquisition of the necessary technical intelligence for the development of a practical counter-device."*[17]

This mid-war work continued to yield dividends in the war against Germany. "During the Allied invasion [of Normandy in June 1944], NRL-constructed equipment successfully protected ships by giving repeated false commands to the bombs from the deception transmitters," Lorenzen recalled.[18]

The retrieved Henschel 293 was not the only piece of enemy electronic warfare ingenuity that was captured and returned to NRL so that the Special Projects Division could analyze it and devise counter-

measures. This always made Lorenzen one of the first at NRL to get a look at any new captured enemy equipment. Toward the end of the war, he and the NRL team received a load of equipment that had come off of a German submarine that the Navy had captured off the coast of New England as its cargo of spies was disembarking. Among the innovations in this equipment that surprised Lorenzen was the use of tape recorders for storing data.

Throughout the war, the captured equipment kept NRL and the entire U.S. countermeasures effort respectful of the enemy's ingenuity. "We continued to be amazed at the German ingenuity and clever, rugged packaging techniques," Lorenzen recalled. "What we also saw was the need for broader-coverage equipment that would be capable of handling not just one threat but a whole spectrum of threats operating in any given portion of the frequency spectrum."[19] It didn't take long for his group to have visions of "universal systems" for countering any and all threats, but efforts toward that sort of technological

The remains of Japanese radar installations like this one were sent back to NRL for analysis and the development of countermeasures.

utopia would have to take a back seat to the need for "quick and dirty" solutions to the stream of immediate threats assigned to NRL and other countermeasures researchers at other U.S. labs.

Lorenzen remembers one such urgent request from the Marine Corps as they fought Japanese forces in the Pacific region. They needed a rapidly deployable radar jammer. "We built a simple 'Chick' jammer in an aircraft flare tube," Lorenzen recounted. "This was a simple jammer with a parachute to carry it down, which would float in the water near the transmitter site and continue to jam the radar".[20] In a sense, the NRL team was returning a favor to the Marines. Earlier, in August of 1942, the Marines had unexpectely recovered a Japanese early warning radar system when they captured Henderson Field on Guadalcanal in the Solomon Islands. A. Hoyt Taylor, the boss of Lorenzen's boss, later recalled what happened:

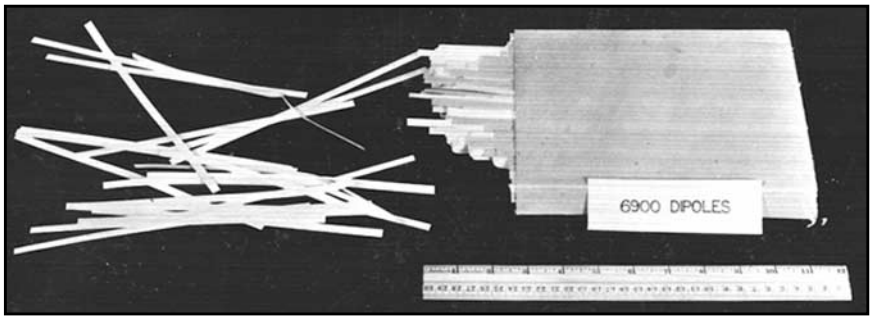
> *"The frequency of the transmitter was determined from the name plate and the information cabled to NRL. Within three weeks, our engineers, working in around-the-clock shifts, had devised a suitable jamming device and a frequency analyzer which could detect signals from similar Japanese transmitters. These countermeasures were shipped by air for immediate use in the Pacific."*[21]

All of these electronic countermeasures were among the leading-edge technologies of the day. They came in the form of various shaped antennae, wires, cables and racks of electronic boxes loaded with glowing vacuum tubes, resistors, and other electronic components. The boxes were covered with a variety of dials, scopes, knobs, switches, and sockets on the outside.

One of the more remarkable and most feared countermeasures of the war, however, was a decidedly low technology type first developed in England. The British called it Window. Americans called theirs chaff. The Germans, from whom the simple principle of this countermeasure could not be hidden, called it Dueppel.[22]

Early chaff consisted of multitudes of metal foil strips or metallized paper that were cut or bent to specific dimensions corresponding to the frequency (or wavelength) of the radar systems they were

made to fool. Thousands of these were then bound together into packets, which were then ejected from planes by hand, or later from automatic dispensers. To radar operators, the clouds of slowly descending chaff appeared as additional blips. So a cheap packet of metal strips you could hold in your hand could appear to radar operators like a bomber or sometimes even like a full-fledged destroyer. The deceptive power of these metal pieces resided in the physical fact that radar reflected from them with disproportionate vigor because their carefully chosen physical dimensions essentially tuned them to be optimal reflectors.



Ejected from an airplane, a package of 50 of these aluminum foil strips, called chaff or Window, would produce a radar echo equal to that of several bombers.

When British researchers first developed Window, they were so amazed at its deceptive power that neither they nor the other Allies dared use it in battle for fear of giving away the store to the enemy. Once those little metal strips did their job, they would fall to the ground. One look at them by an enemy radio or electronics scientist of even mediocre talent and the secret would be out. Unbeknownst to the Allies, however, the Germans had already happened onto their own version of Window. They, too, feared that using the countermeasures almost certainly entailed losing the monopoly they thought they had. So they too dared not use it.

The hold on chaff ended in December 1943 when the 8th Air Force first put it to use. By the spring of 1944, airmen would measure their

monthly consumption in several hundreds of tons.[23] Window and chaff and Dueppel would fall from the sky with great effect during the all-out invasion at Normandy. This low-tech, high-concept countermeasure has never disappeared. Since World War II, it has spawned rather sophisticated variations on the original themes and researchers in NRL's Tactical Electronic Warfare Division have made an international name for themselves by consistently pushing the envelope of chaff technology.

NRL wartime work in electronic countermeasures became the equivalent of a new chromosome that thereafter would influence the Laboratory's character and evolution. Howard Lorenzen later assessed the aftermath of the Laboratory's wartime countermeasures research for a military historian:

"After the war, the group grew quickly, especially once the Cold War started. We became the technical arm of the Navy for electronic warfare. Once the organization attained departmental status [at NRL], I was made head of the department. But, it can all be traced back to the work we did in the war."[24]

Today, NRL's Tactical Electronic Warfare Division works on a mind-boggling portfolio of research that has evolved from its WWII roots along with a half-century of progress in sensors, electronics, computers, and information and communications technologies.

Antisubmarine Warfare—The U-Boat Menace

As the silent war of the electromagnetic beams was going on above the land and sea, another set of military technology battles was being waged under water. At NRL, this was the domain of the Sound Division, the lesser known fraternal twin of the Radio Division.

When U.S. Navy ships in Pearl Harbor began shattering and sinking under the onslaught of Japanese bombs and torpedoes, the Fleet was just beginning to exploit underwater acoustic detection techniques, that is, sonar. In addition, during the days, weeks, and months that followed the attack, German submarines were regularly spotted from

U.S. coastlines. Tens of U.S. merchant ships were sunk each month; sometimes coastlines were stained with oils slicks from destroyed tankers.[25]

On both sides of the Atlantic, Nazi U-boats were overwhelmingly winning the "sink or be sunk" contest; in 1941, U-boats sank 1,118 ships while the Allies sunk only 30 German U-boats as well as five Italian submarines. After the United States entered the war, merchant ship losses averaged 75 per month while U-boats were sinking at the rate of only 3 per month.[26]

At this early stage of American involvement in the war, the Battle of the Atlantic was being lost. And of every 100 U-boats that Allied ships detected, 95 got away.[27] The Pacific was no safe haven either. Japanese subs lurking in the waters of Far East were sinking an average of 10 American merchant ships per month.

The submarine was so menacing that the United States quickly assembled an enormous infrastructure of research with a specific mission to stop the carnage wrought by the submarines. More than a year before the Japanese attack on Pearl Harbor, the National Defense Research Committee had begun work to counter this threat by recruiting scientists and engineers, mostly from academia, to the arena of underwater acoustic warfare. When the Nazis took France in June 1941, Dr. Vannevar Bush, President of the Carnegie Institution, used the NDRC as a model to create a more encompassing coordinating body known as the Office of Scientific Research and Development. By 1945, the OSRD, with NDRC as a suborganization, had recruited over 32,000 scientists and engineers; 2,500 of them were employed in NDRC's Division 6, "Undersea Warfare."

Like their NRL brethren in the Radio Division, the paltry batch of 15 researchers[28] in the Sound Division found themselves part of a rapidly expanding research and development mission. At least 42 companies and 25 colleges and universities would ultimately join the sonar program. Well-known centers of ocean research, including the Woods Hole Oceanographic Institute on Cape Cod and the Scripps

Institution of Oceanography in San Diego, joined the fray. The NDRC established entirely new laboratories at various institutions with missions ranging from studying the theoretical aspects of sonar to testing, evaluating, and calibrating newly designed equipment.

NRL's Sound Division, which until the beginning of WWII practically had constituted the Navy's entire store of sonar research and development, become a minuscule component of wartime sonar research. Yet its value was disproportionate to its size. A 1946 booklet prepared by the Office of the Chief of Naval Operations to describe what was then the declassified part of the sonar development story assessed NRL's role in this way: "The equipments [sic] developed at NRL in conjunction with the Bureau of Ships Sonar Section and progressively installed in Naval vessels during peacetime, constituted the primary sonar techniques which were employed throughout World War II."[29]

The JK and QB sets were part of this set of techniques. The JKs were passive listening detectors with piezoelectric Rochelle-salt crystals as the sensing elements (see Chapter 3). Under normal conditions, they could detect submarines up to 5 miles away and with bearing accuracies within a few degrees. The echo-ranging QBs were essentially a combination of the JK listening sonar with a sound transmitter that also was based on the Rochelle-salt crystals.[30]

The external equipment for the standard sonar systems included a spherical housing made of rho-c, the rubber material that B.F. Goodrich scientists developed with Elias Klein as part of his effort within the Sound Division to design a better protective housing for the water-soluble Rochelle salt. Inside went the JK or QB equipment immersed in castor oil, which has pretty much the same acoustic characteristics as sea water without the nasty habit of dissolving the crystals. By 1933, the Submarine Signal Company of Boston was producing much of the Navy's sonar gear and the Washington Navy Yard, just a few miles upstream from NRL on the other side of the Anacostia River, was installing them into Navy vessels.

The U-boats of World War II were faster, quieter, and deeper running than their WWI predecessors. So despite the efforts of NRL's Sound Division, British researchers at the Admiralty Research Laboratory, and others, sonar technology and general antisubmarine warfare techniques remained in desperate need of improvement. The miserable score during the Battle of the Atlantic throughout 1942 was the most tragic and obvious sign that something had to be done.

In an NRL report late in the year, Harvey Hayes, superintendent of the Sound Division, reflected the dire situation in these words:

> *"The conclusion is reached that we are losing the present antisubmarine war by such a large margin that measures should be immediately taken to outline, codify, and put into action a more effective antisubmarine program."*[31]

More than merely stating the problem, Hayes recommended specific tactics, including dropping a series of rapidly sinking munitions such as contact and proximity depth charges instead of the slow sinking pressure-fuzed depth charges.

These and other responses to the submarine problem began having positive effects for the Allies in 1943. By then, radio direction finders could pick up submarine transmissions and then send radar-equipped planes to pinpoint the U-boats. If the U-boats submerged to shrug off the radar surveillance, then the planes could drop Radio-Sono buoys that would send out radio alerts to sonar-equipped (or the British equivalent, Asdic-equipped) ships to zero in for the kill. Besides the continual improvement of radar and sonar technology, the undersea warfare researchers were coming up with all manners of gadgetry. There were visual aids like the "Bearing Deviation Indicator" that helped sonar operators aim the equipment more effectively. A "Maintenance of True Bearing" incorporated a gyro to keep sonar beams directed on U-boats even as the fleeing or pursuing ship underwent complicated maneuvers and turns.

Other developments also helped put U-boats on the run: better convoying methods, a growing understanding of how ocean temperature affects the ability of U-boats to hide, and more capable sonar

equipment. In 1943, the Allies lost 598 ships, but they sank 219 U-boats, 22 Italian subs, and 22 Japanese subs.[32]

Just as in the world of electronic countermeasures, the submarine warfaring community was developing countermeasures. For submarines, the equivalent of chaff was to release packets of chemicals that generated regions of bubbles, which appeared as phantom echoes on sonar equipment. To divert sound-seeking torpedos, ships towed sound-generating decoys behind them. NRL had its hands in all of these efforts.

In the summer of 1944, the Germans developed an alarming countermeasure—called the Schnorchel—that made them far less vulnerable to detection via eye or radar. As its name might imply today, the Schnorchel was a stack that could extend to the surface while the submarine as a whole remained at periscope depth. It meant that the U-boat could expel diesel exhaust and draw in fresh air to replenish its batteries under much more stealthy conditions. "Effectively, the Schnorchel had neutralized our antisubmarine air offensive and defeated our surface detection. But, whether schnorchelling, submerged, or bottomed—the Asdic-Sonar teams detected and located the U-boats," stated a 1946 Navy Department account of the sonar story.[33] Help came also from the development of microwave-based radar, which could detect smaller objects more readily than the longer-wavelength radar systems.

The 1944 sea warfare box score tells a lot: 134 Allied ships were sunk but Allied forces killed 202 U-boats and 51 Japanese submarines. The Allies had turned the tide of the Battle of the Atlantic. In a secret but intercepted communique, Grand Admiral Karl Doenitz, the man in charge of all Nazi naval operations during the war, could not have more gloriously congratulated the efforts of his enemy's undersea warfare researchers if he were their mother. Said Doenitz:

> *"For some months past, the enemy has rendered the U-boat ineffective. He has achieved this object, not through superior tactics or strategy, but through his superiority in the field of science; this finds its expression in the modern battle weapon: detection. By*

> *this means he has torn our sole offensive weapons in the war against the Anglo-Saxons from our hands. It is essential to victory that we make good our scientific disparity and thereby restore to the U-boat its fighting qualities."*[34]

With innovations like the Schnorchel, German engineers tried to make good on the Grand Admiral's entreaty, but not before the momentum of warfare had swung inexorably in favor of the Allies.

Building 44: The Unspeakable Specter of Gas

Though not nearly as big as the Radio Division, which was an elephant among mice and cats, the Chemistry Division grew during wartime at a faster rate than any other division at the Laboratory. By 1945, it had grown from a prewar staff of about two dozen to a strength of about 200 researchers distributed amongst 10 sections occupying four fully equipped buildings.

There was a lot of troublesome chemistry going on in the Navy. Metal was corroding. Fuel was spoiling. Torpedo batteries were not powerful enough. There were not enough solid sources of oxygen to meet the demands of submarines. Optical surfaces on gunsights were fogging up. When word of such problems came in, chemists in the Corrosion Section or Fuel Section (later called branches) were tasked to come up with solutions, which they did in the form of such innovations as corrosion-inhibiting paint pigments or defogging agents. Those in the Physical Organic Section developed several "chemical noise makers," which were the submariners' equivalent to the airmens' chaff. When ejected from submarines, these substances simulated propeller and engine sounds, thereby luring German acoustic homing torpedoes harmlessly away from their intended targets.

Chemists in the Special Research Section completed a grab bag of projects leading to a number of lifesaving innovations. Among them were "Sea Marker" and "Shark Chaser," which became part of survival kits for thousands and thousands of U.S. airmen and sailors. The chemical heart of "Sea Marker" was the fluorescent dye sodium fluorescein, which would spread out and glow around a shipwrecked sea-

man thereby marking his location for rescue vessels. "Shark Chaser" was a cocktail of olfactory and ocular irritants designed to repel sharks.[35]

The Chemical Protection Section was born of terror. Although violent death by any means is awful to contemplate, the deadly chemical attacks of World War I held a special power to instill fear. It was the German military that introduced large scale chemical warfare during World War I during which 5,000 soldiers lost their lives in a yellow-green, ground-hugging cloud of chlorine gas. In 1917, in the trenches of Ypres, Belgium, the Germans unleashed a blistering agent, sulfur mustard. It worked by absorption through the skin so not even a good gas mask would serve as protection.

Sulfur mustard caused four hundred thousand casualties during the Great War.[36] What was to stop the Nazis from using chemical weapons on the new fronts of World War II? Indeed, there were reports early during World War II that the Germans and Poles had used mustard gas against each other.

When the war broke out, Homer Carhart was a 27-year-old chemist in a new teaching job at Gallaudet University, a school for the deaf in Washington, DC. He got a call from Bill Williams of NRL's Protective Chemistry Branch. Williams had been an instructor at the University of Maryland when Carhart was a graduate student there. Carhart, now unmistakable for his waxed handlebar mustache and straight-to-the-core clarity, quickly joined the effort on a crash program to develop defensive measures against chemical weapons should the enemy add them to its roster of weapons.

"These preparations included the establishment of secret research programs to develop better protective clothing for the troops and to investigate ointments and salves that might be effective at reducing the blistering effects of sulfur and nitrogen mustard (collectively termed mustard agents) and lewisite, an organic arsenic-containing compound that shared some properties with mustard agents," according to a 1993 book-length report by the Institute of Medicine, which had established a committee to investigate the wartime research into

chemical agents and protection and the effect of this work on some 60,000 human subjects, nearly 2,500 of whom were tested at NRL.[37]

After World War I, the U.S. military consolidated virtually all research or production work involving chemical warfare agents within the Chemical Warfare Service at the Army's Edgewood Arsenal in Maryland. When war broke out in Europe in 1939 and U.S. neutrality appeared less stable in the next two years, the National Defense Research Committee and the Committee on Medical Research, another high-level wartime panel for coordinating crucial research, organized a much larger and expanded chemical warfare research program. The entire Allied research effort in this area was conducted in more than a dozen sites, at least nine of which included the construction of gas chambers in which human subjects in experimental protective clothing could be exposed to chemical warfare agents.

NRL became a key part of this crash effort. Homer Carhart, who remains closely connected to the Laboratory as a senior scientist emeritus, began his NRL career in the heart of this controversial research.

Although crucial, the research was troublesome from the start. Carhart recalls his own personal run-ins with the agents he was making or using: "We were working with live agents, mostly mustard, and occasionally we hurt ourselves, got burned. I was doing some work on phosgene one time and got an overdose of it and couldn't talk for several days because of the problem it created in the bronchial area and the lungs."[38]

Not all of his exposure was accidental. Carhart explains:

"In working with these things and working with protective agents, one of the things that I did was I started to use myself as a guinea pig to see if I could develop neutralizing agents . . . There were a lot of things we tried, so it was not unusual for me to be walking around with a bunch of blisters on my arms."[39]

Even after Dr. Borgstrom, the Chemistry Division's Superintendent, saw these wounds and threatened to fire Carhart if he continued the practice, Carhart persisted. "I finally used myself as a guinea

pig a little too much and became sensitized, so that I was no longer a good guinea pig," he recalled.[40] He wore long-sleeved shirts to hide this practice from Borgstrom.

Young Carhart would raise Borgstrom's ire on another occasion, though he would blame the weather for this one. As Carhart recalls it, Borgstrom arrived at the Laboratory early one morning and caught a strong whiff of what he knew from prior research experience was sulfur mustard. He promptly closed down the building. When Carhart showed up for work, he was the usual suspect. "They didn't know if I had spilled the damn stuff or what the hell was going on," Carhart recalls.[41] It turns out that there was an atmospheric pressure inversion the prior night. As Carhart sees it, this condition overwhelmed the less-than-good hood under which he had been making his own sulfur mustard to substitute for the intolerably impure supply that had been available from other sources.

"That got the ball rolling to give the chemical group its own building," said Carhart. Within a few months, Building 44 had been designed and built specifically for chemical warfare research. It was one story tall with "damn good hoods in it," and facilities for making and supplying the active ingredient (a chloramide) in all Navy-issue ointments as well as the impregnated charcoals used in all Navy gas masks. Two other significant facts about Building 44 characterized its research: it was not built on the grounds of NRL, but rather just south on the grounds of the Blue Plains Sewage Plant; and Building 44 included one of the country's first chambers designed for human testing.[42]

In the wartime context, knowing with confidence what your protective clothing can and cannot do for you during chemical attacks is imperative for crucial decisions on levels all the way down to individuals making immediate life-and-death decisions and all the way up to the highest levels of military planning where the entire war could be won or lost. In the judgment of those coordinating and doing the chemical warfare research, human testing was a necessity, not a luxury. There seemed to be no time for weighing the impossibly

murky and troublesome ethics unavoidably linked to any potentially, even probably dangerous regimen of human testing even though the intention is to save lives in the long run. Indeed, NRL and the other research centers then doing human testing would undergo full investigations a half-century after the fact when they became the focus of a class-action suit and a high level investigation by the Institute of Medicine.[43]

But faced with an imminent WWII chemical threat, NRL's chemical warfare group felt they had a job to do. Under the auspices of the NRDC and the OSRD's Committee on Medical Research, NRL made arrangements for trainees at the Navy boot camp in Bainbridge, Maryland, to come to the Laboratory to serve as subjects. Between 1943 and 1945, sailors who had volunteered for the research detail arrived at the Laboratory at regular intervals. In time, their total numbers would approach 2,500.[44] Most of these sailors were slated for imminent duty in the Pacific where they knew many among them would never return alive. Carhart recalls one of the motivations of these men for coming to NRL: "They were sitting in the outgoing unit, waiting to be sent to the South Pacific, question mark about coming back. Now, they had a chance to stay in the United States for some time longer, several weeks certainly, and to have some more liberty, some more time free. It had its appeal."[45]

Many of these subjects underwent patch tests. This usually entailed exposure of one or several spots on their arms to warfare agents that had been dissolved in solvents before or after applications of some hopefully protective ointment formulation of unknown effectiveness. At NRL, medical doctors assigned to the project monitored the men and made photographic records of the results.

Many of the subjects underwent the more extensive chamber tests. Simple military logic might justify the tests. As Carhart stated it, "If we could put people into a chamber with war gas and protect them, they would be protected in the field."[46]

According to an investigation by the Institute of Medicine in the 1990s, a major goal of these nationwide studies was to determine

"how long, under what conditions of temperature, and under what concentrations of gas, would chloramide- or activated carbon-impregnated clothing afford protection of personnel against chemical attack with vesicants [blistering agents]."[47]

The typical test, often known as a "man-break" test, was as follows. Men, garbed in various preparations of protective clothing, entered a chamber where they were exposed to measured quantities of gas of usually one hour duration. At NRL, chemist Bill Taylor and his coworkers regularly monitored the concentrations of the agents by continuous sampling the chamber air during the tests. Twenty-four hours after the exposure, medical professionals in the Navy's Bureau of Medicine and Surgery, who had legal responsibility for the tests, examined the men for any physiological evidence, such as redness or blisters, that war gas had penetrated the protection. If not, the subjects would undergo additional exposures every day or every other day until they did show such signs.[48]

The first tests were alarming, Carhart recalls. They showed how poor the standard Navy issue protective clothing was. For one thing, the clothing had poor shelf life. The protective compound in this clothing, from a chemical class known as chloramide, had slowly been decomposing, yielding acidic compounds that were eating up the cotton of the clothing. Carhart recalls picking up some of these suits and getting handfuls of shreds. Moreover, chloramide afforded protection against sulfur mustard and lewisite, but little or none against nitrogen mustard.[49]

The preparation of the standard suits had additional problems. Not only did it involve organic solvents that carried their own toxicities, but it involved a binding agent that became gooey and was itself a skin irritant. This yielded very uncomfortable gear. These were just some of the problems that sent the NRL team into the laboratory to find ways to stabilize the existing chloramides, to develop alternative chloramides and other protective materials that could disarm the nitrogen mustards, and to find better ways of actually making and preparing the clothing.

Along the way to this goal, the NRL chemists and collaborators came up with several protection techniques that never had to be used. Carhart recalls some of them. "We developed a little package device over here so a sailor could actually take his ordinary clothing, and take his helmet, put water in the darn thing, and put this little package in like dry soup, and make a mix of the darn stuff, and put it on his clothing. It's surprising what good protection the stuff gave. We developed systems so you could use field laundries, or the ship's laundry, and use the laundry as a method of impregnating the clothing and protecting the people."[50]

One of the most important contributions that Carhart remembers NRL making to the chemical warfare research effort was to incorporate the protective principle of gas masks into the quest for better protective clothing. The way the gas masks worked was to force air to pass through a mass of extremely porous carbon before getting inhaled. Along the way, most organic molecules, which is a large class of compounds including the then known chemical warfare agents, stick to the adsorbent carbon rather than continuing on the air flow into a masked person's lungs. "We worked with the industry to develop different kinds of carbon clothing," Carhart recalls.[51]

The result of collaborations with fiber-manufacturing companies was the development of a new material that was a carbon-impregnated rayon, which could be woven into protective garments. The task involved many engineering problems, not the least of which was to check the damage to the spinnerets wrought by the tiny abrasive carbon particles, which pocked the fibers' surfaces like stones on a rope of clay. This work was so cutting edge and of such high priority that it came to involve one of the world's newest, most promising, and vastly undersupplied materials—nylon. It turns out that the additional carbon weakened the rayon fibers, but by weaving the modified rayon with nylon, fabrics of sufficient strength could be made. DuPont had introduced nylon commercially in 1939 but when the war broke out, the War Department labeled it as a strategic material. It was strong enough to substitute for silk in parachutes and for making tire cords.

Nylon for nonmilitary uses was rare and coveted. "A pair of nylon stockings could buy anything," Carhart recalls.[52]

The carbon-impregnated textile the NRL chemists helped develop might have saved many lives had WWII's battlefields been foggy with war gas. Recalls Carhart: "We were able to weave the stuff with the nylon, so that it would now give you the strength and it would give you the protection. We had fabric made of that, and we had suits made of that. That stuff gave more protection against sulfur mustard [and several other chemical warfare agents] . . . than any chemical clothing."[53]

Though still awkward in design (the men had to cut flies in the suits so they could urinate), these suits underwent rigorous and punishing tests at Camp Lejeune in North Carolina where Marines were training for some of the most decisive Pacific battles, including Iwo Jima. The specter of chemical weapons remained threatening. The NRL group knew they had come up with something worthwhile when the suits that had been worn by trainees wading through swamps or hitting beaches in landing craft fared well enough to return to NRL for retesting on subjects in Building 44.

Hitler had no qualms about using lethal gas as a major means of mass murdering Jews, Gypsies, and other civilians. But, as it turns out, the Nazis did not use chemical warfare agents in battle. One anecdotally offered reason for this reserve was that Hitler had survived a chlorine gas attack during World War I and developed such a personal fear of such weapons (which could creep under the doors of any concrete bunker) that he forbade their use.

Ironically, the only battlefield casualties due to chemical warfare agents occurred after German bombers raided the harbor of Bari, Italy on December 2, 1943. One of the ships that sunk that day was the merchant marine ship SS *John Harvey*. Secretly in its hold were 2,000 sulfur mustard bombs. As the damaged ship went down, sulfur mustard leaked out and mingled with the oil and other debris in the raided harbor. Shipwrecked sailors, medical personnel who cared for them later, as well as civilians from Bari who had been exposed to clouds of

the agent, all became unwitting casualties to an unexpected hazard. The numbers are staggering. Of the 600 victims of sulfur mustard in the harbor area, 83 died. Civilian deaths in the town approached 1,000.[54]

Chemical warfare research at NRL and elsewhere came to a quick stop after World War II ended. Carhart laments that the consequences of such rapid dispersal and disengagement of those involved was that the work and technology were never properly documented. Fear of chemical warfare never disappeared, however. The shift from chemically impregnated protective clothing to the use of textile fibers studded with tiny absorbent carbon particles, which NRL scientists espoused during the war years, was a sound principle to which military researchers would return in later years.

For four decades, hardly a word about the human costs of the chemical warfare research reached public attention. In the 1980s, however, some of the approximately 60,000 U.S. servicemen who were human subjects in the wartime experiments began seeking compensation from the Department of Veterans Affairs for maladies they and their doctors believed derived from that experience. In 1991, the Veterans Administration (VA) sought guidance in the handling of these cases by asking the Institute of Medicine (IOM) to conduct a study into the association of chemical warfare agents used during the wartime research with specific diseases.

The 427-page IOM study that came out of this was published in 1993. The task was immense because records of the research and the human subjects involved generally were either woefully scant or absent. Moreover, no followup studies were ever conducted by any of the research teams involved to see if there were long-term effects on those exposed to chemical warfare agents. It turns out that the most valuable data regarding the wartime experiments came from NRL due largely to Homer Carhart. "I save shoelaces," he says.[55] He also saved a crucial box of records from the chemical warfare research, including the names of many of the test subjects as well as medical photographs of the subjects. To develop recommendations for the VA, the IOM panel subse-

quently was able to use this, other lines of evidence including long-term epidemiological data from workers exposed to toxic agents, as well as information from the aftermath of chemical attacks during the Iran-Iraq war in the 1980s.

The IOM recommended that the VA do everything it could, including public announcements and advertisements, to identify and locate the test subjects (and chemical warfare agent production workers), medically evaluate them, and provide treatment when necessary. Carhart's habit of "saving shoelaces" paid off. The documents he saved from the wartime chemical warfare research enabled the IOM to locate many of those test subjects who were exposed at NRL.

After WWII, Carhart devoted most of his time to such critical Naval issues as making the interiors of nuclear submarines habitable during long submersions and reducing risks and effects of fire throughout the Fleet.

The Navy's Secret Little Manhattan Project

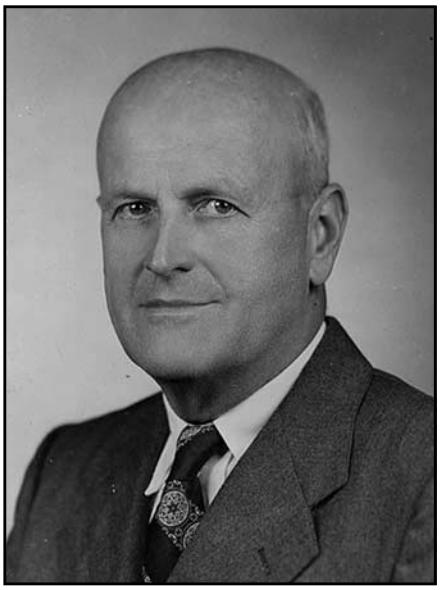
On July 2, 1943, at about 2:30 p.m., Mr. Trafton Robertson, a radio announcer for the Mutual Broadcasting Company, piqued the interest of anyone who happened to be listening to a special live broadcast of NRL's anniversary celebration. "Today is the Naval Research Laboratory's twentieth birthday, so we have brought our Mutual microphones inside these closely guarded walls which shield from prying enemies some of the most astounding secrets that this war has thus far developed," he told his listeners.[56]

Some of the secrets Robertson was referring to already were partially out. In a congratulatory letter to Admiral A.H. Van Keuren, NRL's director at the time, President Franklin D. Roosevelt singled out one of these. He cited "detection of the enemy" as a particularly tough and militarily critical nut that NRL helped to crack. "Our success is proven since we are now able to meet the enemy in the air and on the sea with unsurpassed battle intelligence," the President wrote.[57] He was referring here primarily to radar.

Later during the anniversary proceedings, James V. Forrestal, Under Secretary of the Navy, filled in some details. He praised NRL's pioneering contribution to radar, a technology Forrestal credited with helping to win the Battle of Britain by enabling British fighters to get off the ground minutes before their enemy cohorts had arrived above them. So rather than becoming sitting ducks, the British airmen were able to engage the German fighters in the air where the attackers suffered enough losses to lose the long battle. Forrestal also credited radar with helping the Allies win the battle at Guadalcanal. He put it this way: "a taskforce of our battleships had steamed out of the midnight blackness and at a distance of over nine miles, shooting by radar control, had broken the back of the Japanese striking forces."[58]

While all of this well-deserved self-congratulation about NRL's was taking place, the m.c. of the ceremony and some of the attendees, including Ross Gunn of the Mechanics Division and Rear Admiral Harold Bowen (who recently had left as NRL's director to work in the Office of the Under Secretary of the Navy), undoubtedly were thinking of another top secret project at NRL.

The project began as an insight in the mind of Ross Gunn. As technical advisor to the director of NRL, Gunn participated in high-level Defense Department meetings. On March 17, 1939, he and NRL colleague W.H. Sanders attended a particularly interesting one during which physicist Enrico Fermi, the most recent winner of the Nobel Prize who had arrived from Italy to join the faculty of Columbia University, briefed Navy commanders about a momentous success in the fall of 1938 by German scientists working in Berlin at the Kaiser Wilhelm Institute for Chemistry. Otto Hahn and Fritz Strassman deliberately split uranium atoms by bombarding them with neutrons. Evidence for the process came in the form of barium atoms, which Hahn's former research partner, Lise Meitner had reasoned would emerge from splitting uranium atoms as atomic fragments. Anybody who knew how to plug numbers into Einstein's famous equation describing the equivalency of energy and mass—and Fermi knew how to plug in numbers—



Among other notable achievements at NRL, Dr. Ross Gunn initiated the first nuclear research sponsored by an agency of the U.S. Government.

could see that the splitting atoms could yield vastly more energy compared to any means of energy release so far harnessed by humanity.

Fermi told the gathering in Washington, DC that no one knew if the process could lead to new kinds of weapons. But he and everyone else knew that if an atomic bomb could be made, it would become the most terrible weapon the world yet had seen. The topic of harnessing atomic energy for power production also came up during the meeting. Fermi would subsequently head a research team that achieved the world's first sustained nuclear reaction in a pile of uranium-235 (U^{235}) underneath a gymnasium at the University of Chicago on December 2, 1942. It was a major step toward development of both the atomic bomb and nuclear power.

The March 17 meeting had a profound effect on Gunn, who quickly saw the potential of atomic power for revolutionizing submarine propulsion. He realized that a submarine powered by atomic energy rather than the energy harbored in chemical fuels could remain submerged almost indefinitely. In that case, human psychology rather than the need to refuel or recharge batteries, would become the limiting factor to how long a submarine could remain continuously submerged. The submarine would become an even more awesome and powerful instrument of war.

Three days later, on March 20, Ross Gunn, eight NRL associates, and the NRL director, Captain Hollis Cooley, visited Rear Admiral Harold Bowen, then the Chief of the Bureau of Engineering. (Bowen would

replace Cooley as director of NRL several months later.) They asked Bowen to assign $2,000 to NRL, in the words of a memorandum written after the war was over to, "initiate the first steps in the solution of the uranium power problem."[59] They got the money. In his autobiography published in 1954, Bowen, by then a retired Admiral, claimed that this money was "the first government money spent on the study of atomic fission."[60]

The first problem for nuclear bombs or nuclear propulsion derived from a common reality in the Periodic Table of Chemical Elements. Like many elements, uranium atoms come naturally in several isotopic forms that differ from one another in the number of neutrons they have in their respective nuclei. As it turns out, nuclear fission occurs far more efficiently in the presence of unnaturally high populations of the isotope U^{235}. In uranium ore, this desired isotope is present in the ratio of about 1 to every 143 U^{238} atoms, which has three more neutrons in its nucleus. Gunn knew, therefore, that any practical system of nuclear propulsion entailed having a plentiful source of uranium fuel enriched in the U^{235} isotope. The requirement for U^{235} enriched material is even more critical when it comes to making bombs, which had to be compact enough and light enough to be carried by aircraft.

The task fell first to Roman Miller of NRL's Chemistry Division and T.D. O'Brien, an isotope separation specialist hired from the nearby University of Maryland specifically to work on the uranium isotope problem. The strategy from the start was to synthesize a uranium-containing chemical compound that would exist in the gaseous state under conditions that were not too extreme. Once in the gaseous state, the slightly different masses of molecules containing the different uranium isotopes would provide the physical basis for separating them. Uranium hexafluoride fit the bill. By about January 10, 1940, Miller and O'Brien had gram-sized samples of uranium hexafluoride in hand.

Just three months earlier, President Roosevelt had received a letter signed by Albert Einstein in which the world famous physicist warned

of the imminent potential for physicists anywhere in the world to tap uranium fission for unprecedented amounts of energy. "This new phenomenon would also lead to the construction of bombs, and it is conceivable—though much less probable—that extremely powerful bombs of a new type may thus be constructed," Einsten warned in his letter which was written on August 2 but did not reach the President until October 11.[61]

Within weeks, the President had set up the Advisory Committee on Uranium to keep track of the development in uranium and nuclear research and to recommend actions. Ross Gunn would become a member of the committee. The official start of the Manhattan Project, which would produce the world's first nuclear weapons, was still two years away.

Meanwhile, as soon as the NRL chemists synthesized the uranium hexafluoride, it went to several university laboratories whose secret charge was to develop means of enriching the samples' U^{235}. By the end of February 1940, a scientist at the University of Virginia, on a $13,000 contract with NRL, already had a partially enriched subgram sample of uranium hexafluoride that he obtained with a high-speed centrifuge. At the same time, researchers at Columbia University under a $30,000 contract also had begun centrifugal separation studies as well.

The work that would prove more fateful started more humbly. First for free and then with a $3,500 allotment, Philip Abelson of the Carnegie Institution of Washington (CIW) began pursuing a different separation process—liquid thermal diffusion method. Abelson was a new hire from Lawrence Berkeley Laboratory in California where he had been working on new electron accelerators. That made him one of the few nuclear scientists in the country. His boss was Merle Tuve, the same man who 15 years earlier had used NRL radio transmitters to measure the variable height of the ionosphere.

The basic idea of the liquid thermal diffusion method was to put dissolved uranium hexafluoride into a column whose ends were kept at very different temperatures. Since those uranium hexafluoride

molecules harboring the lighter U^{235} atoms diffuse slightly faster to the warmer side of the column than do those molecules with heavier uranium isotopes (mainly U^{238}), the lighter molecules end up enriching on the warm side of the column. This U^{235} enriched solution then becomes the starting fluid for a next iteration in a diffusion tube and so on. In each cycle, the proportion of U^{235} (still forming the center of uranium-hexafluoride molecules) by the warm side of the column increases. In time, technicians would withdraw the uranium hexafluoride and then covert it into metallic uranium enriched in U^{235}.

Abelson recalls that soon after he began working on the process at CIW, which meant first building all manners of columns, he found himself running out of space, Tuve got nervous about the space-consuming trend. To relieve his angst, Tuve arranged for Abelson to move his uranium project to a more spacious setting at the National Bureau of Standards, which was then just a few miles away down Connecticut Avenue. The director of NBS, Lyman Briggs, was a member of the Uranium Committee and was more than happy to accommodate Abelson and Tuve. Through Briggs and Tuve, Ross Gunn was kept well informed of Abelson's doings.

Abelson had hardly got up and running in his new NBS setting when he realized he needed to increase the size of the diffusion tubes yet more. That design change had the troubling consequence of entailing higher pressure steam than he could get at NBS. That started the machinery in motion that would result in Abelson's second major venue shift within half a year of arriving in Washington.

Gunn had been attracted to the process Abelson was set on because it looked practical, the kind of process you could scale up to massive scales. So when he heard that Abelson needed a more capable source of steam, he invited the CIW scientist to NRL to take a look around. Abelson liked what he saw and on July 1, 1941, he became an NRL employee. Adjacent to the boiler house near the waterfront where NRL butts against the Blue Plains Sewage plant, Abelson and his new NRL collaborator, John (known as Jack) Hoover, set up

column after column, each time changing the spacing between the hot and cold walls of the tube. Everything about the tubes seemed to matter—their lengths, diameters, and the difference in temperature between their hot and cold walls. Money for this and the other isotope separation studies came from the Navy Bureaus of Ordnance and Engineering, which each kicked in $26,000, and from the Army Ordnance Department, which provided $50,000.

By late 1942, Abelson's NRL staff had increased by four and he had several contractors working on specific problems in theory and analysis. They had arrived at a working set of column conditions and built a pilot plant of 12 columns, each 48 feet tall. The enriched material they were harvesting from these columns represents some of the first substantial amounts of slightly enriched uranium ever obtained. On December 10, the little riverside curiosity, which few people at the Laboratory had clearance to know about, received a visit as unexpected as it was fateful.

On that day, a colonel of the Army Engineers by the name of Leslie R. Groves arrived without warning at the office of NRL director Admiral Bowen. At the time, Bowen was unaware that Groves was running the super-secret Manhattan Project that officially had begun on December 6, 1941, the day before the Japanese attack on Pearl Harbor. Groves asked to see the small pilot plant that Abelson and his associates had built. Approximately six and ten weeks after his visit, Groves' technical advisory body paid two visits to NRL to assess the plant and the liquid thermal diffusion process for its potential in helping the bomb project.

According to a memorandum on the history of the uranium separation work at NRL issued in 1946 and signed by its participants, "It is reported that the technical advisory committee was favorable to our method, but the building of a liquid thermal diffusion plant was vetoed by someone higher up."[62] Whatever the committee's actual recommendations, liquid thermal diffusion did not then become a component of the bomb project.

Although it appeared that neither NRL nor the Navy would be playing any part in the Manhattan Project, liquid thermal diffusion remained the number one candidate for acquiring the material needed for nuclear propulsion (which required less enrichment than did bombs) and the Navy was going full steam ahead. In June 1944, NRL proposed the construction of a 300-column production plant to Vice Admiral Edward L. Cochrane, chief of the Bureau of Ships.

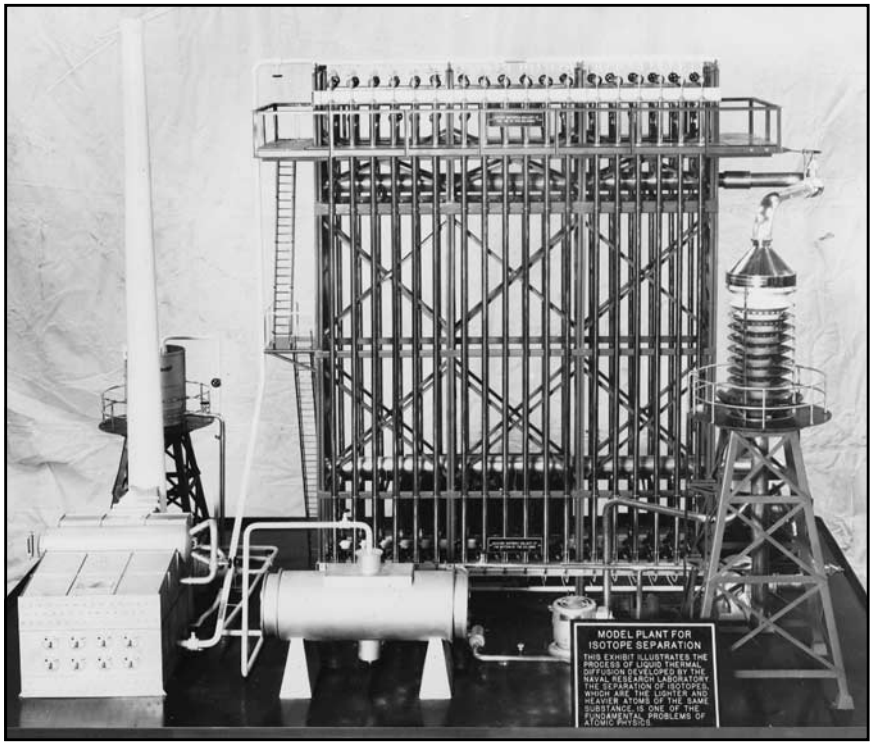
In post-war memoranda about this move, the Laboratory stated an additional rationale for the plant. "The purpose of this plant was to supply insurance against failure of part of the Army's separation program and to provide the Naval Research Laboratory with materials for study of atomic energy," stated the August 9, 1945 memorandum to the Chief of Research and Invention, who was none other than former NRL director, Rear Admiral Harold Bowen.[63]

As it was when Abelson made his move from NBS to NRL, steam remained a key commodity in the diffusion process. With a 300-column plant on the horizon, however, there would be a need for massive amounts of high-pressure steam. As home to the Naval Boiler and Turbine Laboratory, the Philadelphia Navy Yard was the place to go for lots and lots of steam. This site would become the location for the secret, two-million-dollar isotope separation facility. Abelson remembers living on the road between Washington and Philadelphia after construction of the plant began in November 1943.[64]

Just as the plant neared completion the following June, NRL was shocked to learn that the War Production Board was going to turn down their request for the uranium hexafluoride, the starting material without which the new plant would be idle. Not only was this chemical the feedstock for the separation process, but Abelson and his NRL colleagues were the ones who came up with the very process for producing large amounts of the material in the first place. When the NRL team attempted to circumvent this obstacle by shifting to an alternative method of making the feedstock based on abundantly available uranium oxide ores, these alternative starting materials also were

denied them. With aggressive pressure by high level Navy officers, this *de facto* embargo against the Navy's uranium isotope program was finally lifted. By the end of June 1944, the Philadelphia pilot plant began production.

Meanwhile, Abelson had become aware that the isotope separation plant at Oak Ridge, Tennessee, which relied on a gaseous diffusion process, was badly behind schedule. He began to worry that the entire bomb project might be in jeopardy. A logical consequence of this, he thought, was that the liquid thermal diffusion process just might be an ace in the hole for the Manhattan Project. He wanted Robert Oppenheimer, scientific director of the Manhattan Project at Los Alamos, New Mexico, to know what NRL had to offer at the Phila-



A liquid thermal diffusion plant for separating uranium isotopes, like the one shown in this model, was built at the Philadelphia Navy Yard in 1943. In 1944, a larger plant went into operation at Oak Ridge, Tennessee, where it speeded up the production of uranium for the country's first atomic weapons.

delphia plant. Already frustrated by the veritable locking out of the Navy vis-à-vis participation in the bomb project, Abelson chose to circumvent the conventional means of communications within the Manhattan Project. This is what Abelson told historian Richard Rhodes:

> *"I wanted to let Oppenheimer know what we were doing. Someone in the Bureau of Ships knew one of the people in the [Navy] Bureau of Ordnance who was going out to Los Alamos. I remember that I met the man at the old Warner Theater here in Washington, up in the balcony—real cloak and dagger stuff."*[65]

Rhodes fleshed out what happened next: "Abelson briefed the Bureau of Ordnance (BuOrd) officer about the plant he was building. He said that he expected to be producing 5 grams a day of materials enriched to 5 percent U^{235} by July. This vital information the BuOrd man carried to Los Alamos and passed along to Edward Teller. Teller in turn briefed Oppenheimer. Oppenheimer apparently conspired then with Deke Parsons, the Hill's ranking Navy man, to concoct a cover story: that Parsons had learned of the Abelson work on a visit to the Philadelphia Navy Yard. With the Navy thus protected, Oppenheimer on April 28 alerted Groves."[66]

All of this transpired in the weeks following completion of the Philadelphia plant. Admiral Bowen later recounted what followed: "On 26 June, 1944 the blueprints of the Naval Research Laboratory were turned over to Colonel Fox of the Manhattan [Project] to facilitate the construction at Oak Ridge, Tennessee, of a new plant using the Abelson-Gunn process with 2,200 elements or seven times the capacity of the Navy plant at Philadelphia."[67] That summer, Leslie Groves himself paid a visit to the Philadelphia plant as well, his second personal enounter with the liquid thermal diffusion process.

By the last week of August, Harvard University President James Conant, a chief science advisor to Colonel Groves, had recruited 10 enlisted soldiers with technical skills. Arnold Kramish, who was on detail at the Philadelphia plant from Los Alamos where he had been

working on the detonators for the first atomic bombs, recalls Conant's pitch:

> *"[He] told us very little about what he was asking them to do, and he cautioned them that the job would be very dangerous, testing a new and untried process. 'But,' he said, 'you will be winning the war.'"*[68]

Their mission was to work at the newly operational liquid thermal diffusion plant in Philadelphia. Meanwhile, construction of the 2,200-column Oak Ridge plant had begun. Since most of the engineering problems, including ones with lethal potential, already had been discovered and solved, the Oak Ridge plant went up in record time. By the fall, usable material was coming out of the columns.

On September 2, a week after the Oak Ridge contingent arrived (and the same day that the future president George Bush was shot down over the island of Chici Jima in the Pacific), something went terribly wrong at the Philadelphia Navy Yard. At 1:20 p.m., a swift and tragic series of events began when a cylinder of uranium hexafluoride feed stock exploded in the transfer room and fractured nearby pipes coursing with searing steam. When uranium hexafluoride mixed with the water of the steam, an instantaneous reaction produced hellish mists of hydrogen flouride, one of the most aggressive of acids.

Arnold Kramish vividly recalled what happened:

"There were three of us in the transfer room at the time—myself and two civilians, Peter N. Bragg, Jr. of Fayetteville Arkansas, and Douglas P. Meigs of Owings Mill, Maryland. We inhaled large quantities of uranium compounds and suffered whole body acid burns. Peter and Douglas, both of them civilian engineers, died soon thereafter".[69] Four other civilians and four other soliders were injured in the blast. Abelson even took in several caustic lungfuls of the stuff but did not need hospitalization.

Perhaps the most tragic aspect of the accident was that the project was so secret that, in Kramish's words, "for decades the families of Peter Bragg and Douglas Meigs never knew how they died."[70] Bragg's

parents died without ever learning what happened. Not until Kramish called Peter's brother, Braxton Bragg, in 1987 did a representative of the family finally find out. After unyielding pressure from Kramish and Braxton Bragg, the Navy, for whom Bragg was hired as a chemical engineer at the time of the accident, finally acknowledged Bragg's ultimate sacrifice. On June 12, 1993, Captain Paul Gaffney II, then the Commanding Officer of NRL (now Chief of Naval Research), presented Bragg posthumously with the Commanding Officer's highest civilian medal—the Meritorious Civilian Service Award. The ultimate sacrifice by Douglas Meigs, who was a contractor of the H.J. Ferguson Co. in Cleveland (and as such not a direct employee of the Navy when he died in Philadelphia), has yet to be officially acknowledged.

After the accident, engineers repaired the damage and the plant continued to produce moderately enriched uranium. By the time the Philadelphia Facility closed in early 1946, it had produced just over 2½ tons of enriched uranium. This modestly U^{235} enriched material became feedstock for yet another separation process at Oak Ridge, whose more thoroughly enriched U^{235} became part of the radioactive heart of the first atomic bombs.

"A large fraction of the uranium isotopes embodied in the Hiroshima and Nagasaki [the Nagasaki bomb actually was plutonium-based] bombs were processed by the Abelson-Gunn method," Ross Gunn told the Special Committee on Atomic Energy of the U.S. Senate soon after the war. "We were credited with shortening the war by a week or more, in spite of the delaying tactics and fumbling politics imposed on us by some members of the Manhattan Project."[71]

A week may not sound like much, but a week of world war is different from a week of a world at peace. Just consider the human costs. Estimates of deaths during the roughly six years of World War II range up to 54 million for a weekly average of 180,000. The number of injuries was far greater. It is a strange calculus. After all, the number of Hiroshima and Nagasaki casualties due to the atomic bombs also reached into the hundreds of thousands. For the United States, at least,

an earlier ending to World War II meant more lives saved and fewer families shattered by premature death and endless grief.

NRL and the New World

From outer space, the third planet from the Sun undoubtedly looked quite the same after the war as it had throughout human history. But nothing, anywhere truly was the same. National boundaries had been redrawn. Entire familial lineages had ended abruptly, depriving the world of the future saints and murderers those lineages may have harbored. The seeds of the Cold War almost instantaneously were sown. The simultaneous angst and promise of the new nuclear age had begun to infiltrate both individual and collective psyches.

The Naval Research Laboratory had grown from adolescence to adulthood in a growth spurt that only wartime emergency could have demanded. It was more than the number of buildings and people that were different at the Laboratory, however. As the war began, NRL was one of the country's only existing military laboratories with a stated, albeit little-practiced, mission of scientific research. In that sense, it was like a scout amongst Government laboratories with the unstated purpose of seeing what tax-funded scientific research can do for the nation.

During the war, the nation's reliance on and commitment to science expanded dramatically. Through the National Defense Research Committee and the Office of Scientific Research and Development, it seemed as if the entire national nexus of technical talent in the governmental, academic, and industrial sector had been organized to wring as much out of the intelligent application of science and engineering as it was naturally possible. The wonder weapons of World War II—radar, proximity fuzes, atomic bombs—all were born of science and science-guided engineering. The war had proven beyond a doubt that a country's scientific resources were every bit as strategically valuable as the number of bombers in the Army Air Corp or the number of destroyers it could put to sea.

When the war ended, the brilliant organizational machinery of wartime—NDRC and OSRD—began dismantling. And there, still on the banks of the Potomac River, was NRL, its contingent of more than 2,000 researchers—a pair of future Nobelists soon to join them—unsure of what they and their Laboratory had become or where it was heading.

Chapter 7

Harold Bowen and a Born Again NRL

NRL during wartime seemed on its way to becoming the kind of place where a submarine could be built in 15 days, which was the fanciful and unrealistic goal Edison had touted before Congress in support of the Laboratory's creation 30 years earlier. It still was bogged down with the time-consuming responsibility of testing industry-made equipment against specifications. But the relentless flow of radio, radar, countermeasures, and other equipment from NRL during wartime proved that it had the makings of a *bona fide* invention factory relying as much on the manufacturing skills of its machinists as on the engineering abilities of the research and development staff. However, the Edisonian vision for NRL would prove shortsighted in the end. It would become more than a mere invention factory. Along the way, of course, there would be some striking moments.

Consider the "unsatisfactory fitness report" that the Secretary of the Navy, Frank Knox, placed into the personnel file of NRL director Admiral Harold Bowen in 1941. The report rated the Admiral as a very "capable engineer and possessed of great courage in pressing experimental projects." It also rated Bowen's dealings with the nation's most powerful civilian scientists as exceptional. "Rather belligerent and temperamental in his contacts outside of the Navy" is how the report stated it.[1] That character trait would have repercussions for Bowen, for NRL, and for American science in general.

Vice Admiral Harold G. Bowen, commanding officer of NRL, at a time when the Laboratory was becoming a home to basic as well as applied science and engineering

Bowen, then 57 years old, had been a Navy man all of his life. He graduated from the Naval Academy in 1905 and then served variously on ships and shore stations. A 1914 master's degree in mechanical engineering from Columbia University set him into a lifelong Naval career with a mission to improve the Navy's machinery. From 1917 until 1931, he served as a technical administrator in the lower echelon of the Naval hierarchy. After that, he entered a higher profile arena where one's acquired friends and enemies tend to be more powerful and where their actions tend to be more consequential.

Throughout the 1930s, Bowen served first as Assistant Chief of the Bureau of Engineering and then as Chief. At the bureau, he was the aggressive champion of an R&D program for a new Naval propulsion system based on high-pressure, high-temperature steam. Out of this effort came the vast amounts of steam at the Philadelphia Navy Yard that was the heart of Philip Abelson's pilot plant for uranium isotope separation during the war.

During his tenure at NRL, Bowen set some lasting trends into motion. He successfully argued NRL's case on Capitol Hill, leading to

increases in Congressional appropriations for the Laboratory from $370,000 in 1939 to $1,479,500 in 1941. Congressman James Scrugham, whom Bowen had befriended, was instrumental in this outcome. The increased money from Congress as well as from the Navy bureaus showed up in the form of a doubling in the NRL's physical plant to 58 acres, a near septupling of personnel to over 2100, a more than doubling of the number of buildings from 17 to 42, and the purchase of land on the western shore of the Chesapeake Bay for the construction of an annex that became a critical site for testing off-the-bench radio, radar, and countermeasures equipment.

Bowen greatly valued NRL's role and its potential for increasing the technical quality of the Navy. But his assignment in 1939 as NRL's director by Acting Secretary of the Navy Charles Edison was in large measure an attempt to decontaminate some bad air that had accrued between Bowen and other top Navy officers and officials.[2]

In a bid for a long-term solution, Edison also shifted NRL from its place under the former Bureau of Engineering to the haven of the Secretary's own office. Though not ideal to Bowen, the situation was tolerable and Bowen did an admirable job bringing about and overseeing NRL's most intense growth spurt.[3]

Edison also gave Bowen a second hat as Technical Aide to the Secretary of the Navy, a job that had no specified responsibilities. "The Technical Aide designation was made to save face for me," Bowen later assessed in his autobiography.[4] In this obscure capacity, however, Bowen managed to make headway in a long-term goal of centralizing control of Naval research. That action would pit him against formidable opponents.

Admiral Bowen's bulldog approach to human relations in and out of the Navy would have different consequences for himself, the Naval Research Laboratory of which he was director between 1939 and 1941, and the Navy as a whole.

At about the same time that Secretary Knox, who replaced Secretary Charles Edison, filed the unsatisfactory fitness report, Admiral Bowen and NRL were transferred from the Office of the Secretary of

the Navy back to the cognizance of a bureau, namely, the Bureau of Ships. For Admiral Bowen, the shift was a resounding slap in the face since it rendered him subordinate to the very office that he thought he ought to have been chosen to run two years earlier.

For the Laboratory as a whole, the effects of the administrative shift were relatively innocuous. In his own accounting of the NRL's first 25 years, A. Hoyt Taylor remarked that the administrative shift was largely unfelt at the Laboratory since the vast majority of work was for the Bureau of Ships anyway.[5]

Bowen rode out his personally demeaning placement until his NRL assignment came to an end in mid-1942, after which he handed over the directorship to Admiral Alexander H. van Keuren, who served in that slot until the war ended.

That was not the end of Bowen's troubles. "His humiliation was not yet complete, for his enemies within the Navy barred him from a major command and nearly caused his retirement by a medical review panel," explains MIT public policy analyst Harvey Sapolsky in his book *Science and the Navy*. "Only a growing friendship with the Under Secretary of the Navy [James Forrestal] saved him from being forced to collect an early pension in the midst of the greatest war in the Navy's history."[6]

It is wise to make friends in high places because you never know who is going to die. When Knox died in the spring of 1944, Under Secretary Forrestal became Secretary Forrestal. After the war, Bowen's close connection with Forrestal would help the Admiral become the last thing that his enemies might have wanted—the man in the Navy with the most power ever over the direction of Naval research and development. Throughout the mid- and late-1940s, that power would even end up spilling beyond the borders of the Navy at a time when the nation's scientific intelligentsia were wrenching through a high-stakes soul search whose outcome would define American science, and the way it is sponsored, to this day.

The happy turn of fortune for Bowen in 1944 and 1945 came only at immense initial cost to NRL and the Navy. Most notably was

the Navy's conspicuously minor role in the wartime Manhattan Project, the ultimate showcase of the world-changing creations of which collective human intellect and ingenuity are capable. The Navy's diminutive presence in this historical project was due, at least in part, to Admiral Bowen's brusque way with the civilian scientists who had organized it.[7]

One of those scientists was Vannevar Bush, not a man to be on the wrong side of if you harbored high ambitions in the world of American science.[8]

Bush had been Dean of Engineering and Vice President of the Massachusetts Institute of Technology before becoming President of the Carnegie Institution of Washington. When war broke out in Europe in 1938, he also was Chairman of the National Advisory Committee for Aeronautics (NACA), which Sapolsky describes as "a civilian agency which had been established in 1915 to promote the scientific development of aviation and which had been given authority (in June 1939) to assist the military in the development of combat aircraft."[9] The prewar basic research by NACA on airfoils was widely exploited during WWII by both sides. NACA served as a model from which Bush, by Presidential authority, created and organized the National Defense Research Committee beginning in mid-1940. The NDRC would be to militarily-relevant research what NACA had been to aviation research.

Among the NDRC's founding members were such titans of science as Harvard University President James Bryant Conant, MIT President Karl Compton, and Frank Jewett, president of Bell Laboratories. The NDRC's liaison in the Navy was none other than Admiral Bowen, the director of NRL and the Technical Aide to the Secretary of the Navy. From the start, Bowen was uncomfortable with the growing civilian presence in military technical planning and research.

When France fell to Germany in 1940, the NDRC concept expanded into the more encompassing and powerful Office of Scientific Research and Development of which NDRC became a major component. Bush glided into chairmanship of the parent OSRD. In so

doing, he became as close to being a czar of American science as anyone ever had been before or since.

The time for a blowout between NRL Director Bowen and Bush's suddenly powerful research organizations was rapidly approaching. Soon after the NDRC formed, it absorbed the Uranium Committee, which had provided the conceptual starting point in early 1939 for NRL to become the first government agency out of the blocks in the quest to apply nuclear fission. As a consequence of this shift of control over the Uranium Committee, military planning regarding nuclear phenomena fell under the jurisdiction of NDRC regardless of NRL's pioneering foray into the area. Moreover, the NDRC, whose members deathly feared that German scientists would build an atomic bomb, quickly focused attention and resources onto atomic weapons and away from Bowen's and Ross Gunn's interest in nuclear propulsion.

As liaison to NRDC for the Navy, Bowen was one of the few in the Navy privy to the potential applications of nuclear fission and to the administrative structure that would emerge to manage nuclear research. That was only one reason why a clash between Bowen and the NDRC was inevitable. In a memorandum to Secretary Knox dated December 14, 1940, Bowen proposed that the Naval Research Laboratory be officially renamed as the Naval Research Center, which would supervise all Naval research "on any subject of interest to the Navy."[10] This tactic would, in effect, create an in-house NDRC function within the Navy. If such a center were to actually be established, Bush's OSRD and NDRC, and its majority of academic types, might be denied control of Naval research.

The conflict came to a head just months before the United States entered the war. Harvey Sapolsky described the situation: "Admiral Bowen's brusque assertion of the Navy prerogatives in weapons research . . . antagonized Vannevar Bush and the other prominent scientists who were attempting to organize a civilian-directed weapon development program, and in 1941, he was forced out of his senior post in Naval research." The effect was far more than merely personal.

"Bowen's clash with civilian scientists was in large measure the cause of the Navy being excluded from participation in the Manhattan Project," Sapolsky surmises.[11]

As it happened, NRL's uranium isotope separation, ostensibly for nuclear propulsion studies, did become an integral and grudgingly acknowledged part of the bomb project. What's more, that work developed into the equivalent of a new chromosome in the laboratory's genome that henceforth would influence the mission and character of the Laboratory. In 1946, for example, many members of the Laboratory—particularly in the Optics Division—would become part of Project Crossroads, the first set of postwar nuclear weapons tests in the Pacific. After that, NRL would remain an important component of the Nuclear Age and the awful Doomsday Machine that would emerge out of the fledgling Cold War.

As it happened also, Bowen came back from the professional exile to which his opponents had hoped to relegate him. And in so doing, he would catalyze the creation of the Office of Naval Research, which would change the course of NRL, research in the Navy, and even the entire context of American science.

The concept of ONR was first envisioned in late 1944 when Secretary Forrestal received a proposal from Admiral Furer, who then was the head of the Office of the Coordinator of Research and Development (CRD), which was the technical link between civilian-run scientific organizations like the OSRD and the Navy's materiel bureaus. Furer's proposal, which first was formulated the previous year by a small group of CRD officers known as the Bird Dogs, was to create a central organization to plan and guide the Navy Department's research.[12]

On May 19, 1945, Forrestal established the Office of Research and Inventions (ORI). It subsumed the functions of the CRD and the six-month-old Office of Patents and Inventions that had been created to preempt expensive patent infringement claims that were likely to emerge after the war. ORI also was assigned the responsibility of plan-

ning postwar research. Moreover, it took over the Naval Research Laboratory. The Office of Research and Inventions was in some respects the Naval Research Center that Bowen had proposed earlier to Secretary Knox.

As ORI's chief, Forrestal appointed Admiral Bowen. In principle, Bowen had emerged from nearly being barred from the technical planning of the Navy to become, in theory at least, the most influential of all Navy technical men ever.

In what was at least a pragmatic change of heart, Bowen immediately took measures to reverse his reputation as "belligerent and temperamental in his contacts outside of the Navy." He and his staff began wooing academic scientists, partly because Bowen hoped many of those who had been involved in the Army-run Manhattan Project might end up helping Ross Gunn realize his 1939 vision of a Navy propelled by nuclear energy.

Bowen was keenly aware of the postwar reality that large-scale science had become a vital means for the development of new and improved military technologies. In the post-WWII era, the Navy would need an organization akin to an OSRD or NDRC. The Office of Research and Inventions, which less than a year after its creation was renamed as the still extant Office of Naval Research (ONR), was the answer. Created by an act of legislation, ONR, which was directly under the auspices of the Office of the Secretary of the Navy, would rapidly become a model for a growing roster of institutions administering funds to researchers. Among those institutions are the Office of Army Research (ARO), Air Force Office of Scientific Research (AFOSR), and the National Science Foundation (NSF), all of which were established in the 1950s.

Bowen did make one last gambit to subsume nuclear propulsion R&D under ORI with NRL as the main research center. Even in late January 1946, two months after the Chief of Naval Operations (CNO) had set up a special office—The Deputy Chief of Naval Operations for Special Weapons, or OP-06—to oversee the development of nuclear

weapons and guided missiles to carry them, Bowen still shipped off dissenting memoranda to his bosses.

On January 26th, Bowen sent a six-point policy proposal on the subject of "Nuclear Energy for the Navy" to the Secretary of the Navy and the Chief of Naval Operations. "Legislation now pending for federal control or supervision of work in nuclear physics is of vital importance to the Navy," Bowen wrote. "Piecemeal comment by the Navy, obtained by the usual process of shopping around for the views of bureau and office chiefs, will endanger the strong position which the Navy must take or else face relegation to a minor role. We must agree upon and announce a firm policy."[13]

His proposal was comprehensive. It included research and development in nuclear propulsion, nuclear munitions, nuclear medicine, countermeasures to nuclear munitions, and basic nuclear science as well as a program to train Naval personnel "in the field of nuclear energy and its applications."[14]

But it was too late. Officers at the Bureau of Ships, who wanted a major role in nuclear propulsion for their own bureau had already established an alliance with OP-06. During internal Navy discussions about where Navy nuclear work (in collaboration with the soon to be formed Atomic Energy Commission) would be centered, the Bureau of Ships won out. Admiral Hyman G. Rickover, one of the few officers who could beat Bowen in a contest of will and aggression, ultimately would garner the credit for ushering the Navy into the Nuclear Age.[15]

Although ORI would not become the Naval planning center of nuclear R&D that Bowen had envisioned, he and ORI colleagues helped prepare a legislative bill that would give the new organization longevity beyond his own ambitions. On August 3, 1946, President Harry S. Truman signed the bill establishing the Office of Naval Research. Bowen, a man in a high place who nonetheless had been muscled out of the quest to create a nuclearly propelled Navy, relinquished his post as the head of ORI in 1947 and retired with the rank of Vice Admiral.[16]

While all of this shuffling and reorganization was going on in the upper echelon of the Navy, research leaders at NRL were engaged in a parallel internal effort to redefine their Laboratory. There was a continuum of work going on with a small amount of basic research comprising one extreme, the testing of equipment on the other, and a whole lot of applied science and engineering in between. The unanimous call among NRL researchers was to drop most of the testing functions (except during war emergencies) and to shift its overall research agenda toward the more basic research side of the continuum. The scientists had more than sympathetic backing from the NRL's new military commander, H.A. Schade, who took over the helm of NRL from Admiral van Keuren (Bowen's successor at NRL) at the end of 1945.

Members of a steering committee that Schade had set up to guide the postwar remaking of NRL articulated the deep and perhaps most important reason why NRL had to become a haven of basic research: "It is one of the peculiarities of higher technical talent that individuals possessing it have a greater interest in the problems of science than they do in specific engineering applications. Accordingly, if the requisite technical talent is to be maintained at the Naval Research Laboratory, and if development work is to take full advantage of advances in pure science, this institution will have to engage in scientific work that is not immediately related to engineering development of applied research [emphasis in original]. This character of work is generally called 'Research.'"[17]

The end of War World II and the creation of ONR ensured that NRL, ONR's primary in-house research outlet, finally would have fertile ground for the growth of basic research alongside, and in complement to, the Laboratory's more established history of applied research. Rather than relying on funds from the mission-oriented Navy bureaus, large portions of NRL's research budget began to come from ONR, which was independent of any bureau. In that sense, NRL found itself in its best position ever to emulate the nation's great corporate laboratories just as NRL's founders envisioned it should back in the era of

World War I. Research that was in the near- or long-term interest of the corporation—in this case, the Navy—was fair game. Finally, basic research had become an officially sanctioned and financially supported component of NRL's research portfolio.

To lure top-notch talent in the postwar years when demobilized scientists would have many career options, some prominent members of the NRL community even proposed that the Laboratory combine the best of corporate lab-life with the perks of the academic lifestyle. Ross Gunn was one of them:

"The great attraction of university life is the three month summer vacation accompanied by a two week break at the Christmas holidays. I think we could better our employment position if we could establish the work of this Laboratory on a nine-month a year basis . . . It seems to me that 9 months duty with the 26 day leave prorated and a salary of 75% of the base salary might provide flexibility enough so that we could compete, probably quite successfully, with the universities."[18]

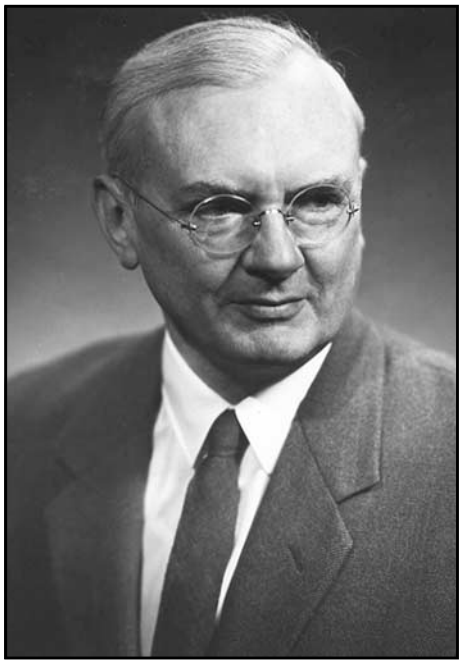
Even without the promise of summers off, the new postwar NRL began attracting scientists of the highest caliber. Perhaps most emblematic was the arrival in 1946 of Jerome Karle, who had done plutonium metallurgy for the bomb project at the Metallurgical Laboratory located at the University of Chicago. He actually began working for NRL in 1944 as part of a research contract with his graduate supervisor at the University of Michigan. Thirty-nine years after arriving at NRL, he and NRL colleague Herbert Hauptman (who arrived at the Laboratory in 1947) would become co-recipients of a Nobel Prize for work that helped make X-ray crystallography a household tool for chemists and physicists seeking to reveal the anatomy of molecules and materials (see Chapter 11). It would be quite a victory for the Laboratory because the Prize was awarded to Karle and Hauptman for their unabashedly basic research—not applied science, engineering, or equipment testing. It was a dramatic endorsement for the vision of Gunn and his colleagues to build an academic model of research into NRL's culture.

With Jerome Karle arrived his wife, Isabella Karle, who also was destined for greatness. Some say her mathematical insights into problems of crystallography should have earned her part of the Nobel Prize that her husband and Hauptman would share. Isabella Karle's early work at NRL provided key mathematical tools that opened up to definitive crystallographic analyses enormous classes of chemical compounds previously considered too complicated for such procedures. Like her husband, she would go on to win a raft of science's most coveted awards and honors, including the National Medal of Science in 1995.

The Karles were just two of the new breed of researchers that would help usher NRL out of its relative isolation behind a fence of military security into the larger and more open fraternity of the civilian scientific community. Another was Herbert Friedman, the man who actually hired the Karles. Friedman himself was hired into the Physical Optics Division by Hulburt in 1941 to develop new kinds of light and radiation detectors. This was fitting since Hulburt was hired in 1924 with the then dreamy vision that basic research would soon take hold at the Laboratory. It actually took nearly 25 years for that to happen.

Although Friedman's initial work during WWII centered on developing radiation measurement tools, he would become smitten with a remarkable spoil of war—the opportunity to put measurement tools atop the world's most powerful rockets that the Nazis used as terror weapons toward the end of the war. Friedman would become a visible, top-tier, pioneer in rocket-borne research. He would help launch NRL, the country, and humanity into the Space Age. A profile of Friedman that appeared in the September 22, 1960 edition of *The New Scientist* assessed his career with these words: "the contributions which he has made to the exploration of space stand in comparison with those of any other single person."[19] Even today, Friedman continues making contributions in his role as chief scientist emeritus of the E.O Hulburt Center for Space Research, an entity created at NRL to attract talented graduate students and future NRL luminaries.

Richard Tousey, who died in 1997 at the age of 89, was hired at about the same time as Friedman. After the war, he, too, would fall head over heels into rocket-borne research. Whereas Friedman would help the world see the way the cosmos color the sky and bathe the Earth in invisible X-rays, Tousey would do the same for ultraviolet radiation. Like a tag team, the two would help make NRL one of the most important centers of space science prior to the Congressional creation of the National Aeronautics and Space Administration (NASA) in 1958.



Richard Tousey in 1961

Like bookends, the work of the Karles and of Friedman and Tousey would come to bracket the vastly diverse scales of the universe, from the diminutive inner space of crystals to the vast reaches of outer space. Almost every level and type of phenomenon became legitimate foci for research at NRL, so long as there was some defensible connection to Naval interests and needs.

In keeping with the postwar trend toward a more academic model of research, the Laboratory created a new top office—director of research—designated for civilian occupation. In 1949, Hulburt became the Laboratory's first director of research. With this new office in place, more effective planning was possible between the Laboratories support services and its research program.

A new, more academic research culture was taking root at NRL alongside the older engineering culture that had characterized NRL since it opened. Although this new research culture was new, it started

off with robust support. Not only did the likes of Ross Gunn, Herbert Friedman, Richard Tousey, the Karles, and many others within NRL's gates embrace it, so too did the Office of Naval Research from which much of NRL's research budget would come in these transitional years. Admiral Bowen may have lost NRL the chance to become a center of nuclear research, but he ended up securing for the Laboratory the right, even the mandate, to do the kind of basic research that would earn it respect in the scientific community at large.

Chapter 8

Turning Vengeance Weapons into a Space Age

Nothing influenced the fate of NRL's postwar research program and image more than an instrument of warfare designed by Nazi scientists and engineers—the Vergeltungswaffe, the Vengeance Weapon. Built in the world's largest underground factory by slave laborers who were systematically worked to death,[1] the rocket-powered missile became known more familiarly as the V-2 bomb, the weapon that rained terror down on English territory toward the end of the war.

At launch, each V-2 stood 46 feet high, weighed 14 tons (including a one ton warhead), and typically could travel nearly 200 miles in an arc that would take it to an altitude of over 60 miles.[2] Of the 3,000 V-2s produced by the Nazis by the end of the war, about 1,000 reached England.[3] Although the rain of V-2s on Londoners was terrifying and deadly, the V-2 had no bearing on the outcome of the second great world war. It was after the war that the V-2 rocket, sans warheads, would change the world. The Naval Research Laboratory would have everything to do with it.

The man most responsible for steering the V-2 into NRL's fate was physicist Ernst Krause. Krause grew up on a farm in Wisconsin and earned a bachelor's degree in electrical engineering during the Depression years when jobs were scarce. In lieu of a job, he continued his education, earning a PhD in physics. In 1938, the year Germany invaded Poland, he joined Claud Cleeton's Communications Sec-

urity Section in NRL's Radio Division. The section's proposed mission was to develop a microwave-based system for sending secure messages. From there, Krause ascended quickly during wartime to become coordinator of guided missile research—an offshoot of pioneering NRL work in the 1920s in radio-controlled aircraft. He later succeeded Cleeton as section head. During the war, Krause had known as much as anyone about guided missiles since his section worked on many key aspects of such weaponry including telemetry, guidance, and countermeasures. He had also learned the important managerial skill of coordinating the activities of many differently trained researchers to achieve very complicated ends.[4]

At the end of the war, the U.S. Army had captured the subterranean V-2 factory near Niedersachswerfen just before the treaty-sanctioned Russian occupation of this part of Germany had actually begun. At first, no one at NRL knew of this acquisition. As preparations for the transition to the Russians were underway, the Army packed up 360 metric tons of V-2 parts and equipment and shipped the rocketry booty back to White Sands, New Mexico where the Army was establishing a missile testing ground. The Army wanted to use the V-2s as a tool for learning how to handle and launch big rockets.[5]

Meanwhile, Krause had been learning about the German missile and rocketry work. He was among a cadre of American scientists who went to Europe on postwar technical missions to interrogate German scientists and engineers. One of the frightening discoveries of these missions was a plan by German scientists to build a 118-foot long submerged cylinder that Nazi submarines could tow to the coasts of the United States, raise to a vertical position by flooding one end, and then use the skyward pointing tube to launch V-2 strikes.[6]

Krause returned from Germany with a rocket-filled vision of NRL's near future. New weapons were one thing, but in the spirit of NRL's postwar campaign to replant basic science on its grounds, Krause began pushing the idea of rockets as an exciting new tool that would bring a new era of upper atmosphere research. With rockets, NRL's

scientists finally would have a means of lofting measuring instruments beyond the often obscuring, even blinding, effects of the atmosphere.

Krause was not alone in his enthusiasm. NRL's military director, Commodore Schade, had been a major participant and designer of the Navy technical mission to Europe and was well aware of the German work in guided missiles and rocketry.[7] Moreover, even before anyone at NRL knew about the V-2s captured by the Army, Milton Rosen, one of Krause's colleagues, had proposed building a research rocket. NRL now had the means and the will to bring rockets into its research portfolio.

Krause's lobbying paid off. On December 17, 1945, what previously had been known as the Guided Missiles Subdivision of the Special Electronics Research and Development Division became known as the Rocket Sonde Research Subdivision (or Section). Unlike later rockets that would send satellites into orbit, a rocket sonde merely shoots as high as its fuel will take it before falling back to Earth, a trip that lasts only a few minutes at best.

Krause was assigned head of the new section. Its functions were defined in Laboratory Order No. 46-45 as follows: "to investigate the physical phenomena in and the properties of the upper atmosphere with a view to supplying knowledge which will influence the course of future military operations." To carry out these functions, the section was charged with doing the basic research to develop the "techniques, instrumentation, and devices required."[8] Its members would become some of this country's first rocket scientists by reading the intelligence reports of the technical missions to Europe.[9]

The Rocket Sonde Research Section would drop like an intense dye smack into the swirling center of NRL. It would color much of the basic research that over the next few decades would put NRL more visibly on the scientific map then it had ever been before. John Hagen, a radio researcher at NRL during the war, played a lead role in bringing the world into the Space Age. This role would place him squarely in the media spotlight in the late 1950s. He later looked back and

summarized NRL's history up to then as a three-stage structure. In the 1973 *Report of NRL Progress*, an annual accounting of research at the Laboratory, Hagen wrote: "The Naval Research Laboratory was born out of World War I. It grew to maturity in preparing for World War II, excelling in its achievement during the War. It blossomed into a full-fledged scientific institution in applying the talents of its people after the war."[10] The biggest petal on this blossom was rocket-based science.

When the Rocket Sonde Research Section formed, the Army already had contracted the Jet Propulsion Laboratory (which budded from the California Institute of Technology (Cal Tech) during World War II and is now operated by Cal Tech for NASA) to develop a rocket that could carry 25 pounds of meteorological equipment to altitudes of about 20 miles. But the rocket that would come out of this program, the Wac Corporal, would be too small to carry enough of a scientific payload high enough to meet the Rocket Sonde researchers' needs. So Krause and his team were poised at the end of 1945 for the long haul of developing a rocket that could meet their specific needs.

Then on January 7, 1946, a cadre of members of the section learned from Lt. Col. J.G. Bain of the Army Ordnance Department about the captured cache of V-2 parts, enough perhaps to reconstruct 100 rockets.[11] The Army's interests in firing the rockets largely were military in nature—to learn how to handle, use, and track rockets of V-2 dimensions. But Bain also indicated that the Army was interested in gathering data about the upper atmosphere. If anyone was going to be shooting rockets around the upper atmosphere, they needed to know what that place was like—its temperature ranges, compositions, and pressures. This was a research endeavor the Army was ill-equipped to pursue on its own.

So there was the U.S. Army about to fire the world's biggest and most powerful rockets, but they had no atmospheric measurement tools to loft on them. And there was NRL with a new research section aiming to do rocket-borne research of the upper atmosphere, yet expecting to wait 2 years before having a suitable rocket in hand made

by a not-yet specified contractor. When Bain invited the Rocket Sonde Research Section to take part in the effort to measure properties of the upper atmosphere, the idea "was enthusiastically received and accepted," Krause wrote in the section's first report on their V-2 work.[12]

NRL was not alone in its interest in rocket-borne research. The Army Signal Corps Laboratory, which had developed radar alongside NRL in the 1930s and during wartime, was getting in on the wave. So was the Applied Physics Laboratory, a legacy of the wartime NRDC link to Johns Hopkins University (whose initial mission was the development of proximity fuzes). These were among the dozen organizations with scientists interested in the captured V-2 as new research tools. General Electric (which the Army contracted to run White Sands),[13] Watson Laboratories, the National Bureau of Standards, as well as several universities were all in on the rockets.

In mid-January, the "V-2 Upper Atmosphere Research Panel," which was composed of representatives from these interested parties, convened for the first time to coordinate research. Its first act was to elect Krause as chairman,[14] a move that immediately put NRL at the titular forefront of rocket-borne research in the United States. Just three months later, on April 16, 1946, the first American-launched V-2 roared skyward from White Sands. Some 60 more V-2s would follow suit over the next 4½ years. NRL's Herbert Friedman, who witnessed many of these launches, wrote:

> *"No matter how many times you witnessed it, the launch of these rockets was always inspiring. After the short-lived bursts and rapid acceleration that characterized the firings of small rockets, the slow, majestic rise of the V-2 and the sudden vanishing of the roar of the rocket in the eerie quiet of burnout was a breathtaking experience. Silent, snaking vapor trails marked the passage of the rocket through the stratosphere, and sound returned only near landing when shock waves reverberated from the mountains."*[15]

The program had a healthy portion of difficulty, however. Though far more powerful than the Wac Corporal, V-2s in fact were designed to transport explosives into enemy territory, not to carry scientific in-

strumentation to great atmospheric heights. "Eleven hundred pounds of lead have been poured into the nose of a V-2 when the instrument load was insufficient to provide static stability," recalled Milton Rosen and Richard Snodgrass, members of Krause's Rocket Sonde Research Section.[16] The V-2's technology also was replete with bugs, not made any easier by the fact that these were German-designed vehicles being assembled in the United States with American crews, albeit with the help of some of the German scientists and engineers that had developed the missile in the first place. According to Friedman,

> *"The first five of the huge rockets all returned nose down in streamlined flight and buried their pulverized remains in craters about 30 feet deep and 80 feet in diameter. One reversed direction from north to south and headed for El Paso, Texas. It crossed the Mexican border and struck next to Tepeyac Cemetery, about a mile and a half from Juarez. The impact barely missed a warehouse full of commercial blasting powder and dynamite. This even may be recorded as the first U.S. ballistic missile strike on foreign soil."*[17]

Krause and others in the rocket science arena always had considered the V-2s as stopgap vehicles for a new field of rocket-borne research that would outlast the supply of the German missiles. Even as preparations for the first White Sands V-2 launch was underway, Krause and Rosen of NRL agreed with the Applied Physics Laboratory to jointly oversee an APL-developed scientific rocket—called the Aerobee—based on an engine designed by the Aerojet Engineering Company.[18] And for the longer term supply of more capable rockets, NRL began designing its own rocket. It would become known as the Viking.

Despite the harrowing crapshoot that each V-2 launch amounted to, NRL researchers quickly began reaping the kinds of scientific riches they had envisioned would come with rockets. The first to bring home gold was Richard Tousey and his colleagues in the Optics Division who had become infected with the enthusiasm of Krause's Rocket Sonde Research Section.

Tousey was hired into the Optics Division in 1941 to do research on the upper atmosphere. It is no surprise that E. O. Hulburt, the first scientist hired at NRL with the expressed freedom to choose his topic as an academic might, would be the one to hire scientists like Richard Tousey and Herbert Friedman who would realize the ideal of NRL as a bastion of basic research unfolding side-by-side with applied research and engineering.

When word of NRL's access to V-2s started percolating beyond the founders of the Rocket Sonde Research Section, Hulburt immediately saw immense potential. After all, he had devoted much of his research to revealing and measuring the physical features of the upper atmosphere that affect long-distance communication. This led to important results including empirically derived protocols enabling Navy radio operators to determine what wavelengths to use at different times and locations. Useful as that may have been, Hulburt and his colleagues still wanted to understand the atmospheric phenomena that coerced them into developing such protocols in the first place.

Everyone knew that radiation from the Sun was what set these upper atmosphere mechanisms—including the fluctuating character of the ionosphere—into motion. A theoretical understanding of what was going on had been elusive, however. A big part of the problem was that so much of that solar radiation could never make it beyond the absorptive upper reaches of the atmosphere to measuring instruments below. Hulburt could see that rockets could break through the blindness imposed by the very atmosphere he wanted to understand.

To get his division in on the new game, Hulburt challenged Tousey to put a spectrograph on a V-2. That way, as he and Tousey both knew, an instrument capable of detecting the spectrum of ultraviolet radiation would for the first time soar above the stratospheric ozone layer which absorbs all UV wavelengths shorter than 3000 angstroms. (The ultraviolet spectrographs the NRL researchers contained special gratings of ultrafine lines that reflect different wavelengths of UV radiation to different degrees, thereby spatially separating the many com-

A V-2 rocket is raised into launching position at the White Sands Proving Grounds in Nevada on December 5, 1946.

ponent wavelengths of a UV source into its individual components. The separated light can be projected onto and recorded by a photographic plate. The resulting exposure represents the source's rainbow of UV light, otherwise known as a UV spectrum).

Tousey's interest in measuring the extreme ultraviolet radiation began in his graduate days when he worked under Harvard University Professor Theodore Lyman. Lyman had developed techniques to measure UV spectra emitted by excited chemical species such as hydrogen atoms that are trapped inside of a vacuum where air would be unable to absorb the more extreme UV wavelengths. One of those hydrogen-derived wavelengths, measured at 1215.7 angstroms, became known as Lyman-alpha.

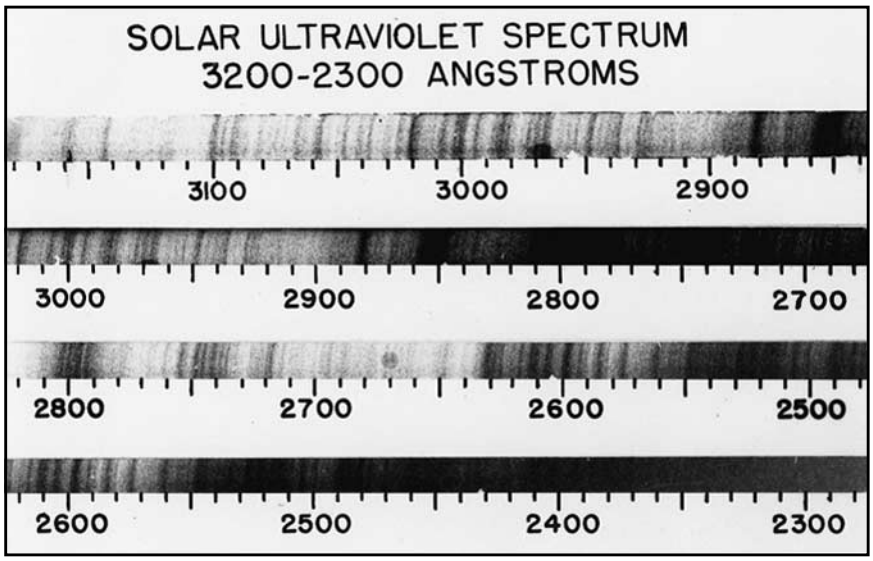
Atmospheric researchers began to suspect in the 1920s that Lyman-alpha emission might play a large role in the electron-energizing

mechanisms behind the ionosphere. This was not merely an academic issue since radio fadeout appeared linked to changes in the ionosphere wrought by solar activity. Knowledge of this Sun-ionosphere-communications dynamic, therefore, became important to the Navy.

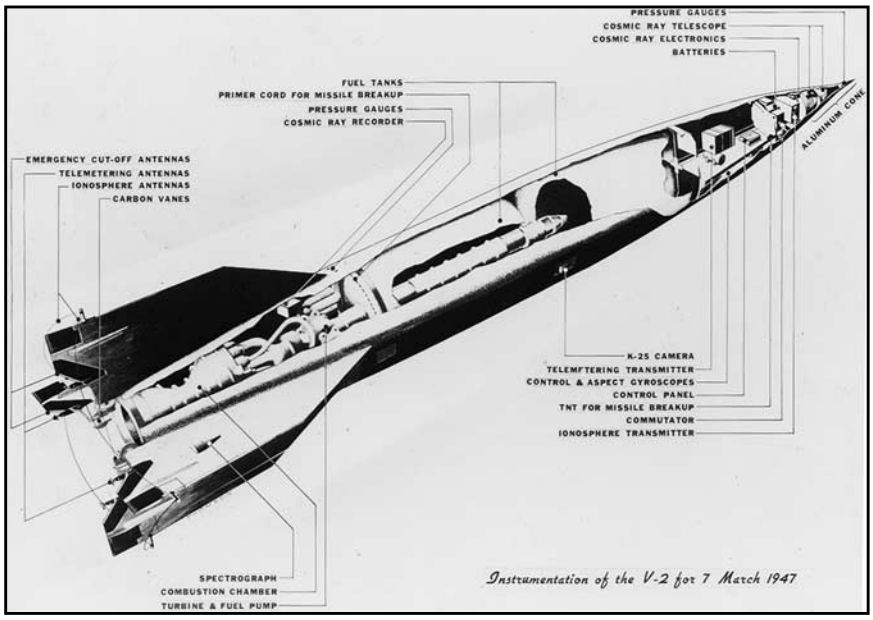
One possible mechanism behind the fadeouts, which could interfere with Naval communication for days, involved the injection of solar energy (in ultraviolet and X-ray ranges) into atoms in the Earth's upper atmosphere. This process would generate populations of free electrons in certain regions of the upper atmosphere, thereby affecting the ionosphere. And that could help explain such phenomena as fadeouts that coincide with high sunspot activity. Without direct measurement above most or all of the stratospheric ozone levels where most of the extreme ultraviolet radiation (including Lyman-alpha) is absorbed, however, no one could tell if this mechanism was anything more than an intellectually satisfying story. Hulburt, Tousey, and their colleagues hoped a UV spectrograph in the nose cone of a V-2 would help them to separate fact from fiction in this scenario.

Their first try took place on June 28, 1946. It was the sixth V-2 shot. The rocket lifted off from its launch site at White Sands and then careened back to Earth. With nothing to slow its descent, its impact created a crater from which virtually nothing from the rocket, including the spectrograph, was recovered intact or even in recognizable form.

The ending would be different for the twelfth V-2 flight, which took place on October 10. Tousey had equipped it with a new spectrograph, this time locating it on one of the rocket's four stabilizing fins rather than in the more vulnerable nose cone. Also, upon its descent, operators remotely blasted the V-2 into less streamlined parts that would descend more slowly. This time, Tousey was able to retrieve the spectrograph. It harbored data no one had seen before—the solar UV spectrum down to 2200 angstroms. This heretofore unmeasured part of the Sun's UV emission was called the "new UV." A subsequent V-2 flight on March 7, 1947 yielded 300 new UV lines between 3000 and 2200 angstroms, with which the NRL scientists were able to



(a) On March 7, 1947, NRL scientists, using a V-2 rocket as a platform for measurement equipment, obtained this solar ultraviolet spectrum showing more detail and extending to shorter wavelengths than was possible with earthbound instruments.



(b) Schematic depiction of the instrumented V-2. Note the fin location of the spectrograph that produced the above UV spectrum.

identify the presence of 17 chemical elements in the Sun.[19] These were the shortest UV wavelengths ever measured from the Sun, but the spectrum did not reach low enough to include the Lyman-alpha line, an extreme UV wavelength a full 1000 angstroms shorter than any in the "new UV."

These first flights only whetted the scientists' appetites. After all, the atmosphere not only relentlessly screened UV radiation below 3000 angstroms from earth-bound and balloon-borne instruments, but it also had blocked transmission of many, not all, of the even higher energy cosmic emanations, including X-rays and gamma rays. The same was true for much of the infrared radiation and low-frequency radio waves below 20 kilohertz. In effect, before 1946 and the first V-2 flights, the atmosphere had blinded scientists to a plethora of astronomical "colors" that harbored endless discoveries about the atmosphere, the Sun, and the universe.

Spectrographic measurement of those shorter and fainter wavelengths was hampered by the V-2's tendency to spin and precess as it rode out its parabolic path from launch to peak to crash site. The lithium fluoride crystal windows of Tousey's spectrographs would only directly point at the Sun when the windows happened to have the correct orientation as the rocket spun rather unpredictably.

To gather better and more revealing data, the NRL team decided to develop a "sun-follower," a gadget that would rely on a photoelectric tube to monitor the location of the Sun with respect to the rocket orientation and then send signals to a mechanical servo system that would reorient the spectrograph in the nose cone so that it would spend more precious seconds of the few minutes each V-2 was aloft actually pointing toward its solar target.

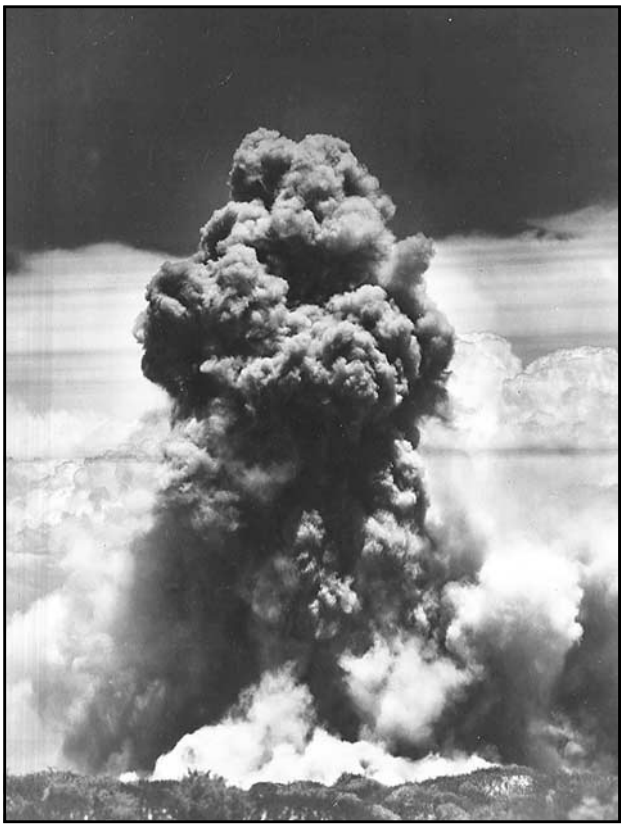
"Most of the sun-follower's electronic and mechanical systems were adopted directly from a radar tracking unit developed at MIT's Radiation Laboratory during the war, with the substitution of a light-sensitive receiver for the radio-frequency radar system," according to historian of technology Bruce Hevley who carefully investigated NRL's

role in early rocket-based astronomy.[20] The NRL team was quickly able to adapt the wartime radar tracker into a peacetime star-tracker.

Unfortunately, Tousey and his colleagues were frustrated in their attempts to be the first to measure the coveted Lyman-alpha emission by a string of five consecutive launch failures involving V-2 rockets and one newly available Aerobee rocket that NRL had received. Better fortune befell a group at the University of Colorado who had developed a less weighty sun-follower under an Air Force contract. Their stabilized spectrograph finally did bag the world's first Lyman-alpha measurements of the Sun from the upper atmosphere in 1953. Tousey followed with a definitive observation just months later in 1954.

Amidst all of the bad luck in the late 1940s, however, Tousey's team developed an alternative means of measuring not only UV radiation but also a portion of the X-ray spectrum (with shorter wavelengths than UV) that abuts the extreme edge of the UV spectrum. The principle of this alternative measurement was thermoluminescence. UV or X-ray radiation would hit carefully chosen phosphors, chemicals that emit light when exposed to radiation (they're in your TV). This light, in turn, would expose film. The intensity of exposure qualitatively indicates the intensity of the radiation. Moreover, by using different filters that would allow only preselected ranges of radiation through to the phosphors, the approximate wavelengths of the incoming radiation could be determined.

Of the six V-2s that Tousey equipped with thermoluminescence systems, he was able to retrieve data from four. The first success was on February 17, 1949. It revealed the unusual presence of X-rays below an altitude of 79 miles. None of the other experiments duplicated that result, probably because none of the others flew at a time when solar activity was high. During that first success, ground stations simultaneously monitored ionospheric disturbance. This happy concurrence would help the NRL scientists to discern the different atmospheric roles played by extreme UV radiation and X-rays from the Sun.



The spectacular look of failure in the then nascent business of scientific rocketry

Five weeks after the flight, the Navy touted the meaning of the result in a press release. [The] "intense . . . ultraviolet rays apparently produce the ionospheric layers necessary for long distance radio transmission," the release suggested, "while sudden bursts of X-rays apparently cause radio fadeouts and disrupt radio communication . . . On flights when intense X-rays were detected, solar flares were observed by astronomers and radio fadeouts occurred all over the world during the time the rocket was in flight."[21]

All four successful thermoluminescence experiments detected radiation in a swath of ultraviolet wavelengths including the Lyman-alpha emission. During the fourth flight, the data even included much more detailed information about the rocket's behavior, a bonus that enabled Tousey's group to eke out more science from their thermolu-

minescence data. For one thing, they were able to deduce the intensity of solar-derived extreme-UV radiation, and thereby the amount of energy the Sun injects into the atmosphere. Their findings confirmed previous suspicions by others that a disproportionate amount of solar UV radiation is in the sub-3000 angstrom regime. They also were able to calculate ozone concentrations at different atmospheric heights up to about 70 km.[22]

The thermoluminescence data were intriguing. However, they were the result of a largely indirect, qualitative measurement since the mere presence of exposure was not enough to determine exactly which wavelengths were reaching the film. There was plenty of incentive for other researchers, including Herbert Friedman, to develop more direct and quantitative techniques for measuring solar radiation at various levels of the atmosphere.

Just as A. Hoyt Taylor's technological interest in high-frequency radio communication had steered the Radio Division into scientific issues such as the way the ionosphere affects the propagation of high-frequency radio waves, the interest of Krause and his colleagues in the Rocket Sonde Research Section in rockets for upper atmosphere work was opening new scientific doors, this time in astronomy. By 1950, rocket science and upper atmosphere research accounted for over 8% of NRL's research and development budget, amounting to almost $1,500,000.[23]

Krause, the man who got NRL into the rocket business, left the Rocket Sonde Research Section in 1947 when his responsibilities in the arena of nuclear weapons testing became a higher priority. He handed the baton to Homer Newell under whom Milton Rosen would oversee development of the Viking rocket, which NRL would begin to use after the V-2 supply had dwindled. Another group within the section focused on measurements of those atmospheric properties such as temperature, pressure, and composition that were critical unknowns needed for developing next-generation rockets such as the Viking.

Meanwhile, the Optics Division had tasted the scientific fruits attainable with rockets. Richard Tousey, who came to NRL as an expert

in laboratory spectroscopy was transforming himself and his colleagues into some of the country's first rocket-based astronomers. At about the same time, in 1949, Hulburt shed his role as head of the Optics Division to become the first civilian director of research at NRL, an administrative novelty thoroughly in line with the Laboratory's concerted effort to emulate the academic model of research. His ascent also ensured that rockets would continue rising in importance and profile at NRL.

The same year Hulburt became director, one of his hires in the Optics Division, Herbert Friedman, took the same opportunity as Tousey did to steer his own career into the nascent field of rocket astronomy. Friedman studied solid state physics in the late 1930s at Johns Hopkins University before joining NRL's Metallurgy Division in the summer of 1940.[24] At Hopkins, Friedman had learned to handle X-rays for analyzing materials, a skill that seemed to fit nicely with the very origins of the Metallurgy Division in the late 1920s when division patriarch, Robert Mehl, developed techniques for analyzing the quality of welds, casts, and forged metal parts by passing radiation through the metal and onto recording film.

When Friedman joined the division, however, he found that it had moved away from Mehl's scientific approach of relating a metal's internal microstructures to its good and bad properties. Instead, the focus had shifted toward a more empirical approach of improving metals and alloys by tweaking this or that practice at the foundry. It was a strategy more apt to produce results quickly, that is, better metal for the Navy, but it did not satisfy Friedman's craving to push the boundaries of fundamental knowledge about the material world. Since Friedman was more attracted to the more fundamental studies, he convinced himself that he would have to leave NRL.

Hulburt snatched up the disillusioned Friedman before he and his talent could follow through with his intention to leave NRL. After all, X-rays are a form of light and that means Friedman's skills were in sync with the Optics Division. One of the first successes Friedman scored in the pre-V-2 days under Hulburt was to use X-rays to help

precisely orient and cut crude quartz crystals so they could have preselected radio oscillation frequencies. This turned out to be of critical importance during the war when the supply of more easily oriented, higher quality crystals was cut off. The accomplishment later was credited with saving millions of man hours.[25]

Friedman's ticket to rocket-based science began when he became the Laboratory guru for photon counters. On one side of these usually cylindrical devices there often is a window made of materials chosen to allow particles or photons of only certain energy ranges into the tube's gas-filled interior. The light entering the tube ionizes a molecule of the gas, triggering an avalanche of electrons. So, very tiny amounts of light can produce a large amount of ionization, which then is readily detectable by electrodes in the tube. The most widely recognized photon counter is the Geiger counter, which detects emissions from decaying radioactive atoms.

Since photon counters measure radiation more quantitatively than photographic techniques, Friedman was able to use them to make such measurements as the thickness of paint on a ship and the level of fuel in a tank. The principle was much the same as Mehl had used in the late 1920s with his gamma-ray radiography, only instead of relying on film to record the data, electrical signals feeding to an oscilloscope or a chart recorder did the job.

It took Friedman several years longer than Tousey to get into the rocket astronomy business, partly because new photon detectors were in high demand during the nuclear weapons tests in the Pacific just after the war. Since radiation is one of the primary products of nuclear explosives, Friedman and his photon counters became critical components of these efforts. Indeed, the collective talent at NRL for measuring physical phenomena in general meant that many at the Laboratory, including Hulburt, Tousey and Krause, would participate in the tests.

It was soon after the A-bomb tests in the Bikini Atoll that Friedman inadvertently became hooked on solar flare research. He, Peter

King of the Chemistry Division, and several others were assigned a secret, high-priority project to develop a means of detecting atmospheric nuclear explosions. One part of the detection system involved the placement at air weather stations of automatic photon counters sensitive to the gamma radiation from nuclear fission products.

Beginning in late 1949, Friedman, then head of the division's Electron Optics Branch, began to send some of the radiation detectors he and his colleagues were making to the highest altitudes ever achieved. "When the great solar flare of November 1949 occurred, possibly the greatest on record, we obtained excellent measurements of the penetration of solar cosmic rays up to 20 GeV [billions of electron volts], from Arctic to Antarctic latitudes," Friedman recalls with bittersweetness. The data was secret, however, so he and his colleagues could not share their unique data with the open scientific world. It was the kind of data that would have made the career of a young scientist. "I resolved then to pursue studies of the flare phenomenon in the unclassified rocket program."[26]

This approach was far different from Tousey's. For one thing, the electronic detection of radiation in Friedman's photon tubes was more readily and precisely quantifiable than photographic detection. Moreover, there was no need to recover the tubes since their electronic signals were radioed to receivers on the ground. The real-time telemetering of data had the additional advantage of allowing Friedman to mesh his own data with rocket performance and position data from ground tracking records.

The first battery of Friedman's detectors flew on September 29, 1949 to a height of about 94 miles (151 kilometers). It was the 49th V-2 flight from White Sands. "As the radio signals came in, we first read Lyman-alpha extreme ultraviolet at about 75 kilometers followed by soft X-rays at 85 kilometers," Friedman recalls.[27] When all of their data came in, Friedman and his colleagues were able to identify X-rays as the form of radiation most responsible for the ionization that underlies the ionosphere. In addition, they found that the UV radia-

tion passes through this layer without causing ionization, and is absorbed at a lower atmospheric level.

Friedman's group had beginner's luck with their first V-2 flight. The next V-2 they had an opportunity to fit with photon counters exploded on the launching pad, burned furiously, and surrounded the blockhouse with billowing smoke. With that loss, Friedman learned firsthand about the devastating mood swings of the big V-2s.

When the smaller and more reliable Aerobee rockets started becoming available, Friedman became an instant fan. He hoped to use them to study solar flares. Although, the first generation of Aerobees could not reach V-2 altitudes, stretched versions of Aerobees with longer fuel tanks outreached the V-2s. In an arena where higher is better, the Aerobee became the workhorse research rocket.[28]

Friedman and others interested in using rockets for studying solar flares still had a big problem. Solar flares occur with a suddenness and unpredictability that did not match well with the long preparation time of an Aerobee, which had to be used within an hour or two once its fuel was pressurized. Success depended entirely on the extreme luck of a solar flare occurring just in those few hours out of each average month when one happens to have an Aerobee fueled, pressurized, and ready to go.

An answer came in by way of Jim Van Allen, then at the Applied Physics Laboratory and destined for immortality as the discoverer of the magnetic belts that circle the Earth and that bear his name. Van Allen's idea was the Rockoon: a small, relatively simple rocket (like the 9-foot long Deacon) is tied to a 150,000 cubic foot polyethylene balloon. The balloon carries the rocket to a height of 25 km. It hovers there all day, if need be, until it could be fired by radio command at the first sign of a solar flare.

In July 1956, Friedman, James Kupperian, Jr., Leo Davis, Robert Kreplin, and other NRL colleagues sailed with ten Rockoons from San Diego aboard the USS *Colonial*, an LSD (a ship designed for dispatching materiel onto a beach-head), to a site about 400 nautical miles off of the California coast. "Each morning we launched a bal-

loon trailing a string of corner reflectors [for radar tracking] below which dangled the rocket," Friedman recalls. "Then began the chase. We could not permit the Rockoon to get out of range of our radio cut-down command, but the upper-air winds were faster than the lumbering LSD. It helped that the winds reversed in the course of the day, so that we could let the Rockoon travel away from us toward the California coast in the morning, then catch it coming back in the afternoon."[29]

On the first days, there were no solar flares. "Sunday was a day of rest, and with no Rockoon aloft to observe the Sun, it produced two very good flares," Friedman wryly recalls. "On the fourth day we were all at lunch except for Bill Nichols and Bob Kreplin when a flare erupted. Bob reacted quickly and fired the rocket. It caught a weak Class I flare, but the observation of a strong X-ray flux at 70 kilometers was clear-cut. We had proven that solar-flare X-rays are the key to the production of radio fadeout."[30]

While Tousey and Friedman were leading teams along parallel and complementary lines of rocket-borne research in the first half of the 1950s, NRL as an organization was about to take just about the

With the October 5, 1954 flight of a camera-bearing V-2, NRL scientists assembled this photo-composite showing approximately 1.25 million square miles of the world's surface. The caption of this press photo included the following claim: "The Navy believes that this is the largest Earth area ever photographed from one spot at one time."

deepest plunge any organization in the world had taken into the nascent field of rocket-based research. As the V-2 supply dwindled and the Aerobees and Rockoons began to fill in the gap, those in the Rocket Sonde Research Branch were realizing its original ambition to develop its own rocket—the Viking. Unlike the V-2, which was not steerable, the Viking had a gimbaled engine that could guide the vehicle by directing thrust at different angles. Moreover, it was larger and so could carry heavier payloads than the Aerobees and take those payloads much higher.

Under contract by NRL, the Glenn L. Martin Company in Baltimore built the Viking using an engine designed by Reaction Motors, Inc. under a separate Bureau of Aeronautics contract.[31] Krause assigned Homer Newell, Jr. and Milton Rosen to oversee the project. The Viking project would lead to the construction of 14 variously configured rockets. The last two Viking rockets became part of the optimistic national goal of putting an artificial satellite into orbit around the Earth as part of an international scientific mission, called International Geophysical Year (IGY), to study the Earth as a whole.

The first seven Viking firings occurred between May 3, 1949 and August 7, 1951.[32] Viking 4 stood out because it was fired from the deck of a ship, the USS *Norton Sound*. Launching from an at-sea platform made scientific sense since the structure of the atmosphere varies at different geographic locations. But the shot also demonstrated the military potential of ship-launched missiles reminiscent of the Nazi plan to tow launching tubes to the U.S. coasts. There was no shortage of failures. For example, the lightweight aluminum fins on Viking 6 buckled and collapsed mid-flight, sending the rocket into an unscheduled landing 7 miles from the launch site.

Viking 7 was the last of the first-generation Vikings, which were 49 feet tall and weighed nearly 5 tons. It went up at 0:59 a.m. on August 7, 1951, and when its engine burned one second longer than was needed to break the altitude record, Milton Rosen and his Viking colleagues had wide eyes as the rocket continued to coast higher and higher. Its ascent ended at 136 miles, shattering the previous record

of 114 miles set by a V-2 launched nearby almost five years earlier. Only this time, the rocket that held the record was conceived of, designed, and built in the United States under the direction of NRL.

The next three Vikings under the original contract with the Glenn L. Martin Company would be fatter and heavier, a slight sacrifice in aesthetics for the hope of attaining higher altitude. They would demonstrate, however, that rockets still rose on a cloud of thrust and a prayer. This new Viking series started out ominously on June 6, 1952, when the Viking 8 rocket ripped from its tie-down blocks during a test firing of its motor and then crashed in the desert about four miles southeast of the launch site. The next Viking's engine stopped earlier than expected, reaching a height of 135 miles, about 50 miles shy of its intended peak.

The June 30 firing of Viking 10 turned harrowing when the rocket's tail section exploded, setting off a fire. Despite the unintended pyrotechnics, no one was hurt. Workers were even able to quash the fire soon enough to salvage much of the rocket. The rocket was rebuilt and, like Lazarus coming back from death, the reconstructed Viking 10 soared upward from White Sands on May 7, 1954 to a record-equaling height of 135.9 miles.

In between the death and resurrection of Viking 10, NRL awarded the Glenn L. Martin Company another contract for four more Vikings. Viking 11 surpassed the performance of its predecessors, taking the record to 158 miles. The NRL scientists were able to retrieve the armored steel film cassette from an aerial camera that survived the rocket's crash landing. In it was a cache of spectacular high-altitude portraits of the Earth, revealing magnificent cloud formations and global weather patterns. The then novel pictures ran in many newspapers and magazines. Viking 12's January, 1955 launch did not live up to the building expectations that came with Viking 11. But its camera produced some of the best high-altitude pictures of Earth yet.

As exciting as all of the Viking firings were, they were expensive, on the order of $400,000 per shot. And the scientists who had spent many months designing experiments or equipment to fly on the rock-

ets never quite knew what to expect. There never were guarantees. Smaller, more reliable rockets like the Aerobees and Wac Corporal would become the workhorses for sounding rocket studies in which the flights lasted only a few minutes. Big rockets retained unambiguous military potential as delivery vehicles for guided missiles, but their future role in scientific research was uncertain because of their expense.

In the summer of 1954, during early planning for the International Geophysical Year (slated to run from July 1, 1957 to December 31, 1958), the fate of big rocket science would be sealed. Members of the International Scientific Radio Union, the organization that originally proposed the IGY, recommended that the IGY community consider the audacious idea of artificial satellites as platforms for research. There were no such things at the time, only on-again, off-again sounding rockets like the Vikings that were unable to achieve conditions for reaching orbit.

This launched the collective imagination of the IGY community into orbit. Later in 1954, the U.S. National Committee (USNC) for the 67-nation IGY set up advisory groups to study the feasibility of launching a satellite sometime during the 18 month International Geophysical Year and secondly to determine whether a satellite would genuinely boost research. To no one's surprise, the answers were yes and yes. With the nods of advisory bodies, the USNC proceeded in 1955 to draw up plans for a satellite program.

On July 29, 1955, the White House publicly announced jointly with the Belgium-based Special Committee for the International Geophysical Year (IGY's international headquarters) that the United States intended to launch "small unmanned earth-circling satellites" as part of the IGY. "This program will for the first time in history enable scientists throughout the world to make sustained observations in the regions beyond the atmosphere," President Eisenhower's press secretary, James Hagerty, told reporters at the White House.[33]

The timing of the announcement was in part due to fears that the Soviet Union would snatch the glorious moment.[34] Four days later,

Moscow announced that the Soviet Union also would have its own satellite in orbit during the IGY.

No one knew exactly how anyone was going to put an artificial satellite into orbit. No rocket on Earth could do it. At the time of Hagerty's announcement, a high level committee known as the Stewart Committee (convened at the behest of the Assistant Secretary of Defense Donald Quarles) was charged with deciding who, in fact, would get a shot for the once-in-history shot at being the first to put a satellite into Earth orbit since the Moon showed up there billions of years ago.

The Air Force might have been a contender but its development work on the Atlas rocket, which was slated to become the launch vehicle for an intercontinental ballistic missile, by law had to take precedence over a scientific rocket project. That left two tight-knit and proud groups of rocket designers—one at NRL under men like Homer Newell and Milton Rosen, and one at the Army's Redstone Arsenal under the auspices of Wernher von Braun, the German rocketeer most behind the V-2s whom the Army had snatched for their own after the war.

The Army proposed the Orbiter, some of whose components already had been under development with funds from the Office of Naval Research.[35] It called for a multistage rocket that could put a 5-pound satellite into orbit. The NRL proposal was for a three-stage rocket using a Viking-based design for the lower one or two stages and newly designed upper stages. Rather than a 5-pound payload, however, the NRL proposal called for 40 pounds of scientific instrumentation. NRL also could boast of a virtually ready-to-go radar tracking system, called Minitrack, that NRL researchers John Mengel and Roger Easton already had developed to track Viking projects. This was no small concern since the challenge of finding and tracking a 5- or 40-pound satellite in the vast expanse of outer space mocked the trouble of finding a needle in a haystack.

The Stewart Committee assessed the pros and cons of each proposal and sent their report to the Secretary of Defense on August 4.

The committee vote was close but the majority favored NRL's proposal over the Army's. It took another head-to-head round involving detailed reports and testimonials by generals, scientists, engineers, and company executives before the Stewart Committee made their final decision.

On September 9, it became official. NRL had won stewardship of the satellite program, which became known as Project Vanguard, and NRL would never be the same.

The basic objectives were to build a satellite launching vehicle, get one satellite into orbit, track it in orbit, verify its orbital path, and accomplish one scientific experiment all before the end of the IGY.[36] Recent analyses by historians of declassified documents from the National Security Council reveal that the science-centered Project Vanguard was part of a hidden agenda for President Eisenhower and the national security community. By launching a scientific satellite during the IGY, the U.S. would be able to establish a legal precedent by which the jurisdiction of sovereign states over their own air space would *not* extend to outer space. With a "freedom of space" definition established, it then would be quite legal to fly surveillance satellites directly over Soviet territory. For the topmost level of the U.S. government, therefore, the Project Vanguard story was a cover.[37]

Even if the Project Vanguard scientists were being unwittingly used in this way, the scientific opportunities they saw in satellites remained as exciting as they possibly could get. "Recognizing that the project was of a magnitude greater than that for which a division was geared to handle and that the successful development of the project would call for talents from many divisions in the Laboratory, the Director, Capt. Tucker, and the Director of Research, Dr. Hulburt, decided to form a group outside the division structure to carry out the project," recalled John Hagen, superintendent of the Atmosphere and Astrophysics Division (1950-1958) and Director of Project Vanguard.[38] *Life* magazine would later describe Hagen's experience in Project Vanguard as "one of the most trying ordeals ever imposed on an American scientist in the course of his work."[39]

Hagen had three years to pull off the task, which required as much administrative orchestration as technical innovation. The Vanguard team organized into groups devoted to designing the rocket, designing the grapefruit-sized satellite, miniaturizing instruments and telemetering equipment so they could fit into the satellite, and developing a global rocket and satellite tracking system. Scheduling, budgeting, and liaison with other parts of the Defense Department also fell under the aegis of Hagen and the Vanguard team. Moreover, the team had to work closely with the Glenn L. Martin Company, the prime contractor on the Vanguard project, to build the launch vehicles. What's more, the team had to secure and modify a part of the Army's missile launching site at Cape Canaveral so that it would be suitable for Vanguard rockets.

"In the end, because the Air Force and Army claimed full occupation of launch facilities and since Vanguard had no military priority, we were forced to build our own hangar, blockhouse, and launch stand," Hagen recounted.[40] "All the while, the Scientific Program group worked with the committee for the IGY of the National Academy of Sciences to select a series of experiments from scientists around the country and then to work with those scientists in preparing the experiments so that they would stand the rigors of launching and flight".[41] It was a non-stop orchestration of thousands of people distributed across the country working on scores of projects at a cost of millions of dollars.

The first blow came early after NRL had signed a letter of intent with the Glenn L. Martin Company. Unknown to NRL, the company previously had also been selected as the prime contractor for a top-priority Air Force project to develop the Titan, a second-generation intercontinental ballistic missile. Many of the Martin engineers who had worked on NRL's Viking rockets were now assigned to the Titan project. That left Vanguard with a less experienced Martin crew.

Although, the Martin company was responsible for the overall rocket system, many other companies supplied components. The first-stage engines and pumps came from General Electric. The Aerojet-

General Company was contracted to supply the second-stage rockets incorporating a guidance packet supplied by the Minneapolis Honeywell Company. The third stage had its own set of contractors.

The plan was to build up to a satellite launch with a set of six test vehicles, designated TV-0 through TV-5. The first two would use up the two leftover Viking rockets and test out new telemetry as well as the new third stage. TV-2 would be the first test of the newly designed first stage, which essentially was a Viking with a more powerful engine. TV-3 would be the first full test of the three-stage design. Assuming enough information about rocket performance had been gleaned from the prior tests, TV-4 would shed some of the testing instrumentation and telemetry, making way for TV-5, which would embody the final launch vehicle including a dummy of the satellite. Following the test vehicles would come seven satellite-launching vehicles or SLVs.

Roger Easton and John T. Mengel were responsible for getting the tracking system ready. Easton and colleagues already had developed a radio guidance system, the Minitrack System at White Sands, and this became the basis for the Vanguard tracking system (and later for the Global Positioning System by which anyone anywhere could establish their latitude, longitude, and altitude with astounding accuracy). With a series of stations separated every 500 or 600 miles in a north-south line from Blossom Point, Maryland, through the southern states, and Central and South America all the way south to Chile, the researchers designed a "radio fence" that could track the satellite. Additional Minitrack stations went up in Australia and South Africa. The prototype station at the Naval Electronics Laboratory (NEL) in San Diego, which was not positioned to track Vanguard satellites, would be among the first stations to verify that the Space Age had begun.

With launches going from the Florida coast and tracking stations set up all over the world, the Vanguard team established a control center at NRL with teletype connections to all relevant locations, which included a link to the Vanguard Computing Center in Washington equipped with an IBM 709 computer for orbital computations.

Things were moving nicely along by the spring of 1957. By then, the first two test launches, TV-O and TV-1, had demonstrated that a third stage indeed could be ignited in the near vacuum of the upper atmosphere. Nothing could be taken for granted in this fetal stage of the Space Age.

Then, with TV-2 installed on launch pad on October 4, 1957, the Vanguard team and the rest of the world heard a revelation that could not have been more shocking. According to a *Life* magazine article about Hagen's rough ride as director of Project Vanguard, the morning started out for Hagen at an IGY meeting in Washington on missiles and rockets. At the meeting, Hagen had sought out Sergei Poloskov, a Russian rocket expert. "Hagen asked if the U.S. would be given time to change its radio tracking equipment should the Russians soon launch a satellite," the article reported. "Poloskov smiled and said plenty of notice would be given."[42]

That evening, Hagen skipped an evening cocktail party at the Russian embassy and returned to his home in Arlington, Virginia. There his 16-year-old son Peter relayed news that had just been called in on the phone: the Russians had launched a satellite—Sputnik I. Hagen was stunned.

Herbert Friedman recalls the immediate aftermath:

> *"Public reaction was initially mild, reflecting President Eisenhower's comment that 'it does not raise my apprehension one iota about national security.' The numbness wore off quickly, and public figures began to decry the shameful situation with the usual accusations of administration penny-pinching, shortsightedness, lack of vision, and general stupidity. Truman blamed the McCarthy era for having deprived America of its best brains. By implication the Vanguard team was a bunch of second-raters. The Senate Preparedness Committee chaired by Lyndon Johnson immediately began an inquiry into the status of U.S. rocket and satellite programs."*[43]

Scooped, Hagen and the Vanguard team had to push on. They successfully launched TV-2 on October 23, 1957. It carried a two-ton

payload to an altitude of 109 miles before coming back to Earth 335 miles downrange. Two weeks later, the Soviets launched Sputnik II and its canine passenger Laika.

The launch of the Sputniks may have raised blood pressures at NRL to record levels, but an unfortunate miscommunication following a White House briefing by Hagen and several colleagues on Project Vanguard would raise pressure to the bursting point. Hagen recalled what happened: " . . . we briefed President Eisenhower, giving him a very factual report of our standing and telling him that we had planned in December to launch the first full-fledged test vehicle in the Vanguard program, emphasizing it was only a test vehicle which had a very remote bonus—a satellite. This was the TV-3, the first attempted launching of a complete Vanguard vehicle with all three live stages, as well as the first flight of the second stage."[44]

Although TV-3 always had been planned as an engineering test whose outcome would build into the real thing, perceptions that it actually was the real thing were about to get way out of hand. On November 11, 1957, shortly after the briefing, James Hagerty, Eisenhower's press secretary, released a statement saying that Project Vanguard would launch a satellite in the near future. "In other words," Hagen said, "our first live three-stage launching was billed as a satellite launching success in advance and committed us to a public deadline with an untried vehicle."[45] Once released, there was no stopping the media frenzy. No matter what the rocket scientists might think, the U.S. citizenry was convinced that NRL would launch the U.S. answer to Sputnik at the very next Cape Canaveral firing on December 6.

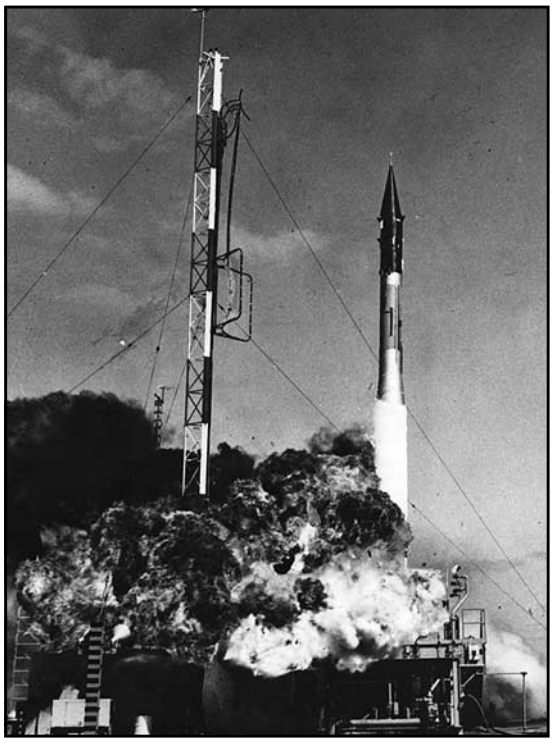
With the world watching, and after several tension-amplifying weather delays, the countdown went to zero. Again, Friedman recalls the moment:

> *"When the rocket flame ignited on December 6, the vehicle rose only a little over a meter and faltered. As it fell back, the fuel tanks ruptured and the rocket rumpled to the ground enveloped in hellish flames and billowing smoke. From the top of the three-*

stage rocket the silvery 6-inch satellite plummeted 25 meters through the flames and bounced on the concrete deck. There our wounded bird, its antenna badly bent, radiated a futile signal at 108 megahertz."[46] *[Roger Easton later retrieved the satellite and brought it home, where he kept it in a closet.]*[47]

Amidst all of the subsequent report writing and public humiliation, Hagen and his team still had a test schedule to complete. But there would be no mercy. On January 22, a series of delays scrubbed the scheduled flight of America's second attempt to answer the Sputniks. The ridicule was brutal. "The Soviet delegation to the United Nations jokingly offered to include us in the USSR program of technical assistance to developing nations," Friedman recalls.[48] The joke at the Pentagon was a new Navy salute—a hand clasped to the forehead.[49]

Stuck plugs and a leaky fuel system on subsequent days prolonged the delay. That's when Wernher von Braun and his rocket crew with



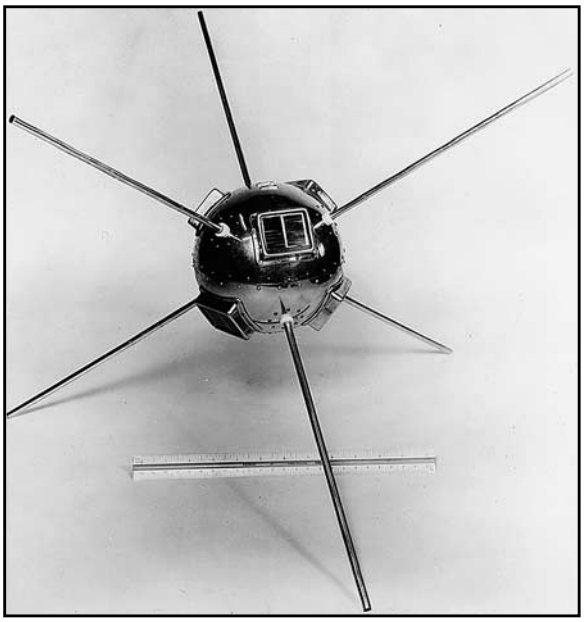
The world watched on December 6, 1957 when this, the first firing of the complete three-stage Vanguard Program rocket burst into flames just two months after the Soviet Union had successfully launched its first Sputnik satellite.

the Army Ballistic Missile Agency, whose top priority mission had been the development of intermediate-range and intercontinental ballistic missiles, received authorization to launch their satellite-tipped Jupiter C. On the night of January 31, the Army's Explorer I satellite indeed had begun circling the Earth, a fact all too clear to the Navy men tracking its orbit with the Minitrack system they had built specifically for tracking Vanguard satellites. In the end, it was the Army, not the Navy, that Americans would remember as meeting the Soviets in the space race.

Hagen's ordeal was not yet complete. After several more delays in early February, another satellite-tipped Vanguard rocket finally lifted off but it broke up after reaching a little more than four miles. On March 8, the next launch attempt, a plug involved in the fuel pressurization process failed to come free. The luck of the Irish finally came Hagen's way at 7:15 a.m. on St. Patrick's Day, March 17. This Vanguard rocket soared upward to deliver its 3½ pound satellite, which Soviet premier Nikita Kruschev had dubbed "the grapefruit," into orbit.

Although Project Vanguard suffered every PR calamity in the book, it was an astounding achievement in rocketry from an engineering point of view. In just 2½ years, a new rocket system and satellite had gone from an all-paper design stage to a successfully launched satellite. The legacy of the project's rocket designs would trace through several NASA and Air Force vehicles including the Delta booster, which would bring the United States into the era of manned space flight. Moreover, the Minitrack system would become the basis of all satellite tracking, including the advanced and comprehensive space surveillance system code named SPASUR.[50] With SPASUR, the U.S. could detect unannounced launchings of satellites by foreign nations.

In addition to these engineering and surveillance developments, the Vanguard I satellite yielded a modicum of new scientific information. Among them were more data about the subtly nonspherical shape of the Earth and the periodic variations in the density of the upper atmosphere.



Model of the satellite, known as "the grapefruit," that NRL successfully launched into orbit on March 17, 1958

To Hagen, none of these were the most important outcome. "The greatest achievement of Project Vanguard," he opined, " . . . was the development of a group of dedicated and talented scientists and engineers who came to understand thoroughly, perhaps the hard way, the overall complexities of the space programs."[51] Indeed this legacy of human talent, expertise, and ambition would have lasting effects both within and without NRL.

The first major ripple began swelling into a major new wave of the Space Age just weeks after Vanguard I went into orbit when President Eisenhower set into motion a series of actions that led to the creation of the civilian National Aeronautics and Space Administration (NASA) on October 1, 1958. By then, there were pockets of rocket expertise at NRL, the Army Ballistic Missile Agency that had put Explorer 1 into orbit, the Air Force Cambridge Research Laboratories, the Jet Propulsion Laboratory (JPL), and several other places. Among these, however, NRL supplied the largest portion of NASA's initial technical staff.

"It was a foregone conclusion that NRL's Vanguard group—150 strong—were to become part of NASA, as they did on November 16,

1958," according to one of NASA's own accounts of its early history.[52] "As it turned out, NRL also provided the great bulk of NASA's sounding rocket know-how when, on December 28, 1958, John Townsend, Jr., transferred to NASA, as did 46 NRL scientists and engineers in the Rocket Sonde Research Branch that began with Ernst Krause's vision in 1946. So about 200 NRLers became part of NASA's initial staff.

This large contingent of NRL researchers became the professional nucleus of NASA's Beltsville Space Center, the NASA facility in suburban Maryland just north of Washington that would become the center of NASA's unmanned space programs. When the Beltsville Space Center was renamed the Goddard Space Flight Center in 1959, former NRL staff held many top management positions as well as comprising the bulk of the Center's talent in sounding rocket science and technology. Moreover, a cadre of the pioneers and leaders of NRL's rocket research and design effort—including Homer Newell, Milton Rosen, and John Hagen—also took over high level positions at NASA's headquarters in downtown Washington, DC. It is no exaggeration to say that these men and their many NRL colleagues who worked on the rockets from the V-2 days onward through the Viking and Vanguard programs are among that group of people responsible for the advent of the Space Age.[53]

Even after the great exodus of rocket expertise from NRL to NASA, some very powerful roots were left behind. A small remaining contingent of these rocket scientists immediately began regrowing. One of them was Marty Votaw. "He thought that the Navy should stay in space," recounts Peter Wilhelm, who began working for Votaw in late 1959 in the newly formed Satellite Techniques Branch.[54] Wilhelm grew up in Yonkers, New York, earned a degree in Electrical Engineering from Purdue University, and worked on classified submarine electronic development at a Chicago engineering firm before joining NRL.

"Votaw convinced people that staying in space was important and that the Navy shouldn't get out of the business," Wilhelm recalls.[55] After Votaw first convinced the NRL Director of Research Robert Page and other decision makers to reestablish a small satellite group, Votaw

scrounged up $100,000 to get the new branch off the ground. "There was still some residual hardware around that NASA had not scoffed up," recalls Wilhelm.[56] A junior member of the branch, Wilhelm's first task was to build radio frequency transmitters for Solrad I, NRL's first post-Vanguard satellite, whose mission was to measure solar radiation, a research goal snugly linked to Taylor's and Hulburt's ionospheric studies in the 1920s. Besides Votaw and Wilhelm, who now directs NRL's Naval Center for Space Technology, there were a handful of others in the new branch that comprised NRL's own post-Vanguard seed in the field of satellite engineering.

The first project of NRL's regenerating space science group—Solrad I—proved to be a good omen. The satellite's name is a contraction of the phrase "solar radiation." Solrad I was larger than the grapefruit-sized Vanguard satellite, but not by much. Like fraternal twins in a womb, the NRL satellite and a navigation satellite called Transit (built by the Applied Physics Laboratory affiliated with Johns Hopkins University) sat together in the tip of a Thor Abel rocket. On June 22, 1960, the rocket shuttled Solrad I into orbit where for the next 10 months it telemetered data about the Sun to NRL scientists. This achievement was simultaneously a birth of satellite navigation, which NRL would get into in the biggest way, and an optimistic rebirth for NRL's solar scientists.

This time, luck was abundantly on NRL's side. Not only was the launch a success, but the cosmos cooperated with Herbert Friedman and his colleagues, who had built X-ray and ultraviolet detectors on the hypothesis that solar X-rays were indeed responsible for radio fadeouts. A rival idea was that Lyman-alpha emission from the Sun, which is ultraviolet radiation, was to blame. With the two kinds of detectors aboard Solrad I, the NRL scientists had the means of performing a critical test and hopefully settling the issue.

"Shortly after we went into orbit, only a few days later, there was a major explosion on the Sun, a major event," along with radio disturbances, Wilhelm recalls. "And what we saw from the satellite was a huge increase in X-rays, but the Lyman-alpha emission was pretty much

constant. So that nailed it more precisely than before."[57] Friedman was right. Solar X-rays delivered the energy driving ionospheric disturbances. An important question of solar physics had been answered. Solrad I marked the beginning of an unending stream of satellite engineering advances and space science discoveries made by NRL researchers.

Solrad I was the first of 14 Solrad satellites whose collective mission was to characterize the Sun's radiation reaching the Earth's upper atmosphere. The failed launch of Solrad II was a sobering reminder that space science would be no cakewalk. The next launch three months later had mixed results. Aboard a Thor-Able-Star rocket was the first Low Frequency Trans-Ionospheric satellite (LOFTI I), whose mission was to determine whether low-frequency radio waves could penetrate the ionosphere well enough to be used to communicate with submerged submarines. Unfortunately, the satellite failed to separate from another satellite on which it was riding piggyback. Despite that snafu, LOFTI I collected data for 36 days before falling into the upper atmosphere and disintegrating. Moreover, the mission answered the question it was designed to answer: the ionosphere was too disruptive to allow for reliable submarine communications with circuits that go through the ionosphere. Data like that would move Navy decision makers to build enormous, land-based, low-frequency antennae.

The next launch suffered a similar fate: the satellite failed to separate. The next two launches failed completely. Though the fact offered little solace, no one else in the young rocket business was doing much better. There is no shortage of film clips from these early years showing rockets blowing up on launch pads or going astray soon after launch. In the rocket business, one must crash before one flies, a truism that was later transformed at NRL into the adage: "You can make mistakes, just don't launch them."[58]

Finally, with NRL's seventh post-Vanguard satellite launch, on December 13, 1962, the road began to smooth out. This time, a Thor-Agena rocket successfully carried a pair of classified satellites, a cali-

bration satellite for the ground-based Space Surveillance system (SPASUR) and the tiny, 3 kilogram, Calsphere I satellite, whose role was to help satellite trackers on the ground get better at identifying specific objects in space. Since 1960, NRL has been involved in more than 30 launches, collectively bearing more than 80 NRL-built satellites (see launch manifest on the next page).

Besides measuring solar radiation and calibrating satellite tracking systems, NRL-made satellites have harvested massive amounts of basic data that became crucial for subsequent satellite design and for overall thinking about how the space environment can further the Navy's mission and capabilities. Some satellites measured gravitational gradients over the Earth, which is important for such things as the general design of orbital trajectories for satellites. Some have monitored the thermal effects on satellites and components of cyclic heating and cooling as the spacecraft circle into and out of the Sun's light. Still others have investigated the propagation of various low- and high- frequency radio wavelengths through the ionosphere for space-based communication, the measurement of drag on satellites as a function of altitude, and the placement of orbiting atomic clocks for submarine navigation and position determination. In addition, many launches have carried classified payloads.

So routine did NRL's presence in space become, that it is now just another bullet on the Laboratory's curriculum vitae. Yet some accomplishments do stand out. One of them is commemorated in the main hallway of the Smithsonian Institution's Air and Space Museum in Washington, DC. There, millions of visitors stop by a mock-up of Apollo 16's landing module on a simulated Moon site. In front of this scene is a duplicate of the Far Ultraviolet Camera/Spectrograph, which was designed at NRL by engineer George Carruthers.

The real Far Ultraviolet Camera, whose golden surfaces still reflect sunlight from the Moon, constituted the first and only lunar observatory. Once it was set up on the surface of the Moon by the Apollo 16 crew—a perch where there was no UV-absorbing atmosphere as on Earth—the camera snapped 178 pictures of the ultraviolet light from

NAVAL CENTER FOR SPACE TECHNOLOGY
NRL SATELLITE LAUNCHES

Launches	Satellite	Name	Purpose	Weight	Vehicle	Launch Date	Useful Lifetime	Comment
1	1	SR I	Solar X-rays	42	THOR-ABLE-STAR	22 June '60	10 mo.	First solar satellite
2	2	SR II	Solar X-rays	40	THOR-ABLE-STAR	30 Nov. '60	-	Launch vehicle failed
3	3	LOFTI I	Low freq. radio	57	THOR-ABLE-STAR	22 Feb. '61	Decayed 36 days	No separation
4	4	SR III	Solar X-rays	40	THOR-ABLE-STAR	29 June '61	5 mo.	No separation
5	5	SR IV A	Solar X-rays	55	THOR-ABLE-STAR	24 Jan. '62	-	Launch vehicle failed
	6	LOFTI II A	Low freq. radio	60	THOR-ABLE-STAR	24 Jan. '62	-	
	7	SURCAL I	SPASUR calib.	5	THOR-ABLE-STAR	24 Jan. '62	-	
6	8	SR IV B	Solar X-rays	55	SCOUT	26 Apr. '62	-	Launch vehicle failed
	9	SR V	Solar X-rays	-	-	-	-	Never launched
7	10	PL 120	Classified	55	THOR-AGENA	13 Dec. '62	36 mo.	Operation satisfactory
	11	PL 121	Classified	55	THOR-AGENA	13 Dec. '62	36 mo.	Operation satisfactory
	12	SURCAL II	SPASUR calib.	9	THOR-AGENA	13 Dec. '62	36 mo.	Operation satisfactory
	13	CALSPHERE I	Object identification	3	THOR-AGENA	13 Dec. '62	Passive	Decayed 6 mo.
8	14	SR VI	Solar X-rays	85	THOR-AGENA	15 June '63	Decayed 47 days	Operation satisfactory
	15	LOFTI II B	Low freq. radio	65	THOR-AGENA	15 June '63	Decayed 33 days	Operation satisfactory
	16	PL 112	Classified	60	THOR-AGENA	15 June '63	Decayed 42 days	Operation satisfactory
	17	Dosimeter	Radiation counter	85	THOR-AGENA	15 June '63	Decayed 45 days	Operation satisfactory
	18	SURCAL III	SPASUR calib.	9	THOR-AGENA	15 June '63	Decayed 19 days	Operation satisfactory
9	19	SR VII A	Solar X-rays	89	THOR-AGENA	11 Jan. '64	23 mo.	Operation satisfactory
	20	GGSE I	Grav. grad.exp.	84	THOR-AGENA	11 Jan. '64	48 mo.	Operation satisfactory
	21	PL 135	Classified	65	THOR-AGENA	11 Jan. '64	21 mo.	Operation satisfactory
10	22	DRAGSPHERE I	DRAG exp.	2	THOR-ABLE-STAR	6 Oct. '64	Passive	Operation satisfactory
	23	DRAGSPHERE II	DRAG exp.	21	THOR-ABLE-STAR	6 Oct. '64	Passive	Operation satisfactory
11	24	SR VII B	Solar X-rays	103	THOR-AGENA	9 Mar. '65	52 mo.	Operation satisfactory
	25	PL 142	Classified	106	THOR-AGENA	9 Mar. '65	15 mo.	Operation satisfactory
	26	GGSE II	Grav. grad. exp.	130	THOR-AGENA	9 Mar. '65	44 mo.	Operation satisfactory
	27	GGSE III	Grav. grad. exp.	130	THOR-AGENA	9 Mar. '65	16 mo.	Operation satisfactory
	28	SURCAL IV	SPASUR calib.	10	THOR-AGENA	9 Mar. '65	5 years	Operation satisfactory
	29	DODECAPOLE I	Object identification	9	THOR-AGENA	9 Mar. '65	Passive	Operation satisfactory
12	30	TEMPSAT I	Thermal design exp.	19	THOR-ABLE-STAR	13 Aug. '65	3 mo. design life	Operation satisfactory
	31	LONG ROD	Object identification	6	THOR-ABLE-STAR	13 Aug. '65	Passive	Operation satisfactory
	32	SURCAL V	SPASUR calib.	11	THOR-ABLE-STAR	13 Aug. '65	7 years	Operation satisfactory
	33	CALSPHERE II	Object identification	8	THOR-ABLE-STAR	13 Aug. '65	Passive	Operation satisfactory
	34	DODECAPOLE II	Object identification	9	THOR-ABLE-STAR	13 Aug. '65	Passive	Operation satisfactory
13	35	EXPLORER 30 SR VIII (PL 145)	Solar X-rays	125	SCOUT	19 Nov. '65	24 mo.	Operation satisfactory
14	36	PL 137	H.F. wave prop.	90	ATLAS-AGENA	18 Mar. '66	5 day design life	50% satisfactory
15	37	PL 151	Grav. grad.exp.	115	THOR-AGENA	31 May '67	4 years	Operation satisfactory
	38	GGSE IV	Grav. grad.exp.	187	THOR-AGENA	31 May '67	5 years	Operation satisfactory
	39	PL 153	Grav. grad.exp.	169	THOR-AGENA	31 May '67	6 years	Operation satisfactory
	40	GGSE V	Grav. grad.exp.	231	THOR-AGENA	31 May '67	6 years	Operation satisfactory
	41	TIMATION I	Navigation	85	THOR-AGENA	31 May '67	24 mo.	Operation satisfactory
	42	CALSPHERE III	Object identification	10	THOR-AGENA	31 May '67	Passive	Operation satisfactory
	43	CALSPHERE IV	Object identification	7	THOR-AGENA	31 May '67	Passive	Operation satisfactory
16	44	EXPLORER 37 SR IX (PL 155)	Solar X-rays	197	SCOUT	5 Mar. '68	6 years	Operation satisfactory
17	45	ORBIS CAL I	H.F. wave prop.	67	ATLAS-BURNER II	16 Aug. '68	-	Launch vehicle failed
18	46	ORBIS CAL II	H.F. wave prop.	85	ATLAS-OVI	17 Mar. '69	7 day design life	Lau. veh. poorly oriented
19	47	PL 161	Grav. grad. exp.	220	THORAD-AGENA	30 Sept. '69	12 mo.	Oper. sat. till battery fail.
	48	PL 162	Grav. grad. exp.	223	THORAD-AGENA	30 Sept. '69	6 mo.	Op. sat. till cmd. sys. fail.
	49	PL 163	Grav. grad. exp.	225	THORAD-AGENA	30 Sept. '69	3 years	Operation satisfactory
	50	PL 164	Grav. grad. exp.	227	THORAD-AGENA	30 Sept. '69	6 mo.	Op. sat. till cmd. sys. fail.
	51	TIMATION II	Navigation	137	THORAD-AGENA	30 Sept. '69	6 years	Operation satisfactory
	52	PL 176	Classified	50	THORAD-AGENA	30 Sept. '69	2 years	Operation satisfactory
	53	TEMPSAT II	Thermal design exp.	30	THORAD-AGENA	30 Sept. '69	8 mo.	Operated for design life
	54	CONE	Object identification	7	THORAD-AGENA	30 Sept. '69	Passive	Operation satisfactory
	55	CYLINER	Object identification	6	THORAD-AGENA	30 Sept. '69	Passive	Operation satisfactory
20	56	PL 170A	Drag. exp. (gold plate)	1.6	THOR-BURNER II	16 Feb. '71	Passive	Operation satisfactory
	57	PL 170B	Drag. exp. (polished Al)	1.6	THOR-BURNER II	16 Feb. '71	Passive	Operation satisfactory
	58	PL 170C	Drag. exp. (polished Al)	1.6	THOR-BURNER II	16 Feb. '71	Passive	Operation satisfactory
21	59	EXPLORER 44 SR X (PL 165)	Solar X-rays	263	SCOUT	8 July '71	7 years	Operation satisfactory
22	60	PL 171	Grav. grad. exp.	271	THORAD-AGENA	14 Dec. '71	8 years	Operation satisfactory
	61	PL 172	Grav. grad. exp.	271	THORAD-AGENA	14 Dec. '71	-	Operation satisfactory
	62	PL 173	Grav. grad. exp.	282	THORAD-AGENA	14 Dec. '71	-	Operation satisfactory
	63	PL 174	Grav. grad. exp.	282	THORAD-AGENA	14 Dec. '71	-	Operation satisfactory
23	64	TIM. III/NTS-1	Navigation	1132	ATLAS-F	14 July '74	5 years	Operation satisfactory
24	65	SR 11A (PL 175)	Solar X-rays	403			15 mo.	Operation satisfactory
	66	SR 11B (PL 177)	Solar X-rays	403	TITAN IIIC	14 Mar. '76	40 mo.	Operation satisfactory
25	67	MSD	Upper stage/dispenser	1299			41 days	Operation satisfactory
	68	181	Classified	432	ATLAS-F	30 Apr. '76	7 years 9 mo.	Operation satisfactory
	69	182	Classified	432			7 years 9 mo.	Operation satisfactory
	70	183	Classified	432			7 years 9 mo.	Operation satisfactory
26	71	NTS-2	Navigation	1711	ATLAS-F	23 June '77	Operating	Operation satisfactory
27	72	MSD	Upper stage/dispenser	1299			31 days	Operation satisfactory
	73	191	Classified	432	ATLAS-F	8 Dec. '77	6 years 3 mo.	Operation satisfactory
	74	192	Classified	432			6 years 3 mo.	Operation satisfactory
	75	193	Classified	432			5 years 3 mo.	Operation satisfactory
28	76	LIPS I	Devel. test exp.	102	ATLAS-F	8 Dec. '80	-	Launch vehicle failed
29	77	LIPS II	Devel. test exp.	123	ATLAS-H	9 Feb. '83	8 years	Operation satisfactory
30	78	LIPS III	Solar cell exp.	138	ATLAS-H	15 May '87	6 years	Operation satisfactory
31	79	LACE	Laser exp.	3175	DELTA II	14 Feb. '90	3 years	Operation satisfactory
32	80	TLD	Upper stage/satellite dispenser	1600	TITAN	8 June '90	4 years 8 mo.	Operation satisfactory
33	81	CLEMENTINE	Light wt technology Moon mapping Autonomous operations	508	TITAN II G	25 Jan '94	5 mo.	Operation satisfactory
	82	INTERSTAGE	Radiation & micrometeroid detection	107			4 mo.	Operation satisfactory
34	83	TIPS	Tether physics and survivability experiment	118	TITAN IV	(deployed) 20 June '96	Operating	Operation satisfactory

4/97

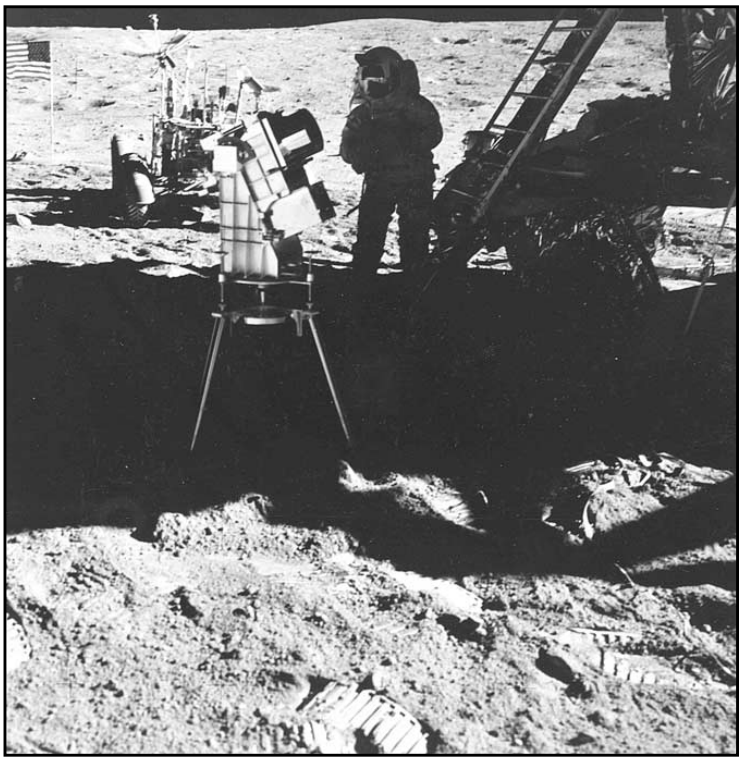
Manifest of NRL space launches spanning from 1960 to the late 1990s

the Earth, cosmic gas clouds, and star clusters. What magnifies Carruthers' accomplishment, which stands high merely by technical criteria, is that he was a veritable Jackie Robinson in the world of astronomy when he worked on the project in the late 1960s. "Back in my day, there really and truly was no African American role model in astronomy that I could look to," Carruthers recalls.[59] Now he has become one.

Another highlight was entered in NRL's space science resume during the following decade when John-David Bartoe[60] and Diane Prinz were chosen as payload specialists in NASA's Space Shuttle Program. The two NRL scientists underwent extensive astronaut training, including rides on specialized 707 aircraft whose roller-coaster-like flight paths provided nauseating, 20-second snippets of weightlessness.[61] On July 29, 1985, Bartoe and the rest of the crew of the Challenger soared into space.

Aboard were two NRL-made instruments—the High Resolution Telescope and Spectrograph (HRTS) and the Solar Ultraviolet Spectral Irradiance Monitor (SUSIM). The HRTS was designed to observe the high energy physics going on just above the disk of the Sun within the solar corona. The SUSIM instrument's charge was to observe that range of solar UV radiation that is the main source of energy driving the dynamics of Earth's upper atmosphere.

Bartoe ended his once-in-a-lifetime orbital adventure on August 6th when he returned to Earth with the HRTS and SUSIM instruments and a rich cache of new data that have become important in the ongoing quest to understand the complex physics occurring within, on, and above the Sun, as well as the solar-driven phenomena in the Earth's upper atmosphere. Upon Bartoe's glorious return, Diane Prinz, who served as science program manager on the ground during the mission, was looking forward to her own turn on a subsequent shuttle mission. But those plans evaporated in the aftermath of the disaster in 1986 in which the same shuttle Bartoe flew on—the Challenger—exploded soon after launch, killing the seven astronauts aboard.



An Apollo 16 astronaut faces the Far-Ultraviolet Camera/Spectrograph that NRL scientist George Carruthers designed.

Even before the tragedy, however, the pace of space science and satellite building at NRL had slowed. After an earlier rocket failure in late 1980, the pace of satellite launches for NRL diminished to one every three to four years, except in 1990 when NRL launched two satellites. Part of the slowdown was due to the shift in national emphasis from expendable rocket launches to the Space Shuttle concept involving reusable rocket components. The explosion of the Challenger only exacerbated the trend of increasing the intervals between launches.

A good part of the slowdown, however, was a natural consequence of the spiraling cost and complexity of each space mission. For most of the satellite-building community, each new project involved more people, more organizations, more parts, more sophistication, and

more management to integrate it all. With so much material, financial, human, and emotional resources sitting atop tons and tons of rocket fuel—a situation in which the risk of failure would never become negligible—each project took far more time to become ready for launch.

Because NRL's satellite engineering budget had always been in the minor league compared to NASA's, NRL's satellite engineers never had the option of adopting the bigger, more expensive trend in spacecraft design, according to Wilhelm. So when Daniel Goldin, director of NASA, publicly announced that his civilian space agency was taking on a new philosophy of "smaller, better, cheaper," there was a familiar ring to it at NRL.

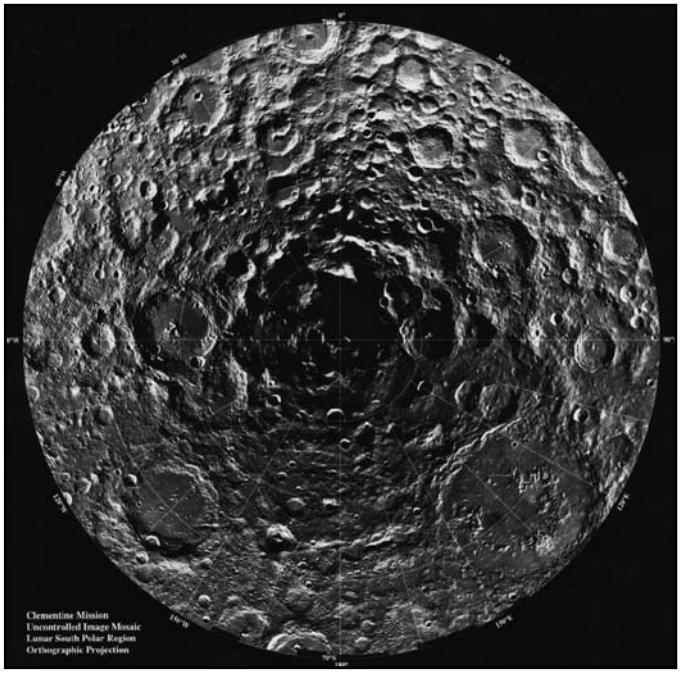
Most emblematic of this design philosophy was the successful 1994 launch of the Deep Space Program Science Experiment, more familiarly known as *Clementine*.[62] The purpose of the mission, which was funded under the Strategic Defense Initiative (SDI) and its subsequent incarnation as the Ballistic Missile Defense Organization (BMDO), was to test new lightweight sensors, imaging technologies, and other components and to see if a spacecraft could home in on a distant target, in this case an asteroid. As an experienced satellite engineering facility within the military establishment with a track record for successful, on-budget launches, NRL's Naval Center for Space Technology became a natural darling of SDI.

A mere 22 months after Lt. Col. P. Rustan of the Strategic Defense Initiative Organization asked NRL to come up with the details for a mission, *Clementine* was on its way on a mission with both military and scientific goals. The military goal, now under the auspices of BMDO, was to see how well an inexpensive, quickly engineered spacecraft might use new generations of sensors, communications technologies, and other equipment to zero in on and observe space-based objects, in this case, the Moon, the Earth, and an asteroid. The scientific payoff would be the most detailed study of the Moon ever, including a comprehensive mapping of the Moon using nearly a dozen

electromagnetic bands. The planners knew that the resulting data would comprise an enormous database about the Moon's topography, geology, mineralogy, and geophysics.

Besides BMDO and NRL, the *Clementine* team also included NASA (for its Deep Space Network for satellite tracking), the Lawrence Livermore National Laboratory (for the cameras), the Air Force (largely for carrying out the launch), the Jet Propulsion Laboratory (for the asteroid encounter), and nearly 50 private companies.

NRL began receiving funding for *Clementine* in March 1992. On December 30, 1993, the satellite was shipped to the Vandenberg Air Force Base in California. There a team of engineers placed *Clementine* aboard a Titan II rocket. On January 25, 1994, the rocket soared into space. Within three months, *Clementine* already had completed an unprecedented mapping of the moon, including its dark side. That



The Clementine Mission not only imaged the Moon in unprecedented detail, but it also found signs of water (as ice) in the Moon's south polar region (shown above).

done, mission control engineers fired thrusters on *Clementine* so that it would leave lunar orbit and head off to a near-Earth asteroid. Unfortunately, a software glitch caused the spacecraft to fire virtually all of its thruster fuel. In addition to setting the spacecraft into a dizzying spin, the loss of the thruster wiped away any chance of achieving the second goal of the mission—intercepting and mapping an asteroid. Although hopes spiked in February 1995 when engineers were able to recontact the spacecraft and communicate with onboard computers, they still were unable to salvage the asteroid mission.

Disappointing as that was, the *Clementine* mission became an instant classic. It was widely acclaimed in the media as a breakthrough demonstration of how space projects would be done in the future. Even President Bill Clinton went on record about the mission's success. A year after the Moon data started pouring into NRL's makeshift mission control in an unassuming rented brick building in Arlington, Virginia, Clinton stated that "The relatively inexpensive, rapidly-built spacecraft constituted a major revolution in spacecraft management and design; it also contributed significantly to lunar studies by photographing 1.8 million images of the surface of the moon."[63]

According to Paul Regeon and NRL colleagues who worked on *Clementine*, the multispectral imaging of the moon stands out as the mission's most important result. Moreover, data indicated that the massive Aitken Basin at the Moon's South Pole is the deepest basin in the solar system, reaching some eight times deeper than the Grand Canyon.

One of the most tantalizing results from observations of this sun-shielded basin was the then unconfirmed hint of the presence of ice based on reflections of radio frequency energy emerging from the basin. That is an exciting finding because the presence of water of any kind on the Moon opens the possibility that the Moon may have harbored life at one time. Moreover, if water is available on the Moon, the futuristic vision of building manned bases on the Moon becomes that much more realistic.

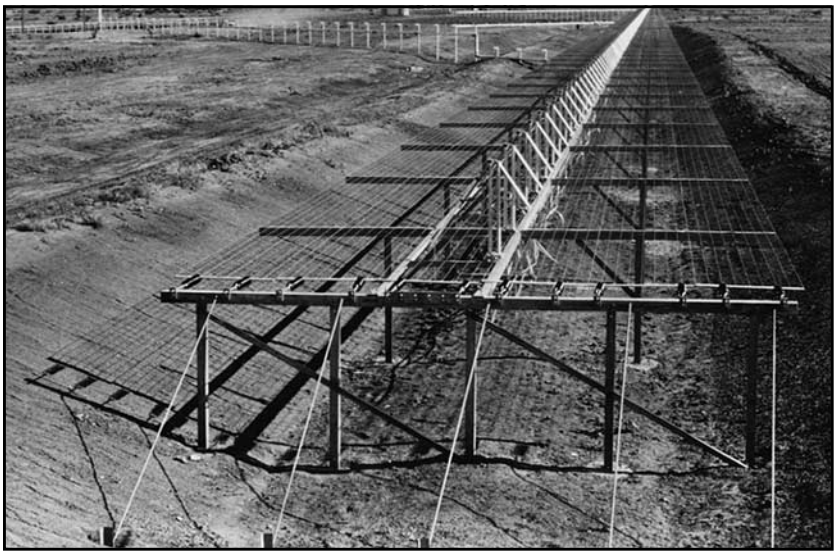
Soon before this book went to press, the planetary science community received additional evidence of the presence of water on the Moon. Measurements of the Moon's surface by instruments on the Lunar Prospector, which NASA launched on January 6, 1998, confirmed the presence of ice not only in the Aitken Basin where *Clementine* first had found signs of water, but also in craters on the Moon's north pole.

One of NRL's proudest and most celebrated roles in the space science and technology arena already is having far ranging consequences in both the military and civilian realms. It began in the mid-1950s with a seemingly ancillary part of Project Vanguard. Yet this ancillary project proved to be the seed of today's most sophisticated navigational system—the Global Positioning System (GPS).[64]

The rocket and its satellite payload were the most obvious components of Project Vanguard. But to confirm that a launched satellite actually had begun orbiting the Earth, it was critical to be able to track the satellite and plot its trajectory. For that, Roger Easton and colleagues at NRL proposed, designed, and built the Minitrack system. Centered on several ground stations along the satellite's expected flightpath, the system detected and precisely timed signals emanating from the satellite's radio transmitter. The slight differences in the time that signals would be received at the different ground stations provided the key for calculating the satellite's position, altitude, and velocity.

The Minitrack system also could detect and track quiet satellites that emitted no signals so long as radar signals could be bounced off the satellites to receivers on the ground. The ability to detect satellites passively became the technical basis of the Naval Space Surveillance System (NAVSPASUR), which became operational in 1961 and remains an active part of the North American Aerospace Defense Command (NORAD).

Easton says he realized soon after conceiving of the Minitrack system that satellites carrying ultraprecise clocks, which could transmit navigational signals synchronized to a master clock, would enable anyone receiving those signals on the ground to calculate their own



A series of surveillance transmitting antennae like this one at Lake Kickapoo, Texas, comprised a surveillance system developed by NRL to detect unannounced radio-silent satellites passing over the United States.

locations at sea, on the ground, or in the air. The concept of using satellites for location-finding and navigation on Earth was the logical flip side of the concept of using Earth-based radar to track satellites.

There were additional calls in the 1950s for better navigational tools. When nuclear submarines carrying nuclear-tipped Polaris missiles became a central pillar of U.S. military strategy, the problem of accurate, rapid navigation at sea took on new and awesome proportions. Since a submarine's on-board inertial navigation system could not avoid drifting during long deployments, the submarine needed to surface from time to time to reestablish bearings, say, by tracking stars from a deck-mounted instrument. Only with such recalibrations of its on-board navigational system could a submarine commander establish where in the world he was with enough accuracy to confidently program the trajectory of his missiles in the woeful event that World War III broke out. To tell a missile where to go, you have to tell the missile where it is starting from.

With so much strategic value concentrated into the new classes of submarines beginning in the late 1950s, the need for ever better and

faster navigational technologies became paramount. Since this was a time when satellites were getting launched with increasing regularity, it is no surprise that Navy researchers began to think about satellites as an answer to the new navigational demands. In 1968, the Joint Chiefs of Staff made the push for new location-finding systems official by stipulating requirements for a system capable of precisely locating military forces wherever in the world they might be. Satellites eventually would provide the solution.

The Navy's first foray into using navigation began in the late 1950s at the Applied Physics Laboratory of Johns Hopkins University, just as Soviet rocket scientists and their counterparts in the Navy and Army were putting the world's first artificial moons into orbit. The project was known as Transit, or more verbosely as the Navy Navigation Satellite System.

The Transit satellites did in fact provide submarines with the capability of determining their locations in about twenty minutes rather than the hours it would take by more conventional means such as star-tracking or radiolocation techniques relying on several transmitters. A submarine made a positional fix by surfacing and receiving a sequence of precisely timed transmissions from a Transit satellite passing overhead. This procedure enabled navigators to accurately calculate the satellite's location, thereby transforming the satellite into the equivalent of a fixed star by which navigators have plotted their locations for centuries. With appropriate corrections for the motion of the Navy vessel during the series of receptions from the satellites, navigators on the vessel could get a fix on their own position faster than ever before. The Transit system became operational in 1963.

The Timation (derived from the words time and navigation) program, the next generation of navigation satellites, began the following year at NRL. The technical backbone of the Timation satellites was ultraprecise spaceborne clocks, which could govern the emission of ranging signals that receivers on the ground could time with clocks synchronized with the satellite's clocks. Ranging signals from several

satellites then could be picked up by a navigational receiver in which the necessary calculations and corrections could be made to pinpoint the receivers' location on Earth. NRL scientists quickly began to adapt a quartz-based oscillator (the heart of the clock) for service in space as well as determining the most efficient constellation of satellites for providing worldwide coverage.

According to Easton, one of the early experiments to test the technique of determining locations passively took place in October 1964 along the brand new route 295 that runs along the bottom of the District of Columbia and links into the Capitol Beltway at the East end of the Wilson Bridge. "That was where we ran a car down 295 with a pseudo Timation transmitter in it, and we received signals back in Building 58," Easton later recalled.[65]

Almost three years later, on May 31, 1967, the first Timation satellite went into orbit. It demonstrated that a surface vessel could determine its position within two-tenths of a nautical mile using the time-synchronized signals from a satellite. Easton could not have predicted what future the first Timation satellite would harbor. Indeed, it would evolve into the powerful and much applauded navigational tool now known as the Global Positioning System (GPS).

Timation I entered a polar orbit at an altitude of 500 miles. Throughout the rest of the year and into the next, the satellite underwent various tests, including navigational experiments using boats, aircraft, and trucks. Timation II went up in September 1969 with what was hoped to be an improved quartz oscillator. It actually performed less well than the clock on Timation I because it was more sensitive to radiation effects in orbit.

Timation III, which at launch was renamed as Navigation Technology Satellite One, went up in 1974. It was a testbed for the first space-based atomic clocks. These were supplied by a Munich-based company, Efratom, and then modified for rocket flight and orbital service. The satellite also included an experimental transmitter, known as the 621B project, built by the Air Force as part of a military-wide

coordination of navigation projects. NRL's Timation Project and the Air Force's Project 621B became the germs for the NAVSTAR Global Positioning System, which is known in short as GPS.

First conceived of behind closed doors at the Pentagon in 1973, the 24-satellite Global Positioning System was completed in 1993. Interestingly, one of its technical roots goes at least as far back to the mid-1940s when researchers including Alan Berman's Nobel-Prize-winning graduate advisor at Columbia University, Isidor Isaac Rabi, floated the idea that an atom's supremely high-frequency oscillations could serve as the basis for ultra-accurate clocks. Good clocks have been at the heart of good navigation for centuries.

The Air Force was chosen to administer the entire project. One of NRL's primary responsibilities was to move the development of space-qualified atomic clocks forward. This involved NRL researchers as well as those at a number of companies working on a contractual basis. Aboard Timation II , for example, were the first prototypes of cesium-based atomic clocks, which, in principle, could provide satellites with clocks of unprecedented accuracy and stability.

Roger Easton was NRL's primary contributor and visionary associated with the GPS. He not only helped conceive of the overall system of satellites, but oversaw the design, testing, and validation of the rubidium and cesium-based atomic clocks without which the system's accuracy and almost miraculous location-finding abilities would have been impossible.

With the major decisions about the system made by the mid-1970s, the last thing to do was to get the system up and running. Satellites, atomic clocks, rockets, and a thousand and one details all had to be worked out, integrated and put in their respective places. The system designed included 24, car-sized Navstar satellites, each weighing nearly a ton, and to be built by Rockwell International. Engineers worked out an orbital geometry such that anybody with a GPS receiver anywhere on the planet would be in contact at any time with at least four satellites. The multiple links are crucial for the speed and accuracy of the navigational calculations.

The first operational Navstar satellite went up in 1978; by 1993, the full complement of 24 satellites was in place. The Global Positioning System has become a major navigational technology crucial for military operations, but now also used in the commercial and private arenas for things as varied as fishing and wilderness hiking.

The CNN-reported Gulf War provided the most striking publicly revealed military application of GPS to date. Who can forget General Schwarzkopf's almost gleeful press briefings on the pinpoint accuracy sometimes achieved by America's newest smart weapons? At the very beginning of the offensive, the GPS guided cruise missiles from Navy ships hundreds of miles in the Persian Gulf directly into Iraqi defense radar antennae. And the great sweep of armored forces across the trackless desert was possible only because of GPS instruments on tanks, artillery, and logistics vehicles.

From there, the GPS has been present in the military in many ways everyday. Perhaps the most dramatic use of GPS took place on June 6, 1995. At 2:08 in the morning, downed American F-16 pilot Captain Scott F. O'Grady finally risked radio communication as his comrades flew over the Serb-controlled territory he had been hiding out in ever since his own plane had been shot down four days earlier. Using a GPS receiver hidden inside his life vest, O'Grady was able to determine his own longitude, latitude, and altitude (although he was on the ground) to within a few hundred feet. With that intelligence, a Tactical Recovery of Aircraft Personnel (TRAP) team of the 24th Marine Expeditionary Unit was able to extract O'Grady from behind enemy lines a mere four hours after F-16 flyers first picked up their comrade's distress call.[66]

While GPS's most sophisticated abilities remain within the military domain, its publicly available features have been put to use in all kinds of ways. Trucking companies track their fleets and plan routes using GPS, as do sea-based shipping companies. Now anyone who wants to buy one can carry an inexpensive GPS receiver. Civilian pilots, airline pilots, cartographers, construction engineers, road builders, telecommunications companies and even high-end automobile

sellers have put GPS to use. All of that in only three years since the full system has been up and running.

In 1992, the National Aeronautics Association (NAA) recognized the principals of the GPS development team—NRL, the U.S. Air Force, Aerospace Corporation, Rockwell International Corporation, and IBM Federal Systems Company—by awarding them its 1992 Robert J. Collier Trophy. This award is presented annually, in NAA's words, "for the greatest achievement in aeronautics in America, with respect to improving the performance, efficiency, or safety of air or space vehicles, the value of which has been thoroughly demonstrated by actual use during the preceding year."[67] The NAA cited the GPS team for "the most significant development for safe and efficient navigation and surveillance of air and spacecraft since the introduction of radio navigation 50 years ago." NRL's copy of the Collier Trophy has been strategically located for maximum visibility in the lobby of Building 43.

Clementine and the Global Positioning System happen to be triumphs with unclassified components that can be included in this book. However, most of NRL's satellite science and engineering story cannot yet be told publicly because much of that story involves classified projects. What can be said is that NRL so far has built over 80 communications, navigation, and others kinds of satellites for the Navy and other customers in the Defense and Intelligence communities. As such, NRL has played a major role in the emergence of space technology over the past 40 years. The motto of the Naval Center for Space Technology, the present incarnation of NRL's satellite engineering crew, remains as gung-ho as ever: "To Fly What Has Never Been Flown Before."[68]

Chapter 9

NRL, Nuclear Fallout, and the Cold War

Just as NRL found itself after World War II in the spectacular birth pangs of the Space Age, it also found itself with the kind of expertise badly needed as the nascent Nuclear Age collided with ominous post-war geopolitical developments. Even before the dust of World War II had settled so that the world could grasp the tragedy, the global political environment began to cool down to what became known as the Cold War. Not only would NRL feel the breezes of the nascent Cold War, but it also would become a central player in the emerging high-technology era, and the ultimate stakes that came to characterize the Cold War.

Indeed, the Cold War was beginning even as the Army snatched up the bulk of Germany's V-2 program at the secret Baltic coast site of Peenemunde in 1945. When the Army left with the rocket parts and a cadre of German rocket scientists including Werhner von Braun, Soviet occupational forces were in the process of taking over the region by international agreement. After the Soviet Union recovered land it had lost to Germany, Poland, Finland, and Japan, it went further, forcing Czechoslovakia, Romania, and Hungary to hand over territory that never had been part of the Soviet Union. Moreover, wherever its forces were in occupation, repressive Communist governments and closed societies were put into place.

"From Stettin in the Baltic to Trieste in the Adriatic, an iron curtain has descended across the continent," is how Winston Churchill

would famously assess the situation in a speech at Fulton, Missouri in 1946.[1]

The Testing Begins

Nothing could be more emblematic of NRL's immediate linkage to this worrisome new world order than its role in the United States' nuclear weapons testing program that began with Operation Crossroads at the Bikini Atoll in July 1946. Following the detonation of a test bomb by the Manhattan Project and the bombs dropped on Hiroshima and Nagasaki, the bombs detonated during Operation Crossroads were the world's fourth and fifth nuclear detonations—one above Bikini and the other in shallow water.

The primary goal of the detonations was to see what happens to military equipment, including naval ships at sea, when confronted by a nuclear blast and its aftermath. Nuclear weapons were a curious technology; although their blasts were entirely man-made phenomena, they were poorly understood from a scientific viewpoint. In a sense, nuclear detonations provided physicists with awesome novel objects in the universe replete with all manners of interesting thermal, optical, electromagnetic, mechanical, and other effects. From the perspective of NRL's academically minded scientists working under a

As part of Operation Crossroads, this underwater detonation of a nuclear device on July 25, 1946 at Bikini Atoll sent a tower of water and debris skyward.

military research laboratory's roof, nuclear blasts were almost like having suns to study on Earth. Nuclear blasts were scientifically enticing.

The Manhattan Project yielded not only bombs; it also yielded thousands of scientists and engineers well-versed in the ways of nuclear reactions and their emanations. So much of the expertise that was required to scientifically observe and measure the behavior of nuclear blasts came from this wartime community. Although NRL was largely excluded from the Manhattan Project, at least partly due to Admiral Bowen's antagonistic relationships with Vannevar Bush and his Office of Scientific Research and Development, the Laboratory's visionaries, like Bowen and Ross Gunn, made sure they and their colleagues kept their toes in the nuclear waters. Indeed, Gunn and Phil Abelson drew up a set of engineering plans for a nuclear submarine in 1946[2], years before the quest for nuclear propulsion became Rickover's own. With Operation Crossroads, the Laboratory went in deeper, taking the equivalent of a full-body dive into those nuclear waters. This is evident from NRL's supplying 75 of the 450 personnel involved in the electronics-related measurements at Bikini.[3]

E.O. Hulburt and John Sanderson of the Optics Division and Ernst Krause of the Rocket Sonde Research Section had organized and led the overall NRL weapons testing program. This was an exciting time, filled with career-changing decisions for many NRL researchers. About ten percent of the Laboratory's technical forces would become entangled in the 12-year stint of above-ground nuclear weapons testing. The primary goal of Operation Crossroads for the NRL team was to measure the total optical energy emitted by the blasts as well as to photograph the spectra[4] so as to gather diagnostic data about the nuclear phenomena occurring during the blasts.

After Crossroads came nuclear testing projects with equally cryptic names: Sandstone, then Greenhouse, Buster-Jangle, Tumbler-Snapper, Ivy, Upshot-Knothole, Castle, Teapot, Redwing, Plumbob, and finally, in 1958, Hardtack. That was just months after the Soviet Union put Sputnik into orbit, thereby fanning fears about a new ability to deliver nuclear warheads from intercontinental ballistic missiles.

During Operation Ivy, researchers went to great extremes to make measurements of the bomb's radiation outputs. Shown is a plywood tunnel harboring evacuated tubing that conducted signals from the bomb to measuring instruments located two miles away.

Hundreds of NRL scientists at all levels participated in these many tests, at which they made various and ever more sophisticated measurements. Louis Franklin Drummeter, Jr., a new NRL hire in 1948, would be among the most thickly involved. Drummeter, then 27 and a former plumber with a PhD in optics, had heard about NRL from a Johns Hopkins University classmate, Harold S. Stewart, who was on study leave from NRL where he was head of the Radiometry Branch. That connection led to an offer for a $20 per day job by John Sanderson, then acting associate superintendent of the Optics Division. Viewing the job initially as a stop gap before landing a university position, Drummeter took the job and then spent his entire professional life at NRL, eventually becoming the Associate Superintendent of the Optical Sciences Division before retiring in 1982 as the Acting Associate Superintendent of Research for Electronic Science and Technology.[5] Even now, 16 years after retiring from NRL, Drummeter remains connected to the Laboratory as a consultant.

After first applying his know-how in infrared detection to the problem of detecting exhaust trails of a submarine's snorkel, Drummeter

became the assistant head of the Radiometry Branch in 1949 where he would begin a long-term and intimate relationship with nuclear blasts. Beginning in 1951 with Operation Greenhouse, he would witness 20 nuclear blasts through 1955. Along the way, he and NRL colleagues had to develop techniques and equipment for making detailed and often exquisitely rapid measurements of all kinds of radiation. Drummeter points out that Stewart was the key architect of the optical measurements, which included designing specialized instruments.

These measurements often were unprecedented in the need to snatch radiometric and optical measurements in the millionths of a second between the detonation of a bomb and the consumption of the measuring instrument in the bomb's obliterating wake. To carry out some of these measurements, NRL's shop workers constructed evacuated tubing that could conduct signals from the bomb to measuring instruments far enough away that they could survive the blast. "At the time, the design and construction of such vacuum systems was a large and major engineering undertaking in itself," Drummeter recalls.[6] Some of these optical measurements were fundamental to the design of the first generation of thermonuclear weapons (hydrogen bombs), according to Jack Brown, a retired NRL research manager who has played many roles in the development of nuclear weapons.[7]

In Operation Buster-Jangle, Drummeter and coworkers measured the spectrum of so-called Teller Light, which the famed Manhattan Project nuclear scientist and champion of the hydrogen bomb had predicted would exist following a nuclear detonation. Teller Light, an emission of X-rays from atmospheric molecules stimulated by the energy from the bomb blast, had been measured previously. But the NRL work revealed the spectrum—or distribution of wavelengths—of the Teller Light. The high-speed measurement technique needed to take a snapshot of the short-lived Teller Light was crucial for determining both the size of the blast and the efficiency of the nuclear

reactions that occurred in the device's core. The optics team also was able to identify the molecules responsible for light emission.

There were plenty of moments of high drama during this era of above-ground nuclear testing. Drummeter, one of the many NRL scientists who participated in the above-ground bomb testing program in the 1940s and 1950s, recalls moments of mortal fear. On one occasion, he was so close to ground zero that he had to crane his neck as far back as possible to watch the evolving mushroom cloud. And Drummeter recalls one blast that he didn't think he would return from. "Something went wrong," he recalls. "We were 25 miles away, but it kept getting bigger and bigger and bigger." And then, of course, it stopped well before consuming him. He learned later that the blast was about twice as big as it was expected to have been.[8]

By the end of his tenure as head of the Radiometry Branch, Drummeter and his colleagues had produced scores of classified reports. "The work laid the foundation for all that is known about the emission of thermal radiation from nuclear explosions in air," Drummeter says. "These data underlie all the effects data in handbooks and the prediction of thermal radiation from weapons of all sizes."[9] As such, NRL's researchers contributed mightily to the development of at least some of the data on which was based the United States' nuclear warfare strategy.

Losing the Nuclear Monopoly

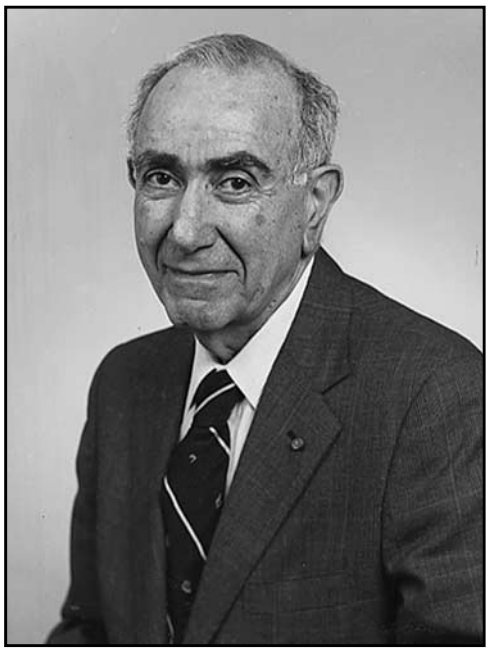
The first years of nuclear weapons testing were performed when the United States retained a monopoly on such weaponry. Yet everyone knew that the physics and engineering behind nuclear weapons were open books, albeit ones with plots so complex that only the most ambitious and clever readers would penetrate their meaning. But sufficient ambition and cleverness were out there, especially in the expansive Soviet Union. So it was just a matter of time before other countries would break the American monopoly. When the United States began its program of above-ground testing of nuclear

weapons in the Pacific, there was no way to know whether somebody else was blowing up their own test weapons somewhere halfway around the world.

In 1947, this hole in intelligence capability led Admiral Lewis Strauss, a member of the newly formed civilian-based Atomic Energy Commission, to start a process that by decade's end would lead President Truman two years later to make the startling announcement that the United States already had lost its monopoly on nuclear weapons.

The process began when Strauss was surprised to learn from Secretary of Defense James E. Forrestal that the United States had no means for long-range detection of a Soviet detonation of an atomic bomb. Strauss then pressed the Office of Naval Research, which in turn looked to NRL to supply the detection means that Strauss so sensibly wanted.[10]

After ruling out sound or seismic signals as the basis for detection technologies (at least in the early years of the nuclear arms race), radiation effects became the Laboratory's focus. Herbert Friedman, an expert in radiation detectors in the Physical Optics Division, joined the project. Among the other key scientists were Montgomery Johnson in the newly inaugurated Nucleonics Division and Ernst Krause of the one-year old Rocket-Sonde Research Branch.



Dr. Herbert Friedman in 1966

Since the call for long-range detection came about a year before the Project Sandstone nuclear blasts,

NRL scientists began working on several fronts so they would be ready to put those blasts to use for the goal of developing long-range detection techniques. One of those fronts centered on special filter paper from NRL's chemical warfare protection work. The paper was adapted to collect airborne particles over a period of days, after which the paper would be placed under a radiation counter. If the detector picked up radiation, the likely cause would be a nuclear blast upwind. Johnson favored another possible technique for long-range detection: lofting Geiger counters with tethered balloons to a height of 20,000 feet where they would be able to pick up gamma rays from the fission products of a distant nuclear blast.

Friedman and his colleagues in the Optics and Chemistry Divisions went for the most sensitive technique—an array of seven gamma ray detectors (Geiger tubes) so arranged to greatly reduce natural gamma ray signals from natural, cosmic sources. Each detector was a metal cylinder 2-feet long by 2-inches in diameter, filled with chlorine-neon gas and sealed with glass caps. NRL produced all of the electronics for powering the detectors and making sense of the signals generated within them. One hundred of these detectors were secretly shipped from NRL to universities, Naval stations, and other government stations all over North America from the Aleutian Islands in Alaska to Panama as well as eastward out to Bermuda.

"Several well-known physicists maintained security by operating the instruments from their own homes," wrote Friedman, Irving H. Blifford, and Luther Lockhart of NRL's Chemistry Division, who also became involved in the long-range detection project. "For example, H. Victor Neher of Caltech wrestled a 400-pound unit into his attic and the editor of the *Physical Review*, John Tate, had one in his back yard."[11]

The first test of all of this equipment came after the Sandstone tests. Wrote Friedman, Blifford, and Lockhart: " . . . filter paper collectors on the NRL dock on the Potomac River in Washington, DC, obtained positive responses at roughly the same time as the balloon-

borne Geiger counters at NRL's Chesapeake Bay Annex and the gamma-ray detectors on the roof of NRL's optics building responded."[12]

An unexpected clue to a more sensitive test literally rained on Friedman's and Blifford's gamma ray detectors in early 1948. After observing a rise in the ambient gamma-ray activity when it rained, the scientists put a 2-inch deep collection tray above the counters. As the tray filled, the natural radioactivity rose sharply. The rain was washing the radioactivity out of the sky and bringing it down into the tray.

The question then became whether there was some way of concentrating the rain-carried radioactive fallout so that Friedman and his detector experts could not only sense radioactivity when it is there but also determine the chemical identities and half-lives of the radioactive material. This way, the data would provide a signature by which the fallout could be associated with tests by specific countries. Friedman put the question to Peter King, superintendent of the Chemistry Division.

King put Luther Lockhart onto the problem and he quickly found the necessary technology at the Dalecarlia Reservoir in Washington, DC. Called flocculation, the well-known technique called for the addition of small amounts of chemicals such as aluminum sulfate into water. The additives then bind suspended silt and organic matter to an extent that the resulting complexes settle out of solution and can be collected for chemical analysis. King calculated that the technique, when adapted for collecting radioactive particles from rainwater, could concentrate radioactivity in samples by factors of 10,000,000 or so, making the technique sensitive to even small amounts of fallout.

To test the new possibility, Lockhart set off for the Virgin Islands shortly after the Sandstone tests with the quest to find fallout-laden rainwater in the island's concrete water-collection cisterns. Of the 2,500 gallons of suitably old rainwater that he found and treated with a flocculation agent, he came back to NRL with 5 gallons of settled floc for chemical analysis. The floc contained yttrium-91, cerium-141, and

cerium-144 in ratios that matched what would be expected to have come from the Sandstone bombs.

Emboldened, Peter King sent a young chemist in his division, Jack Kane, on a water collection adventure that took him to Shemya, the last island on the Aleutian archipelago, and from there to Kodiak, Alaska. These places were as close to Soviet territory as you could be and still be in the United States. The negative results of these July 1948 collections indicated that the Soviets had not yet exploded any nuclear devices, at least not above ground.

Additional collections by Kane in the Truk islands of Micronesia (now known as the Chuuk Islands) and the hills of Moen as well as a collection from the Chemistry Building's roof (which King had had the division's janitorial crew scrub with brushes to prepare for the tests) helped the long-range detection group settle onto a protocol by April of 1949. Thousand-square foot sections of new corrugated aluminum roofing would serve as rainwater collectors. At the first sign of possible fallout from filter-paper or gamma-ray detectors, the rainwater would be collected, flocculated, and the resulting floc analyzed. At this point, the top secret bomb detection project became known as Project Rainbarrel.

Its projected budget of $80,000 was a mere ghost of the $32 million budget for an Air Force proposal in which early detection would come from a squadron of B-50's flying filter-paper scoops for collecting airborne radioactive particulates. Cheap maybe, but Project Rainbarrel was criticized for its reliance on rain falling over a collection station. A plane can take off at a moment's notice, but rain comes when God says so.

The critics were silenced sooner than anyone originally thought would be possible. On September 10, 1949, air monitors at NRL picked up positive readings. Three days later it rained and samples were collected also containing fallout. At the same time, sensitive gamma-ray detectors at Kodiak picked up signals, so Alaskan rainwater was collected, flocculated, and air-shipped to NRL for analysis. These samples

also contained radioactive fallout. Corroborative signals also came from filter paper scoops aboard an Air Force B-50 flying between Japan and Alaska. (There had been an earlier cue from a signal detected by an infrasonic microbarograph array on the day of the test but the chemical analysis of the radioactive materials served as the definitive detection while also revealing details of the Soviet bomb design.)

On September 22, Herbert Friedman and Peter King reported the alarming results of their analysis in Top Secret Restricted Data NRL Report 3536. Entitled, "Collection and Identification of Fission Products of Foreign Origin," the report deduced from the data that the fission producing the detected isotopes occurred "probably not earlier than 24 August."[13] The next day, on September 23, 1949, President Truman announced that the Soviet Union had detonated its first nuclear bomb, which the United States military dubbed Joe-1.

A subsequent examination of the radioactive floc retrieved from the Kodiak site by Lockhart and chemist colleague Richard Baus revealed that Joe-1 contained the artificial element plutonium. Confirmation of this came from Maurice Shapiro of NRL's Cosmic Ray Laboratory, who as was able to capture in a thick stack of photographic emulsions the emissions of the Kodiak fallout sample as measurable streaks characteristic of the decay of plutonium atoms. Although Truman announced to the world that the Soviets indeed had exploded a nuclear bomb, the evidence that Joe-1's blast came from plutonium and not just sufficiently enriched uranium remained top secret more than 12 years later.

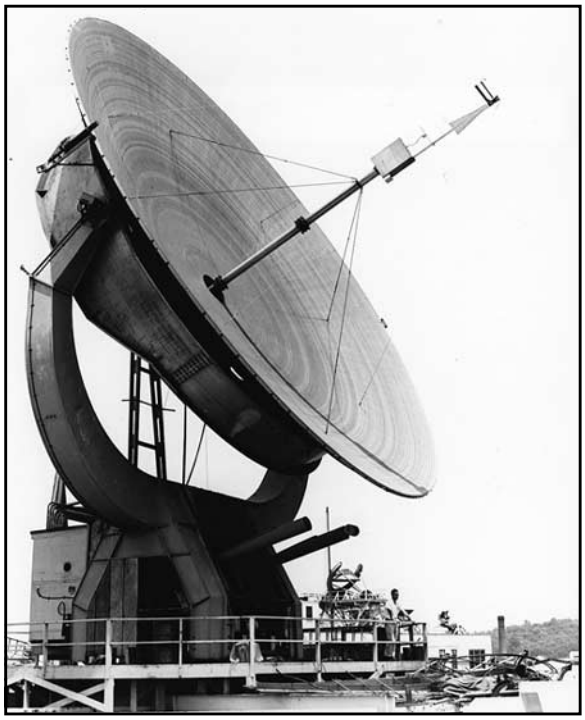
Listening In On the Other Superpower

The 1949 detonation of Joe-1 was the preamble to a U.S.-Soviet Cold War relationship that would become dominated by a nuclear warfare deterrence philosophy known as MAD, or Mutually Assured Destruction. At the same time that Project Rainbarrel's aluminum bins were collecting Joe-1's radioactive fallout, NRL's new astronomers under the direction of John Hagen were eagerly anticipating the in-

stallation of what became known as the "big dish" atop what is now Building 43 just a few months later. It was a case of astronomical science and Cold War intelligence-gathering going hand in hand.

A February 13, 1951 article on the front page of the *Washington Post* told its readers that the Navy expects to use the dish-like radio telescope to "find out much about the mysteries of heavenly bodies through the energy they radiate." Solar flares, galactic radiation, and the size, shape, and composition of the Moon and Sun were among the probable topics of study. "They may also tune in any intelligence-directed signals from outer space—that is, 'signals' beamed to this earth by any 'beings' inhabiting other worlds," the article said. That same ability to listen to signals coming from out there meant the dish would be able to hear signals that started here on Earth, went spaceward, and then somehow got reflected back earthward, say, by the Moon.[14]

When workers did complete NRL's "big dish," it was the world's largest, steerable radio telescope for short radio wavelengths. It re-



NRL's landmark, 50-ft radar telescope in 1956 when researchers were still using it to probe planets and other cosmic objects

mains an eye-catching technological monument that to this day sits atop NRL's administrative building. The 13-½ ton, 50-ft diameter reflector is set in an 11-ton ring and cross-girder system atop a 12-ton yoke, all mounted on a steerable 27-ton, twin, 5-inch gun mount stripped of its guns and breech mechanisms. To increase the dish's chances of picking up the faint radio emissions from stars whose light is too distant to be seen with optical telescopes as well as from other radio-emitting cosmic phenomena, its paraboloid surface was machined so that actual deviations did not exceed about 1⁄16 inch from the mathematical equations specifying its shape. The closer a radio telescope's shape is to perfection, the less noisy will be its reception and the better it will be able to take radio portraiture of the invisible universe.

The first published studies by the Radio Astronomy Branch of the Atmosphere and Astrophysics Division reported radio emissions from enormous clouds of gas including the Orion Nebula, as well as emissions from more discrete sources. The big dish's ability to listen in on shorter-wavelengths uncovered new regions of ionized hydrogen in space that had been invisible to longer-wavelength radio telescopes. When the Big Dish pointed at Venus, Mars, and Jupiter, NRL researchers were able to make thermal measurements of these planetary neighbors. The big dish helped scientists discern variations in the brightness around the solar and lunar disks and to measure the increased solar radiation during times of high solar activity.[15]

In 1959, NRL's C.H. Mayer teamed with Columbia University's Charles Townes, the soon-to-be inventor of the laser, and other colleagues in a project that improved the Big Dish's radio eyesight by a factor of 13. The heart of the improvement was a newly available maser, which could amplify the tiny microwave signals coming in from such cosmic radio sources as planets and stars better than previous amplifiers. The word "maser" is an acronym that stands for microwave amplification by the stimulated emission of radiation. One year after his work with Mayer, Townes would invent the laser (light amplification by the stimulated emission of radiation) with ONR funding.[16]

The big dish atop Building 43 was just the beginning of NRL's love affair with ever bigger radio telescopes. Just as Mayer and Townes were finding out how masers could push the envelope of radio astronomy, NRL's next radio telescope would try to do the same thing by increasing the size of the dish itself. In 1958, at Maryland Point on the Potomac River about 45 miles downstream from NRL, the Laboratory completed construction of an 84-foot parabolic antenna capable of pointing anywhere in the sky and tracking any celestial object from horizon to horizon.

Bigger yes, but the Maryland Point radio telescope was small compared to the great 250-foot moveable dish erected by British astronomers at the Jodrell Bank Experimental Station of the University of Manchester.[17] NRL's new radio telescope held a consolation record, however. It was the world's largest radio telescope mounted equatorially, which meant it could be steered with a relatively simple clock mechanism.[18] With these and a host of smaller radio antennae, NRL had developed a versatile new telescopic window on space, complementing the rocket-based astronomy and astrophysics program that had been underway since the Laboratory attained access to V-2s. All of this antennae-building also was stimulating ideas of the Cold War variety.

It was NRL's communications scientists, those in the lineage of A. Hoyt Taylor, Leo Young, and Louis Gebhard, who would make a bid to procure truly gargantuan antennae for the Cold War's extra-scientific demands. Foremost amongst this group was James H. Trexler. Trexler, who helped support himself during college as an amateur radio technician, joined NRL in 1942 as a junior radio engineer. His first assignment was in the Measurement and Direction Finding Unit before becoming part of the Radio Countermeasures Branch. He later would become head of the Space Technology Branch of the Electronic Warfare Division, one of the Laboratory's most secretive areas. Indeed, the public reasons Trexler and the Navy put forward for the construction of several enormous antennae during the 1950s were at best complementary to the primary classified objectives.[19]

In Trexler and NRL came a convergence of history, interest, national defense and technical capability that led to Operation Moon Bounce, also known as the Communication Moon Relay (CMR). With its assets distributed around the world, the Navy was troubled by the long distance radio communication cut-offs and irregularities caused by Sun-driven ionospheric storms. After all, a serious interruption of communication from command headquarters to battle formations at sea could lose a battle. Any techniques that could fill in communication gaps would be welcome.

In 1946, after learning that Army Signal Corps' researchers had detected radar signals that had reflected from the Moon, Donald Menzel of the Harvard College Observatory proposed to the Navy Department that the Moon could be deliberately used as a reflector for radio signals. Menzel had served as Naval Reserve commander during World War II and advised the Joint and Combined Chiefs of Staff as a member of their radio propagation committee. That proposal would find its way to James Trexler, who back in his college days at Southern Methodist University had tried reflecting high frequency radio waves from meteor trails as part of a radio propagation study. That put Trexler into the small club that was apt to have radio, communication, and cosmic objects in the same thought.

In 1948, a paper in the *Proceedings of the Institute of Radio Engineers* suggesting that the Moon itself might have an ionosphere stimulated Trexler to calculate the requirements for an antenna that could send signals to the Moon. By the end of June, he realized that many radar systems around the world already were close to the specification. And that meant that signals from these powerful antennae might already be bouncing from the Moon back to the Earth. Apparently, no one had yet tried to listen for the reflections.

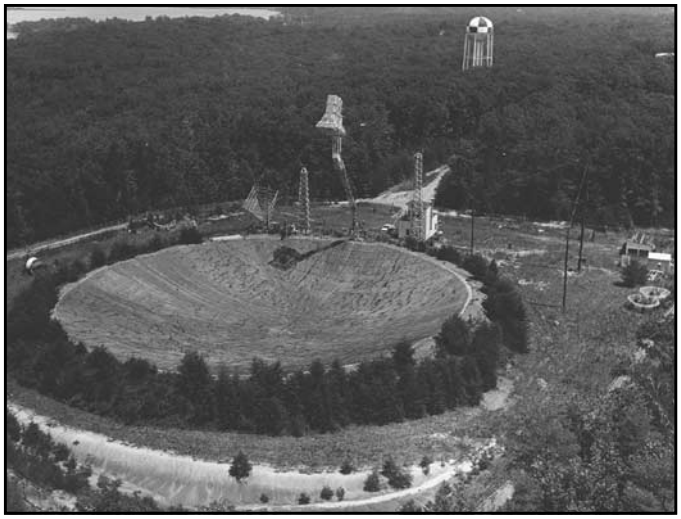
"The strictest security should be maintained as to the existence of such intercept devices since the enemy could with little difficulty restrict the operation of there [sic] sets to avoid Moon contact," he wrote in his laboratory notebook. "One immediate application of the system would be the detection and anylisis [sic] of the Russian Radar

signals that have been monitored at 500 Mc [million cycles per second] near Alaska."[20]

The first effort to follow up on this insight came in the form of two long-wire antennae on the grounds of Blue Plains, the immediate southern neighbor of NRL, where the Chemical Protection Branch had built their gas chamber during the war. By the first half of 1950, the results were good enough to Trexler and Howard Lorenzen, his immediate supervisor, that they put in a request to Captain Frederick Furth, NRL's military commander, to pursue a next generation of tests with more powerful antennae. By June 1950, Navy leadership officially included the Moon as part of its intelligence gathering "equipment." First referred to under the code name "Joe," the Navy served up $100,000 for the project which it renamed project PAMOR (Passive Moon Relay).

In the waning days of 1950, heavy equipment began scooping ton after ton of earth from a site at Stump Neck, Maryland, which was part of the Navy's Indian Head Propellant Plant. When it was finished, the parabolic antenna measured 220-ft by 263-ft. Its 3-inch by 3-inch iron grid could collect and then steer radio wavelengths at least one meter long into a precisely locatable receiver slung above the grid by cables and booms. The first test on October 21 surprised Trexler. Most of the energy from the reflections of pulses sent at the Moon from a 750,000 watt transmitter were picked up by the huge parabola in such a tiny fraction of a second that Trexler knew the Moon was going to be far more valuable than anyone had expected. Theories had predicted that the entire Moon surface would reflect the signal and thereby arrive back at Earth spread out in time as though a normal voice were replayed at much slower speed. The unexpected coherence of the reflections bumped Trexler's work to a higher priority for the Navy's electronic intelligence program and into a higher security status.

It also indicated that transmitter-Moon-receiver circuits ought to work as part of modern communication systems, which included voice and even video transmission. Over the next several years, Trexler and his Countermeasures colleagues worked out the engineering issues to



NRL built and used this 220-ft by 263-ft antenna in Stump Neck, Maryland, as part of a long-distance communication circuit involving Earth's natural satellite, the Moon, as the reflector of signals from the sender to receiver.

prove this to be true. Their work resulted in PAMOR's programmatic cousin, the CMR (Communication Moon Relay).

In a letter dated June 15, 1954 to Louis Gebhard, Superintendent of NRL's Radio Division and a pioneer in transmitter design, Trexler ticked off a litany of potential uses the project harbored. Navigation, interception and jamming of enemy radar and radio communication, upper atmosphere research and communications with ships, subs, and aircraft. Moreover, he wrote in the letter, "it appears that the fidelity of the Moon circuit is much better than predicted in the possible use of many types of circuits such as high-speed teletype, facsimile, and voice."[21]

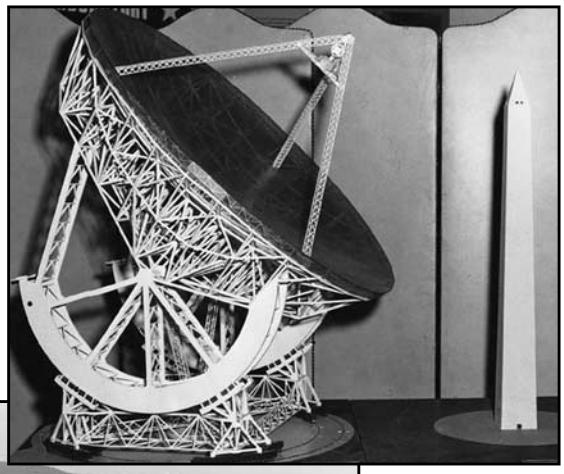
On July 24, Trexler made good on that statement. Two and a half seconds after speaking into a microphone, radio waves sent by the Stump Neck parabola already had carried his voice the 500,000 miles to the Moon and back to an array of simpler and smaller antennae that Trexler's group found would work just fine for communications. "For the first time ever, the sound of a human voice had been trans-

mitted out beyond the ionosphere and then returned to Earth," writes NRL historian David van Keuren.[22] A consequence of such demonstrations was that the development of Moon-based communication circuits became a project in its own right, independent of the system's originally envisioned role for electronic intelligence gathering.

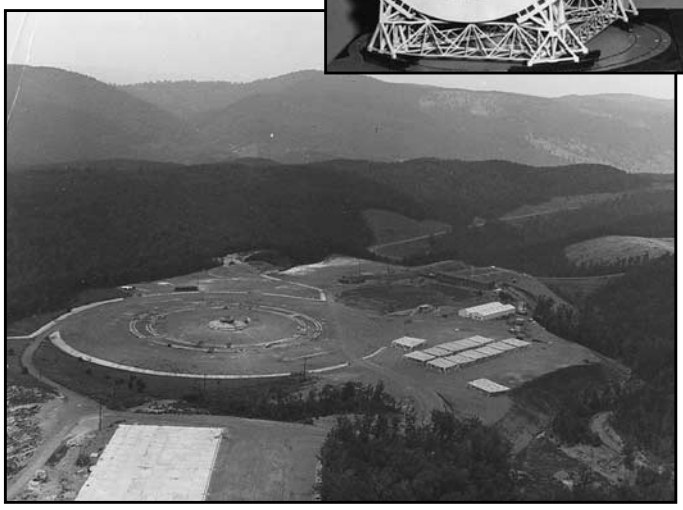
But there was one little obstacle, especially for key military uses under Project PAMOR, such as intercepting weak Soviet radar signals. The 220-ft by 263-ft Stump Neck parabola was too small. Trexler calculated that a truly gargantuan antennae was needed—a 600-ft bowl that was longer than the Washington Monument was tall and whose area would cover 7.1 acres. It would be a 22,000 ton behemoth yet capable of being pin-pointable to any spot above the horizon. Anything that big would require lots of money, direct Congressional approval, and a major lobbying effort. The push began in early 1955.

As part of this effort, NRL pulled off some strategic internal PR stunts that also happened to confirm the communications value of the Moon. On November 29, 1955, Robert Morris Page, NRL's Associate Director of Research for Electronics, sent a transcontinental teletype message via the Moon from the Stump Neck site to Dr. Franz Kurie, Technical Director of the Navy Electronics Laboratory in San Diego, CA where appropriate receivers had been set up. Page to Kurie: " . . . lift up your eyes and behold a new horizon."[23] After some additional engineering work to smooth out some wavering that slightly marred the November tests, Trexler's group flexed their muscles further on January 23, 1956 when the Chief of Naval Operations, Admiral Arleigh Burke, sent a congratulatory message via the Moon to Admiral Felix B. Stump, Commander-In-Chief of the Pacific Fleet.

Among the witnesses was Donald A. Quarles, the Assistant Secretary of Defense for Research and Development. Money followed, including enough to cover a $5.5 million development contract with the Developmental Engineering Corporation to build a demonstration model of a practical long-range naval communication system. Additional intellectual support came by way of the National Academy



(a) This model of the 600-ft, intelligence-gathering dish proposed by James Trexler is shown for size-comparison next to a scale model of the Washington Monument.



(b) Construction in Sugar Grove, West Virginia, began even before all of the engineering and design had been worked out.

of Science's Advisory Committee on Undersea Warfare, which viewed the technology as well suited for submarine-to-shore communication.

By 1959, 11 years after Trexler began musing about radio circuits using the Moon, the Navy had a fully functional Moon-included communication system linking Washington, DC and Hawaii. The next year, NRL and the Navy went public. On the front pages of newspapers and on TV screens was the picture of thousands of officers and seamen on the deck of the aircraft carrier USS *Hancock* in Honolulu spelling out "Moon Relay." The facsimile picture of that scene was sent to Washington via Trexler's Moon relay.

The system no longer required components like the Stump Neck parabola. Instead, it relied on 84-ft diameter transmitters set up at Opana, Oahu and at Annapolis, Maryland, home of the Naval Academy. Much smaller receivers were set up in Cheltenham, Maryland and Wahiawa, Oahu. "The system could accommodate up to 16 teleprinter channels at the rate of 60 words per minute and was capable of processing teletype and photographic facsimiles," according to David van Keuren.[24] The system continued to become more convenient with smaller and more portable receivers and transmitters.

Throughout the technical development of the Moon circuit, others at NRL saw considerable benefit. For one thing, because the Stump Neck antenna could only eavesdrop on the Soviet Union for a few hours each month, the great bowl was largely available to Navy radio astronomers. Moreover, the project entailed the building of a room-sized, electricity-guzzling, vacuum-tube riddled Naval Research Computer (NAREC), which in the early 1950s represented cutting-edge computer technology. Many at NRL would use the NAREC to undertake formidable calculations. Among them were Jerome and Isabella Karle and Herbert Hauptman. For them, the NAREC opened the way to daunting mathematical calculations needed for their seminal work on X-ray crystallography. In the hands of other NRL researchers, NAREC would be applied to calculating trajectories of satellites and long range ballistic missiles.[25]

Meanwhile, even before the first public display of the Moon circuit in 1960, the original 1948 motivation by Trexler for getting into the Moon relay business—listening in on Soviet radio and radar traffic—had become bigger and more secret than anyone had anticipated. The reason: the National Security Agency (NSA), which had been created by way of a secret memorandum signed by President Truman on November 4, 1952, wanted in.

To officials at the new NSA and other U.S. intelligence organizations, the enormous radio ear of the kind that Trexler had proposed building in the backwoods of West Virginia was just the right kind of

device for listening in on Soviet radio and radar traffic.[26] By 1959, the NSA and the Office of Naval Research (NRL's parent organization), had convinced Congress to put $60 million into the project to build the largest moving structure that human beings had ever made. The public cover story was that the big dish was to be the most powerful tool the radio astronomy community had ever seen. In the interest of one-upmanship, it also would be the United States' answer to England's record radio astronomy dish.

But the Sugar Grove project became far more complicated and expensive than its champions had expected. After requests for additional multimillion-dollar chunks of public funding in 1960 and 1961, Congress placed a budget limit of $135 million. Navy analysts calculated that figure to be roughly two-thirds of what would be needed. By 1962, as satellite communication technology began to mature, President Kennedy was receiving counsel from his science advisor as well as the head of the Central Intelligence Agency that the project would end up at best as a marginal deal for intelligence-gathering.

"Eventually it was decided that Sugar Grove would be the ideal replacement facility for the Naval Radio Station at Cheltenham, Maryland," wrote James Bamford in *The Puzzle Palace*, his 1982 history of the secretive National Security Agency.[27] The switch was implemented in May 1969. According to Bamford, "NRL continued to operate a sixty-foot microwave receiving antenna building in 1957 as a prototype" for the 600-footer.[28] He wrote that on July 1, 1975, NRL was relieved of its role at Sugar Grove by the Naval Security Group, which was part of the Central Security Service established by President Nixon in 1972 to "provide a more unified cryptologic organization within the Department of Defense."[29] After that, Bamford's book maintains that the NSA built additional surveillance equipment at the Sugar Grove facility, which it used to keep track of a major portion of satellite-carried international communications. But the giant radio telescope recommended by Trexler was never built.

Cold War in the Abyss

Soon after the looming costs of the Sugar Grove project began to ensure its demise, the Cold War and NRL were entwining in other remarkable and sometimes nightmarish ways. An example of the latter kind began in the early spring of 1963.

On the evening of April 10, Captain Bradley F. Bennett, NRL's military director at the time, was at a dinner party when he learned the news of a tragic accident at sea. The *Thresher*, a newly built nuclear submarine undergoing shakedown tests at sea, had just sunk to a depth greater than 8,000 feet (more than 1½ miles) in an area of the Atlantic 260 miles east of Boston. There were 129 men aboard.[30]

There was no hope for the men: everyone knew that beginning at around 1,000 feet, water pressure would have been sufficiently high to crush the submarine's hull. Bennett's instinct was to immediately call Chester Buchanan, head of a small team of ocean scientists and engineers in the Sonar Systems Branch at NRL that had been developing tools for monitoring the deep ocean.

After a sleepless night, Buchanan handed the Captain a handwritten plan to search for the *Thresher*. The next day, five researchers (headed by Tony Hollins) in Buchanan's branch, and others from elsewhere at NRL and the Hudson Laboratories, boarded the small acoustics research vessel *Rockville* and headed with sonar equipment to the search area to join a growing armada of search vessels. The first team returned to New London after ten days and a second Sound Division team, headed by Burton Hurdle, took the *Rockville* out of New London, Connecticut, along with new equipment to join the search. In subsequent days, yet more NRL personnel, including Chester Buchanan, boarded the *J.M. Gillis* with additional equipment and joined the search.

"Every resource of the United States Navy was thrown into the historic search operation," wrote James H. Wakelin, Jr., Assistant Secretary of the Navy for Research and Development, later in a *National Geographic* magazine article.[31]

The search centered on a 100-square mile area, which is small by ocean standards. But finding a slivery submarine somewhere at the very bottom of 100 square miles of deep ocean was akin to finding a shaving of metal at the bottom of a deep tank of opaque oil. Moreover, trying to steer instruments from a surface ship to a spot 8,000 feet away on the bottom of the ocean was akin, in Wakelin's words, "to a man in a balloon, a mile and a half above the earth, unsure of his own position, trying to drop a fish line through a blizzard into a swimming pool."[32]

The *Thresher* began to reveal itself in mid-June. Using a magnetometer to detect metal and a camera towed from a surface ship, researchers from the Woods Hole Oceanographic Institute and Lamont Geological Observatory photographed portions of the wrecked submarine. Two months later, the manned research vessel *Trieste I*, which was being operated by the Navy Electronics Laboratory, located more wreckage. The bulk of the submarine, however, remained undiscovered by September when bad weather forced Captain Frank. A. Andrews, head of the search operations at the site, to postpone the rest of the search.

The loss of the *Thresher* was a wake up call for the Navy. In a summary of the *Thresher* search operation in 1965 highlighting the Navy's inadequacy in deep-sea search, location, and rescue, Captain Andrews wrote that the tragedy "demonstrated only too clearly the degree of ignorance and inability which surrounded the entire business."[33]

When search operations resumed in 1964, NRL's recently procured research vessel, *Mizar* (a converted Arctic resupply ship), which would later be customized with a central well through which instruments or tow lines could be lowered into the water, became the pivotal element. Under the direction of Buchanan, other members of the team had fitted a tow-vessel with a battery of cameras, strobe lights, side-looking sonars, a rechargeable battery, and a scintillation detector for detecting radiation. Projecting from the prow of the tow vessel like a nose was a magnetometer, which would trigger the lights and cam-

NRL's oceanographic research ship Mizar

eras at the first "sniff" of metal. The *Mizar* also was in communication with a bottomed navigational acoustic transponder so that it would be able to pinpoint the exact location of the *Thresher* in case it were found. This was crucial because drift and currents relentlessly shifted the ships' and towed vehicles' positions relative to the ocean bottom.

Success came quickly this time. "In the first eight hours of search, *Mizar's* towed vehicle photographed the tail section of *Thresher*," wrote Captain Andrews with palpable pride.[34] That was June 27, 1964; over the next days and weeks, the *Mizar's* crew located and photographed the main portions of the *Thresher's* hull. More than 50,000 photographs were taken.[35] Moreover, the navigational data enabled the NRL to direct the manned *Trieste II* to land directly atop a portion of the *Thresher* hull where it could take close-up photographs. Unable at first to see signs of the hull, the crew of the *Trieste II* thought the *Mizar* had steered them awry. But when the crew member who was looking out of the viewing port took a closer look, he realized the *Trieste II* had alighted directly on top of the *Thresher's* remains.

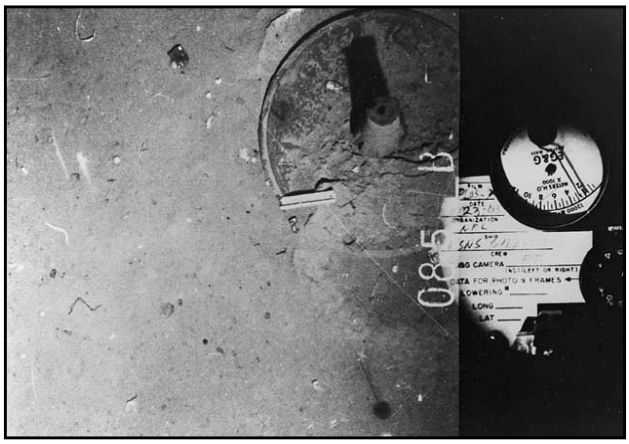
"Probably the most significant improvement in search effectiveness following the 1963 search effort was the installation of underwater tracking equipment (UTE) on the USNS *Mizar*," Andrews wrote. "The Naval Research Laboratory deserves great credit for this accom-

plishment, for without it the almost complete photography of the visible portions of *Thresher's* hull would have been impossible."[36]

In addition to photographing the wreck, radiation measuring instruments on the *Mizar's* towed vehicle and on *Trieste II* answered a burning question: was radioactive material in the submarine's reactor leaking into the ocean? The 1964 instrument readings indicated there were no radioactivity levels above expected background levels attributed to naturally radioactive atoms in the ocean water and sea bottom. Therefore, either the reactor had remained intact or any radioactivity that was going to leak already had.

On-site analysis of the remains found during the *Thresher* operation confirmed what everyone already knew—that as the submarine had sank through its "crush depth," it was crushed like an aluminum can by the enormous oceanic pressure. But the search did not provide answers to the more important question of what went wrong in the first place to send one of the nation's cutting-edge submarines and its highly trained crew to their demise. Recovering the wreckage from an ocean depth of 8,400 feet with the hope of answering that question would have amounted to an Apollo-scale operation with no guarantee that the coveted answers would be found. The *Thresher* remains on the ocean bottom today.

The search for the lost submarine turned out to be merely the first of a highly dramatic series of deep-ocean searches for Buchanan and



Photograph by an NRL team of the Thresher's *anchor*

the men in his branch, which was renamed as the more general Deep Sea Research Branch.[37] The next Cold War sea search drama began on January 17, 1966, when a hydrogen bomb that had ejected from a disabled U.S. bomber fell into the Mediterranean Sea off of Palomares, Spain. Eighteen days later, the *Mizar* and a contingent of NRL scientists was on its way to the scene. It was a politically charged event. For one thing, Allied nations could place restrictions on the flying of nuclear bombers over their territory, or worse, the bomb and its secrets could have fallen into undesirable hands.[38]

The search began at a location pointed out by a Spanish fisherman who had seen the bomb fall. While the crew of the *Mizar* searched with the ship's towed instruments, the manned, 22-foot *Alvin*, which the Woods Hole Oceanographic Institute operated for the Office of Naval Research, was scouring the steep and rugged sea floor looking for the bomb in an area just southeast.

As in the *Thresher* search, Buchanan's team and the *Mizar* located the lost military asset and provided the navigational guidance for deep submersibles. In place of the *Trieste* submersible were the *Alvin* and the *Aluminaut*, which was owned by the Reynold's Aluminum Company and retained for the search under contract. With a special undersea telephone to the oceanauts in the *Alvin*, which was about to embark on its first scientific mission when it was called to the H-bomb search, the *Mizar* could guide the submersible much as an air traffic control tower guides aircraft.

On March 15, the *Alvin* spotted the bomb at a depth of 2,800 feet. Since it could remain submerged for only short periods of time, the *Aluminaut*, which could remain submerged longer, was directed to the spot. It served as a marker so that the *Mizar* could use its navigational and location finding equipment to obtain a precise fix on the bomb. That, in turn, enabled the *Alvin* to bring recovery equipment to the bomb.

First, the crew of the *Mizar* lowered a steel lifting line and "work table" to the site of the bomb. Then the crew of the *Alvin* used the

vessel's telerobotically controlled arm to entangle the lifting line around shroud lines of a parachute attached to the bomb.

So far so good. But just as the bomb was lifting from the bottom, the lift line broke. The nuclear weapon slid further down the steep slope. In a second recovery attempt on April 8, the *Mizar* directed *Alvin* back to the sight. Despite a harrowing few minutes when the crew of the *Alvin* quickly maneuvered to avoid getting entangled in the parachute shroud, the *Mizar* hoisted the bomb to its deck.

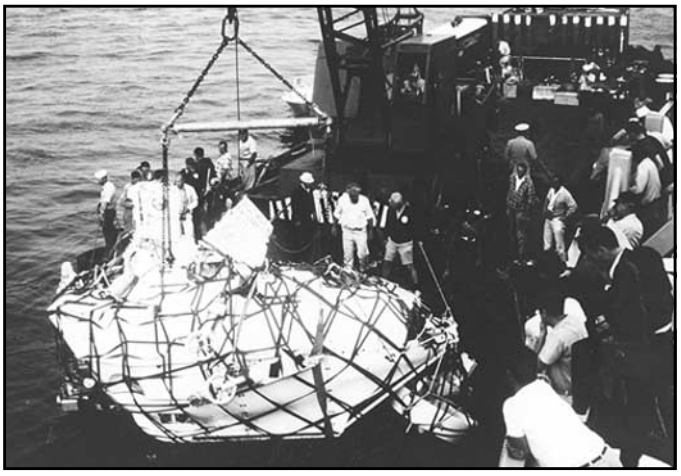
Two years later, just as Buchanan's team was testing a new wide-angle camera with increased film capacity, the *Mizar* and NRL scientists were again called upon. On May 27, 1968, another submarine, the USS *Scorpion*, had tragically sunk to the bottom of the ocean west of Azores with the loss of 99 officers and men. During its 172 day search cruise between June 2 and November 22, 1968, the *Mizar's* crew relied on their home-made "fish"—a towed aluminum cage and platform bearing magnetometers, sonars, cameras, and other equipment attached to the *Mizar* by a 20,000 foot armored umbilical. The "fish" camera photographed a bent piece of metal at a depth of about 10,000 feet 18 days into the operation, but it could not be clearly linked to the *Scorpion*.

The search went on for another five months elsewhere before the *Mizar* and its "fish" returned to the site of the bent metal. There, a magnetometer and side-looking sonar both picked up signals diagnostic of a man-made object. Photos taken of the site revealed a large section of the *Scorpion's* hull. At the end of a subsequent run with the "fish," the tow cable gave way just as the "fish" was breaching the surface and the instrument-laden platform joined the *Scorpion* nearly 2 miles below. That the cable had worked at all was testimony to the detailed physical investigations and mathematical modeling that NRL researchers had conducted in order to better understand the kind of behavior to be expected from long underwater tow cables. Despite the loss of this valuable equipment, the operation yielded over 150,000 photographs continuously covering 12 square miles of ocean bot-

tom. The final 10,000 of those photos, which revealed the *Scorpion's* hulk and debris, were taken with a spare "fish" after the primary "fish" went down. The *Scorpion* and its occupants were not retrieved.

Even before the *Mizar* returned, word of yet another deep sea loss came through. On October 16, 1968, the *Alvin* went down off the Coast of Martha's Vineyard due to a handling mishap. But since the *Mizar's* equipment was in bad need of refurbishing, upgrading and replacement, it wasn't until the following June that the vessel steamed out to the site to search for the *Alvin*. The previous five-years worth of practice on such items as lost submarines and thermonuclear weapons paid off. After only four days of searching, the *Mizar's* sensors found the *Alvin* at 5100 feet. From photographs, it appeared that the submersible was in fine shape save for some damage to the propeller assembly.

The recovery effort included the *Mizar*, several other surface ships, and the *Aluminaut*. After initial failures to attach a toggle bar that was part of the lifting apparatus to an open hatch on the *Alvin*, and some delay due to rough weather, the *Aluminaut* dove again and successfully attached the bar to the *Alvin*. Tension was high because the next step of hoisting the *Alvin* to the surface required that a 4½ inch diameter nylon line hold together under these conditions. Although calculations suggested the operation ought to work, no one had ever at-



Successful conclusion of the Alvin *salvage operation*

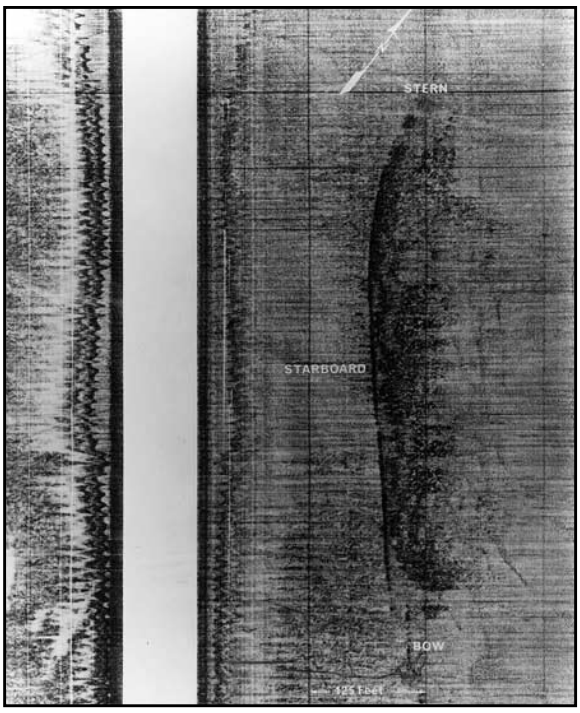
tempted such a feat. Rather than pulling the *Alvin* completely out of the water, the *Mizar* towed the submersible to shore where she was pumped dry and later refurbished.

Calls for new search operations continued coming in. On March 4, 1970, the French Navy submarine, *Eurydice*, sank in the Mediterranean near Toulon. The French government quickly asked for U.S. assistance. After getting the go-ahead from the Chief of Naval Operations, the *Mizar* set off across the Atlantic on March 25. One month later, the first photos of the *Eurydice* were in hand and a transponder was placed amidst the debris so that the French Navy could later return to the site with their own deep sea submersible, *Archimedes*.

The same year, the *Mizar* played an important role in the controversial scuttling of an obsolete Liberty Ship *LeBaron Russel Briggs*, whose holds had been laden with 418 steel-encased concrete vaults, each filled with 30 nerve-agent rockets. After heated Congressional hearings and court actions that followed the public announcement of the plan, the scuttling took place on August 18, 1970 about 240 nautical miles east of the Florida coast in a 16,000 foot basin.

NRL's technical role was to participate in the pre-scuttling survey to characterize the marine life and chemical composition and to conduct several post-scuttling surveys and analyses to monitor the effects of the procedure. In October, the *Mizar* conducted the first post-disposal inspections. Sonar and magnetometer readings showed that the hull had remained intact and water samples taken were all devoid of detectable nerve agents or expected breakdown products. The *Mizar* obtained similar results in four subsequent returns to the site, the last one in January 1974.

Throughout the Laboratory's era of searching the deep sea floor, NRL scientists and engineers developed and honed sensors, cameras, hoisting techniques, more controllable towed platforms, and a host of other technologies that subsequently served both for searches and fundamental investigations of deep-ocean phenomena and environments. Despite the track record of NRL's deep-sea search research and development team, the cost of running the *Mizar* had become too



Sonar image taken by NRL of the scuttled LeBaron Russel Briggs

high. NRL transferred the *Mizar* to the Naval Electronics Systems Command and with that ended the Laboratory's era of deep-sea floor searches.

Walter Brundage, an Acoustics Division researcher who had been involved in the deep-sea searches, later remarked that it was only natural for NRL to relinquish its near-monopoly on deep-sea search technology. By the mid-1970s, the Woods Hole Oceanographic Institute had developed its own "fish," ANGUS, or the Acoustically Navigated Geophysical Underwater Survey. The Scripps Institution of Oceanography had its own version, Deep Tow. "The Navy could turn elsewhere for help on deep-sea floor missions and the Laboratory could turn its research and development elsewhere," Brundage concluded.[39]

Making Nuclear Submarines Habitable

Ironically, nuclear submarines like the ill-fated *Thresher* never would have had a chance to become part of the awful Cold War stale-

mate of Mutually Assured Destruction without NRL chemists. They spent the 1950s and 1960s identifying and solving myriad gas chemistry issues central to keeping the interior of a nuclear submarine habitable.[40] When the USS *Nautilus* made history in 1956 by becoming the world's first deployed nuclear submarine, NRL scientists knew their fingerprints were all over this accomplishment.

Before the advent of nuclear propulsion, submarines spent most of their time cruising on the surface. Non-nuclear submarines were more like surface ships that had the ability to intermittently submerge.

"With nuclear reactor-powered submarines, it became evident to NRL chemists that the period of submergence would no longer be [so] limited . . . and that additional far-reaching measures to control the bubble of air [the vessel's atmosphere] would soon be needed," recalls Carhart, who in 1998 remains an active emeritus scientist at NRL and is widely viewed as the Navy's guru on fire science and prevention. During the first half of the Cold War, however, the NRL's chemists' work focused more on making closed submarine environments safe and habitable for as long a time as possible. "It was obvious that means for the continuous replenishment of oxygen, removal of carbon dioxide, hydrogen, carbon monoxide, and other contaminants, and monitoring would be a must," Carhart noted.[41]

In the early 1950s, as many as 20 NRL chemists under the leadership of Bill Zisman simultaneously worked on the submarine atmosphere habitability problem. Failure to solve the problem would mean that an increasing load of "indoor pollution" during a cruise of a nuclear powered sub would force the vessel to surface way before military planners had hoped. The advantage of a revolutionary nuclear propulsion system, therefore, was at risk of being squandered.

Proof that the NRL chemists had gone a long way toward solving the indoor air pollution problems on nuclear submarines came by way of the "Habitability Cruise" in 1955. A cadre of NRL chemists boarded the USS *Nautilus* with a battery of analytical instruments for identifying volatile chemicals in the air. The *Nautilus* was able to stay

submerged and habitable for 11 days, a length of time that until then had been unheard of in the submarine world. As exhilarating as that was, the NRL chemists did make some troubling observations. One of them was an unexpectedly high level of the kinds of hydrocarbons found in paint solvents.

"Since the first few nuclear submarines were the object of almost constant visits by important and interested people, surfaces that needed it were touched up, in the good old Navy tradition, even while submerged," Carhart recalls.[42] The amount of volatile hydrocarbons was so great at times that in as little as two days it could saturate the beds of activated charcoal that were part of the submarines' ventilation systems to remove odors.

The obvious solution was to end the practice of painting surfaces inside of submerged submarines where there was no way to vent the volatile paint vapors from the vessel. "It was difficult to break the 'tradition' of painting at the slightest provocation but in time it was done, with NRL's encouragement," Carhart recalls.[43]

Not all traditions die so easily. The tradition of smoking on board submerged submarines was one of them. The conditions aboard a submarine were austere enough that to take away the privilege of smoking, one of the few perks available to the sailors, was simply not an option during the era of the first generation of nuclear subs. As a result, invisible carbon monoxide from the burning tobacco as well as smoke became contaminants that had to be scavenged from the air.

Rather than relying on a behavioral solution as they did for the paint solvent problem, NRL chemists this time turned to a World War I era catalyst. Called Hopcalite, it could oxidize carbon monoxide to the less toxic carbon dioxide when moderately heated. The carbon dioxide then could be readily removed from the air. The problem with moderately heated Hopcalite, however, was that it tended to absorb organic compounds from the atmosphere, which could then react with explosive force in the bed of catalyst particles.

That problem could be solved by heating the catalyst hotter yet, since the additional heat would destroy any adsorbed organic compounds before they could build to explosive levels. The trouble with that solution, on the other hand, is that very hot Hopcalite starts to break down refrigerant molecules (CFCs), which occasionally leaked into the submarine interior from the submarine's cooling and refrigeration systems. With Hopcalite, this could become dangerous since some of the breakdown product of the CFC molecules would be in the form of airborne hydrochloric acid and hydrofluoric acid—both very strong, corrosive, and injurious materials. "The thin line of compromise in temperature to optimize burning and minimize halogen acid production had to be found, and was," Carhart states.[44] Later, NRL chemists helped to find more stable refrigerants, thereby further reducing the hydrofluoric acid danger, he adds.

Carbon monoxide from burning tobacco was an invisible poison that Hopcalite and other catalysts could take out of the air, but the visible smoke from cigarettes also was a problem. Early tests indicated that tobacco smoke accounted for about 75% of the aerosol, or visible particulate haze inside of submarines. The solution of the NRL chemists in this case was to modify highly efficient electrostatic precipitators so they could clear 12,000 cubic feet of submarine air per minute.

There were other more insidious problems that became apparent once the larger and more obvious habitability problems had been solved. One of these was a strangely extensive degree of corrosion on new submarines. The NRL chemist/sleuths identified the culprit as methyl chloroform, a solvent that was being used for the first time as part of the adhesive systems for sheets of insulation along the hull. The methyl chloroform, a toxic compound better left outside of a submarine, was entering the catalytic burner used to break down other contaminants, yielding a combination of hydrochloric acid and vinylidene chloride. The acid was causing the corrosion and the vinylidene chloride was even more toxic than the methyl chloroform.

That revelation spelled the end of methyl chloroform use on submarines.

"In similar vein, NRL has had to play detective repeatedly and by finding sources of lachrymotors [tear-jerking emanations like onion vapors and tear gas], irritants, poisons, etc., was able to eliminate many causes of discomfort and danger," Carhart recalls. Their detective work sometimes turned up surprises. "Who would have thought that by allowing men to bring aboard their propellant-type shaving creams and deodorants, something on the order of 30 pounds of fluorinated propellants of undetermined composition would get "dumped" into the atmosphere on a single patrol?"[45] Once in the atmosphere, these propellants then would transform by way of the sub's catalytic burners into troublesome airborne agents.

Since NRL chemists equipped with laboratory analytical equipment were not going to be assigned to each submarine to keep track of atmospheric conditions, the habitability chemists began developing a series of chemical analysis machines that could be put on-board and run by trained sailors. The first was the Mark I Analyzer. Later models still in use in the 1970s monitored oxygen, carbon dioxide, carbon monoxide, hydrogen, and refrigerants. To keep track of the hydrocarbon contaminants, the chemists developed a specialized gas chromatograph, the Total Hydrocarbon Analyzer, which was first installed on nuclear submarines in the early 1970s.

These monitoring devices were precursors to a more sophisticated yet user-friendly system known as the Central Atmosphere Measurement System, or CAMS, which was designed under the auspices of Fred Saalfeld, who left NRL in 1982 as superintendent of the Chemistry Division and joined ONR where he now is Deputy Chief of Naval Research. Progeny of the first CAMS remain in use today aboard the United States' fleet of nuclear submarines.

Making Nuclear Tipped Missiles That Don't Break

A group of NRL researchers adept in the minutia of materials science and engineering also helped usher in the age of nuclear warfare.

The cold reality that things break, shatter, corrode, rip apart, and otherwise disintegrate always has been a sobering part of the human experience in general, and the Naval experience in particular. The downing of the *Thresher* was a dramatic reminder of how terribly wrong things can go. Ever since the late 1920s when Robert Mehl took little medical radium pellets to Norfolk to uncover flaws in enormous ship castings, NRL has contributed solutions to the perpetual Naval concern about its assets breaking for both expected and unexpected reasons.[46]

Consider George R. Irwin, a materials researchers who devoted his NRL career to the questions of why and how things break. When he arrived at NRL as a graduate fresh from the University of Illinois in 1937, he joined the Ballistics Branch of the Mechanics Division where his task was to better understand what makes armor better or worse. The branch, one of several in the Mechanics Division, had built a number of compact silencer-equipped guns that they used in their study of ballistic impacts on materials. "Because of the convenience, variety, and speed of testing thus permitted, NRL soon gained a leadership position in the development of aircraft and personnel armor, which continued through the Korean War period," Irwin later recalled.[47]

During World War II, NRL had focused its work on immediate problem solving rather than the slower sort of research required for studying the detailed physical and chemical mechanisms behind the strength, brittleness, and fracture-resistance of materials. In accordance with the general realignment of the Laboratory toward more basic research after the war, Irwin began turning to the tougher, longer term problem of what makes materials go bad. The most important of these, known as "fracture mechanics," reached into the heart of an issue near and dear to the Navy (and, in fact, to anyone else who has watched hopelessly as a wine glass or plate fell to the ground to end up in shattered pieces). To study fracture mechanics is to study why things break. It is the way to learn if you can do anything about it. During World War II, the Navy was reminded over and over again of the im-

portance of this issue as one after another after another of the welded steel hulls of its 2,160 Liberty ships cracked,[48] sometimes completely in half.

Irwin knew that the roots of such problems reached deep into the anatomy of materials. When he and his colleagues started the work, no one even quite knew how to articulate the question of what makes a material more or less apt to fracture. Irwin argued that a material's "fracture-toughness" ought to be measured in terms of its resistance to allowing small, even microscopic cracks to proliferate or grow. After all, as the Liberty ships proved all to well—small cracks become bigger cracks that become bigger cracks that become the fractures that make things break into pieces.

Throughout the 1950s, they applied their increasingly sophisticated and science-fed intuition in material fracture to solve the kinds of practical problems that turned heads. Irwin had his favorite list: "In chronological order, these were the development of stretch-toughened Plexiglas™ [used for cockpit canopies among other things], the pressurized fuselage fractures of the DeHavilland Comet commercial jet airplane [the plane that ushered in the ongoing era of large-scale jet travel], the sudden fracture of heavy rotating components of large steam turbine electric generators, and the hydrotest [a water-pressure engineering test] fractures of the ultrahigh strength steel rocket chamber for Polaris [missiles]."[49]

The last of these had everything to do with submarine nuclear warfare. The mission of the Polaris missile was to sit inside of bays on stealthy nuclear submarines until their nuclear payloads were needed in the war to end all wars—an all-out nuclear war between the U.S. and the USSR. To test welds used to make the Polaris's ultrahigh-strength steel rocket chambers, engineers filled the chamber with water and applied increasing amounts of pressure. In the autumn of 1957, so many welds were failing under these conditions that managers feared the missile program would fall behind schedule, a situation that could lead to all kinds of embarrassing political and military

repercussions. Even those rocket chambers that passed the hydrotests were still not tough enough to endure the conditions of an actual firing rocket, Irwin recalled.

The main responsibility for solving the potentially show-stopping problem fell onto Irwin's shoulders. He recruited five NRL colleagues and a handful of others from other military facilities and universities for a crash effort to get the Polaris program back on schedule.

Within months, the team had discerned the problem and figured out what was needed to be done to correct it. The problem centered on tiny microscopic cracks left behind in the steel welds. These then became starting points for crack growth and proliferation under the stressful conditions of the hydrotests. Particularly alarming was that these initial welding flaws could be so small that no known in-situ inspection technique could detect them. The only way to discover them, therefore, was to take a sample from the weld and put it under a microscope. But that entailed cutting a hole in the very rocket chamber that was supposed to go into a Polaris missile.

The initial solution, which was put into place at the end of 1958 at the Aero-Jet Corporation where the chambers were being made, was to grind the welds smooth. This got rid of the initial cracks, thereby removing the seeds of larger, possibly catastrophic cracks. The more expensive solution, which came later, was to buy more sophisticated welding equipment with which Aerojet engineers could better control the welding process to begin with. These welding practices segued right into the Minuteman Missile program, which was about one year behind the Polaris program.

By studying the detailed, often microscopic physics going on behind the scenes of a material going sour, Irwin and his colleagues helped to develop a very basic understanding of material weaknesses and flaws widely applicable in the Navy and elsewhere. Their professional peers recognized the work with awards as well as by using the work as starting points to delve further into other materials-related fields such as metal fatigue, stress corrosion cracking, and adhesion.

George Irwin, who followed his NRL career by becoming a professor at the University of Maryland, and his colleagues did not get banner headlines in newspapers. Yet their esoteric and pioneering investigations into tiny cracks left marks on the most awesome weaponry the world has ever seen while simultaneously pushing forward fundamental knowledge about how materials work.

So seminal and lasting were Irwin's influences on the field of fracture mechanics that the organizers of a major technical conference in the materials world, known as the ASM-TMS Materials Week, saw fit in September 1997 to convene a special G.R. Irwin Symposium to honor Irwin for his lifelong accomplishments. In the symposium's inaugural address, Bahkta Rath, Associate Director of Research in NRL's Materials Science and Component Technology Directorate, had this to say:

> *"Professor Irwin's contribution is a blend of physical concept, mathematical analysis, and test procedure, which allow the results of laboratory tests to be directly useful in predicting the fracture behavior of real structures. Now an established part of the general discipline of structural engineering, Fracture Mechanics allows design against plastic deformation. There is no other achievement of recent decades in the area of design procedure, that we know of, that compares with his contribution."*[50]

Testing Goes Underground and Other Places

The infrastructure of Mutually Assured Destruction—the heart of Cold War Strategy for thirty years—has thousands more components than meet the public eye. Missiles, warheads, submarines, and planes are just the most obvious components. The varied career of David Nagel, now superintendent of the Condensed Matter and Radiation Sciences Division, is a reflection of that truth.

When Nagel had first heard of the Naval Research Laboratory in 1962, he was a twenty-something officer finishing a two-year tour at sea with the Navy following his ROTC experience at Notre Dame University. He had just finished delivering a nuclear reactor to

McMurdo Station in Antarctica where it seemed, perhaps ironically, that nuclear power could serve as the environmental answer to large and messy traffic of oil-filled 55-gallon drums. "I was in a monsoon south of what was then called Ceylon (now Sri Lanka), when the teletype clicked out a message on its yellow paper saying that Lt. Nagel's next duty station was NRL," Nagel recalls.[51]

He reported for duty at NRL in June 1962, just months before the last legal above-ground nuclear tests would be conducted. Nagel's ongoing kaleidoscopic experience at NRL represents the strange and rich brew churning at the Navy's corporate laboratory. Almost immediately he began working with NAREC, the Naval Research Computer, on missile defense calculations. The NAREC, acquired, in part, to support the Stump Neck antenna, was a mammoth machine built of thousands of vacuum tubes, miles of wires, and which required an entire branch of people just to maintain and operate it. It was one of the most powerful computers on Earth at the time. It was, in Nagel's words, "a homemade vacuum tube supercomputer." Today, a laptop with a Pentium microprocessor would run circles around it.

The impetus for the work, which occupied Nagel for more than a year, was the Navy Space Surveillance System (NAVSPASUR), which had grown out of the NRL's Minitrack system that just a few years ear-

The room-sized Naval Research Computer, or NAREC, which was used at NRL from 1954 until 1972

lier had tracked the first man-made satellites. NAVSPASUR already had radar beams monitoring the heavens for satellites flying over U.S. territory. The question military planners wanted answered was whether the same system could be used as a missile defense warning system. The task boiled down to programming the computer to run orbital mechanics calculations (that can describe the trajectory of such things as moons and missiles). Programming NAREC and other computing machines of its ilk in the early 1960s, however, was to know the machine down to its tubes. Since an entire night's run would be lost if a tube burned out, Nagel often would sleep at NRL with a set of code sheets on hand. That way, if a tube did go cold, he would tell the NAREC operators what binary code (a series of ones and zeroes, represented by certain tube settings) to reestablish so the calculation could continue.

After his NAREC days, Nagel moved to a secret antisubmarine warfare program. "The issue was whether you could see on the sea surface a temperature or other difference due to the passage of a submerged submarine," says Nagel. Since the general idea here was to detect submarines by means other than the traditional sonar technologies, it was called nonacoustic antisubmarine warfare. "That is why it was known as 'unsound research'," Nagel jokes.

Part of the project involved airplanes equipped with infrared scanners passing over submarines looking for temperature differences while a ship dragging an array of temperature sensors would go through the submarine's wake. Nagel's role in these exercises, which took place off the coast of Rhode Island, was to build an instrument that could automatically record the ship's heading and rudder movements. From this data, the locations and times of the temperature measurements could be readily and carefully documented.

This tack was reasonable enough, but it was costly. To cut down on the expense of these at-sea experiments, NRL pursued another route. Nagel was in on this one, too. A two-man submarine would leave its berth in Annapolis and arrive at the Chesapeake Bay Bridge by evening.

Already there, inside of a boxcar-sized laboratory hanging under the bridge's eastern span, was Nagel, several NRL colleagues, a lab's worth of radar and infrared instruments, and recording equipment. Nagel would phone rudder commands to the submarine below to make sure it would pass directly underneath the instruments. "I had a bull horn to warn away other boaters," he recalls.

The results were negative. There appeared to be no reliable thermal signal that would betray the location of the submerged submarine. "Whether it can be done I flat don't know," says Nagel, adding the often-heard phrase at NRL that "if I did know, I couldn't tell you." Indeed, a lot of NRL's important accomplishments over the last few decades remain classified and untellable.

After narrowly escaping recruitment by Admiral Rickover to become a nuclear submarine driver, Nagel shifted gears, joined the Navy reserves, and began working as a civilian for LaVerne Birks in the X-ray Optics Branch. If nuclear submarines were not in Nagel's future, nuclear weapons were. In a conversation during an airplane flight that Birks had with Wayne Hall, NRL's Associate Director of Research

NRL researchers conducted submarine detection experiments from this gondola laboratory suspended below the Chesapeake Bay Bridge.

for General Sciences, Hall suggested to Birks that he take a look at the nuclear weapons testing arena, which international treaties and agreements had relegated to being underground after 1962.

"I remember Birks coming back and talking in hushed tones . . . that maybe there was something to do in that arena," Nagel recalls. At the time, weapons designers at the Lawrence Livermore and Los Alamos weapons laboratories were designing hydrogen bombs that would release more than half of their energy in the form of X-rays. The idea here was that such weapons could disable Soviet nuclear-loaded reentry vehicles by exploding nearby and sending out a fast-as-light front of X-rays intense enough to vaporize the reentry vehicle's skin and further damage it with the resulting impulse. That was the theory, but the only sure way to know if the weapons worked as intended was to measure the kinds and intensities of energy coming out of them. "The assessment of X-ray emission from nuclear weapons was a very, very key thing at that time," Nagel recalls. That's why the X-ray Optics Branch, including David Nagel, became regulars at the crater-pocked Nevada Test Site.

Birks, Nagel, and their colleagues decided they ought to get a definitive, detailed X-ray spectrum from these weapons as a baseline for a range of weapons effects studies on various materials, components, and even entire reentry vehicles. Money for each test came in chunks of $50,000 to $70,000 from the Defense Atomic Support Agency, which later became the Defense Nuclear Agency, which later became the Defense Special Weapons Agency. With this support, Nagel and colleagues built X-ray measuring equipment that they hauled to the Ranier Mesa in Area 12 of the test site. Amidst their work on the most terrible weapons ever made, "we would look at mustangs running wild," Nagel recalls.

Once at the test site, he and his handful of colleagues would take the equipment several hundred feet underground through mined shafts to a vacuum system that was 20 feet in diameter. X-rays from a nuclear device placed some distance away would travel down vacuum

pipes and, thereby, into NRL's measuring instruments. After a shot, Nagel explains, "they would open the plug at the end of the tunnel and we would don oxygen breathing apparatus, suit up like we were on the Moon, and, sometimes in knee-deep water, move in and recover our equipment using flashlights." Therein lie the nitty-gritty details of a Cold War.

After an initial string of a half-dozen failures, Nagel recalls the team's first success. "We actually got a spectrum that was on scale, quantifiable, and, by any measure, a breakthrough," Nagel says. No one before had obtained a fine-scale X-ray spectrum of a nuclear explosion. The NRL team was able to measure the energy and the wavelengths of the emitted X-rays so well that they saw an unexpected X-ray line. They surmised it was due to the presence of silver.

"We went to Dave Hall at Livermore and said, we think your bomb has silver in it," Nagel recalls. "He smiled. We never found out what the silver was for."

About twice each for five years, Nagel and his colleagues in the X-ray Optics Branch would intermittently spend weeks at the Nevada Test Site. Their measurements on the blasts got more and more sophisticated, but for Nagel the work was becoming routine and uninteresting. For some in the business, nuclear weapons testing gets boring. So the NRL bomb-testers gladly handed over their tools and responsibility to the Lockheed Palo Alto Research Laboratory and to people they had gotten to know from the Los Alamos and Livermore labs, whose missions were officially centered on nuclear weapons. "It had been wonderful in its own way," recalls Nagel, but it was time to get out of the business.

But Nagel did not get out of the business completely. Although he had begun to expand his own research portfolio with more fundamental physics studies using some of NRL's powerful instruments for probing the interaction of radiation and matter (such as a Van de Graaff ion accelerator), nuclear weapons research began to touch him again. Another division in the Laboratory, Plasma Physics, also would

follow up on the military conundrum that came with the nuclear weapons test ban—answering such questions as what happens to a nuclear warhead when it is struck with the X-ray energy from another nuclear weapon (launched to intercept the incoming one) without being able to blow up any nuclear weapons to help answer the question.

In the early 1970s, NRL had built one of the leading, high-powered neodynium lasers in the world using a series of glass amplifiers acquired from France as well as others designed at the Laboratory. This effort took place early in a long-term and ongoing commitment to plasma physics, which focuses on the intriguing form of matter in which atom's negatively charged electrons and their positively charged nuclei dissociate from one another to form a kind of soup of electrons and nuclei. Plasmas like this form when the vast energy of nuclear explosions or intense laser pulses interact with the atoms and molecules in the atmosphere or with nearby liquid and solid materials.

"Laser targets would go from room temperature to a million degrees on a scale of nanoseconds (billionths of a second)," Nagel recalls. "These targets were more than red hot, more than white hot, more than UV (ultraviolet) hot, they were X-ray hot." So there was Nagel, a member of a very good X-ray group with access to a world class laser that could produce high energy plasmas, which emitted eminently publishable X-ray data with a flick of a switch.

The situation went several ways. One was in the direction of basic research. Since materials on Earth had never been subjected to such powerful laser blasts, new results were practically guaranteed just by putting some stuff in the way of the laser. "We shot Lincoln in the temple on a penny one day and recorded the spectra," Nagel offers to illustrate the kind of fun the group was having. This work yielded many papers, including several that earned Nagel and his colleagues a name in the field of plasma physics. (Much of the success of these studies depended on NRL's LaVerne Birks and John Gilfrich of the X-ray Optics Branch, who led a long-term effort to develop and im-

prove a technique known as X-ray fluorescence analysis, which is now used around the world for everything from compositional analysis of materials to pollution monitoring.)

The other direction taken by this work was again toward the nuclear testing arena. Each nuclear test in Nevada cost taxpayers tens of millions of dollars. And since these had to occur underground, it was hard to know how the results related to more strategically relevant uncertainties like what happens when nuclear explosions go off just above the ground or high up in the atmosphere. In lieu of seeking the right to explode weapons in the air, the Defense Nuclear Agency looked for alternative sources of the bomb-like X-rays.

That is how machines like powerful lasers and electron beam machines that can simulate the effect of nuclear blasts on smaller scales under more controlled circumstances came to dominate NRL's involvement in weapons testing in the 1970s and thereafter. "The weapons simulation work has evolved greatly," says Nagel, who took on his present job as head of the Condensed Matter and Radiation Sciences Division in 1985.

That evolutionary development also took some other branches that had little or no relevance to weapons simulation and the Cold War. "We went from using plasmas for weapons testing work to using them for X-ray lithography," or the patterning of microelectronic chips using X-rays instead of the longer wavelengths chip companies generally have used. The idea here is that the shorter X-ray wavelengths enable electrical engineers to pack more circuitry on the same chip area. That, in turn, would yield more powerful microprocessors and other electronic devices.

The inspiration for Nagel to enter into such a project emerged after a visit in 1971 from Martin Peckerar (now head of the Surface and Interface Sciences Branch in the Electronics Science and Technology Division), who then was working on X-ray lithography at Westinghouse's Advanced Technology Laboratory in Maryland. "It occurred to me that we were getting enough X-rays from these laser

plasmas to do exposures not in an hour (as in Peckerar's efforts), but in a microsecond or less," Nagel says. In time, Peckerar and Nagel patented a laser-plasma-based X-ray lithography process and continued working in the area with funding from the Defense Advanced Research Projects Agency. A laser at the University of Rochester even licensed the patent and began developing it toward commercialization until the company went broke and its director committed suicide, Nagel says. X-ray lithography remains as one of the electronics industry's candidate next-technologies for chip making and laser-based methods could become part of this future. For Nagel that would be a welcome offshoot from the weapons simulation work that got him into the X-ray lithography business to begin with.

Make-believe Nukes

Weapons simulation work continued evolving at NRL, of course. In the middle of this evolution for the past 20 years has been Timothy Coffey, NRL's Director of Research since 1982. Born in Washington, DC, he earned an electrical engineering degree at the Massachusetts Institute of Technology before receiving a PhD in physics from the University of Michigan in 1967. His own research life became deeply linked with military research during his first post-school job at EG&G in Boston. There he began working on the antiballistic system known as "Safeguard." NRL also had a hand in this program, and it was through NRL contacts at EG&G that Coffey ended up first being drawn toward NRL.[52]

Coffey's entry onto NRL's staff in 1971 came by way of Alan Kolb, a plasma physicist who had agreed to create a capability in the Plasma Physics Division to take on the key part of the so-called high-altitude nuclear explosion program for the Defense Atomic Support Agency. The crux of the problem was to determine what happens in a nuclear explosion at very high altitudes where military planners hoped they could intercept incoming Soviet missiles. Whether such an ABM system would work, however, hinged on whether the debris from the

intercepting nuclear weapon or the enemy's incoming weapon significantly interacted with the rarefied atmosphere at high altitudes or the Earth's magnetic field. High Altitude Nuclear Effects, or HANE, is how people in the know referred to such phenomena.

If the bomb-atmosphere coupling were strong, then a lot of ultraviolet and other radiation would result. The expanding front of radiation, in turn, would create ionization that would blind radar systems, making it hard or impossible to determine if the intercept attempt had worked and if other missiles followed the first. That, in turn, would reduce an ABM system to a veritable crapshoot.

Although the high-altitude problem was central to high-level nuclear weapons and defense strategy, solving it fell squarely within the realm of fundamental plasma physics. It was the kind of problem that fit perfectly within the vision of a military corporate laboratory where the most basic science would have critical consequences for national defense. After securing funds from the Defense Atomic Support Agency in 1967, Kolb was able to set up a plasma physics program along with another program aimed at creating X-ray simulators for testing the effects of nuclear weapons on materials and components of military hardware.

By the time Coffey came to work at NRL in 1971 to become head of the Plasma Physics Dynamics Branch (under Kolb's Plasma Physics Division), Kolb had built up a powerhouse program involving top-notch plasma physicists (as NRL employees, contractors, and consultants) from around the country. "I found myself coming from what I considered, as far as my interests were concerned, to be a backwater up in Boston, into the middle of this exploding area with lots of money," Coffey recalls.

Plasma physics at NRL was not the only thing exploding at the time. Coffey and his family actually arrived in the Washington area in 1968 just as some of the most violent moments of the civil rights movement were unfolding. "My family flew into Washington just as the city was burning down," he recalls.

Although society was undergoing explosive changes at the time, after 1962 no one had been exploding nuclear weapons in the atmosphere. Coffey knew the only way to tackle problems like the high-altitude nuclear effects problem was to develop bomb-less experiments—computer models and new high-energy laboratory tools and experiments that could somehow serve as surrogates for the phenomena that occur in real nuclear explosions. The results of these approaches could then be compared with the limited cache of data from tests up to the final 1962 series of atmospheric bomb tests.

Among the more consequential developments during Coffey's tenure in the Plasma Physics Division were machines capable of delivering short pulses of massive amounts of power to various solid targets, thereby producing the kinds of X-rays that come out of nuclear explosions. Coffey started working on the NRL campus soon after a second-generation, pulsed-power machine known as Gamble II was completed at NRL. Gamble II stored energy slowly but released it an instant. It could deliver 1 terawatt (trillion watts) of power several times a day. Although that shot of power lasted for only 50 billionths of a second, during those instants it amounted to more than the combined electrical power capacity of the United States. By exposing such items as military electronics and spacecraft components to the radiation produced using Gamble II and its subsequent upgrade in 1978, Coffey led NRL plasma physicists to improve their ability to assess the effects of nuclear weapons including the survivability of crucial parts of military machinery in the event of nuclear war.

Not only did Coffey find himself amongst some of the nation's most talented plasma physicists at NRL, he also found himself in the middle of a politically hot arena. NRL was joining other government laboratories including Los Alamos, Lawrence Livermore, and Sandia as well as contractor laboratories, all of whom were investigating the high-altitude problem. Congressional interest was high. There also were competing camps in the Department of Defense

that either favored or opposed the antiballistic missile concept, which was the basis for interest in high-altitude nuclear effects.

Laboratory machines, such as Gamble II as well as powerful lasers capable of producing the kinds of physical effects expected from nuclear explosions, was one of the two major areas in which Coffey immersed himself. The other, computer-based simulation of nuclear and atomic processes, provided, in principle, even more versatility.

In the early 1970s, computers were still big, lumbering, and exquisitely slow by today's standards. Coffey recalls spending plenty of his weekends at Oak Ridge National Laboratory (where the Abelson-Gunn isotope enrichment method was implemented during World War II) where he could use one of the nation's most powerful computers to run calculations. "I got into the business at this point of overseeing development of some of the biggest computer codes that were ever written," Coffey says. He spearheaded development of computer codes (programs) that could simulate the complex fluid motions and interactions (along with electrical, magnetic, thermal and other accompanying effects) that occur at various parts of the atmosphere during nuclear explosions. Since these were and continue to be such untrodden territories, the work not only led to important results for military planners but also to more fundamental scientific understanding of plasma processes in the Earth's ionosphere. Today's efforts at NRL in computational science and techniques for fields ranging from ship and submarine design to flame and fire dynamics can trace important roots to this work.

Coffey made his first move up NRL's management ladder in 1975 when he became Superintendent of the Plasma Physics Division. The move expanded his responsibility from the theory, math, and computer-heavy field of modeling high-altitude weapons detonations into other big science and engineering arenas. One of these centered on the development of high power lasers as part of the nation's nuclear fusion research program. "The core of the design team that ultimately designed the [Lawrence Livermore National Laboratory, LLNL] Shiva

and Nova lasers [for fusion power research] came out of this laboratory," Coffey says. The LLNL program has been the flagship U.S. research effort in so-called inertial confinement fusion in which banks of laser beams compress fuel to the point of nuclear fusion.

In the late 1970s, Coffey found himself and his division engaged in a big-stakes battle with the laser fusion researchers at LLNL including John Emmet, a former NRL branch head in the Plasma Physics Division who left NRL to run LLNL's Inertial Confinement Fusion program.

By that time, the laser fusion program had gotten to the point where it would take as much as one billion dollars to go to the next stage, a high-level decision that depended on such arcane issues as precisely how laser energy couples to the charged particles in a plasma. Since NRL was well known by then for its expertise in such areas, the Department of Energy often looked to NRL for advice.

"They really needed us as an independent voice on what was really going on so that the exuberance of people trying to sell the next biggest laser was tempered by the realities of what the plasma was doing," says Coffey, who became a regular on advisory panels created by the Department of Energy to help make the big-money, fateful decisions inherent to the inertial confinement laser program. NRL's role in revealing fundamental issues important to the goal of inertial confinement fusion now continues with the very large, Department of Energy-funded, krypton-fluoride laser facility, known as NIKE (after the Greek goddess of victory). NIKE's primary function is to examine issues connected with laser beam uniformity and a variant of inertial confinement fusion known as direct drive.

In January 1980, Coffey took another big step up the management ladder by becoming the Associate Director for the General Science and Technology directorate, one of three main organizational arms of the Laboratory's research portfolio. Less than two years later, he stepped up to become the Director of Research in charge of 3,800 full-time personnel, more than half of them PhD scientists and equiva-

lently trained engineers. Now he was responsible for the Laboratory's entire research and development portfolio, not merely that part of the portfolio focused on nuclear weapons effects.

Red Scares (Or Not) and Secret Capabilities

A few years before Coffey took over the helm of the research program at NRL, his predecessor, Alan Berman, took on a high-priority, classified project that he says amounted to about as much fun as he ever has had on the job.

On September 22, 1979, an aging U.S. surveillance satellite, part of the Vela nuclear detection system, detected what appeared to be the optical signature of a nuclear explosion in the air off the coast of South Africa.[53] Since the optical signature reported by the Vela satellite was considered ambiguous and the Air Force did not detect any radioactive material, the Laboratory was requested to exploit available geophysical measurements—including underwater acoustic data—to determine the geographic location of the signal's source. Hopefully, that exercise would solve the existing ambiguities. This led to a secret investigation headed by then NRL Director of Research Alan Berman, whose background in underwater acoustics and surveillance made him particularly suited to determine if there were any corroborating acoustic or other evidence of a bomb blast.

"I put together a team and we looked at all evidence all over the world, including high levels of radionuclides (fallout) in the pancreases of Australian sheep," recalled Berman, who left the Laboratory in 1982, 14 years after he had come in from a university-operated but Navy-supported research facility to become NRL's fourth director of research. "We found acoustic signals that occurred at various locations and times that we had predicted should have occurred . . . so we put it all together and we hypothesized that an explosion had happened near Marion Island and Prince Edward Island [about 1,200 miles southeast of South Africa], and since this was a South African island, the source of the signal was probably South African."

The issue was politically sensitive. "[We] brought this back to the White House and there was a group there that objected strongly to it because it wasn't the answer they expected to hear," Berman recalled. Members of the South African government recently vindicated the conclusion of the report, Berman says, by admitting they had tested a nuclear weapon on September 22, 1979. Berman learned much later that the Presidential Distinguished Senior Executive Service Award he received after the episode was, in his words, "apparently a recognition that the NRL analysis was correct."

This was not the only special, high-priority Cold War project that had fallen onto Berman and the NRL staff. In the early 1970s, for instance, NRL became the center of a top secret project in the arena of submarine detection that was so massive that the budget of the Laboratory was effectively doubled. That amounts to a project of the several hundred million dollar range. Berman recalls that the drama began when an admiral at the Pentagon had called him to an urgent meeting. "He went on to explain that he had just come back from an overseas trip and some folks had shown him some remarkable things that nobody understood and he wanted me to get involved immediately," Berman recalls in necessarily cagey language.

That began a period of two years during which Berman was double-hatted directing NRL and this massive, top priority project. Researchers dropped what they had been doing to become part of new working teams. "Buildings were taken over suddenly and windows disappeared from buildings," Berman recalls. "You know that a research area is black when windows are taken out and cinder blocks get put in."

Berman remembers the time as a mix of exhilaration and the kind of high anxiety and stress that he never wants to experience again. "I was getting calls from the White House on a regular basis," Berman recalls. Even so, NRL's effort was not initially fruitful, Berman admits. It did not yield an understanding of the physics behind the apparent new means of submarine detection that was at the center of the project.

The program subsequently left NRL and became a "major classified program" that went on for many years. Public knowledge of whether this program produced a new capability will have to wait many years either until the presumed new military capability is no longer cutting edge enough to remain classified or until it is used under the revealing lenses of CNN cameras.

Between this submarine detection project and the Vela satellite incident, there was yet another high priority mission that Berman and his diverse NRL staff was asked to take on. The mysterious episode began about breakfast time on December 2, 1977. That's when many residents living near the Atlantic coast in New Jersey began hearing strange rumblings, blasts, booms, and other sounds. Something about them seemed big, very big. "Sounded like a truck hit the back of my house," is how one resident in Tuckerton, New Jersey, described an early afternoon boom on December 2. Earlier that day a Brigantine, New Jersey, man reported hearing a "very strong blast" that he said shook his house violently for three or four seconds. Strange thing: he was inside, but his wife, who was outside, did not hear the blast.[54]

This was not a case of people hearing things that were not there. The Lamont Doherty Observatory at Palisades, New York, for one, had a microbarograph (a sensitive instrument for measuring changes in air pressure) running on that same strange December 2 afternoon. At 3:04 p.m., it picked up a signal so strong that the instrument's recording pen darted to the top of the chart paper where it stayed for 15 seconds until it was manually released.

The "sounds" went on day after day like that. Often one neighbor would think his house was falling down while a neighbor working outside in the garden next door sensed nothing unusual. For the next month and a half, people as far north as Nova Scotia and as far south as Georgia reported similar experiences, though most of the reports came from residents of the New Jersey coast.

All the while, the mystery intensified. The CIA, Coast Guard, Air Force, and Navy all reported having no idea of what could be causing

the booms. Media reports included speculation about the causes of the sounds. Supersonic aircraft, meteor fireballs, earth tremors, UFOs, and unannounced nuclear tests of some kind were among the guesses. One eminent university scientist claimed it was exploding methane seeping out of the ocean bottom and a precursor to a major earthquake. Given the apparent magnitude of the events, and the possibility that some kind of weapons testing might be involved, it was inevitable that the Department of Defense would become implicated.

On December 28, Gerald P. Dinman, the principal deputy of the Undersecretary of Defense for Research and Engineering, circulated a memorandum about the events:

> *"Over the past few weeks, considerable interest has evolved regarding the unexplained acoustic phenomena which have occurred off the east coast of the U.S.," Dinman wrote. "The Department of Defense has been asked to investigate these incidents to try and explain their cause and, if appropriate, their effects."*[55]

Dinman continued:

> *"Accordingly, it is requested that the Navy perform a short, intensive investigation of these incidents in an attempt to discover their cause. It is suggested that the Naval Research Laboratory, due to its multidisciplinary technical capability, could perform this function. Close coordination should be maintained with the Central Intelligence Agency, as they have been tasked to investigate these incidents also."*

A week after Dinman's memorandum, during which there were more acoustic incidents, the Chief of Naval Research officially charged NRL with the task of getting to the bottom of the mystery. And within hours, NRL had created a dozen-member task force, including Alan Berman, NRL's director of research and himself an ocean acoustics expert. Also on the task force were experts in technical areas likely to be relevant—combustion phenomena, plasma physics, atmospheric dynamics, undersea acoustic phenomena, ocean science, and environmental and geophysical science. Another ten would join the group as needed.

The task force systematically searched every possible clue that might help solve the mystery. Any commercial or government activity that could have generated acoustic energy on a massive scale and any tool that might inadvertently have measured such releases became prime targets. Historical records and reports of unexplained noises also became research resources. During their historic trek west, Lewis and Clark reported hearing loud noises[56] while in the Rocky Mountains. In the late 19th Century, multiple observers in the delta of the Ganges River in India reported hearing sounds like distant artillery. Half a century later, people on or near Seneca Lake in upstate New York, reported similar "dull booms."

Interesting as these apparent historical precedents were, they didn't move the investigation forward. One of the major tactics to solving the problem was to question all military and nonmilitary organizations that conceivably could have been carrying out some kind of activity that lead to acoustic discharges of the kinds reported. The initial round of such questioning came up empty. Research and development officials of the Army, Navy, Air Force, Defense Nuclear Agency, and Defense Advanced Research Projects Agency all ruled out any activity within their own domains that could be responsible. Ditto for quarry operators, petroleum companies, and other firms that might have been using explosives for doing geophysical, seismic, acoustic, or other sound-generating investigations at the time of the mysterious acoustic events.

With this unanimous chorus of "it wasn't us," the NRL task force began considering a range of well-known, little-known, and conjectural phenomena that could be responsible. Was it possible that the annual additions of 5 million tons of wet sludge to a massive sewage disposal site outside the entrance to the New York Harbor had begun to release huge volumes of methane into the atmosphere where the gas might then be exploding? A quick but convincing study by NRL's Chemistry Division ruled out methane. Was it possible the events were due to unusual meteors akin to the famous 1908 Tunguska meteor

that devastated a remote area of Siberia and that was recorded by seismometers around the world? Analysis of seismometer data failed to reveal any Earth shocks of the magnitude consistent with this hypothesis.

There were several important clues already in, however. For one thing, only people inside or near structures reported the "sound" or rumbles. That suggested the events themselves were infrasonic, that is, low-frequency air vibrations below audible ranges. The audible sounds people reported derived from nearby structures set into motion by the infrasonic energy. By correlating citizen reports of the infrasound events with the more precisely timed occurrences picked up by instruments such as those at the Lamont Doherty Observatory and a network of other observation stations in New England, the NRL team was able to roughly localize a likely point of origin of the events. From these calculations, it seemed the mystery sounds in New Jersey were originating many tens of miles off the coast near the popular summer retreat of Long Beach Island in areas reserved for military flight operations.

The timing of the events also suggested to the NRL task force that some sort of human activity, rather than some natural phenomena, was the likely culprit. Even with that logical constraint, there was as yet no smoking gun. The task force was able to conclusively rule out such possible causes as nuclear explosions, exploding ordnance, missile or satellite launches, civilian aircraft, ship disasters, civilian use of explosives, and geophysical exploration using explosives.

A break in the investigation came when the task force revisited the possibility that high-performance military aircraft were causing the mystery. By modifying a program for underwater acoustics calculations, the task force was able to show that the sounds could be correlated with Air Force and Marine flights in the exercise areas. Moreover, the calculations showed that during the periods in question, a combination of temperature inversion in the atmosphere and high-speed south-to-north winds could create an acoustic duct that would

efficiently transport very low frequencies as far as 50 or more miles from where the sounds were generated.

"Interviews with military pilots established that they do not maintain precise records of their periods of supersonic flight," the task force wrote in a preliminary summary report of their investigation in March 1978. But more careful analyses of whether aircraft with supersonic capabilities were present in or near designated training areas off the coast of New Jersey and Charleston, South Carolina at times of unambiguous reports of the sounds revealed a correlation of the "smoking gun" variety.

In interviews, pilots flying on days during which the mysterious acoustics had been detected reported performing the high-speed climbs, sharp turns, and other maneuvers in their training zones that were likely to have caused the sonic disturbances. "On every occasion when significant reports were made by residents and confirmed by scientific instruments, supersonic-capability aircraft were found to be operating in nearby [training] areas," the task force concluded in their final report of their investigation. Just as significantly, none of the noises was detected when military aircraft were *not* engaged in supersonic flights in the designated areas. In all likelihood, the mystery had been solved with no UFOs or meteors in sight. An equally convincing correlation of supersonic Concorde flights and ducting conditions pinned event that were also occurring in Nova Scotia to a Concorde turning-point off the Nova Scotia coast.

The solutions were straightforward. Changing flight patterns, avoiding particularly sharp maneuvers in the western borders of the training zones, and working around meteorological conditions particularly conducive to propagating infrasonic energy from the supersonic flight would diminish or even put an end to the sounds that had been mysterious just a few months earlier.

There have been additional "the-White-House-needs-to-know" missions given to NRL. One of the most important ones was to help NASA uncover why the Mars Observer spacecraft, which in 1993 was

to be the first U.S. spacecraft to study Mars since the Viking missions of the mid-1970s, suddenly lost communication with mission control on August 21, 1993.

NRL Director of Research Timothy Coffey led a board of scientists and engineers in search of the answer. "We were challenged to conduct an extraordinarily complex investigation in which we had no hard evidence to examine nor communications with the spacecraft," Coffey noted when the board's final report was released on January 5, 1994. With a deficit like that, no absolute conclusion would be likely. But, Coffey said, "after an extensive analysis covering every facet of the mission, operations, and hardware, I believe that we are justified in arriving at the conclusions we have."[57]

In short, the investigation team concluded that the loss of communication with the spacecraft followed a rupture of a fuel line leading to a pressurized escape of both helium and fuel, monomethyl hydrazine. The escaping gases then probably propelled the spacecraft into a spin fast enough for the spacecraft to automatically enter a contingency mode. This, in turn, would have interrupted stored command sequences programmed to turn on the transmitter while preventing the spacecraft's solar panels from orienting themselves properly, leading to a discharge of the batteries.

These and other findings of the investigation team uncovered additional technical and managerial vulnerabilities. "Their work will help and guide us in formulating a corrective action plan to help ensure future success as we plan for recovering our Mars science exploration objectives," said Wesley Huntress, Jr., Associate Administrator for NASA's Office of Space Science, when the phone-book-sized final report was released.[58]

The Flip Side of the Cold War

NRL's role in aboveground and underground nuclear weapons testing, simulation of nuclear weapons and their effects with high-energy machines and computers, and intermittent investigations into

mysterious and potentially threatening phenomena were all reflections of the Laboratory's immersion in the Cold War. It would be so until the Berlin Wall fell in 1989. Yet the other side of the Laboratory's "split" personality, the part hungry to learn more about the world simply because there was more to learn, also would take alternative paths forward into the Nuclear Age. To be sure, nuclear weapons held the highest drama when it came to nuclear technology, but it was just part of the enlarging world of nuclear science and high-energy physics of which many NRL scientists were determined to remain a part.

In recognition of the wider implications of nuclear science and technology, NRL had established a nuclear physics group in October 1947 under the leadership of Ernst Krause, the same man who made sure NRL would have access to the captured V-2 rockets. A month later, the group became known as the Nucleonics Division. One coveted portion of the nuclear technology arena that NRL had to acquiesce to others was nuclear propulsion.

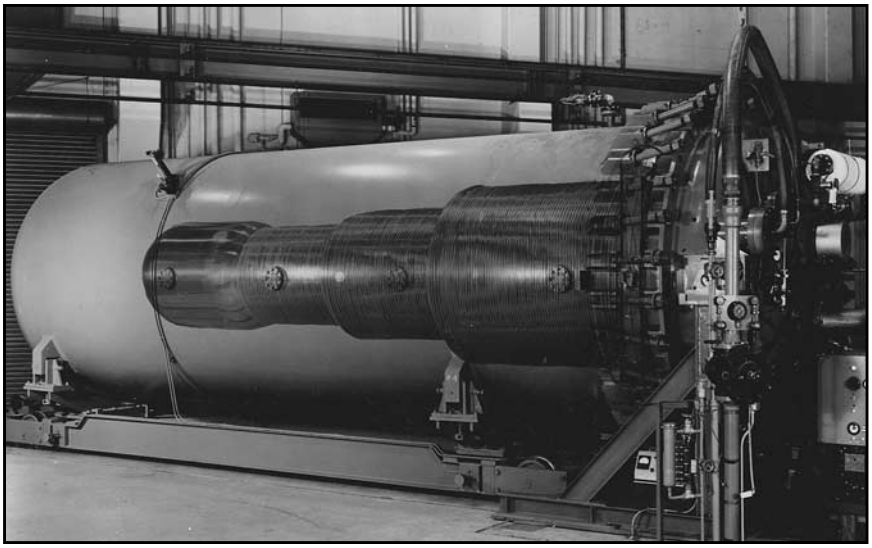
This was a bitter pill to swallow since Philip Abelson and Ross Gunn came up with a preliminary design for a nuclear propelled submarine as far back as 1946. But Vice Admiral H.G. Rickover, head of the Bureau of Ships, had successfully maneuvered within the newly formed Atomic Energy Commission to win control of the engineering and development of nuclear-powered submarines, the possibility of which was first outlined in a classified NRL report by Abelson, Gunn, and several colleagues.[59] In retrospect, elders of the Laboratory rate the decision as a correct one since a nuclear propulsion program would have irreparably deflected the Laboratory from its broad-based mission.

With bomb testing already part of the Laboratory's fabric, and nuclear propulsion left to others, NRL researchers turned to the thousands of other avenues of nuclear and high-energy physics, most notably the acceleration and use of particles like electrons and protons for studying and altering materials.[60] During WWII, the Laboratory already had gotten its hand into the world of accelerators when it

built a 20 MeV (million electron volt) Betatron. This was a machine that could accelerate electrons up to energies sufficient to produce X-rays, which NRL researchers put to use largely for analyzing the interiors of metal components including foundry castings and high-explosive shells. In its major role in testing materials without having to destroy the samples, the Betatron was in direct lineage with the gamma-ray radiography technique pioneered by Robert Mehl in the early days of NRL's Metallurgy Division. It had the advantage, however, of being able to reveal smaller defects. The Betatron went on-line for the first time in early 1945.

In 1952, the Nucleonics Division began assembling another type of accelerator—a Van de Graaff machine—that could accelerate positively charged nuclear particles such as protons (the nucleus of a hydrogen atom) and the nuclei of heavier atoms. A 30-foot long pressurized tank filled with electrically insulating gases surrounded the large, half-ton accelerating terminal. To house the accelerator and the control room along with the electrical and other equipment needed to operate it, the Laboratory built an entirely new building with a cavernous interior. By 1954, the new accelerator was accelerating protons up to 5.5 MeV, enough for them to penetrate atomic nuclei in dime-sized targets of materials such as aluminum foil or to knock neutrons out of target atoms. The neutrons, in turn, became probes for examining the detailed internal anatomy of materials.

The Van de Graaff's initial workload focused on basic measurements on a large variety of particle-bombarded nuclei to determine and quantify the kinds of nuclear reactions in which different elements participate. But the accelerator's ability to produce a range of charged particles meant that it could produce emanations similar to those that satellite-borne instruments might be expected to encounter. The Van de Graaff could serve as surrogate to cosmic sources of particles and thereby help to calibrate sophisticated detectors intended for duty in space. Moreover, since charged particles from the accelerator cannot get through more than the surface region of materials, the



This double-exposure of the NRL 5-MeV Van de Graaff accelerator shows the accelerator component normally hidden within the instrument's steel pressure chamber.

accelerator also became an important tool for studying surfaces. By bombarding surfaces with particles of specific energies, it became possible to detect specific contaminants or ultrathin coatings on surfaces by analyzing the types of radiation that emerged once the samples were irradiated. These kinds of studies can help uncover how and why materials age, fatigue, and wear.

By the late 1950s, the hunger for more powerful, higher energy machines began to have its effects. The Betatron, NRL's electron accelerator, already was heading toward obsolescence. At 5:15 p.m. on June 27, 1963, the Laboratory's next generation electron accelerator, the Linac, yielded its first beam of electrons, which smacked into a copper target, causing it to become radioactive. Like its predecessor, researchers put the Linac to use for such jobs as calibrating space-intended detectors by exciting elements to energy levels at which they would emit radiation previously produced only in cosmic sources. Another type of study relied on the Linac's ability to induce specific radiation responses in the elements of samples, thereby enabling

chemists and materials scientists to make precise analyses of the samples' chemical composition.

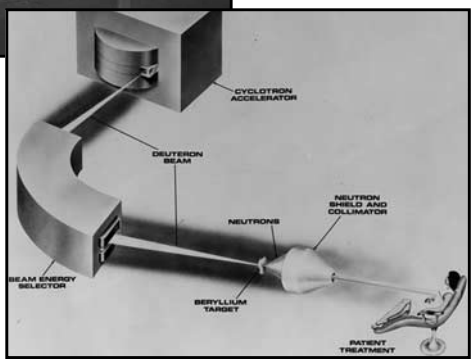
Another foray into "Big Physics" was a circular cyclotron able to accelerate positively charged protons, or larger nuclear particles, up to 75 MeV. It, too, needed its own new building, which was erected without windows on the south end of Bolling Air Force Base, NRL's immediate northern neighbor. In the basement of the building went a 250-ton accelerating magnet housed within a massive vault isolated by thick concrete walls and enormous steel doors. Another 80-ton magnet extracted only those types of particles a researcher wanted for a particular experiment. The building housed additional equipment for transporting the resulting filtered beam from the cyclotron to experimental stations and an electronics-filled control room. By the time it was dedicated in March 1967, the cost of the facility was $5.5 million.

Most cyclotron work centered on studies of the structures and properties and materials, but in the fall of 1973, a trickle of cancer patients began entering the windowless building for radiotherapy. The idea here was to locally inject tumor-killing radiation where it was needed by carefully aligning the tumors with a neutron beam created with the cyclotron. This program eventually was transferred to civilian hospital settings. The cyclotron closed down in the mid-1980s. Its building now houses the Naval Center for Applied Research in Artificial Intelligence, which reflects the general trend toward computational tools and information technology.

Perhaps the single most amazing part of NRL's plunge into the realm of nuclear science was to land its very own nuclear reactor within sight of the nation's capitol. On April 7, 1954, the day after the Defense Department asked Congress for the authority to build the reactor at NRL, the *Washington Post* and *Times Herald* ran a front page lead story with the headline, "ATOM REACTOR ASKED HERE."

Given the audacity of the idea, it is no surprise that Ernst Krause again was a key figure in getting the idea through the powers that were. Of course, it was only natural for a research division known as the

(a) The control room of NRL's cyclotron



(b) Diagram depicting the cyclotron's sometime role as an instrument for cancer radiotherapy

Nucleonics Division to want a reactor. "But it was unheard of to place such a machine in a populated area, especially Washington, so near the nation's capital," Krause recalled in a 1982 interview with historian David DeVorkin.[61] Nevertheless, Krause and his associates were able to convince the Atomic Energy Safety Committee and its famous chairman Edward Teller (father of the hydrogen bomb), that NRL could build and operate a safe nuclear reactor.

A Congressional appropriation of $996,000 for the Washington, DC area's first nuclear reactor came through in the summer of 1954. Construction of the "swimming pool" reactor began in mid-1955. In this design, the reactor rests within a 150,000 gallon pool about 40 ft long by 26 ft wide by 20½ feet deep. On September 15, 1956, the Atomic Energy Commission granted NRL a license to operate the facility at an initial level of 100 kilowatts. Two days later, the first chain reaction of nuclear disintegrations began to occur in the small reactor.

In his January 17, 1957 speech dedicating the new reactor, Charles S. Thomas, Secretary of the Navy, told his audience what to expect from the new reactor:

> *"There is no way of predicting what we will learn, but it will be used to study the structure of matter including such practical applications as the structure of new alloys. It will be used to create and study new substances, to make chemicals radioactive for direct study and to produce chemical and biological changes. In the reactor, radiation effects upon materials of all kinds—plastics, metals, cable coverings, transistors, and electronic components—will be studied. Shielding problems applicable to propulsion will be investigated. Some day, this research may lead to nuclear power for trains and planes. All of this knowledge will lead to quicker development of atomic power for peace and industry."*[62]

Ten years later, in 1966, there would be seven research reactors in operation around Washington, DC, including NRL's reactor, which

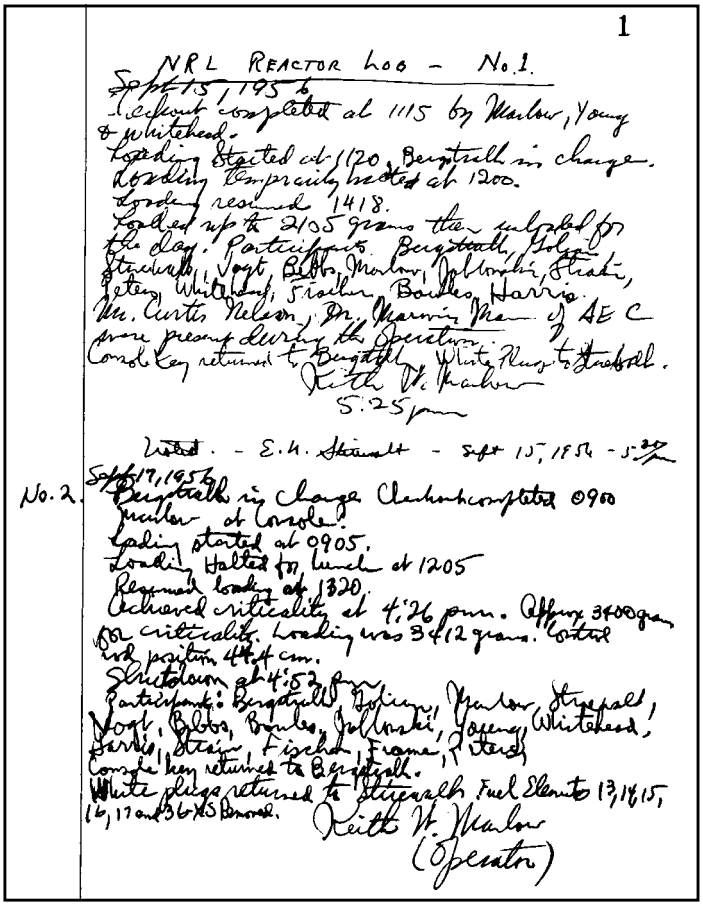
The core assembly of NRL's research nuclear reactor, which first hosted chain reactions in 1956, is shown suspended in a pool of shielding water.

by then was operating at 1 megawatt. But an hour's drive north at the National Bureau of Standards in Gaithersburg, Maryland (now called the National Institute of Standards and Technology), a more powerful 10 megawatt research reactor had begun operating. Like the NRL reactor, neutrons generated from the nuclear reactions inside of the reactors core served as powerful analytical probes for determining the internal and surface anatomies of all manners of samples.

The great irony of nuclear physics is that its atomic and subatomic objects of study are superlatively diminutive, yet its research tools are about as big and expensive as scientific instruments get. It is true that NRL's nuclear physics facilities helped maintain a base of expertise in an area of physics that NRL would not have had otherwise, but in the 1970s, NRL aimed to broaden its research efforts. One way to realize that goal was to leave much of the big and expensive physics of nuclear science to others who wished to specialize in that capital-intensive field. On June 20, 1970, NRL shut down its historic reactor. The deactivated and decontaminated swimming pool reactor now has a submerged bed of sand that the Physical Acoustics Branch uses to investigate such things as the challenges of detecting munitions buried in shallow waters where the Navy expects near-future conflicts are most likely to unfold.

The Nuclear Age, the Cold War, and NRL all co-evolved. It has been an era marked by an astounding quickening and diversification in the realms of science and technology in general. In the past few decades, the increasingly important roles of microelectronics technology, information, computational tools and techniques, new and more capable materials, global and local communication, and local and global sensing and surveillance all have become apparent in the overall portfolio of NRL's expertise and research organization. Tools for analyzing, manipulating, and simulating the world as it unfolds on atomic or cosmic scales, and during time intervals as small as trillionths of a second or as grand as billions of years, have become increasingly more powerful, sophisticated, and revealing.

All of this scientific and technological evolution has pushed the envelope of NRL's more historically rooted disciplines such as chemistry and optics. It also has opened up entirely new fields such as information technology and biomolecular engineering. And that is just the point of the Naval Research Laboratory—to have the people and resources required for going further and deep into known territory or for pioneering into the unknown.



1

NRL REACTOR LOG - No. 1.

Sept 15, 1956

Reflector completed at 1115 by Marlow, Young & Whitehead.

Loading started at 1120, Bergstrath in charge.

Loading temporarily halted at 1200.

Loading resumed 1418.

Loaded up to 2105 grams then suspended for the day. Participants: Bergstrath, Bolger, Steudel, Vogt, Gibbs, Marlow, Jablonski, Straka, Peters, Whitehead, Fralick, Boulles, Harris, Mr. Curtis Nelson, Dr. Marvin Mann of AEC were present during the operation.

Console key returned to Bergstrath. White Plugs to Steudel.

Keith W. Marlow

5:25 pm

Noted. - E.H. Steudel - Sept 15, 1956 - 5:27 pm

No. 2.

Sept 17, 1956

Bergstrath in charge. Check completed 0900 Fowler at Console.

Loading started at 0905.

Loading Halted for lunch at 1205

Resumed loading at 1320.

Achieved criticality at 4:26 pm. Approx 3400 gm for criticality. Loading was 3412 grams. Control rod position 44.4 cm.

Shutdown at 4:53 pm

Participants: Bergstrath, Bolger, Marlow, Steudel, Vogt, Gibbs, Boulles, Jablonski, Yaggey, (Whitehead), Harris, Straka, Fischer, Frame, Peters

Console key returned to Bergstrath.

White plugs returned to Steudel. Fuel Elements 13, 14, 15, 16, 17 and 36 XS Brand.

Keith W. Marlow

(Operator)

NRL reactor log with entry under September 17, 1956, indicating the reactor's first operation at "criticality," or under conditions allowing sustained chain reactions to occur

Chapter 10

From a Golden Era to Reality Checks

To watch NRL's changing organizational charts since the end of World War II through the Cold War and onward to the present moment is to see a large research organization navigating the interacting tides of science, technology, public opinion, and politics. Organizational and administrative changes have occurred at every level of the Laboratory from the top leadership downward. New research directorates, divisions within directorates, branches within divisions, and sections within branches have never stopped emerging, coalescing, getting renamed or reoriented, or disappearing altogether.[1]

The Nucleonics Division, for one, was created after World War II as fallout from the nascent Nuclear Age in which nuclear weaponry and other technical areas specific to nuclear-based phenomena and technologies would become chronically important. A quarter-century later, the division would disappear as an identifiable entity as its components morphed into new divisions, such as Plasma Physics and Radiation Science.

The previously singular Radio Division split into three divisions, each focusing on different territories of a field that diversified and speciated at a dizzying pace during and after World War II. This tripartite division covered traditional areas such as vacuum tube and antenna research, areas that came to the fore during World War II such as search radar and countermeasures, and nontraditional areas including psychology.

The Solid State Division came to be in 1954, partly in response to the invention of the transistor by three physicists at Bell Laboratories in late 1947. Interestingly, Bernard Salisbury, a vacuum tube designer at NRL, had gotten close enough by the summer of 1948 to inventing the transistor that the Navy initially wanted to share credit with Bell Laboratories for what has become one of this century's most important inventions. After a meeting at NRL with a contingent of managers and scientists from Bell, however, the Navy withdrew its claim. Salisbury was on the right track, but he had not yet observed transistor-like behavior in his gold-coated copper-oxide gadget.[2]

Some of the organizational changes have been less concrete. In 1954, NRL's rocket-based science and technology programs and weapons testing efforts revealed how complex NRL's tasks were becoming. To anticipate a growing need to handle such programs, the Laboratory created the short-lived Applications Research Division. Its maiden branches in Data Processing, Engineering Psychology, Operational Research, and Systems Analysis reflected the multidisciplinary needs to make modern technology—and its ever larger systems such as rockets and atomic weaponry—work. Some of these efforts merged with others to become the Laboratory's present day Information Technology Division, which has links virtually everywhere now that computers and simulation tools have become ubiquitous in all phases of Naval operations and research.

One of the more fundamental organizational changes since World War II happened in 1949 when the Laboratory inaugurated the office of the Director of Research to be held by a civilian scientist. With a civilian at the head of NRL's technical program, NRL's post-WWII senior scientists felt it would be easier to attract and keep the high quality recruits they wanted. The first three directors of research up until 1967 were all home-grown. They had come up from the ranks to run the Laboratory during what many consider to be a golden era for American science, when money came easily and public support was high.

The first director of research, Edward O. Hulburt, was apropos for the Laboratory's renewed vision of itself as a university-like workplace. What's more, the academic and gentlemanly Hulburt always had championed the way rigorous fundamental science can find important Naval applications. He served until 1956 when Oscar Marzke, then Associate Director for Materials, took over the directorship for a short time during 1956 and 1957, before leaving NRL to become Vice President of Fundamental Research at U.S. Steel. The third director of research was Robert Page, whose ambition and engineering expertise hastened the creation of the United States' first Naval radar systems in the 1930s and during World War II. Page served until 1967, by which time the Laboratory was destined to transform along with the rest of society.

Another large scale and lasting change in the Laboratory occurred in 1953 under Hulburt's watch. The Laboratory's 13 divisions were divided amongst three new, broader categories—Electronics, Materials, and Nucleonics. Each of these larger organizational units, now called directorates, got its own associate director of research. That way, the civilian director of research would not have the unwieldy and perhaps overly challenging requirement of being directly responsible for so many different research programs.

The director of research and associate directors, who became known as "the archangels," sit at desks along "Mahogany Row"—the series of paneled offices in Building 43. This layer of upper-management, in their role as the Research Advisory Council, or RAC (and known inside NRL as "The Rack") has became an important conduit of information and advice for the Laboratory's director of research and commanding officer in the job of setting the Laboratory's research agenda. One way the RAC serves this role is through a key annual ritual. Laboratory researchers vying for a portion of the so-called "6.1" and "6.2" money (earmarked for basic and applied research, respectively) that comes to NRL each year from the Office of Naval Research parade to Building 43 with handouts, viewgraphs, and other supporting materials. There they argue their case before the RAC. Larger is-

sues and longer-term strategic planning are more likely to occur at the "RAC retreat," a several day think tank session convened early each year.

The creation of the civilian directorship of research at NRL in 1948 helped to boost the Laboratory's ability to respond to the increasing complexity and magnitude of the Navy's R&D program. The creation of this office in no way diminished the responsibilities of the Laboratory's military Director, who maintained authority over the operation of the Laboratory. However, ambiguities about the respective authority of the Laboratory's two top offices sometimes arose. So in 1977, the NRL Director was redesignated as the Commanding Officer. And a year later, the Laboratory's civilian Director of Research and Commanding Officer began operating within an official framework of joint executive management within a single administrative unit. It has been that way ever since. While the Commanding Officer remains the final authority over all internal matters, he and the Director of Research jointly plan and manage all aspects of the Laboratory.

In its present configuration, the Laboratory has three technical directorates—Systems, Materials Science and Component Technology, and Ocean and Atmospheric Science and Technology, as well as the Naval Center for Space Technology (NCST), which is not officially a directorate unto itself yet functions somewhat like one. There also is an administrative directorate, called the Executive Directorate, and a Business Operations Directorate, whose collective divisions cover such functions as financial management, contracts, and supply.

Each research directorate has its evolutionary history sketched out in the changing organizational charts. In 1966, for example, the Nucleonics Directorate morphed into a directorate called Research For General Sciences. It subsumed most of what was covered in the former directorate while adding an Ocean Science and Engineering Division, including the Deep Sea Research Branch that became so busy with search and rescue operations. The new directorate also included the Plasma Physics Division, whose birth derived largely from the global ban on above-ground nuclear tests in 1962. Timothy Coffey, the

Laboratory's present director of research, would get his start at NRL as a contract employee in this division in the late 1960s. The creation of the Ocean Sciences and Engineering Division within this new directorate reflected the Navy's ever growing need to understand everything it could about the world's oceans, which to many had become the Cold War's most strategic venue. After all, it is in the oceans that the superpowers' most credible threat and deterrent, nuclear submarines carrying nuclear warheads, prowled.

That oceanic research trend continued the following year, in 1967, when the Laboratory expanded the Ocean Science and Engineering Division to become a new, strangely named fourth directorate—Research For Oceanology, a name that connoted a larger sphere of topics than a more traditional term like oceanography might have. The present-day Ocean and Atmospheric Science and Technology Directorate evolved, in part, from this directorate.

The year the Research for Oceanology Directorate was born, 1967, was a turning point for NRL. It falls squarely within a transitional period from the "Golden Era" of science, which Hulburt, Marzke, and Page enjoyed when they were the Laboratory's research directors. It was an era when public support for science was extremely high. With such marvels as the atomic bomb, radar, proximity fuzes, nylon, synthetic rubber, and antibiotics, Americans saw science as the key to winning wars and improving the quality of life. It was worthy of their support and tax dollars.

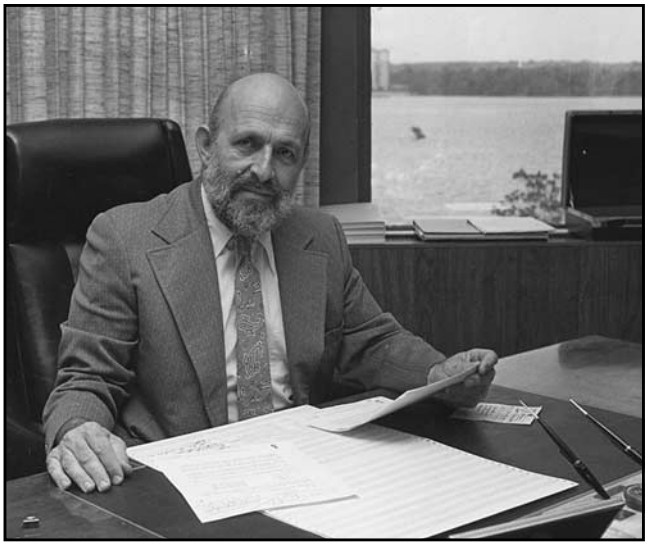
The Cold War, the Korean War, the nuclear arms race, and the Soviet launch of the Sputnik satellites all injected a sense of urgency in the American mindset about the need to nurture and promote domestic science and technology. Much of the enormous R&D infrastructure that was constructed during World War II to tackle specific technical problems, such as the proximity fuze and radar, remained in place. Funding came from the Department of Defense, which was created in 1947 in the National Security Act, or later from the Department of Energy. Even in 1950, when Congress established the National Science Foundation to support science in universities, national

security was the primary rationale for its establishment. The following two years saw the creation of the Army Research Office and the Air Force Office of Scientific Research, both of them modeled at least in part on the Office of Naval Research, which Congress created in 1946.[3]

With funding agencies for scientific research proliferating and funds available for the new agencies to distribute, times were good for research. Moreover, it was the military sector that pretty well set the overall agenda. Throughout the 1950s, an average of 81% of overall Federal research and development funding came from the military sector. With the passing of the National Defense Education Act in 1958, the same year NASA and the Advanced Research Projects Agency (now DARPA) were established, qualified students were assured access to a college education. The Sputnik satellites spurred Congress to more than double Federal outlays for research and development between 1958 and 1965. The prevailing attitude on the street and in Congress was that whatever was good for science would be also good for the country. More than that, there was some sense that national prestige, even national survival, depended upon preeminence in science now that the Soviet Union had proven itself capable of such feats as building nuclear weapons and putting satellites into orbit.

It was a fine time to be running a science and technology research facility like NRL. Old-timers like Louis Drummeter and Homer Carhart now recall it as a period when rank-and-file researchers never had to worry about money. For any reasonable project, the money just seemed to be there. Says Carhart: "We didn't worry about money. We'd just go and say, 'hey, we're going to work on this' and salaries got paid and we did things as needed. It was quite effective."[4]

The new era marked by Alan Berman's arrival would constitute a reality check. The honeymoon of public support for science and technology, and the almost carte blanche attitude when it came to funding, would begin ending in the mid-1960s during the escalation of the U.S. involvement in the Vietnam War. Not only did the material needs of the war itself absorb part of the Defense Department's basic research budget, but as "an unpopular war," it led to public scrutiny



Director of Research Alan Berman at his desk in Building 43. Berman was director from 1967 until 1982.

of the government-science connection. Many researchers at universities whose funds came from the Department of Defense became the foci of campus protests where antiwar activists considered military research money to be morally tainted.

The Mansfield Amendment of 1970 was an early legislative instrument designed to make sure DoD-supported research, in the legislation's wording, would have at least "a potential relationship to a military function or operation." Berman notes that the language of the legislation was porous enough to support almost any project NRL researchers were doing, but the law did shrink the amount of money flowing outward to universities from DoD funding agencies like the Office of Naval Research. Whereas in the 1950s, the DoD funded a clear majority of all Federal research and development, by the end of the 1970s the proportion was closer to one-fifth, which amounted to just over $2 billion.[5] Total Federal spending for R&D now is about $78 billion.

When Berman began his directorship at NRL, the proportion of government funding slated for research and development began a gradual eight-year decline, though in actual dollars the trend remained

slightly upward. During this period, a new ethic of accountability began to infiltrate the scientific community, NRL included. The consequences on funding would not be as dramatic for the Laboratory as it was for academic scientists at universities, but the need to justify and account for money requested and spent already was becoming a permanent part of the Laboratory's research culture. More and more of the staff found themselves doing what they rarely had had to do before—writing proposals, competing for money, and filling out increasing volumes of paperwork.

Throughout the 1960s, the Laboratory also underwent a spate of new construction on grounds that had previously been part of the Washington Navy Yard just north of the original Laboratory buildings and adjacent to the Bolling Air Force Base. Today's Chemistry Division, Electronics Science and Technology Division, and Space Sciences Division as well as a portion of the Laboratory's administrative services are all in buildings erected at that time and place.

With so much physical and psychological change going on in the 1960s, it was only fitting for the Laboratory to hire Alan Berman as the new director of research. Berman had been a Navy researcher for years but never was at NRL. He had begun his own research career on projects for the Navy as a graduate student at Columbia University and later became the director of the Navy-supported Hudson Laboratory (whose mission centered on antisubmarine warfare). Still, Berman was an NRL outsider when he took over the reins from Robert Page.[6]

Unlike Hulburt, Marzke, and Page, Berman had no personal history invested in NRL. So he had no particular allegiances or personal baggage to accommodate as he negotiated a new path for NRL during the Vietnam era and up to the early 1980s—the penultimate decade of the Cold War that had provided the clear context for Berman's entire career in military research.

Berman's life intersected with NRL's institutional history when Captain Tom Owen, NRL's military director at the time, invited him to apply for the directorship. According to Berman, Owen exercised a strong-arm approach to placing new blood in the Laboratory's lead-

ership as well as to applying more business-based management tactics to the Laboratory's operation. After convincing himself there was enough good raw material at NRL, Berman accepted the offer to become the Laboratory's fourth director of research.

His goals were simple, at least in theory. "I wanted NRL to be a modern, high-class laboratory that was competitive in terms of professional excellence and I wanted it to be involved with things that would make a difference to the Navy," he recalled in his New York accent thirty years later.[7] And he took on this mission with what would become a legendary mix of intensity, energy, intelligence, and micromanagement.

When Berman first reported to work at NRL, he requested a copy of every article in the scientific literature that had been authored or co-authored by a member of the present staff. He then immersed himself in the deluge of paper for the next month. It was his way of getting a first-person sensibility for the range of research going on at NRL. He also immediately began a managerial practice that became famous. Called "Breakfast with Berman," the director would meet each morning with a different branch head, having reviewed a continuously fattening file on the branch the night before. "I always looked forward to 'Breakfast with Berman' because I knew he would tell me something about my branch that I didn't know," recalls James Murday, now superintendent of the entire Chemistry Division.[8]

With this management style, Berman equipped himself to make decisions from both the top-down and the bottom-up. As did any director of the Laboratory, he had to negotiate the Laboratory's interests within higher military and political contexts (with the help, of course, of the military director). To do that, he would find himself in settings such as the Pentagon or before House and Senate Subcommittees controlling funds for the Office of Naval Research, which had been a major source of basic research funding for NRL since ONR's formation in 1946.

Berman championed NRL as a place where bench scientists could do top quality research, get recognition for their work by their peers,

and be happy doing it. Without a strong and steady connection to the general scientific community, he knew there would be little hope of maintaining and attracting the kinds of scientists by which an institution can maintain respect in the scientific community. As for those who would be NRL scientists, he made great demands. A 4.0. grade point average was almost mandatory for any viable candidate. And for those already at the Laboratory, he used the "Berman algorithm" in which he used inputs such as the numbers of journal papers published, conference presentations given, and the like, to calculate professional advancements such as raises and the timing of promotions.[9]

Prior to Berman's arrival, NRL researchers published their work primarily in internal Laboratory formats rather than in the kinds of journals that would make them and NRL more visible contributors to the scientific community. By the time Berman left the Laboratory, the staff was publishing far more often in the open peer-reviewed journals than in internal or classified publications. It was a shift that clearly helped lift NRL's prestige and visibility.

Berman set out during his fifteen-year tenure to reshape the Laboratory's research portfolio in a way that balanced scientific and technological trends, funding realities, and the Laboratory's unique place at the cross-section of Naval, Defense and intelligence communities, as well as the general science and technical communities. While closing down research facilities such as the swimming pool reactor, and later the cyclotron, which he deemed too expensive and otherwise inappropriate for NRL, he strengthened other research areas such as electronic warfare, electronics technologies, information technology, and optical science.

"Survival of a modern army and navy really is a function of electronic warfare capabilities," Berman told an interviewer in 1982.[10] He noted in particular that the threat of low-flying antiship missiles concerned him greatly during his tenure at NRL. Key technical challenges included detecting incoming missiles, having effective countermeasures (such as new generations of chaff and other types of decoys), and rapidly processing and disseminating data for evaluating threats

and controlling responses. Optical components, new radar systems, computer software, and new electronic gadgetry were all part of the answer to these new missile threats, which is why Berman encouraged these areas at NRL.

"There is a perpetual battle that has been going on between missile designers and decoy designers as to who beats whom," Berman said. "The [electronic warfare] group here has been absolutely spectacular in that regard."[11] That explains in part why much of the limited amount of major new construction that took place at the Laboratory in the 1970s and 1980s was the erection and later expansion of facilities for the Tactical Electronic Warfare Division.

Halfway through his directorship, in 1975 and 1976, even the strong-willed Berman was overtaken by a controversial, politics-driven decision to move much of NRL's own expertise in ocean science and technology off campus to a newly formed Navy research unit created ostensibly to bolster the Navy's ocean-based R&D. For many of those at NRL and at the Naval Oceanographic Office in nearby Suitland, Maryland, who also were caught in the middle, this was an unwelcome, wrenching transition. It entailed relocating their work and their lives to Bay St. Louis, Mississippi at a vacant, former part of NASA's Stennis Space Center. There, the NRL contingent consolidated with related Navy research programs to form the Naval Ocean Research and Development Activity (NORDA). At the time of the move, Senator John C. Stennis of Mississippi was the Chairman of the Armed Services Committee.[12]

The political debate within and amongst Congress and the Pentagon, as well as court battles to stop the move and life stories of those directly affected, played out in scores of newspaper articles and editorials. In the end, the move took place anyway. There would be additional, though less wrenching organizational changes involving NORDA and other Navy ocean and atmosphere research groups years later during the directorship of Berman's successor, Timothy Coffey.

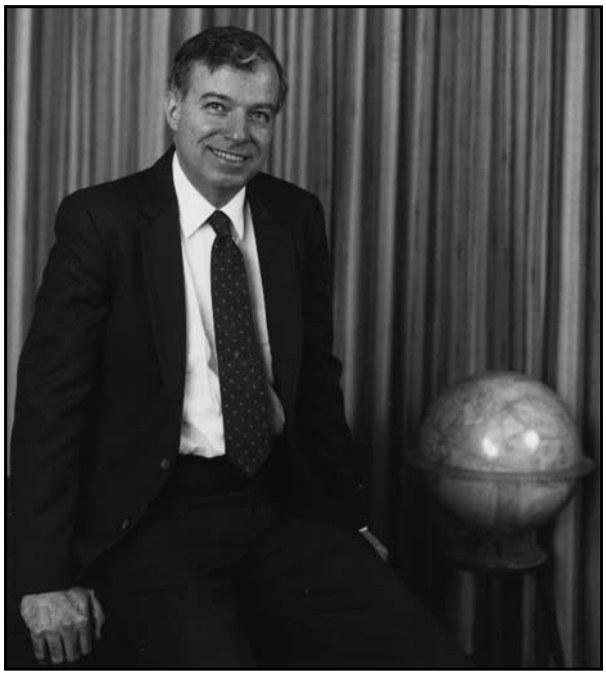
Berman began his NRL directorship during a trend of overall budgetary austerity for military research and development. After reaching

a level of about $184 million in 1973, NRL's research appropriations took a dip and then flattened at $173 million for several years. During the Carter Administration, however, funding levels began rising again, reaching nearly $215 million by 1979. These numbers do not include classified sums of money supporting black programs, including a vast program—known as Project Sierra—centered on a new and poorly understood means of detecting submarines. By the time Berman left NRL in 1982, the Laboratory's acknowledged research budget had increased to nearly $270 million.[13]

Berman left amidst the military spending spree that came with Ronald Reagan's presidency. He handed the research directorship off to the present director, Timothy Coffey, who had been taking on ever more responsible positions since he joined the Laboratory as a *bona fide* employee in 1971 to head the Plasma Dynamics Branch of the Plasma Physics Division.

Military R&D spending in the United States rose precipitously during Coffey's early years as the Laboratory's fifth director of research since 1949. Spending nearly doubled between 1981 and 1985 and rose even more steeply after that due to the costly and controversial Strategic Defense Initiative (now known as the Ballistic Missile Defense Initiative and more popularly as Star Wars) that former-President Ronald Reagan believed could lead to a high-tech defensive umbrella impervious to a rain of nuclear warheads from the Soviet Union.[14]

For NRL, SDI money flowed largely through specific doors such as those of the Optical Sciences Division and of the Naval Center for Space Technology, which was inaugurated in 1986 as the Navy's lead laboratory for space technology. "It was an amazing time," recalls Tom Giallorenzi, superintendent of the Optical Sciences Division when SDI became part of the R&D picture. "People were coming to my door from SDI asking us to take projects on for like a hundred million dollars . . . That was a time that won't repeat itself, but it was an interesting time."[15] Although his division did receive SDI money for some



Director of Research Timothy Coffey. Coffey has been director since 1982.

laser projects, Giallorenzi points out that large influxes of money from single sponsors can have double edges.

There are long term risks, he says, because big blocks of money earmarked under specific programs for specific goals can fundamentally change the character and course of a research division. Since these changes do not necessarily coincide with NRL's longer term mission, injections of money from programs like SDI can—if managers are not careful—deflect a division's expertise and resources into what ultimately become dead-ends.

Despite the intermittent influx of support to some parts of NRL, the Laboratory's overall unclassified research budget fluctuated between $478 million and $571 million from 1985 to 1989, the year the Berlin Wall crumbled. The budget then moved upward to a peak of $810 million in 1993 before dipping back to the roughly $750 million level of the past few years.

When Coffey first came to the Laboratory in 1971 to head the Plasma Physics Branch, his own technical expertise meshed perfectly

with the technical challenges associated with the then nearly decade-old ban on testing nuclear weapons in the atmosphere. Yet the Cold War was in full swing. So an enormous amount of research was relying on surrogate laboratory tests, physical theories, and computational simulations to reveal and understand the probable effects of nuclear weapons.

Since nuclear blasts turn any nearby materials (like atmospheric gases, concrete, or people) into plasma—a soup of naked atomic nuclei and electrons—Coffey made it his business to bolster NRL's strength in theoretical and experimental plasma physics. Funding came from such sponsors as the Defense Nuclear Agency and the Department of Energy. Among other things, this kind of research requires high-energy machines for creating plasmas and the technical expertise to observe and understand how these plasmas behave. It also requires the development of sophisticated theories and access to ever more powerful supercomputers to help scientists both understand the results of experiments and link these to what one might expect from nuclear explosions in different settings.[16]

Like most things in science, these particular strengths have proven themselves useful for other kinds of investigations as well. Creating and studying plasmas for the purposes of understanding the effect of nuclear detonations, for example, requires many of the same kinds of laboratory and cognitive tools needed to pursue such national goals as laser-induced nuclear fusion for generating power. That is why the Laboratory now has a massive krypton-fluoride laser system, known as the NIKE laser, which the Department of Energy supports as part of its overall laser fusion effort (with Lawrence Livermore National Laboratory serving as the flagship facility).

Another spin-off from the earlier plasma work, which Coffey has nurtured, has been the Laboratory's growing strength and visibility in the areas of nonlinear dynamics and chaos. Chaotic systems, like plasmas or the weather, are those whose behavior can unfold in dramatically different ways, yet according to definable rules and mathematically describable models.

And this has led some NRL researchers into unexpectedly promising directions. Louis Pecora, who heads the Nonlinear Effects in Materials and Structures Section in the Materials Physics Branch of NRL's Materials Science and Technology Division (within the Materials Science and Component Technology Directorate) says, "Our group is involved in studying nonlinear dynamics in materials and electronic circuits."[17]

The Cold War surely is why NRL became strong in plasma physics, which is why research like Pecora's and his colleagues' on nonlinear phenomena now are part of the Laboratory's research agenda. But the most consequential influence on NRL during Coffey's tenure so far has been the *ending* of the Cold War. "The end of the Cold War has significantly changed the strategic and tactical situation for the United States Navy," Coffey has said. And naturally that has been leading to significant changes at NRL.[18]

With the changing geopolitical realities, military strategists have shifted their focus away from Cold War simplicity—a potential global conflict with the Soviet Union—to more complicated scenarios. "Conflicts impacting U.S. national interests will now be regional in scope and location and will be waged, from a Naval perspective, in the coastal seas adjacent to points of contention . . . like the Persian Gulf and the coast of Mozambique," Coffey said in 1993 at a conference on the history of oceanography.[19]

Whereas tracking Soviet nuclear-powered submarines across the North Atlantic, North Pacific, and even under the Arctic ice mass was a mainstay responsibility of the Navy in the Cold War framework, it is far less important in the post-Cold War framework. In Coffey's words, "Navy emphasis will now be placed on command and control of coastlines and narrow seas; including amphibious assaults, aircraft strikes, mine warfare, special operations, surveillance and resupply will become common."[20] Moreover, he adds, submarine threats are now more likely to come in the form of quiet diesel-powered submarines in shallow water, rather than from the deeply submerged nuclear submarines so emblematic of the Cold War era.

With threats like these on the radar screen, Coffey has been overseeing a corresponding shift of NRL's research agenda. Although deep-ocean environments remain crucial to Naval operations, the oceanography of coastal and littoral waters now has taken on increased military significance. In these locales, fog and other consequences of air-sea interactions that effect the performance and capabilities of weapon and surveillance systems are more likely to become militarily significant. The acoustic environment of these locales differs from the deep-sea and Arctic settings the Navy had gotten used to during the Cold War. To be prepared for conflict, Coffey says, the Navy needs to thoroughly understand these and the many other differences between warfare in deep water and warfare in shallow water and coastal areas.

One of the most dramatic organizational changes that followed in the wake of the Navy's increasing need to monitor, understand, and exploit the diverse shallow water and coastal environments took place in 1992. That is when the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) with about 475 employees at sites located at Bay St. Louis in Mississippi and at Monterey, California, merged with NRL.

For many involved, including William Mosely, head of NRL's Oceanography Division located at Bay St. Louis, this was a homecoming of sorts.[21] Seventeen years earlier, many NRL ocean scientists were among those who moved from NRL's Washington, DC campus in the mid-1970s to the Mississippi facility as part of that controversial consolidation to form the Naval Ocean Research and Development Activity (NORDA). In a second wave of administrative consolidation in 1989, NORDA merged with the meteorology-based Naval Environmental Research and Prediction Facility in Monterey and several other small laboratories under the offices of the Chief of Naval Research to form NOARL. So with the NOARL-NRL merger in 1992, some scientists who had been NRL employees prior to 1975 before leaving for Stennis to become NORDA employees, returned to the NRL fold, albeit remotely from their Mississippi location.

With this new, more unified staff of ocean science researchers, NRL has begun to put together an unprecedented array of science, theory, and tools for understanding and predicting sea and weather patterns on local, regional, and global scales, according to Eric Hartwig, who had been Director of Ocean Sciences at ONR before becoming Associate Director of Research for NRL's Ocean and Atmospheric Science and Technology Directorate in 1992.

"We develop the oceanographic models and acoustic models the Navy uses for ASW [antisubmarine warfare]," Hartwig offers as an example of how his directorate's ocean science work links to Navy operations.[22] There are similar linkages for the models designed to predict ocean currents and large- and small-scale weather patterns, including those driven by the cyclic surges of warm El Niño waters in the Pacific. During the Persian Gulf conflict, Hartwig notes that researchers now under his wing delivered to the Fleet an experimental model that they hoped could predict how mines that had broken from their mooring lines would drift. That's the kind of information that can save ships and lives. "It turned out it worked," Hartwig says.

The shift from the Cold War, deep-water context to the anywhere-in-the-world shallow water and coastal context has shown up at NRL in smaller ways than the merging of NRL and NOARL. Consider what has become of the concrete cylindrical tank that used to host the core of the swimming pool reactor. Its nuclear core was decommissioned and removed long ago, but the tank in which the core had been submerged still sits inside of the cavernous Building 71. Now the tank is filled with water overlying a ten-foot layer of sand, which makes for an idealized simulation of conditions near shorelines. Researchers in the Physical Acoustics Branch are using this facility to develop acoustic methods for finding and recognizing objects, such as mines, buried in the sand.

Besides working to tailor the Laboratory's expertise to match the present and projected needs of the Navy, Coffey always has identified one of his most important roles as nurturing the coexistence of NRL's several research cultures. As he sees it, the Laboratory hosts three major

cultural components.[23] One is the direct descendant of NRL's original research culture of applied science and engineering. It began with men like A. Hoyt Taylor, Harvey Hayes, and Robert Page and continues today in many of NRL's divisions including the Radar Division, Tactical Electronic Warfare Division, and Optical Sciences Division.

It is a research culture characterized by an engineering mindset that applies what is known to make new things while maybe also revealing new science to make those things better or more capable. It is a culture resembling those at industrial research centers where investigators apply science and engineering to develop specific technologies, abilities, or products that further the interests of its corporate parent. It is a culture also that often is cloaked in secrecy; its results resemble corporate secrets whose revelation to others would spell the loss of some commercial advantage. In NRL's case, however, such a loss of advantage would likely be perceived as going beyond commerce into the realm of national security.

Since Navy decision-makers and commanders can see the link between the accomplishments of this culture—which include such technologies as radar systems, electronic countermeasures, new fouling-resistant surface coatings for naval vessels, and new secure communications links—and the Fleet itself, this is the part of the Laboratory that can most easily convince (and evidently has done so since 1923) the Navy Department's top decision-makers that NRL holds an important and worthy place in the Navy's overall R&D effort.

The second component of NRL's research culture that Coffey has been nurturing began to thrive at NRL only after WWII. Edward O. Hulburt was the original human seed of this cultural component, which first began proliferating in the Laboratory in the 1940s with researchers like the husband-and-wife crystallographers Jerome and Isabella Karle and space scientists Herbert Friedman and Richard Tousey. More akin to academia than industry, the bias of this culture is pure research, to push the bounds of knowledge. If research spawns applications for the Navy, so be it, but denizens of this culture often perceive such results as spin-offs of their work rather than drivers. Yet,

the intended product of such research—new basic knowledge about the world—is what reveals the boundaries in which technology can emerge at all.

The research of this culture generally is of a more fundamental nature. Its natural line of communication is the open, refereed scientific literature from which scientists make or break their own reputations as they tell their peers what they learned. Members of this culture are the ones who could and did earn NRL a place on the scientific map. They are the ones who have been in a position to make NRL a respected brand name capable of attracting quality scientists, who are the ones that can push the horizon of possible technologies further and further.

Coffey identifies the roots of NRL's third major research culture as going back to the Laboratory's earliest days in the 1920s when Hulburt and Taylor studied the ionosphere in order to understand the medium in which the products of the Laboratory's radio engineers had to operate. No one could have guessed at that time what would sprout from those roots—rocket science and the Space Age. It is a more secretive culture whose products help to keep NRL on the minds of the military and intelligence communities. When the National Reconnaissance Office wants a new space technology idea tested out, one place they turn to is the Naval Center for Space Technology. NCST, which formed in 1986, also established a strong link with the Strategic Defense Initiative Organization (now the Ballistic Missile Defense Organization). One standout of this linkage, the *Clementine* mission, has become an instant classic in the "smaller, faster, cheaper" paradigm sweeping the satellite engineering community.

"The research guys are the people who keep the Laboratory as a recognized player in the scientific community," Coffey says. "The Naval systems guys [like those in the Tactical Electronic Warfare Division and the Optical Sciences Division] are the ties with the real operational Navy and they are the ones the Navy sees as the reason to have NRL."[24] Both of these communities need each other, Coffey says, because the basic researchers make a scientific name for NRL and that

reputation helps bring in the applied scientists and engineers whose technology wins over the hearts of the Navy community.

The Laboratory's multiple personality harbors special challenges. For example, a significant portion of NCST's program has been supported by a single sponsor whose own short- or long-term agendas need not merge seamlessly with those of the Laboratory. "They are in their own community and are still largely a community we can't talk too much about," says Coffey.[25] At the same time, adds Peter Wilhelm, NCST's director, the Center's location within the respected NRL community has made it the space engineering facility of choice for the less visible space technology world inhabited by the military and intelligence communities.

Like any large and long-lived organization, the Laboratory has had to wrestle with aging facilities and institutional inertia as well as the larger military and governmental currents in which it must operate. With its retinue of aging and outdated facilities, maintenance is no trivial matter for the Laboratory. The situation can get critical every now and again. That happened in a big way when the roof of Building A-59, the gargantuan facility devoted to spacecraft engineering, construction, and testing showed symptoms of failure (during high winds and heavy snows) in the late 1980s about the time the Berlin Wall was crumbling. Finding money for the emergency repair was less of a concern than making sure several high-priority, classified projects could continue on schedule.[26]

The aging of NRL's physical plant has been progressing at a time when military construction (MILCON) funds have been inadequate and getting tighter. Due to special entrepreneurial skills to procure more general military funds external to the Laboratory's normal budget, some new buildings—including the beautiful Optical Sciences Division building—have gone up within the last decade or so. For the most part, however, the Laboratory has been resorting to a cheaper route—renovating existing buildings. One by one, NRL's buildings, including Building 71 (the old reactor building) and Building 30 (which now houses the Center for Biomolecular Science and Engi-

neering), have become mere shells of their former selves with entirely new and modernized interiors.

Buildings are crucial parts of an institution like NRL. But without good people working in them, the buildings don't mean much. Maintaining a healthy balance between talented new blood and experienced old blood in the research ranks has been getting tougher, Coffey says. For one thing, the overall growth in the country's science and technology communities has meant that competition for young scientists, who bring with them the new ideas and approaches needed to keep military research on the leading edges, has gotten stiffer. Partly as a result of this, the proportion of veteran researchers, whose experience and wisdom is invaluable for recognizing flaws and pitfalls (even though they are more susceptible to sticking to outdated concepts and data), has steadily increased. The problem has been exacerbated by the Federal salary caps that have made it impossible for government research centers like NRL to offer salaries to top candidates that match what the candidates can make in the private sector.[27]

There are more ominous troubles to contend with as well. Since the late 1980s, the larger tides in the Department of Defense and in the Government in general have put NRL and many other government laboratories on the defensive. Their existence is not a given anymore. Congressional demands for more direct, clear relevancy to the missions of the parent agencies, and pressures to downsize, have only been increasing with time. Moreover, money-consciousness now appears to be on a chronic upswing at a time when downsizing has become a favorite means of reducing costs.

No institution is free of both small and large problems like the ones enumerated above. Yet it seems that every generation perceives the problems of their own time as the ones that really could sink the ship. That kind of angst is present today at the Laboratory. For the foreseeable future at least, Coffey and other managers in and out of NRL believe the Laboratory is and will remain healthy. The best bet for long-term survival, they say, is to fulfill the Laboratory's directive—to do top quality research whose goal is to bring the Navy new

or improved technology, as well as a better understanding and ability to exploit the vast sea-to-space environment in which it operates. This is made explicit by the Laboratory's formal mission statement:

> *To conduct a broadly based multidisciplinary program of scientific research and advanced technological development directed toward maritime applications of new and improved materials, techniques, equipment, systems, and ocean, atmosphere, and space sciences and related technologies.*[28]

Quantifying and validating the multifaceted and often intangible value of broad-based laboratories, including NRL, has never been easy. But it is just such validations and quantifications that have become central to the way government facilities now earn the right to continue at taxpayers' expense. Coffey notes that this task becomes harrowing when measures of success used by administrators and legislators in the Pentagon or Congress involve time frames too short to accommodate the longer-term payoffs that tend to come from places like NRL, or when those measures of success depend on the tallying of something, even if that something is not necessarily a genuinely telling measure of the value NRL is supposed to produce.

Harrowing maybe, but so long as the Laboratory maintains its reputation as a quality player in the scientific community and as a supplier of innovative, advantage-supplying technology to its Naval constituency, Coffey says he expects NRL to reach more milestone anniversaries beyond the 75th anniversary that it is celebrating this year. His optimism for NRL's future derives from the corpus of consequential work the Laboratory has produced during his own nearly 30-year-long tenure at NRL. The following chapter portrays a small portion of that corpus and the consequences that have come of it.

Chapter 11

Pixels of a Very Big Picture

The continued existence that Timothy Coffey predicts for the Naval Research Laboratory, as well as the respect the Laboratory continues to command in both the military and scientific communities, are testimony to the successful shepherding work of Coffey and his predecessor in the director's chair, Alan Berman, over the past 30 years. Jack Brown, who retired from the Laboratory six years ago, has had a privileged perch from which to observe NRL's last few decades. Having attained the rank of Colonel in the Army before starting a second career at NRL, Brown rose high enough in the hierarchy to see how things work and was connected enough to know about pretty much any classified work going on at the Laboratory. He has been an active participant and diligent student of NRL's recent history.[1]

Every Thursday, Brown arrives at a quiet back room office in NRL's Ruth T. Hooker Library. He's retired, but he can't stay away. His presence and wise counsel are welcomed and solicited by Coffey and others. He started working at NRL in 1971 as Associate Superintendent of NRL's Plasma Physics Division, after having served as a program manager and Director of the Vulnerability Directorate of what then was called the Defense Nuclear Agency, or DNA (formerly the Defense Atomic Support Agency). At NRL, he eventually became an Associate Director of Research for the Support Services Directorate, which no longer exists.

For years, Brown commuted to work with his neighbor Alan Berman. During those commutes, "we solved all of the problems of the world and of NRL," Brown jokes. Even before he arrived at the Naval Research Laboratory, Brown was well acquainted with NRL. As a longtime DNA program manager, he had chosen NRL as the lead DoD laboratory for the challenging task of studying the effects of nuclear weapons at a time when it no longer was legal to conduct tests in the open atmosphere. Brown recalls that NRL was the only place he knew that could adequately assemble everything needed to study the entire problem, from the early instants of a nuclear explosion through the subsequent and evolving effects on the atmosphere and military systems.

In time, Brown has gotten to know and understand NRL as well as anyone. In his view, the quintessential meaning of NRL, and its uniquely broad research spectrum, is to preempt technological surprise on the battleground. It is on NRL's shoulders to provide leading edge naval technologies and to have scientific and technological imaginations that are a match for any real or potential adversaries. And the only way to do that, he says, is to have high quality plasma physicists, acoustics scientists, chemists, specialists in electronics and optoelectronics and optics, computer and information science aficionados, biomolecular researchers, oceanographers, experts at simulating large-scale and small-scale phenomena, materials researchers, systems engineers who can put technologies and techniques together into such things as radar systems or electronic countermeasure systems, and experts of many other stripes all in one place where they can cross the gaps between their respective specialties and integrate their expertise into technology products.

NRL's kaleidoscopic collection of scientists and engineers sum into something like an omnidirectional light that can look all around and up and down in order to see what militarily significant science and technology is on, or even beyond, the horizon. The collective purview of a narrower laboratory would be more like a search light capable of illuminating only what is in front of it.

The Laboratory's research agenda has been expanding—along with science and technology in general—since the end of World War II. With the diversity of topics proliferating so steadily, the administrative task of keeping NRL strong in those areas most likely to be important to the Navy has become more complicated. Moreover, that proliferation has transformed the Laboratory from its earlier, simpler incarnations, where it was possible to hang the Laboratory's research agenda on a comprehensible number of technical themes, into a more complex institution that no longer is simply defined.

Even so, there is at least one clue visible all over the Laboratory's campus, even on its publications and stationary, that graphically attempts to provide the big picture—NRL's four-sector rondelle. It symbolizes the Laboratory's research and development mission in a way that transcends the yearly fluctuations of its organizational charts.

The upper-left sector of the rondelle is a stylized representation of how atoms bond. It symbolizes the Navy's many-faceted relationships with the very stuff of the world from which ships, planes, munitions, radar systems, satellites and all other material things are made. It is where Nobel Prizes can, and in NRL's case, have come from.

The upper-right sector depicts Poseidon's three-pronged staff emerging from the sea. It represents the Navy's need to master the seas, and NRL's striving to provide the Navy with the god-like knowledge and, if possible, control over what lurks both upon and below the water.

The bottom-right sector of the rondelle is a depiction of Vanguard I, the first satellite NRL put into orbit on St. Patrick's Day in 1958. It represents NRL's ongoing quest to understand and exploit space for the benefit of the Navy. That first satellite embodied the engineer's spirit in that it took practical prob-

lem-solving to build it and get it into orbit. It also embodied the scientists' spirit in that it provided a new perch from which to observe the Earth and the cosmos. It represents a well-funded, truly awesome, and often highly classified, component of the Laboratory's R&D personality.

Finally, the rondelle's bottom-left sector—a stylized trace of an oscilloscope—represents the multifarious electromagnetic and other more or less obvious physical phenomena on which so much of the Navy's communications, command, control, and intelligence are based and by which the Navy senses both natural and humanly constructed environments.

Together, the four sectors of the rondelle graphically state that NRL's purview extends from the ocean bottom to outer space and throughout the visible and invisible realms of the world. That all encompassing mission encapsulates how NRL has continued along its now 75 year quest to provide the foundations of knowledge and technology from which come the million-and-one technical details comprising a leading-edge Navy.

Every big picture is made up of parts, just as a TV image is composed of thousands of picture elements, or pixels. Indeed, each sector of NRL's rondelle is itself such a big picture within the overall NRL portrait. What follows are accounts of *only a few of those thousands and thousands of pixels of the Laboratory's expanding research portfolio* during the directorships of Alan Berman and Timothy Coffey.

Unlike earlier chapters of the Laboratory's story, the more contemporary phase of the Laboratory is harder to tell with neat linearity or any kind of defensible simplification. Only as history unfolds will we know with any certainty which of the myriad recently completed or still ongoing projects will end up having dramatic and historically important consequences, which are destined for obscurity, and which will fall between those extremes. Thickening the fog is that many of NRL's important research accomplishments over the past few decades remain secret, which itself is a sign—although surely not proof—that the nation considers the work actively or potentially important.

Despite those disclaimers, there already are a few clear standouts from NRL's contemporary era. One of them is the awarding of the 1985 Nobel Prize in Chemistry to Jerome Karle and Herbert Hauptman for their work in X-ray crystallography. How can it but stand out like a neon sign to the correctness of the Laboratory's post-WWII decision to nurture basic science along with applied science and engineering? The Laboratory's role in the early design and evolution of the Global Positioning System is another clear standout that has brought much praise and prestige to the Laboratory. So has the Laboratory's more recent *tour de force* in the Ballistic Missile Defense Organization's *Clementine* mission, which flew only in 1992, yet became an instant classic in the annals of satellite technology.

But like the talents of child prodigies, those are unusual standouts. The consequences and value of the vast preponderance of work at NRL during the last few decades remains unknown. The following pixels of this work suggest at least part of the big way the Laboratory recently has been striving to fulfill Jack Brown's view of NRL's mission—to preempt technological surprise by discovering what is possible in the first place.

Biotechnological Pixels

In 1967, Joel Schnur, a graduate student at Georgetown University, came to NRL to interview for a summer job with Herbert Rabin and several colleagues of the Quantum Optics Branch.[2] Impressed by Schnur's impromptu seminar on liquid crystals (liquids whose constituent molecules align with one another in a more regimented, crystal-like fashion instead of in a random, fluid jumble and have become important in display technologies such as computer monitors), Rabin hired him.

That was just the beginning. Schnur later landed a post-doctoral position at NRL initially via a program run by the National Research Council that Alan Berman liked because it furthered his long-term administrative aim of bringing top-notch candidates to the Laboratory. In 1973, the Optical Science Division hired Schnur to work full-

time. That's about when the seemingly endless possibilities available through NRL's diverse research portfolio began to inspire Schnur and thereby influence the Laboratory's recent history.

Schnur quickly discovered connections between his liquid crystal work and the work of others at NRL, such as chemist Bill Zisman, a well-known and often-cited expert (Nobel-caliber to some including Joel Schnur) on the molecular structure of surfaces. He also saw connections with the work of researchers such as Jerome Karle, then still a future-Nobel laureate whose work centered on more standard solid crystals. A laser-based laboratory technique Schnur had mastered for his liquid crystal studies led him into an area of unambiguous military interest—energetic materials, a.k.a. explosives and propellants. Using ultrafast laser pulses as optical probes that could take snapshots of extremely fast chemical events, Schnur and colleagues were able to tease out some of the chemical and physical details that sum into a chemical detonation.

By then, Schnur was hungering for ways to use the fundamentals of science for technological development. In 1983, Al Schindler, then Associate Director of Research, gave him the opportunity. Schindler was following up on a directive from Director of Research Timothy Coffey, who could see that the field of biotechnology was taking off and that NRL ought to get its feet wet before the wave of opportunity had passed.

Even though Schnur was in the Optical Sciences Division, Schindler suggested that he run the new initiative. After all, there was a natural connection between Schnur's expertise in liquid crystals (cell membranes, which are important model systems in the biotechnology arena, are composed largely of molecules that arrange into none other than spherical liquid crystals) and the new biotechnology initiative Coffey had in mind. Coffey subsequently added force to Schindler's suggestion by himself inviting Schnur to take on the challenge.

"I was convinced there would be new science coming out of this biomolecular approach," Schnur recalls thinking. "It was engineering

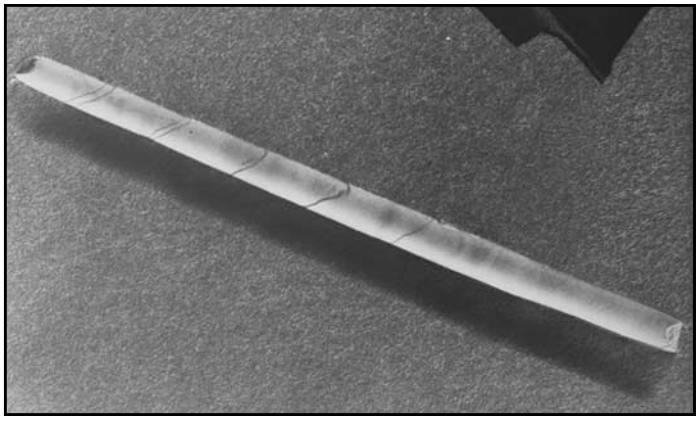
molecules using biology as a role model, making molecules, learning how they assemble and looking for functions for advanced materials."[3]

The timing was right for other reasons. Congress, the Office of Naval Research, and DARPA (Defense Advanced Research Projects Agency)—in short, almost everybody with research money to distribute—saw gold in the realm of biotechnology. While at the time most were thinking along the lines of genetic engineering, Schnur was looking more broadly at molecular design, which made more immediate sense for the Navy. Not only was funding available for biotechnology, Schnur was good at convincing potential research sponsors to put their signatures on paper.

It was neither easy nor particularly smooth, but Schnur and five others from the Optical Sciences Division made the move to the Chemistry Division in 1983 to spearhead the new initiative embodied by the Center for Biomolecular Science and Engineering. They brought with them a half-million dollars of NRL money signed over by Coffey with nods from his in-house advisors, and $1 million from DARPA. In its 15 years of existence, the center has expanded dramatically and now occupies its own renovated building on the Laboratory's main mall.

Schnur recalls that one of the center's most fruitful projects began even before the center existed during a tennis match he had with Tom Walsh, who was head of Electronics at the Air Force Office of Scientific Research. "If only you had long thin objects that were conducting they would be the world's best radar absorbing material," Schnur recalls Walsh saying.[4] Schnur soon convinced himself and colleagues (and Walsh) that the task could be done using lipids, which are long, oily molecules he had become extremely familiar with during all of his liquid crystal research.

Schnur's coworkers in the Optical Sciences Division, Paul Shoen and Paul Yager, opened the door to a solution when they found a way to get lipid-based molecules to arrange themselves into the kind of



This electron micrograph of a lipid tubule is 0.5 microns in diameter and 30 microns long. It is longer than the diameter of a typical human hair.

microscopic cylindrical structures—now called microtubules—Walsh had in mind. The research team led by Schnur suspected that these biomolecular structures, which could serve as temporary skeletons for more permanent coating materials, could lead to more than just radar absorbing materials. They began to envision new more environmentally sound antifouling coatings for naval vessels, new drug delivery systems, and other specialty items based on filling the tiny tubes with different things. So just as Coffey was putting administrative commitment behind the Laboratory's foray into biomolecular engineering by setting up Schnur and his cadre of biomolecular scientists in the Chemistry Division, DARPA came through as a big, patient sponsor.

The tubule research soon worked in synergy with projects of other team members. Bruce Gaber, for one, joined the group in 1977 and brought with him another biomolecular project. The audacious goal of the project was to develop artificial blood using encapsulated hemoglobin molecules inside of liposomes, or little spheres made of lipid-based molecules. Hemoglobin is the oxygen-ferrying protein inside of red blood cells and a liposome is much like a cell membrane. So liposome encapsulated hemogloblin (LEH) resembles blood

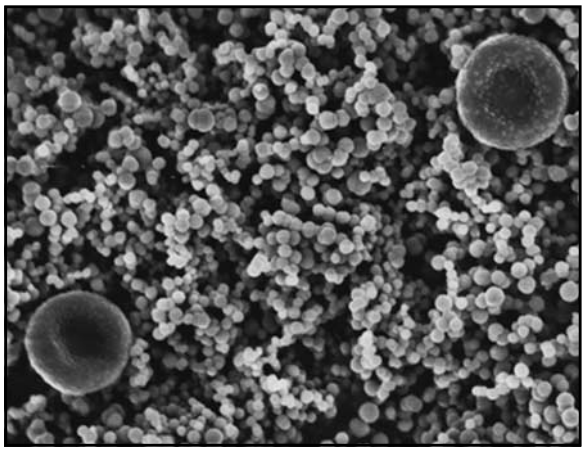
cells in form and function. Along with Gaber, Martha Farmer and Alan Rudolph have been major players in this work.

Frances Ligler would bring another important research capability into the group—developing new sensors for biological and chemical warfare agents and other toxic agents. Her tack was to use exquisitely sensitive and capable biological molecules such as antibodies, which are a kind of protein specialized for recognizing and binding to specific chemical structures such as toxins. By coating these onto optical fibers that could detect when binding had occurred, she and her colleagues have developed a basis for new generations of chemical and biological sensors.

The Center for Biomolecular Science and Engineering grew rapidly from five people in 1983 to 40 by 1986. And by then its budget had grown to $3 million with nothing but more growth in sight. In 1989, the Laboratory committed money to renovate Building 30 along the main mall into a modern facility into which the burgeoning center with its increasing cache of equipment could all move together. By 1994, the building was ready for its new occupants. The roster now includes about 80 full-time staff, which grows by about 50% in the summer with an influx of visiting scientists and undergraduate summer students.

Even a truncated list of the Center's active research topics belies the huge new swaths of science and technology NRL now has within its fence in the dual goals of preempting technological surprise while helping the Navy do more.[5] Lipids are the starting point for new combat care technologies, among them resuscitative fluid (artificial blood) and cryopreservation techniques for increasing the shelf-life of artificial and natural blood supplies. Another of the center's research thrusts centers on how liquid crystals and other organized molecular systems might lead to, among other things, next-generation recording and display technologies.

The center's researchers also are looking into how tubules and other structures made using biomolecules can lead to new ways of



This scanning electron micrograph shows a large population of liposome encapsulated homoglobin (LEH) particles amidst a couple of much larger human red blood cells.

monitoring environmental quality, defending against biological warfare agents, and thwarting marine organisms from fouling naval surfaces such as hulls. Controlling the delivery of medicine, countering mines, making new generations of integrated circuitry, and assembling nanoscale devices (that are measured on the billionth-of-a-meter scale) for uses such as new sensing elements and even for directing the growth of inorganic crystals for electro-optic signal processing, are all on the Center's radar screen. As such, the center hosts a large array of research pixels that together foreshadow some of the ways biotechnology will become part of the Navy's operations.

Hair-Thin, Glassy Pixels

Another set of striking pixels of NRL's big picture emerged from an interaction among researchers in the Optical Sciences Division and the Acoustic Division. The question both groups were asking independently at first was this: what good might optical fibers be for the Navy?[6]

As did many other scientific organizations, NRL first began seriously looking at optical fibers in the early 1970s when glass researchers at Corning Glass Works in upstate New York invented a way to make optical fibers through which light could travel clearly and cleanly for miles rather than the few feet that had been the limit.

In 1976, NRL acoustics scientists, including Joseph Bucaro, C.M. (Mickey) Davis and visiting professor Edward Carome from John Carroll University (University Heights, Ohio), were looking into using optical fibers as sensors of acoustic energy in fluids such as the ocean. For Bucaro and Carome, who was Bucaro's professor a decade earlier when Bucaro was a student at John Carroll University, it was a reasonable pursuit since they knew the pressure waves associated with underwater sound could subtly yet detectably affect the way light traveled down the fibers. In time, they realized they could modify optical sensors with various coatings and in other ways that transformed them into sensors of such phenomena as temperature, electrical fields, and mechanical strain.

Scientists in the Optical Physics Branch, including Tom Giallorenzi, were approaching optical fibers from another angle. "We started working on all components needed for airborne and shipboard [communications] applications" of optical fibers, Giallorenzi recalls.[7] One of the earliest problems he and his colleagues faced was the way even subtle vibrations, of which there was no shortage on planes and ships, could interfere with light, especially as it passed through a coupling from one fiber and into another. These early optical fiber components could even detect voice-induced vibrations. Since acoustics and vibrations are so closely related, it was practically destined that these two groups would themselves couple into an interdisciplinary fiber optics program. It's just the sort of synergy that Brown identifies as one of NRL's most crucial characteristics.

By early 1977, Bucaro says he and Carome successfully demonstrated the first "interferometric fiber optic external field sensor," which is to say, an optical hydrophone. Bucaro believes this was the catalyst that led to the first DoD program in fiber optic sensors. In September, excited by this and further laboratory successes, Davis, Bucaro, and Burton Hurdle (the Division's ocean acoustics guru) went to DARPA seeking support to develop ocean applications for what had been demonstrated in Bucaro's laboratory. As Bucaro recalls it, their DARPA

contact, Captain Harry Winsor, encouraged the NRL researchers to "find a good program manager" and come back with a unified program. By early November, they did just that. Jack Donovan, a hydrophone systems manager just leaving the Naval Materiel Command, was recruited as Program Manager. Davis joined Giallorenzi's group to integrate the work of their respective branches, and together they all convinced one another that optical fibers had to be part of the Navy's future.

With that in mind, the extended group composed a unified proposal to DARPA to develop fiber optic sensor technology that they would demonstrate in the form of a towed acoustic array. DARPA liked what it saw and its subsequent funding gave birth to the Fiber Optic Sensor System (FOSS) program. (According to Mickey Davis, it was no mere coincidence that the project's acronym FOSS, resembled the name of Dr. Fossum, DARPA's new director at the time.) Other funding agencies including the Office of Naval Research and the Naval Materiel Command also supported the project.[8]

The first project—a towable submarine detection system made with a fiber optic-based array of acoustic sensors—married the strengths of the two participating divisions quite naturally. "The Acoustics Division did the acoustic part and Optical Sciences did the optical part and together we were the first to do an at-sea demonstration of fiber optics in a towed array," Giallorenzi noted.[9] One of the most impressive early results came in the guise of a failure. During the first attempt to take the towed assembly into the water, the water pressure broke through the assembly's protective rubber dome and all of the electronics and optical fiber components became flooded. "We dried it out and tried it again and it worked perfectly," Giallorenzi recalls. "Under these conditions of failure, [the Navy observers who would actually make the decision to use such equipment] had never had a sensor that wasn't destroyed."[10]

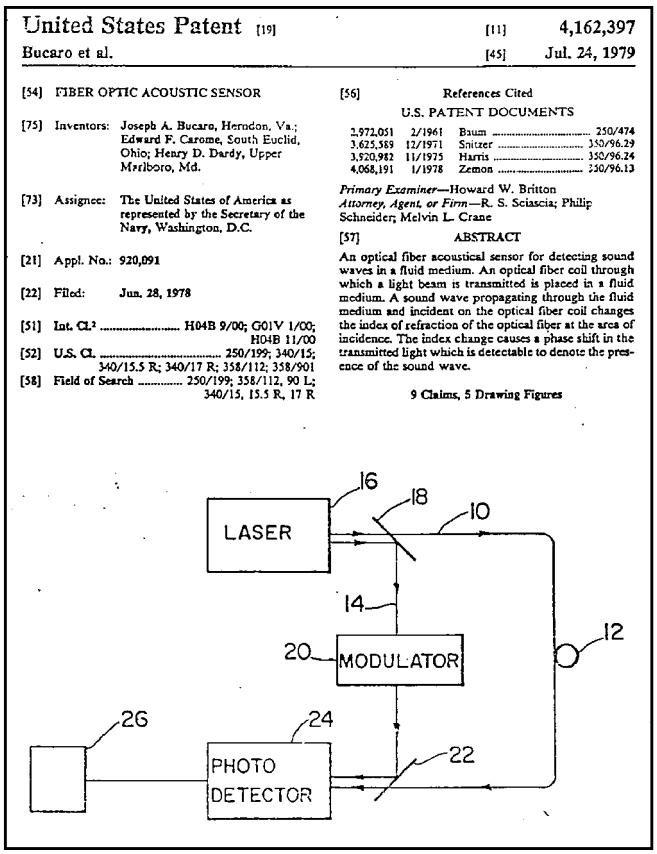
The crux of these optical arrays was an acoustic sensor that worked according to the century-old concept of interferometry, or the mea-

surement of the way two sources of light interfere with one another. The principle here was to mix the light from a reference optical fiber that was shielded from underwater sound with that light traveling in a second fiber "listening" in the water. The result is a characteristic interference pattern that light detectors can monitor. If the second fiber "hears" something, its light changes and that, in turn, alters the interference pattern its light forms with the light of the reference fiber. The changes that are detectable are exquisitely minute; even tiny sounds will affect the interference pattern. That makes for a very sensitive underwater listening device indeed. Bucaro claims that NRL has the first (U.S. Patent 4,162,397) patent for such a device based on work that he and colleagues in the Physical Acoustics Branch had done before the FOSS program got underway.[11]

Besides the fibers, this interferometric system required the development of other components, including couplers and light detectors. The work led to dozens of patents for both the acoustics and optics scientists. The first at-sea tests in the late 1970s and early 1980s of a towed array of fiber-optic-based acoustic sensors included plenty of electronic components as well as optical ones. The reason for this was that the light signals intermittently had to be converted into electronic signals and then back again into light. Though necessary at the time, all of these conversions degraded the quality of the signals and the overall capabilities of the system.

To circumvent this limitation, Giallorenzi and his colleagues began selling the idea of the next-generation towed array. This one would be almost entirely optical—no light-to-electron transitions, except at the end when people, computers, or both would need to make sense of the signals. "Through a good part of the 1980s, we did various phases of development on that array and, in about 1990, it was chosen to be the replacement array for the Navy," Giallorenzi says.[12]

Many of the Navy's surface ships would have been equipped with the NRL-developed "all-optical towed array" by now had the geopolitical situation not changed so drastically just as the technology de-



United States Patent [19]

Bucaro et al.

[11] 4,162,397

[45] Jul. 24, 1979

[54] FIBER OPTIC ACOUSTIC SENSOR

[75] Inventors: Joseph A. Bucaro, Herndon, Va.; Edward F. Carome, South Euclid, Ohio; Henry D. Dardy, Upper Marlboro, Md.

[73] Assignee: The United States of America as represented by the Secretary of the Navy, Washington, D.C.

[21] Appl. No.: 920,091

[22] Filed: Jun. 28, 1978

[51] Int. Cl.[2] H04B 9/00; G01V 1/00; H04B 11/00

[52] U.S. Cl. ..... 250/199; 340/15; 340/15.5 R; 340/17 R; 358/112; 358/901

[58] Field of Search ..... 250/199; 358/112, 90 L; 340/15, 15.5 R, 17 R

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Primary Examiner—Howard W. Britton
Attorney, Agent, or Firm—R. S. Sciascia; Philip Schneider; Melvin L. Crane

[57] ABSTRACT

An optical fiber acoustical sensor for detecting sound waves in a fluid medium. An optical fiber coil through which a light beam is transmitted is placed in a fluid medium. A sound wave propagating through the fluid medium and incident on the optical fiber coil changes the index of refraction of the optical fiber at the area of incidence. The index change causes a phase shift in the transmitted light which is detectable to denote the presence of the sound wave.

9 Claims, 5 Drawing Figures

Early patent for fiber-optic-based sensors invented by NRL researchers

velopment was coming to completion. The end of the Cold War and the fall of Communism beginning in 1989 changed everything, including the perceived need for a new generation of towed arrays for surface ships.

The technology has not languished, however. Instead, it is slated to become a major component of the latest generation of nuclear submarines—the 688 class. "When they put Tomahawk missiles on these submarines, they didn't retain sufficient reserve buoyancy to permit these boats to carry the 42-ton [wide aperture] acoustic array originally specified for the 688s," Giallorenzi says. "They asked us if the fiber array could be lighter," Giallorenzi recalls.[13]

Yes was the answer. "It basically was taking the towed array technology and putting it on the side of submarine," Giallorenzi says. At 18 tons, the system shaved 24 tons off of the new submarine's design. The Optical Sciences Division developed yet another incarnation of the all-optical towed array technology. This one is in the form of a rapidly deployable bottom-mounted device whose significantly smaller size and reduced power needs lead to an extremely powerful underwater listening system that can be quickly and readily deployed almost anywhere. Some of the first tests of this version of the work that began in the late 1970s took place in May 1996 off the coast of San Diego.

As Bucaro, Davis, Giallorenzi, and others intuited more than 20 years ago, optical fibers have become useful components of Navy surveillance systems, communications networks, navigational instruments like gyros, and electronic warfare systems.

Optical fibers also have become important tools for research. For example, researchers in the Physical Acoustics Branch, which Bucaro heads, are using them to investigate the acoustic properties of new, stealthier submarine designs. And Fran Ligler's group in the Center for Biomolecular Science and Engineering is investigating their potential use as sensors for biological and chemical warfare agents.

Superconducting Pixels

There are scores of important pixels that have to do with the materials of which the Navy's high and low technologies are made. Superconductive materials—or substances through which electricity passes resistance-free and therefore with 100% efficiency—constitute one of them. These remarkable materials had largely fallen in the exotica bin ever since a Dutch physicist discovered the phenomenon in mercury in 1911. Nonetheless, NRL had had a small effort in superconductivity going on for years when Donald Gubser, now head of the Materials Science and Technology Division, joined the staff in 1969 straight out of graduate school.[14]

At the time, superconductivity was one of those areas more promising to physicists than to anyone who might have wanted to develop practical superconductor-based technologies for the Navy. Until about 12 years ago, all known superconductors would only work at temperatures rivaling winter on Pluto. Yet if researchers could develop more convenient superconductors that operated at warmer temperatures, the payoffs to the Navy and across the board could be huge in the form of more efficient and powerful motors, magnets, propulsion and transportation systems, or even computers.

In his early years at NRL, Gubser built a unique experimental chamber in which he simultaneously could cool new candidate superconducting materials while pressing them at great pressures within a diamond-jawed anvil that can squeeze objects more strongly than any other tool. It was the type of study that could help reveal just what made these mysterious materials tick so that maybe people could start systematically inventing better ones. "For awhile, we had the world's only instrument that could really go to those pressures at those temperatures," Gubser recalled.[15] He and colleagues, including Stuart Wolf, now head of the Materials Physics Branch, began making names for themselves by their publications and by running conferences.

Gubser recalls getting requests from the Chief of Naval Research to check out various claims (both within and outside of the Navy) about breakthroughs—such as new superconductors that would work at much higher temperatures. The claims invariably turned out to be false or overblown, he says.

Then, in the middle of December, 1986, the arcane world of superconductivity research ignited into a wildfire. The flame reached NRL via a meeting at the Naval Post Graduate School in Monterey where a colleague of Gubser's showed him a preprint of a paper by Japanese researchers that convincingly demonstrated a new superconductor that worked at the record temperature of 30 degrees above absolute zero (30 K or -436° F). "Right there at that point, my life changed," recalls Gubser.[16]

The Japanese paper was a confirmation of work by two researchers in Switzerland who months earlier had quietly reported the first examples of a new class of ceramic superconductors that shed their resistance to electrical currents at record high temperatures. A few days before Christmas, Gubser and Wolf decided, in Gubser's words, "to stop every bit of research we were doing" and focus entirely on the new, so-called, high transition-temperature superconductors (HTSC).[17]

Gubser and Wolf were lucky to have been at NRL. Although they knew their superconductivity physics, they didn't know much about making ceramics. But they were able to make up for their own limitations by drawing upon the experience of NRL's materials researchers. Within days, Gubser, Wolf, and a pair of post-docs were grinding ingredients, mixing the resulting powders, and then sintering the mix into wafers ready for testing. Whenever they made a new material, they could draw on their years of experience to determine what in fact they had made.

The little nucleus of NRL scientists that had begun working on the instantly famous field of high-temperature superconductivity were joined by hundreds, then thousands, of scientists around the world. There was no hotter topic in science in 1987 than superconductivity. Tim Coffey appointed Gubser to oversee the expanding NRL effort and Gubser and his close colleagues found their own profile within the Navy on the rise. When the Chief of Naval Research wanted to find out why the scientific community was going so bonkers and what the Navy was doing about it, Gubser and Wolf were the ones he sought out.

It only took a few years before researchers began to realize that these very exciting materials, some of which remained superconductive at temperatures above 130 K (-336° F), also would prove exceedingly difficult to convert into practical forms. Ceramics, after all, are like rocks. They are brittle and hard to form into the kinds of useful shapes, like wires, that you might want for electrical systems or for windings to make motors. The task shifted from merely finding new

materials to developing some way of coercing these ceramics to behave more like metals when it came to their mechanical properties and to manufacturability.

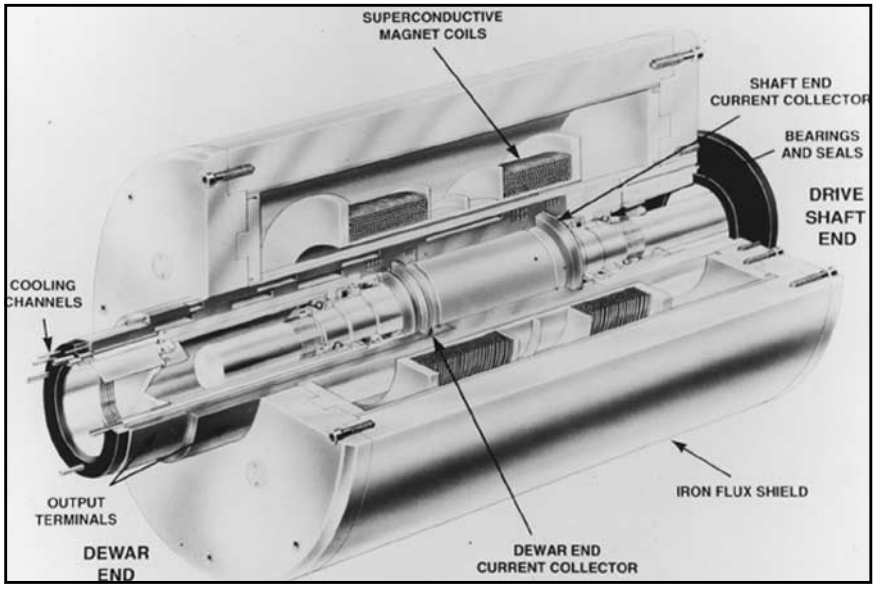
Gubser recalls that he had to walk a fine line between optimism and realism. He felt it was his responsibility to point out to sponsors and Navy leadership in and beyond NRL that these new superconductors had their difficulties and did not constitute a clear ticket for things like faster ships. Yet if he went too far with that kind of reality-checking, funding for the work could disappear. A lot of the early funding came from the Strategic Defense Initiative. Gubser recalls the first and very remarkable meeting SDI officials asked him to attend. "I walked right in and they said we are going to give Don Gubser there from the Navy a budget of five million dollars to do research this year and then we're going to increase it to ten million the following year, and then up to 30 and 40 . . . " The Defense Advanced Research Projects Agency also became a sponsor of NRL's superconductivity work.[18]

The funding never did ratchet upward as dramatically as the SDI officials had suggested, but enough money did flow to get NRL's superconductivity research effort onto a steady, secure basis, which is just what Gubser knew would be needed. In the years since the initial breakthroughs of the mid-1980s, Gubser says NRL has honed its strength in those areas that will give it a good footing for the long haul that will be necessary before new classes of high-temperature superconductors become routine components of the operational Navy. "Our strongest effort is in the fundamentals, understanding the mechanism (of superconductivity), and understanding the fundamental properties of the materials," Gubser says.[19]

Which is not to say NRL has been ignoring the potential applications of these new materials. Not by a long shot. High on the wish-list of applications for the superconductors from the beginning has been new electric propulsion for ships. And a collaborative project with the Naval Surface Warfare Center's Annapolis branch to replace the

superconducting magnets of a motor originally designed using conventional, low-temperature superconductors with magnets made out of the high-temperature superconductor bismuth-strontium-calcium-copper-oxide just recently resulted in the world's highest power superconducting motor ever made with high-temperature superconductors. The motor produced 320 horsepower of shaft power when chilled with liquid helium at 4.2 K and 104 hp when chilled with the less expensive and technically easier to use liquid nitrogen at 77 K. The superconducting wires and coils were made by an industrial partner in the project, American Superconductor, to the specifications of the NRL and NSWC scientists.[20]

The new motor is just one step toward the 20,000 hp motors that submarines need. Still, the advance is clear evidence that the kind of patient work NRL and its collaborators are undertaking could ultimately yield some of the payoff touted by visionaries more than a decade ago. Besides new electric propulsion systems, Gubser and his colleagues hope their work in superconductivity eventually will ap-



Experimental high-temperature superconducting motor developed by NRL in collaboration with the Naval Surface Warfare Center

ply to other technologies important for mine sweeping, energy storage, communications, and radar.

Even if none of NRL's work in high-temperature superconductors were to yield applications soon, however, Gubser and the dozens of other NRL researchers who have kept NRL in the superconductivity game have been doing the job that Jack Brown and others agree is crucial—making sure that the Navy has a very good idea about what high temperature superconductivity really might be able to do if and when it's ready for prime time.

Pixels of Fire

Superconductivity is a pixel of NRL's recent research portfolio that thrives at frigid, cryogenic temperatures. Fire, on the other hand, is a high-temperature phenomenon that is dreaded by a floating Navy, and is the focus of another important pixel of NRL's big research picture. The Laboratory's present research program on fire suppression stems from NRL's earliest days when the originals in the Chemistry Division were tasked with finding out how to reduce fires caused by storage batteries on submarines.

Homer Carhart is a senior scientist emeritus in NRL Chemistry's Division and the Navy's guru on fire suppression. He has 56 years of research and experience behind him (see Chapters 6 and 9) and succinctly states the general problem for a Navy full of ships: "Ships are floating arsenals which are densely packed with explosives, large volumes of fuel and other combustibles, and many men, who—in case of fire, have no place to run."[21]

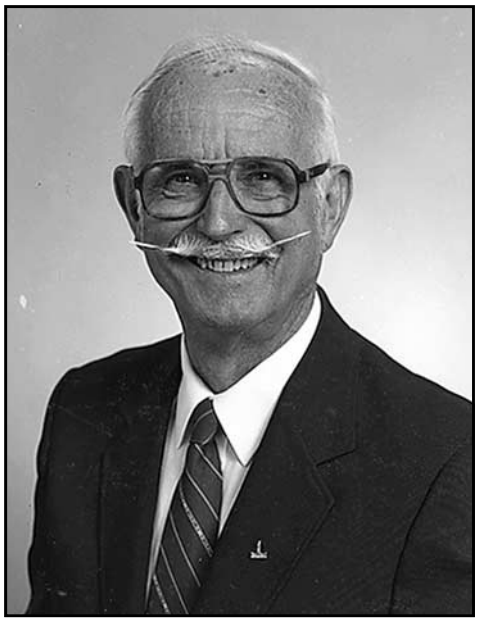
One of the Laboratory's early successes in fire suppression, which Carhart describes from first-hand memory, came out of work done during WWII. That's when Dick Tuve and co-workers developed the "bean soup" fire suppression system. It consisted of a protein-rich concentrate prepared from such ingredients as feathers, fish scales, and soybean residue that was mixed with water and then sent through a special nozzle that aerated the mixture. The result: thick foam that

can blanket and snuff out burning fuel. After the war, NRL researchers and industry collaborators developed a new, more chemically sophisticated version of the "bean soup" known as Aqueous Film Forming Foam (AFFF). In response to the disastrous fires on the USS *Forrestal* and USS *Enterprise* in the 1960s and 1970s, NRL developed and helped the Naval Sea Systems Command (NAVSEA) adapt the AFFF system to flow through a ship's sprinkler nozzles—whose original intention was for protection against nuclear, biological, and chemical weapons—and quench flight deck fires.[22]

The concept was implemented quickly by the Navy and then by other sectors of society. "AFFF systems are now used throughout the world," Carhart says. Purple-K-Powder, or PKP, is another NRL-developed fire suppression system—this one a dry chemical that helps to reduce the fire's heat output and therefore slow down its spread—that has found worldwide use.[23] And, Carhart notes, all major airports have AFFF systems on hand for emergencies.

The more contemporary phase of NRL's fire suppression innovations has been accomplished with a variety of testing facilities that can bridge the crucial gaps between theory, laboratory tests, and real fires. "We are still too ignorant of fire behavior to be able to extrapolate directly from the laboratory bench to the real world," Carhart warns.[24] One test facility at NRL's Chesapeake Bay Detachment, called

A helicopter applies NRL-developed "light water" to suppress an aircraft fire.



Homer Carhart with his unmistakable handlebar mustache

Fire I, is a pressurized chamber specially suited for investigating fire risks and evaluating new firefighting protocols for the submarine fleet. And since its dedication in 1987, the 457-foot, 9,000-ton ex-USS *Shadwell*, which is moored at the U.S. Coast Guard's Fire and Safety Detachment in Mobile, Alabama, has provided NRL and the Navy with a full-scale floating test bed. (The WWII-era ship was named after the house near Charlottesville, Virginia, in which Thomas Jefferson was born in 1743. The house was destroyed by fire in 1770).[25]

Everything about a ship that is important when it comes to damage control is maintained on the *Shadwell*—ventilation, heating and air conditioning, electrical systems, lighting, internal communications. The lessons learned from tests on the *Shadwell* regularly become important parts of the operational Navy in the form of damage control equipment, materials specifications (so that materials like fuels and insulation can be chosen to minimize fire-based risks) and in firefighting and damage control documentation and training.

Success in the fire suppression research and development business comes in the form of fires that don't start, or in Carhart's words

"the nonfire"; fires that don't get out of hand; or fires that get out of hand later than they would have without the additional, research-derived knowledge. "The more successful we are, the less we have to show for it," Carhart says. "You can't document a disaster that doesn't happen."[26]

Solar Pixels

Fire has everything to do with another pixel of NRL's research portfolio—solar physics. Like fire research, its roots extend to the Laboratory's earliest years when the likes of Taylor and Hulburt were learning about the way the Sun interacts and molds the ionosphere, a start that Friedman, Tousey, and their colleagues would later build upon as soon as they could put solar radiation measuring instruments on rockets in the 1940s. The tradition of making ever better and more revealing measurements of solar activity has never been broken.

One of NRL's most consequential modern-day extensions of this tradition in solar physics is in the form of the Large Angle and Spectrometric Coronograph (LASCO). NRL built LASCO in collaboration with groups from England, France, and Germany. The instrument's three corona-viewing telescopes have been aboard the orbiting Solar Heliospheric Observatory (SOHO), which NASA and the European Space Agency jointly launched on December 2, 1995.[27]

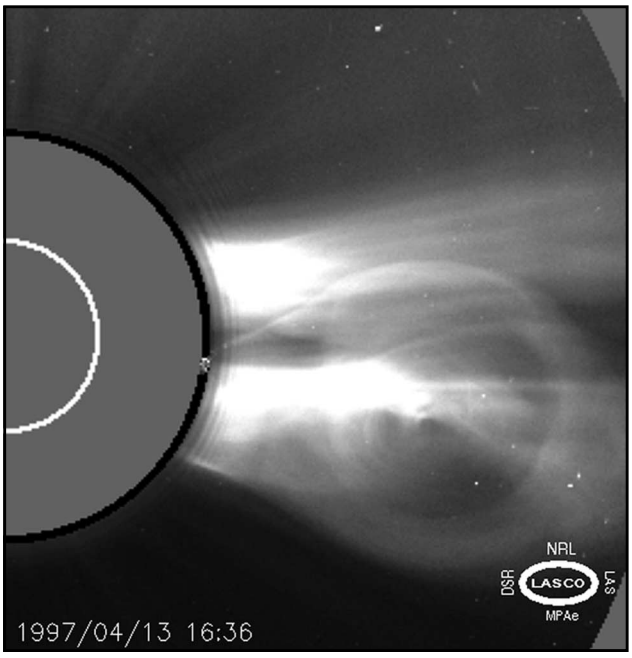
Since it began sending back data in 1996, LASCO has been continuously revealing new details about the turbulent and dramatic conditions in the Sun's corona, which begins above the star's seething, fiery surface and extends outward from there. The instrument relies on a special occulting disc that creates a permanent artificial eclipse so far as the instrument's detectors are concerned. That way, the Sun's more intense emissions cannot swamp out weaker signals emanating from the corona.

The magazine *Aviation Week and Space Technology* described one category of the discoveries being made with LASCO in their May 6, 1996 cover feature.[28] The article included a series of four LASCO im-

ages taken over a period of 8 hours during which millions of tons of solar material were ejected from the Sun's equatorial surface at a speed of 341 miles per second. By the end of the sequence, the ejected material had traveled 10 million miles, or about one-ninth the distance from the Sun to the Earth. "To almost everyone's astonishment, LASCO found equatorial ejections emitted within hours of each other from opposite sides of the Sun," wrote Tufts University astronomer Kenneth Lang in the March, 1997 *Scientific American*.[29] That such concerted action occurs on such a vast scale is startling and not yet understood.

Guenter Brueckner, head of NRL's Solar Physics Branch and the Laboratory's focal point on the LASCO project, says that the LASCO data is leading to ways of predicting when coronal mass ejections (CME) like these occur and what effects they will have on and near Earth. "In the days preceding such an event, multiple magnetic loops appear on our SOHO images of the inner corona. They tell us the Sun is reorganizing its magnetic field," Brueckner says.[30] He and other researchers surmise that this reorganization, which has the effect of concentrating material along certain magnetic "streamer belts" in the Sun, destabilizes the solar atmosphere until these belts blow open to form the massive ejections.

All of this basic solar physics is relevant to Navy concerns. After all, ejected coronal material constitutes the solar wind. And researchers have known for decades that the solar wind affects communications and electrical systems on and near Earth as well as aboard spacecraft. But until LASCO, Brueckner says, "no one had actually seen the solar wind at the Sun."[30] Since human audacity has yet to reach the point where controlling solar activity such as coronal mass ejections is on the table, predicting and understanding them with tools like LASCO remains the goal. "We have made a lot of progress in understanding how CME's evolve, where they come from, how they interact with the Earth, and that has enabled us to come up with reliable forecasting of large geomagnetic storms," Brueckner says.[32]



LASCO image showing coronal mass ejection (CME) of April 13, 1997

LASCO images also reveal what is happening deep within the Sun's interior. One image taken on August 21, 1996, for example, shows a luminous helical string of material stretching in a northwesterly direction (with respect to the observing instrument) as though it were a spring that someone had pulled outward. The magnetic forces generating this coronal structure begin in convective motions inside of the Sun that get swept to the Sun's surface. There, this swirling convective energy gets vented outward, leading to the formation of helical filaments. It's all just the latest installment in NRL's perpetual study of the Sun and its effects on the Earth and Naval operations.

Chaotic Pixels

Gargantuan events such as the coronal mass ejections NRL's LASCO team is investigating, as well as the more terrestrial challenge of understanding fires, are exercises in understanding chaotic situations. A relatively new pixel of NRL research focuses on a burgeoning and still unproved field of science often known for short as chaos. Chaos in

this context does not refer to happenings seemingly devoid of rhyme or reason. On the contrary, it refers to complex and hard-to-quantify phenomena whose specific behavior nonetheless is definable with mathematical clarity.

Chaos scientists investigate a huge range of seemingly disparate phenomena, from the electronic fluctuations within circuitry to changing animal populations and from heart rhythms to weather patterns. Though different in physical and material circumstances, the behavior, or dynamics, of such phenomena often unfolds according to similar, often mathematically definable rules. So many phenomena once thought to be too complex to predict indeed may be predictable, even controllable, as Louis Pecora and his colleagues have been proving.

Pecora, who came to NRL in 1977 to work as a post-doctoral associate in the Materials Physics Branch, has become a well-known part of the chaos research community in the decade since he entered it.[33] He started out as a materials scientist using a rather arcane technique involving positrons (the antiparticle of electrons) for probing the internal microstructures of materials. But by the mid-1980s, Pecora had become smitten with the field of nonlinear dynamics, which subsumes the science of chaos. Timothy Coffey was also convinced that it would be a good idea for the Laboratory to develop its own expertise in the field. So in the mid-1980s, Pecora, along with Thomas Carroll, who Pecora hired as a post-doc, were on their way into new territory.

They started off by investigating a magnetic material, yttrium iron garnet (YIG), which the Navy had used for many years in radar and other systems because it automatically stops an electromagnetic signal, such as an enemy's antiradar jamming signal, from entering and blowing out sensitive electrical equipment if that signal's power exceeds a safe range. That kind of sudden cut-off behavior places this magnetic material squarely within the realm of nonlinear dynamics.

The NRL group's concern was to try and better characterize the material's behavior right near its normal cut-off limit, which in fact

displayed erratic tendencies, sometimes cutting off at higher powers, sometimes at lower ones. Pecora's and Carroll's colleague, Fred Rachford, suggested that the group look especially carefully at the material at power levels approaching those at which the material's behavior becomes erratic. It was the kind of work that conceivably could lead to better, more predictable signal-limiting technologies, which, in turn, could help engineers design more capable and reliable radar and other military systems. Their efforts led in December, 1987 to a paper in the prestigious *Physical Review Letters*,[34] which Pecora believes helped establish NRL in the nonlinear dynamics research community.

Now that they had gotten their feet wet, they began thinking more broadly about topics that both would interest them and the Navy. "Tom and I were searching for other things to do with chaos and we started to talk about communications," recalls Pecora.[35] What came out of that talking was the idea of synchronizing electronic fluctuation in physically separated circuitry of sending and receiving equipment. Says Pecora: "We knew we could characterize these chaotic systems [scientifically], but we thought it would be really neat if you could show somebody how to use them."[36]

They developed the idea further. Their goal, loosely defined, was twofold: first they hoped to find ways of exploiting chaotic electronic fluctuations in transmitters in order to scramble, or encrypt, a signal carrying a message; then they hoped to find a way to synchronize the chaotic fluctuations in the receiver's circuitry with those of the transmitter. The result would be a brand new channel of secure communications.

That idea was good enough for Coffey to approve additional funding. Soon thereafter, the researchers were wheeling an oscilloscope and some homemade circuitry down to the Director of Research's office to show him in no uncertain terms that they were making real headway. There were other good signs. The researcher's patent applications were getting approved—they were up to six by early 1998—

and their work was getting written up in popular magazines and newspapers, including the *Washington Post* and *Science News*, thereby bringing good visibility to the Laboratory.[37]

The work recently has begun extending beyond the Laboratory. "Many variations of synchronization schemes are now being tried with many attempts to apply the results to communications systems," Pecora says.[38] What's more, Dynetics, Inc., a Huntsville, Alabama firm, signed a Cooperative Research and Development Agreement with the Laboratory to explore the use of chaos synchronization as a basis for providing secure communication on notoriously insecure cellular phones.[39]

There are no guarantees that Dynetics, the Navy, or anyone else will successfully convert any of this work on controlling chaos into new secure communications systems. But the effort serves an equally important, albeit less tangible, role for a laboratory charged with remaining on the leading edges of science and technology. For one thing, by studying the impact of chaotic behavior on Navy systems, researchers at least can help engineers avoid or manage chaos when it becomes troublesome. At best, however, their work could create a new leading edge by improving existing technologies or by leading to brand new ones yet to be imagined.

"Present applications should be viewed as just scratching the surface," remarks Pecora.[40] Besides magnetic materials and electronic circuitry, researchers have shown that chaos theory and nonlinear dynamics are applicable to analysis of lasers, heart activity, and the biomedical course of vaccines, among other phenomena. In that sense, the work by Pecora's group fits snugly into Jack Brown's view of NRL as a place for creating beneficial technological surprises and for preempting ones that could prove harmful.

Digital Pixels

Pecora and his colleagues are doing their bit to keep the Navy informed about how chaos might be important for future communi-

cations systems. That places their work in a much bigger portion of NRL's big picture—information science and technology. It's an area that NRL has become increasingly committed to since the late 1960s when the Navy, including Alan Berman and NRL, was learning how information-intensive, data-intensive, and computationally intensive was the challenge of building effective countermeasures to new threats such as high-speed, low-flying antiship missiles.

One very visible sign of NRL's foray into information technology is a starkly white building on the grounds of Bolling Air Force Base. It used to house the Laboratory's cyclotron but since 1981 it has been home to the Navy Center for Applied Research in Artificial Intelligence (NCARAI). "That was directly created by Rear Admiral A.J. Baciocco, then Chief of Naval Research, who thought [artificial intelligence] would become very important," remarks Randall Shumaker, superintendent of the Information Technology Division.[41] The general aim of researchers at NCARAI is to develop computers and robotic systems that are more human-like—systems that can learn from experience, adapt to each other and to humans, and have the ability to carry out the kind of reasoning required for complex decision-making.

Another sign of NRL's commitment to information technology is the Laboratory's acquisition of leading-edge parallel supercomputers.[42] NRL currently has three of the 200 largest computers in the world. This status follows the Laboratory's leap in 1986 when it became the first government laboratory to get a Thinking Machine, one of the earliest massively parallel computers. This entry into parallel computation was part of a DoD/DARPA program whose goal was nurturing this radically different style of computing from infancy into more mature forms that could push the envelope of many other technologies and capabilities.

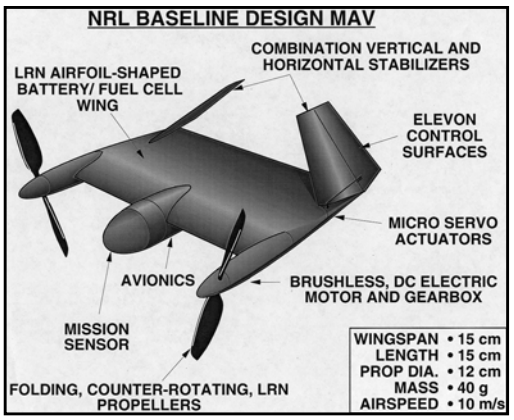
Those efforts have evolved into new supercomputational capabilities. "We are working on protocols to let large numbers of entities—including real people as well as simulated aircraft and tanks, and simulated people—interact in a large scale simulation," says Shumaker

by way of example.[43] One goal of this work, which DARPA is funding, is to develop simulations that can handle as many as 50,000 entities, thereby dwarfing any prior battlefield simulation system in potential complexity.

Shumaker describes another set of leading edge capabilities his division is working on that fall under the new world rubric of virtual reality, or VR. One of them is essentially a fantastically modernized version of the age-old planning table in which military leaders play out tactics by moving little models of tanks, ships, and groups of soldiers like so many game pieces. Only with the VR table, Shumaker says, "you can use electronic models with real-time data feeding in from sensors and other intelligence-gathering systems."[44] Those around the table wear data gloves and special headsets that let them interact with the simulated environment, say, by pointing to spots they would like enlarged or through which they would like to take a simulated walk. The system has worked "extremely well" in Marine exercises, says Shumaker. "We are on the verge of putting these into ships and elsewhere."[45]

In another leap into VR, the Laboratory has acquired and installed in building 34 a virtual reality facility, dubbed the "grotto," which is about as close to the famed Holodeck in *Star Trek: The Next Generation* as can be achieved today. "It's a room with projectors in the floors and walls and ceilings" creating the virtual environments, Shumaker says.[46] The grotto works with either real-world, or simulated, data input into computers that convert that data into orchestrated projections, thus creating simulated environments in three dimensions.

"Suppose you want to train firefighters how to deal with smoke and heat in a realistic but safe setting," posits Shumaker. The grotto ought to help, he answers. "What if you want to evaluate the effectiveness of a new weapon or tactic but don't want to build a town," he posits again. His answer: the grotto. But military settings are only part of the plan. "How would you like to get inside of atomic struc-



Schematic of the MITE MAV. This design weighs in at under two ounces.

ture and look around . . . or look at 10,000 miles of the ocean bottom, and zoom in and out when you want to?"[47] The gadgetry and "oh-wow" character of these kinds of information technologies can overshadow their real value. On the other hand, remarks Shumaker, if these technologies lead to better, faster military decisions, or spawn new scientific or military insights, they also could become crucial parts of the dynamic by which the more tense and violent variety of world events unfold. Which is why the Laboratory is making sure it is right there on the forefront of VR technologies.

Shumaker points out another kind of technology in the works that is anything but virtual—swarms of tiny unmanned micro-air vehicles (MAVs) for intelligence and battle management—that has brought those in the Information Technology together with many other researchers, especially those in the Tactical Electronic Warfare Division. "These are palm-sized air vehicles with small payloads," Shumaker says.[48] One type of research vehicle, aptly known as the MITE (for Micro-Tactical Expendable), has a six-inch wingspan, weighs in at three ounces and has a payload capacity of about one ounce.

Individually, the flying widgets might not be able to do much. But, asks Shumaker, "what if you wanted to search for tanks in a forest. You might let loose a swarm of 50 of these to basically roam around."[49] This kind of new military system can only emerge from combined expertise in such widely disparate areas as lightweight sensors, battery technology, propulsion, search protocols, new materials, robotic control, and communications. Not only does it fit within the

Laboratory's mission to preempt military surprises, but it's the kind of project that stands a chance of becoming more than just a technophile's dream primarily because of NRL's kaleidoscopic expertise.

Internet Pixels

Lee Hammarstrom, an engineer in NRL's executive directorate, is another champion of information technology. Double-hatted as chief scientist of the National Reconnaissance Office, Hammarstrom identifies his own forte as "systems engineering of really big systems"—like the new socially transforming "big" system known as the Internet.[50] Yet even the Internet in its present form cannot begin to move the enormous information products, such as imagery and data from sensors and satellites, that U.S. military and intelligence organizations require for Information Superiority in the modern-day "information race."

Formally known as the "Global Grid" since 1990, this next-generation information infrastructure is in the process of becoming, in Hammarstrom's words, "orders of magnitude beyond the present Internet in speed and richness of protocols."[51] By "richness of protocols," he means the way computers talk to one another and the ways telephony, e-mail systems, data links, video and other forms of data and communications all link together. "This is the key to information superiority" for the Department of Defense, Hammarstrom says.[52] Hammarstrom and several dozen other NRL researchers, as well as many others throughout Government, academia, and industry have been working to realize this goal.

The Global Grid has been under continuous construction for several years. It is a combination of existing and newly developed physical components, such as satellites, optical fiber, computers, data storage systems, and switches, as well as a range of encryption, security, communications, management protocols, and other procedures that ensure the whole system can meet the needs of the intelligence and

military communities that the Global Grid initially has been designed to serve.

An illustration of just how far advanced Global Grid's designers intend it to be is the rate at which a copy of the film *Jurassic Park* could be downloaded. Using today's faster household modems (56 kilobits/second), the transfer would take about 5 days. The transfer would take about 2 days using an ISDN (integrated services digital network) link. Using the Global Grid technology, which already has been extensively implemented throughout U.S. military and intelligence installations, that transfer would take only 3 minutes (at a rate of 155 megabits/second). At the 10 gigabit/second rate, which the more mature Global Grid will have, the entire movie would download in 2 seconds.[53]

The Global Grid initiative also involves how the information coursing through the grid interfaces with people. Hammarstrom points out that the initiative has been ushering along technologies that enable inclusion in the Global Grid of protocols and hardware (such as new cameras), which can allow high definition television (HDTV) visualization to work seamlessly in both television and computer monitor formats.

"NRL has provided the key technical leadership in defining and developing these next-generation capabilities," Hammarstrom says.[54] Consider the role that Henry (Hank) Dardy, chief scientist in the Information Technology Division's Center for Computational Science, has been playing in the emergence of the Global Grid. Dardy has been combining concepts of parallelism in computers with gargantuan and ever-growing information systems like the Internet. The result, says Hammarstrom, has been the development of some new hardware and a lot of information-handling protocols that shuttle almost incomprehensible amounts of data at almost incomprehensible speeds.

A main pillar of this claim has do with a protocol—called Asynchronous Transfer Mode (ATM)—of breaking up all kinds of infor-

mation traffic (voice, video, data, or whatever) into uniform packets that can be more efficiently and rapidly sent and reassembled across an international network of switches specially designed for the ATM protocol. Dardy was a central player in working with specialty companies to get the necessary switches designed and built to sell at affordable prices. "Hank was the first to make real hardware out of the ATM," Hammarstrom says.[55] He also helped transfer ATM technology to companies like Fore Systems and Yurie Systems so that the switches would become widely available. Such switches already have helped manage vast amounts of military information in Bosnia, Haiti, and elsewhere.[56]

Dardy says that ATM technology provides a versatile framework whose compatibility with so many old and new, commercial and military systems explains why it has been integrating with relative ease and swiftness into the next-generation information systems in military and intelligence settings. With ATM technology already diffusing into dedicated military and intelligence networks, and increasingly through industry, academic, and other government sectors, Hammarstrom believes this pixel of NRL research will have an "enormous impact" for both the military and civilian sectors.

He's not the only one saying such things about the role ATM technology is having. "The network has cut the time to compile and build products by orders of magnitude," says Anne Jorefsburg, manager of Microsoft's Information Technology Group. And UUNet, one of the world's major Internet carriers, also has implemented the new switching technology. With testimony like this and a modicum of boosterism, Hammarstrom views Dardy's and NRL's work as fulfilling a maxim that guides his own way of thinking: "Don't ride the wave of technology; but make the wave and shape it."[57]

Electronic Warfare Pixels

It is ironic how ready, almost eager, John Montgomery is to speak about the Tactical Electronic Warfare Division (TEWD), which he has been running since 1985, and how often he will say something like,

"the details of what we did are not repeatable to this day."[58] Such is the conundrum with telling a story about this crucial part of NRL's R&D persona: tales from TEWD are worthy of a Tom Clancy novel, but the best ones cannot yet be told except in the most gray and general hues. Anyone can go to the division's site on the World Wide Web and read a description of the division's research in such areas as "Aerospace Electronic Warfare Systems," "Offboard Countermeasures" and "Integrated EW [Electronic Warfare] Simulation." You'll even find some pretty cool pictures and a handful of hieroglyphic, acronym-riddled lists of this or that system, gismo, or research project. But a few minutes of person-to-person prying invariably yields even more interesting results. "You can bet that any piece of (enemy) missile that we learned about after a battle in the Persian Gulf—that we will look at it, and within weeks come up with a countermeasure for it," Montgomery says without saying much more by way of detail. "TEW is the bridge between people out there in the Fleet and the researchers here who can turn the need for a capability into a real thing."[59]

Bill Howell, the division's Chief Scientist, recalls one request that came into the division in 1988 from the Kuwaiti government during the war between Iran and Iraq.[60] The division had a worldwide reputation for building decoys capable of deflecting heat-seeking and other kinds of something-seeking missiles. He and colleagues went to Kuwait with the mission of building decoys to protect the country's oil terminals, which had the unfortunate trait of being large radar targets in the Persian Gulf. That had the more unfortunate consequence of attracting Iranian missile attacks.

The team quickly came up with a solution—pyramid-shaped floating decoys with special reflectors and other components that magnified their appearance in the eyes of radar systems as well as to the seeking systems of the hostile missiles. Howell and the rest of the team later heard from their Kuwait military contacts about an unexpected kind of evidence that the countermeasures were effective. The story that came back, says Howell, is that "some of the locals, other than military, made small replicas [of the decoys] and were wearing

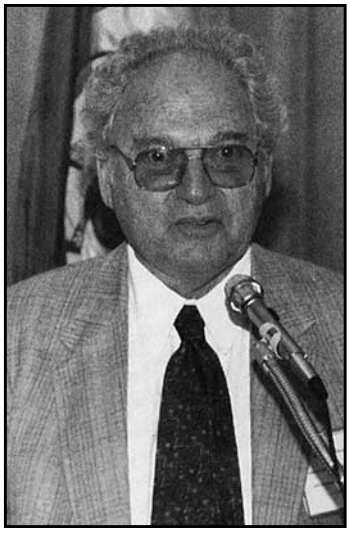
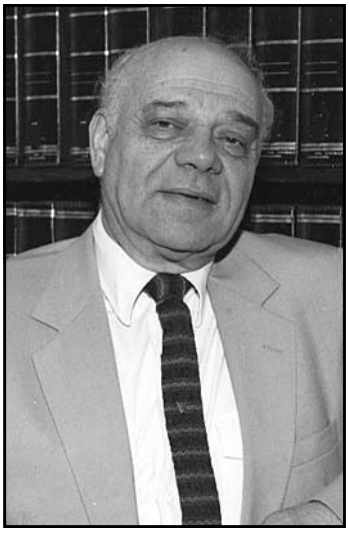
them on their necks and putting them on cars."[61] To them, the replicas must have symbolized protection, Howell speculates.

This kind of quick response work is part of the culture within TEWD. For Desert Storm, Montgomery says, "we had 120 people working on projects with people on cots, sleeping on the floor, working for weeks nonstop."[62]

The division has roots way back to the 1920s, 1930s, and 1940s, when NRL radio engineers were pioneering intercept and jamming countermeasures for communications and then later radar systems. These efforts evolved first into the Countermeasures Branch of the Radio Division in 1951, which enlarged and reorganized in the mid-1960s to become the Electronic Warfare Division before becoming the Tactical Electronic Warfare Division in 1970.

In a schematic history of the division, Allen Duckworth, director of the ENEWS (Effectiveness of Naval Electronic Warfare Systems), notes that the growth in size, funding, and capability of TEWD "allowed the challenges of threat weapons of the 1970s (like heat and other kinds of homing missiles) to be equally challenged with EW counter technology."[63] Among the specific countermeasures TEWD had been developing throughout the 1970s are offboard expendable systems such towed decoys and rapid-blooming offboard chaff (RBOC) for subverting tracking radars (John Montgomery personally worked on these in a rapid response project during the Vietnam War); power sources such as batteries; penetration aids; threat simulation; and techniques for measuring and analyzing the effectiveness of electronic warfare concepts.

Throughout the 1980s and until the present day, weapons systems around the world have become more clever, more computerized, more high-tech in general, and more expensive. Moreover, new kinds of information warfare began to enter the list of serious threats at a time when communications systems and computers were increasing in power, capacity, and sophistication. So, in addition to such traditional work as new and improved versions of chaff, jammers,

Nobel laureates Herbert Hauptman (left) and Jerome Karle.

decoys (including remotely piloted ones), signal processing, and identification systems, TEWD also has been learning how to integrate all of these with command, control, communications, and intelligence systems. All of this, Duckworth points out, has opened the way since the 1980s for the "conception, design, and implementation of future 'intelligent' systems."[64]

John Montgomery says that he would love to tell some of the more dramatic consequences that have come from TEWD products in the field. It's just that they happen to be classified. In some ways, the division itself is like those missile avoiding tactics its researchers have been developing for decades. "We are publicity avoiders, not seekers," Montgomery says. "We (and the users of our products) get no benefit from publicity, only lots of risk."[65]

Nobel Pixels[66]

And then there are those particularly bright pixels among the Laboratory's big picture that flaunt the rich payoff that has come from the Laboratory's post-WWII decision to nurture basic science alongside its older culture of applied science and engineering. No specific

pixel could be more emblematic of this than the awarding of the 1985 Nobel Prize in Chemistry. It went to Jerome Karle, who at 80 remains at NRL in charge of the Laboratory for the Structure of Matter, and Herbert Hauptman, who was a member of Jerome Karle's group until 1961, and is now President of the Hauptman-Woodward Medical Research Institute in Buffalo, New York.

Karle and Hauptman received their award in 1985 for seminal work they and Jerome Karle's wife, Isabella Karle, had begun decades earlier on, in Karle's words, "the structure of materials at the atomic level: in other words, the determination of the arrangements of the atoms in the materials."[67] Research in the physical sciences cannot get much more basic than that.

Isabella and Jerome Karle moved to Washington, DC, to continue their careers at NRL in 1946. They brought with them experience in using the analytical technique known as electron diffraction to determine the structures of molecules in the gaseous state. In the years prior to their arrival, the two had completed their PhD degrees at the University of Michigan and worked on the Manhattan Project before taking jobs at the university. Isabella taught chemistry and Jerome worked there as an employee of NRL on a wartime project for NRL's Chemistry Division.

The Karles' initial work was to improve both the theoretical foundation of electron diffraction as well as the instrumental and experimental aspects of the technique. "The Naval Research Laboratory afforded an outstanding opportunity to pursue this area," Jerome Karle remarks.[68] Not only were senior members of the Laboratory supportive of this fundamental work even though there was no guarantee of a payoff for the Navy, but the Laboratory's top-notch machinists proved crucial in helping the Karle's create new instruments and improve the technique in record time. "This led to the possibility of locating the atoms in a gaseous molecule with high accuracy," Karle says.[69] Key among the improvements in theory was the use of the so-called "nonnegativity criterion," which helped simplify the daunting mathematical aspects of the technique.

Herbert Hauptman joined the group in 1947 with a background in mathematics and experience with radar while serving in the Navy. At the suggestion of Jerome Karle, Hauptman and Karle began looking into the possibility of applying the non-negativity criterion to the analysis of molecules in crystal structures (rather than in the gaseous state) using X-rays rather than electrons. It was a fruitful suggestion. The two investigators quickly adapted the mathematics the Karles had used in electron diffraction of gases for the crystal analyses. They could not have known it at the time, but, in Karle's words "the resulting conditions were such that they contained a major part of the mathematics *now* employed in crystal structure determination."[70] Indeed, at the time there were still major problems to solve, the most challenging one being "the phase problem." The conditions are in the form of mathematical quantities called determinantal inequalities. Work on special inequalities of significance for phase determination was published a year before that of Karle and Hauptman by David Harker and John Kasper, then at the General Electric Company.

To understand the phase problem in X-ray crystallography, you first have to have some idea of how X-ray crystallography proceeds. In 1993, during his comments at a 75th birthday celebration for Jerome Karle, Herbert Hauptman explained the technique about as clearly as anyone might: "A source of X-rays is caused to strike a crystal, the crystal scatters the X-rays in different directions, and the scattered X-rays are caused to strike a photographic plate [now more likely an electronic detector], which is blackened at the points where the scattered X-rays strike the photographic plate. The amount of blackening depends on the intensity of the corresponding scattered X-rays. The positions of the spots on the photographic plate are a measure of the different directions in which the X-rays are scattered. In this way, the so-called diffraction pattern of the crystals is obtained."[71]

The actual diffraction pattern itself, however, was thought to be insufficient for working backwards to directly infer the molecular structure of the crystal. The reason for this limitation was that the spots of an X-ray diffraction pattern yielded data about the intensity of X-rays

scattering from the crystal, but not the phases of the X-rays producing the pattern's spots.

"The phase problem is related to the fact that X-rays travel in the form of a wave and it was apparent that in order to solve crystal structure problems directly it was necessary to know at what part of its wave motion the X-ray wave had been when it scattered from the crystal," explains Jerome Karle.[71] Without that knowledge, the problem had appeared insurmountable. This dilemma was known as the phase problem and seemed at the time to be an ineluctable limitation to the structural information one could glean from X-ray diffraction.

Karle and Hauptman showed how dead wrong that assumption was and thereby helped transform X-ray crystallography into one of the most powerful analytical tools available to 20th Century scientists. The crux of their discovery was that the coveted phase information actually was present in the X-ray diffraction patterns all along, only it took some mathematical insight to realize it. They developed mathematical procedures by which they could extract phase information from the intensities recorded in the diffraction patterns. In other words, they had found a way to beat the phase problem, a necessary step for transforming X-ray crystallography into a priceless method-of-choice for directly and confidently determining molecular structures.

At least Karle and Hauptman were convinced of that. Much of the scientific community remained skeptical. "[Solving] the phase problem was thought to be impossible," recalled Dudley Herschbach, a 1986 Nobel-winning chemist at Harvard University.[72] So anybody claiming to have solved the phase problem might as well as have been claiming to squeeze blood from a stone. "I shudder to think what may have happened to this research project had the administrators of my program felt impelled to act on the judgment of the crystallographic community regarding its value," Karle recalled later, adding that " . . . the phase problem was regarded as insoluble even in principle."[73]

Isabella Karle, recipient in 1995 of the National Medal of Science, is shown here in 1963 preparing a crystal for analysis.

The first kinds of crystal structures to be successfully analyzed with the new approach were ones whose molecules contained a center of symmetry, which limited the complexity of the analysis. The researchers knew, however, that molecules with centers of symmetry constituted only part of the molecular diversity in the world. They also knew that using X-ray diffraction for analyzing the structures crystals devoid of a center of symmetry would require additional insights and ideas.

Isabella Karle became a prominent part of the story in about 1956. She quickly mastered the experimental procedures of X-ray crystallography, thereby providing the Laboratory its own data. Her first study concerned the complex, centrosymmetric crystal of p,p'-dimethoxybenzophenone, whose structure she solved. After Hauptman left the group in 1961, Isabella worked closely with Jerome on a more general methodology—called the Symbolic Addition Procedure—that would enable analysis of a much wider range of crystal structures, namely the determination of the structures of the broad group of crystals that were devoid of a center of symmetry. Noncentrosymmetric crystals are of special importance because they include, to a large extent, the molecules of life. The Symbolic Addi-

tion Procedure was also much more effective than the previous methods with those crystals, which had a center of symmetry.

There were several very difficult problems to overcome. These either were unique to noncentrosymmetric crystals or the problems were even more difficult for the case of centrosymmetric ones. Examples of unique problems were the discovery of useful probabilistic formulas, the development of procedures for their use, and measures of their probability. There was the daunting fact that whereas there are only two possible values for phases in centrosymmetric crystals, 0° and 180°, noncentrosymmetric ones can have any value between 0° and 360°. Another unique problem arose from the fact that, in centrosymmetric crystals, the usual X-ray diffraction data can be satisfied by two distinct structures which are mirror images of each other. It is necessary to have a practical way to select one uniquely or the phase determination will fail. Other problems that had to be overcome arose from the fact that ambiguous mathematical solutions normally occur in this probabilistic methodology and steps must be taken to control the degree of ambiguity. Finally, only partial structures or small fragments often are obtained. It was, evidently, necessary to develop a suitable calculation that could produce a complete structure from a fragment of a structure. The delicacy of the interactions among these various considerations probably accounts for the fact that it took at least 5 years before other laboratories began to pursue investigations of noncentrosymmetric crystals.

During the 1960s, Isabella was using the method to determine various noncentrosymmetric crystal structures, work that inspired many other laboratories to adopt the procedures. By the end of the decade, other researchers incorporated the programs developed for application of the Symbolic Addition Procedure into their codes and added their own variations. Thereafter, the work of the Karles spread more and more, often hidden inside of computer codes that were helping other researchers make sense of their raw X-ray crystallography data.

Over the years, the Karles and their colleagues have solved multitudes of molecular structures. One important early example was for 11-cis-retinal, a molecule in the light sensitive cells of the eye that is pivotal in the translation of light energy into neural signals that the brain can process. The structural data that resulted was key in helping vision scientists uncover the detailed physical mechanisms by which this molecule works its visual wonders. At the same time, Barry Honig and Martin Karplus of Harvard University were performing theoretical calculations on cis-retinal. The X-ray diffraction and theoretical results were in agreement.

In the late 1960s, the Karles reported the structure of reserpine, a compound isolated in 1952 from Indian snake root. Reserpine's effect on cells of the nervous system had made it both a pharmaceutical agent and research tool. NRL scientists helped the U.S. Department of Agriculture determine the molecular structure of barassinolide, a powerful hormone that stimulates plant growth. They helped determine the structures of molecules that pack into explosive materials, as well as molecular structures of proteins, frog toxins, plant alkaloids, and a menagerie of other chemical compounds and minerals.[74]

Jerome Karle points out that the most useful method for determining crystal structures before the phase problem was solved arose from the work of the late A. Lindo Patterson, then at Bryn Mawr. The method is called the heavy atom method and involves having one or a few heavy atoms in a molecule. The solution of the molecule's structure follows from knowledge of the location of the heavy atom or atoms which can be determined from the use of a "Patterson function."

There were limitations to this method, Karle notes. It often was impossible to introduce heavy atoms into molecules, or the molecules that had been successfully modified with heavy atoms would lead to crystal structures different from the unmodified ones. "And so," says Karle, "people used insight, trial and error, and a variety of other approaches to solve structures without heavy atoms."[75] There clearly was

plenty of incentive to try and develop a direct method of structural determination, which is what solving the phase problem made possible.

In 1968, NRL recognized the significance of the Karles' research productivity by establishing the academically modeled Laboratory for the Structure of Matter on campus with Jerome Karle as the director. Seventeen years later, in 1985, the Royal Swedish Academy of Sciences recognized the achievement of Jerome Karle and Herbert Hauptman by awarding them the Nobel Prize in Chemistry. Jerome heard the news amidst cheers and a popping champagne bottle when the pilot of the plane he was on announced that passenger Jerome Karle had won the Nobel Prize in Chemistry. Meanwhile, his colleagues back at NRL were popping their own bottles and fielding media calls. For her pivotal role throughout the years, Isabella Karle also received many prestigious awards, including the Gregory Aminoff Award of the Royal Swedish Academy of Sciences and National Medal of Science in 1995.

Wayne Hendrickson, a former colleague of the Karles at NRL who now is a professor at Columbia University College of Physicians and Surgeons and head of a Howard Hughes Institute at the university, wrote about the Karle and Hauptman Nobel award in *Science* magazine soon after the award was announced. He assessed the work of his former NRL colleagues this way: "Whereas in the early 1960s a single crystal structure could constitute a PhD thesis project, now that same structure might be solved and refined within a couple of hours after the data collection (which itself is timed in hours) is completed. The advance is not only in speed . . . quite large structures can now be tackled: organic molecules with up to 50 non-hydrogen atoms are almost always routine, those of 50 to 100 atoms generally cause little trouble, and structures have been done with more than 200 atoms in the asymmetric unit of the crystal."[76]

And that was more than 10 years ago. "It is estimated that somewhere between 10 and 20 thousand structures are determined each

year," Karle offers as an update.[77] Those structures include minerals, molecules of chemistry and biochemistry, and more recently those of very large macromolecules (such as proteins) that are crucial to the life sciences and medicine. In fact, Karle notes, researchers now can elucidate the crystal structures of molecules made of many thousands of atoms.

"Computers and diffractometers contribute greatly to present-day productivity," Hendrickson wrote in his *Science* article, "but it is the phase-determining methods that are most responsible for making crystallography a reliable 'nonsporting' science."[78]

The analysis of very large molecular structures like those of macromolecules entails the use of a special heavy atom method, which helps to simplify the interpretation of these molecules' extremely complex diffraction data. One of the modern and rapidly growing methods for doing so is a product of the Laboratory for the Structure of Matter. Called multiple-wavelength anomalous dispersion, or MAD, it is a mathematical framework (based on a set of exact linear equations for the analysis of anomalous dispersion data) developed by Jerome Karle in 1980. Both Hendrickson and another former employee of the Laboratory for the Structure of Matter, Janet Smith of Purdue University, have been finding ways of applying MAD (along with high-quality and especially intense X-ray sources from machines known as synchrotrons) to solve previously impossible structural determinations of molecules. One of Smith's studies involves a structure that contained almost 15,000 non-hydrogen atoms.

From neurotoxins to energetic materials, a.k.a. explosives and propellants, the researchers in the Laboratory for the Structure of Matter have accrued an enviable record of structural determinations. Isabella, in more recent years, has made major contributions to peptide chemistry and has been well recognized for her contributions. Richard Gilardi has prepared a compendium of the structures of about 500 materials that are either precursors, intermediates of, or the final products of the chemical synthesis of energetic substances, most of which he deter-

mined himself. Clifford George and Judith Flippen-Anderson have been studying the structures of neuropeptides associated with drug abuse. John Konnert has been studying substances in the crystalline and glassy state, and, more recently, has been investigating the process of crystallization using the Atomic Force Microscope.

Jerome Karle says that a major current interest is the developing field of research which he and his colleagues Lulu Huang and Lou Massa call "quantum crystallography."[79] This field involves the intimate joining of crystallographic results with quantum mechanical calculations and theoretical chemistry. The objective is to enhance the quality and extent of information available from each of the two fields separately. The methodology is broadly applicable to all sorts of crystalline substances. Energetic materials are currently of special interest with the usual objective of helping to develop materials of enhanced performance.

Karle argues that the history of structural chemistry at NRL provides strong testimony for the wisdom of mission-oriented environments (which includes NRL) supporting basic research, even when it is not clear how, or even if, that research will pay off in the form of technology or other applications. "The structural research program originated in a strong interest to enhance the capabilities of the technique of electron diffraction of gases," Karle says. "The value of the non-negativity principle found in this study led to the application of this principle to the phase problem in crystallography, which ultimately resulted in the solution to the phase problem. This solution was adopted throughout the world and generated a great number of investigations that continue to this day."[80]

And the payoff has been great. Not only has X-ray crystallography helped the Department of Defense learn more about the chemistry and physics of decidedly military phenomena such as detonations, it has contributed to many areas of basic science as well as to the chemical, pharmaceutical, petroleum, and many other industries. In this way, says Karle, "the broad investment in basic research reaps the de-

sired reward for national security and the nation's economic and social benefits."[81]

Magnetic Pixels

The Nobel Prize happens to be the science world's highest and most visible accolade. Yet even a Nobelist like Jerome Karle can lay claim to only a limited number of the many pixels comprising the Laboratory's big picture. The pixels attributable to Gary Prinz, a physicist specializing in magnetism who started working at the Laboratory in 1967, represent the way many other NRL researchers also have set off important cascades of scientific and technological developments both within and outside the Laboratory.[82]

Magnetism has been an important field of study at NRL because, in Prinz's words, "you cannot build a radar set without magnetic materials."[83] And NRL has been developing all kinds of radar technologies for more than sixty years. Radar may have provided the impetus for research into magnetic materials, but that research took on a life of its own, particularly after 1955 with the establishment of the Magnetism Branch, which since has undergone many administrative moves, mergings, reorientations, renamings, and other transformations.

Prinz entered the picture when he turned down an offer of a job and higher salary by the famous Bell Laboratories because he liked the intellectual freedom the Magnetism Branch's head, George Rado, gave to those working for him. Prinz's initial work centered on detailed analyses of new magnetic materials with the goal of laying bare the basic physics and detailed atomic structures underlying the materials' behavior. This interest led him into a collaboration with a researcher in the Semiconductor Branch, Robert Wagner, in which they homebuilt their own version of a recently invented type of laser whose emissions were in wavelengths matched for studies of new magnetic compounds involving rare earth elements of the Periodic Table.

Just when the researchers had begun publishing papers at a steady clip using their new apparatus, Prinz intuited that he needed to move

his work in a dramatically different direction if he were going to make important, lasting contributions in the field of magnetism. The new direction Prinz took was away from analyzing existing materials and toward synthesizing new magnetic materials with unprecedented degrees of control and purity. Prinz could tell a good thing when he saw it and when he learned about a new technique—called Molecular Beam Epitaxy—that researchers at Bell Laboratories had been pioneering during the 1970s for growing semiconductor crystals even one atomic layer at a time could, he knew it also would become important for making new magnetic films.

It took some doing, and skillful diplomacy by a savvy colleague of Prinz's who secured $155 thousand dollars from several other ongoing programs at the Laboratory, but in the end Prinz was able to the buy the Laboratory's first MBE machine in 1979. "It opened up a new world and it has become a very broad world," Prinz says.[84] Since an MBE machine works by leaking elemental ingredients into a vacuum chamber in whatever sequence a researcher chooses, the technique is the route to designer crystals with specifications down to the atomic level. And for nearly two decades it has continuously led to collaborations amongst NRL's materials researchers, surface scientists, physicists, and many others with differing expertise.

Results from that first MBE machine in 1979 helped Prinz and others argue for NRL to acquire additional and even more expensive MBE systems, and even to link some of them into more powerful instrument assemblages. The payoff here comes in the form of new kinds of hybrid materials made with MBE-grown semiconductors and MBE-grown magnetic films. In time, others at NRL, including Berend Jonker, found themselves in charge of their own MBE-based laboratories. With more than a decade of learning and experience behind them now, NRL's contingent of MBE users have been routinely inventing, probing, and developing a menagerie of new crystals with potential applications as electronics devices, optical detectors, magnetic recording and reading heads, and new data storage substrates.

Even as researchers were developing film-growing skills with the growing set of MBE machines, Norman Koon (who died in a tragic skiing accident in December 1997) of the Metallurgy Division was examining new compositions—in this case one of neodynium, iron and boron—in search of magnetostrictive materials that change their shape slightly in a magnetic field. Prinz remembers the evening in 1981 that Koon came up from a basement laboratory for making measurements on hard stiff samples with a telling piece of recorder paper in his hand: "I was working late, as we often did then, in Building 60 on the third floor and I was outside of George Rado's office. We were talking about physics problems when Norm came upstairs carrying a piece of recorder paper and said, 'You guys want to see something neat?'"[85]

What he showed Prinz and Rado was a recorder plot showing that it took an enormously high applied magnetic field to reverse the direction of the new neodymium, iron, and boron magnet's own magnetic field. As Prinz recalls it, Rado was skeptical and said something like "nothing switches at fields this high."[86]

Koon evidently knew he had done the measurements correctly and that he just might have happened onto the kind of magnetic material suited for the millions of electric motors made each year to power everything from windshield wipers to fans to tools. "He immediately went and got patents written up," Prinz says. As it happens, other groups around the world who also were probing into these new compositions also were putting in patent paper. "There still are big patent struggles over this," Prinz says.[87]

Prinz continued to concentrate on thin films and not just so far as NRL was concerned. Besides sowing the MBE seed at the Laboratory, he also helped put the MBE/magnetic-materials connection into the minds of those who could support other groups to get going in the new area. For example, he helped convince program managers at DARPA that ever-improving abilities to grow thin films of magnetic crystals could conceivably open routes to new kinds of nonvolatile

computer memories that retain information even in the absence of voltage. That bit of selling has had consequences well beyond the Laboratory itself. Now, besides supporting NRL's effort in this area, DARPA supports those of other laboratories, including ones at Motorola, IBM, and Honeywell.

Prinz sees a big future for magnetic memories, particularly ones made of materials exhibiting so-called giant magnetoresistance (GMR). These are multilayered materials in which the flow of electrical current is dramatically altered depending on the orientation of magnetic fields within the thin magnetic layers, which are separated either by alternating nonmagnetic layers or different kinds of magnetic layers. The French researchers who first reported the phenomena in 1988 credited the earlier work of Prinz and his colleagues on the growth of iron films atop gallium arsenide crystal surfaces with leading them to the discovery.[88] The French team made their discovery by taking the additional step of growing a layer of nonmagnetic chromium over the iron layer and topping these with additional alternating layers of the two metals. GMR research has mushroomed into a high-stakes race because of the value these new materials and related ones have in novel data storage technologies.

For their bid in this race, Prinz and his colleagues have been growing stacks of alternating cobalt and copper layers atop a base of silicon nitride. From the work they have done under patient ONR sponsorship, Prinz expects to be able to fabricate memory arrays with bit sizes about the size of a protein molecule, leading to data densities of about one billion bits per thumbnail-sized area of chip space. That's equivalent to the capacity of scores of 3.5 inch floppies. The nonvolatile, random access memory that Prinz thinks such GMR arrays enable will be immune to radiation, power failures, and most other external disturbances. Moreover, they will consume small amounts of power and only when they are informed with data or when data is read from them.

For those reasons, these multilayer materials have obvious military possibilities. For one thing, says Prinz, they could replace older

generations of bulky, expensive and less reliable magnetic memory technologies still deployed in such venues as Trident Missiles and P3 subchaser aircraft. "More importantly, these could go into all tactical missiles," he adds.[89]

But Prinz envisions even more audacious outcomes. Using GMR structures for new kinds of computer memory is just the first application that comes to mind. He says the materials could also conceivably become the basis of a computer's brain—its microprocessor.

The advantages of this switch could be far-reaching, he says. Conventional microprocessors are the semiconductor-based chips that make a PC a PC, a Macintosh computer a Macintosh, or any specific kind of computer that kind of computer, each with its own pros and cons. They are what the "Intel Inside" logo is reminding PC users about. "What if you wanted to turn your Mac into a Unix system," Prinz asks and then answers, "you can't because the chip you have is the chip you have."[90] But with GMR microprocessors, Prinz says, it would be possible to build computers with reprogrammable microprocessors. That way, software designers could make products that reconfigure the machine into the optimum computer—say, a parallel computer instead of a serially processing computer—for each particular problem.

"There have been a few attempts to make reprogrammable processors" out of semiconductor materials, Prinz notes. But, he says, these ended in failures and had made the idea somewhat far-fetched. "Now, with GMR memory chips, people believe you might be able to do this."[91]

Prinz has no way of knowing if these kinds of visions will flesh out. But he notes with a mixture of pride and regret that there now are precious few other places where such ideas are likely to ever get much attention. That's because high-tech companies that had research groups focusing on magnetic materials have been downsizing or closing down those projects. "We (NRL) now have more technological memory in these areas than industry has," Prinz notes. And those few industry laboratories still working on new magnetic memories remain in the

game largely because they receive support from agencies like ONR and DARPA, which Prinz has helped convince to run research programs in new magnetic materials. In that way, Prinz represents those NRL researchers whose role as experts and advisors have molded the nation's overall research portfolio.

Pixels of Battlefield Omniscience

There is no doubt that the world gets more wired everyday. There are more computers, more databases, more optical fiber trunks and satellite links, more communications systems, more sensors and surveillance systems, more transmitters and receivers: indeed, there is more of everything when it comes to acquiring, processing, transporting and using data. The civilian version of this is sophisticated all right, but it provides just a hint of the digitized battlefield that is in the process of becoming a reality. What the Internet is to the civilian sector, C^4I (command, control, communications, computers, and intelligence) is to the military sector.[92]

Lots of NRL researchers have their imprints on the many, many pieces comprising C^4I and their linkages to the Global Grid (see pages 334 to 336). That involvement stretches all of the way from conception to research to development to implementation. Those in Code 8100—the Space Systems Development Department—sometimes even strap into military aircraft in the penultimate development steps before a new piece of the C^4I system takes its own place in an overall system that makes James Bond gadgetry seem unimaginative.

Consider just one of NRL's more successful and mature contributions—the MATT, or the Multi-Mission Advanced Tactical Terminal. These are at the end of the line of the military's enormous C^4I network. They are the terminals by which the enormous infrastructure of data, intelligence, and analysis gets to the ship commander, the pilot, and even the soldier on the ground.

A key step toward development of these information tools took place in the early 1980s, when NRL engineers designed a remarkably

inexpensive space test. Called Living Plume Shield 2 (LIPS2), the heart of the experiment was to put prototype communication devices onto an expendable part of a launch vehicle—the plume shield—that normally protects a satellite from exhaust particles. "They put attitude controls on it and solar cells," says electrical engineer Charles Herndon, whose own work since he arrived at NRL in 1986 has followed from LIPS2. But the key, he adds, is that "it carried transponder experiments that validated [certain] coding schemes that allowed communication from LEO's, or fast-moving low earth orbiting satellites, to shipboard."[93]

Using such relatively quickly deployed satellites is challenging. "They are traveling overhead for 10 to 12 minutes and their signals have to be robust and work even in the presence of powerful search radars" (and many other potential sources of electromagnetic interference), Herndon points out.[94] Once the communication scheme was validated, the next step was to develop receiving equipment for the Fleet. Look on almost any Naval ship today and you will find an OE82 antenna that links with LEOs. Satellite-to-ship communication was just the beginning of the more extensive communications and data system upon which Herndon and others have been working.

The next step was to build deployable ground-based receiver suites (collections of ground components including UHF satellite communication receiver, cryptographic components, and a message processor), which Herndon and his colleagues did. These suites are known in this acronym-jammed C^4I business as TREs, or Tactical Receiver Equipment. TREs are rugged boxes with receivers, cryptographic cards, and processors for intelligence broadcasts. These turned out so well, says Herndon, that they now are the Fleet standard for tactical receivers.

The TRE work then led in the late 1980s to MATT, the Multi-Mission Advanced Tactical Terminal, which NRL developed for the U.S. Special Operations Command (USSOCOM), which had significant requirements for real-time tactical data. Herndon points out that the

acronym MATT was matched to Captain Matthew Rogers, who saw how the Navy was getting intelligence information to the floating Fleet and wanted the same capability in the cockpits of tactical aircraft. The first MATTs were ready in 1991. They have become standard equipment in EA-6B aircraft whose mission is to gather electronic intelligence (ELINT) on "wild-weasel-like" runs in which the aircraft deliberately fly in an adversary's territory to "light up" and then analyze signals from various radar and other optical and electromagnetic threats within range. Since 1993, MATTs have become standard equipment "in a lot of ground operations," Herndon says.[95]

The sequence from LIPS2 to TRE to MATT is not complete, and it is only one part of the C^{4}I universe. Consider the IDM, or Improved Data Modem. This is the unit that Herndon recently validated by sitting in the back seat of an F-16 trainer. Until the IDM, pilots in the air could only communicate by voice with one another; they were not equipped to share intelligence, targeting, or other data. The IDM, he says, has changed that. So far, over 2,200 IDM units have been built with DoD requirements calling for at least 1,250 more.

Unsung Pixels

There literally are hundreds, even thousands, of other pixels that could complement, supplement, and otherwise join the ones above. But that would merely lengthen, rather than improve on the main point already made by the limited set of pixels. The picture that emerges from the pixels is none other than NRL, a place the Navy can go for a preview of what looms on the technological horizon and for the kind of brain power that can leverage Naval brawn in the world's seas. Beyond platitudes like that, the breadth of NRL's research portfolio defies summarization. And nowhere else but at an NRL, with its unique mix of mission and research cultures, could so much consequential research and development be done by so few for so many contemporary and future defense needs.

Chapter 12

Pushing on the Horizon

When NRL opened for business in 1923, it began to make its way tentatively like a small creek. Its vitality at any time was greatly dependent on dry spells and sudden rain showers. Despite mortal threats in its early years from lack of money or overbearing Navy bosses, who would sooner nip the young laboratory in the bud than see it evolve to have an institutional mind of its own, NRL grew and strengthened over the years. Radar and sonar technologies helped the Laboratory ascend from a small-time job shop for Navy Bureaus earlier in the century into the full-blown corporate laboratory that its founders had hoped it would become.

Even during the Laboratory's first decades, new ideas, people, funding, and resources continuously fed into NRL like tributaries. Then came the turning point—World War II. Like a great rain, the war amplified the steady stream of applied science and engineering that NRL had become before the war and transformed the Laboratory into the mighty R&D river that it has been ever since the war ended.

"You cannot step into the same river twice," wrote Heraclitus, a Greek philosopher born in the mid-6th Century BC. Heraclitus's aphorism concisely captures the quixotic essences of both rivers like the Potomac, whose passing waters NRL has witnessed for the past 75 years, and great institutions like the Naval Research Laboratory itself. A river is a forwardly surging entity in the world that maintains a

lasting identity even as it constantly changes. Great institutions like NRL are the same way. They always are the same and not the same.

NRL's staff has grown from a few score in 1923 to over 3,000 today. The building count at NRL's main campus has gone from 5 to over 100 while the setting has changed from its bucolic, country beginnings into a sparsely treed industrial-looking present. The budget has increased from the million dollar range to edge toward the billion dollar range, all of it supporting work at NRL and its 14 smaller, specialized facilities and support installations around the country. Most importantly, however, the Laboratory has emerged from its scrawny, anonymous beginning as a specialty radio engineering laboratory into a top-tier facility of immense breadth that has imprinted its mark on many of the advanced military and civilian technologies characterizing both our times and those of the near future.

Even a short recitation of the Laboratory's most current portfolio of projects reveals the polymathic result of Thomas Edison's and Josephus Daniel's brainchild:

♦ New stealth materials based on metal-coated microtubules that become part of coatings capable of catching radar energy like a catcher catching baseballs.

♦ Cloaking devices for Navy Seals, special forces, and other aficionados of camouflage, that render users invisible to microwave-based intrusion sensors.

♦ A more secure means of routing messages (Onion Routing) that can thwart attempts by eavesdroppers to trace the path of a message (which can harbor compromising intelligence information) within information networks such as the World Wide Web.

♦ An anti-sniper defense system known as VIPER (Vectored Infrared Personnel Engagement and Return fire) that detects infrared flashes from a sniper's gun muzzle, alerts users to the sniper's presence even before the sniper's bullet arrives, and even guides automatic counterfire.

♦ Applications of a laser-based method (called pulsed-laser deposition) for reassembling the major ingredients of bone—the

protein collagen and the mineral hydroxyapatite—into synthetic structures that mimic real tissue for improved orthopedic implants.

♦ Next generation semiconductor materials to enable radar systems to see more threats, quicker and more accurately, or that expedite the ever-heavier traffic of data and information that will flow through the military's growing C^4I systems.

♦ Using tools like an Atomic Force Microscope to form some of the smallest electronic components possible—measuring in billionth-of-a-meter (nanometer) range—thereby putting them squarely into the range where quantum behavior dominates.

♦ Developing synthetic aperture-sonar (SAS) for next-generation countermeasures against mines in very shallow water contexts of about 10 meters.

♦ Uniting new sensor technologies, unmanned aerial vehicles (some as small as hummingbirds), and communications systems in an effort to develop a badly needed means of identifying chemical and biological warfare agents dispersed as vapors and airborne aerosols, respectively.

And those are merely some of the newest pixels of NRL research. Teams of scientists and engineers at the Laboratory also are investigating new semiconductor structures less vulnerable to damage from both artificial sources of radiation as well as naturally occurring sources such as cosmic rays; the influence of subsurface bubbles on acoustic scattering (important for sonar performance and interpretation); the adaptation of a technique known as nuclear quadrupole resonance for detecting concealed explosives; micro-air vehicles weighing a few ounces that can carry radar jamming equipment, cameras, microphones, chemical and biological agent sensors, and other payloads to carry out military, intelligence, illegal drug interdiction, and other missions; database and data retrieval methods enabling users to rapidly integrate different forms of data—images, texts, numeric data, maps—into forms and displays that help in the process of making tactical decisions and planning missions; an analytical technique for revealing 3-dimensional views of the internal microstructure of ma-

terials; the effect of small-scale ocean waves (capillary waves less than an inch from crest to crest) on the exchange of carbon dioxide between the air and sea; new light emitting devices based on organic molecules suitable for making flat-panel screens that can be rolled up like a scroll and hung up wherever one pleases; computer simulations of new, high-energy fuels; and the coupling of global atmospheric models with ocean models to extend weather prediction from a few days to weeks or even months.

Multiply by ten the preceding catalog of research pixels and that still would only account for a small part of NRL's overall technical portfolio. Few laboratories in the world, and perhaps no other ones throughout the Department of Defense, are home to such a vast swath of research.

One sign of how much NRL's research plays into the nation's general technological landscape emerged in 1997 in an NSF-funded study on research policy that included a comparison of how often the research at different U.S. research institutions was cited in U.S. patents[1]. Presumably, the more any particular institution's research is cited, the more impact that institution has in creating new ideas, technology, and patents.

The study, which broke down the research cited into several categories, such as physics and chemistry, found that over 430 research institutions were cited in a survey of patents granted during the years 1987, 1988, 1993, and 1994. Of those 430 institutions, NRL ranked fifth with respect to the patent citations of physics papers that Laboratory researchers had published. Only AT&T Bell Laboratories (now Lucent Technologies), IBM Corporation, Stanford University, and Bellcore came out ahead of NRL in this analysis. The Laboratory ranked eighth with respect to citations of the Laboratory's engineering and technical papers.

In a separate citation study, this one by the Institute of Scientific Information, NRL ranked amongst the world's top ten institutions when it came to the number of times its researchers' papers were cited by others in 150 materials science journals.[2]

Those rankings notwithstanding, no Government laboratory, no matter how impressive its past or present capabilities, has guaranteed longevity. As budgetary, military, political, social, national, and global contexts change, the roles of nationally supported R&D assets, including NRL, get revisited. The kind of audacious plans that have been no stranger to NRL tend to get more sparse at times, like those during the first term of the Clinton Administration, when Congressional quests to balance the national budget led to such proposals as disbanding long-standing institutions such as the Department of Commerce or the Department of Energy. Rather than expecting annual budgetary increases as it has in the past, the Department of Defense is learning to plan for a more financially austere era.

Military R&D has become vulnerable to larger scale budgetary strains that span up to the levels of the Department of the Navy and all of the way to the Department of Defense. Shrinking funds inevitably bring unpleasant consequences: smaller payrolls, back-pedaling on programs, and overall belt-tightening. But involuntary austerity also can inspire innovation. To do more with less takes genuine creativity.

Those who feel the brunt of budgetary cuts or the pressure to change tend to perceive the magnitude of such challenges as bigger than their predecessors ever had to confront. But big challenges are nothing new at NRL. Indeed, NRL's first quarter-century was marked by several life-and-death struggles. The 40 years following the end of World War II coincided with the Cold War, which provided a political justification to support a large portfolio of military R&D so long as it stood a chance of furthering U.S. military capability. This was a smoother sailing period for NRL, at least so far as its right to exist was concerned. In the last decade, however, the national and global contexts have changed so much that NRL once again is being confronted with the kinds of financial and programmatic challenges that cut to the core as they did earlier in its institutional life.

What is different this time is that NRL has a 75-year record that is replete with documented instances of world-changing significance as well as an encyclopedic list of lesser, though often quite consequen-

tial, scientific, technological, and military payoffs. It is a record of accomplishment that comes of its multifaceted culture in which engineering and scientific mentalities have mutually bootstrapped one another in a context driven by the ever-changing vision of what a leading-edge Navy is. Get rid of the science culture and NRL disappears. Get rid of the engineering culture and NRL disappears. Decrease the diversity of expertise and you flirt with losing the critical mass by which NRL has been able to both react to and anticipate the seething, changing landscape of research and development challenges. That, too, would make NRL disappear.

As NRL enters the last quarter of its first century, it enters an era in which the potential types and sizes of military threats are more varied and less predictable than during the Cold War. It enters an era where blue sea warfare appears of less strategic importance than near-shore, littoral warfare. The Laboratory enters a more budget-conscious era in which technology will be needed to leverage the force of ever smaller amounts of human resources. It enters an era in which information weapons seem on a trajectory to be at least as militarily important as bullets and bombs have been. In brief, it enters a time when the Navy likely would have to invent a Naval Research Laboratory had Thomas Edison and Josephus Daniels not gotten to it first more than 75 years ago.

References and Notes

Chapter One

1. This figure, which was provided by the Office of Naval Research covers only research categories 6.1 and 6.2 (which refer, respectively, to basic and applied research).

Chapter Two

My three major sources for this chapter were Lloyd Scott's *History of the Naval Consulting Board of the United States* (Washington, DC: Government Printing Office, 1920); David van Keuren's, "*Science, Progressivism, and Military Preparedness: The Case of the Naval Research Laboratory, 1915-1923"* in *Technology and Culture* (Chicago: Society for the History of Technology, 1992); and David K. Allison, *New Eye for the Navy: The Origin of Radar at the Naval Research Laboratory* (Washington, DC: Naval Research Laboratory, September 29, 1981).

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9. *New York Times*, July 13, 1915, p 1.
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12. United States, Statutes at Large, Public Laws, vol. 39 (64th Congress, first session) ch. 417, 1916, p. 570, reprinted in David K. Allison, *New Eye for the Navy* (Washington, DC: Naval Research Laboratory, September 29, 1981), pp. 27-28.

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23. Gimpel, op. cit., p. 30, note 17 cites Edison letter.

24. Albert Hoyt Taylor, *The First 25 Years of the Naval Research Laboratory* (Washington, DC: The Navy Department, 1948), p. 4.

Chapter 3

Much of the material for this chapter was derived from the two history narratives by Albert Hoyt Taylor, the ranking scientist at NRL for the Laboratory's first 25 years. One of these works, *The First 25 Years of the Naval Research Laboratory* (Washington, DC: Navy Department, 1948) is rich with broad brushstroke accounts of the research going on in the various research divisions whose number continuously grew during Taylor's tenure at NRL. This dense 75-page account also is rich with first-person, human-interest details that give some sense of what it felt like to be at NRL. The second Taylor history, Radio Reminiscences: A Half Century (Washington, DC: Naval Research Laboratory, 1948),

republished in 1960, is a nearly 250-page account about the ascent of radio technology in the decades predating NRL's commissioning and the several decades following. It is a more rambling and idiosyncratic work, but it is another good source for the early history of NRL.
Another useful source was Herbert Gimpel's 580-page *History of NRL*, which was completed in the mid-1970s as part of NRL's 50th anniversary in 1973. Though typeset, the massive work was never published.

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12. Timothy Coffey, personal communication in which Coffey recalled Charles Townes telling him about the highly rated work; see also H. Henry Stroke (editor), *The Physical Review: the First Hundred Years (A Selection of Seminal Papers and Commentaries)*, American Institute Press (New York: 1995).
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29. Materials Science and Technology Division, History (Washington, DC: Naval Research Laboratory, 1993), Robert Mehl recalls his NRL years in a letter reprinted on pp. 89-95.
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32. Ibid.
33. Ibid., p. 92.
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36. Ibid., p. 93.
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38. Gimpel, op. cit., p. 45; Taylor, *25 Years*, pp. 13 and 24.
39. Bichowsky in Gibbs, op. cit., p. 61.
40. Ibid., p. 62.
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42. Ibid., pp. 65-66.
43. Ibid., p. 66.
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6. Leo Young, quoted by Allison, op. cit., p. 61.
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21. Ibid., note at bottom of p. 38.
22. The following radar story relies heavily on David Allison's wonderful, thorough account in *New Eye for the Navy*.
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Chapter 5

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8. Interestingly, the Army would draw on these negative results when it returned to the possibility of using artificial light to camouflage airplanes during World War II. The Army's Air Corps wanted its torpedo-hunting planes to get within 30 seconds flying time of a surfaced submarine before being detected by vigilant lookouts. At this time, radar equipment was still crude enough that submarines still relied on human lookouts. Since the torpedo-hunters would approach a submarine head-on, the Army wondered if only the front end of the plane needed lighting instead of the entire fuselage. Research conducted under the auspices of the powerful wartime research coordinating organization known as the National Defense Research Committee ended up proving the principle with test flights. By that time, however, radar technology had progressed to the point of rendering the illumination irrelevant as a concealment tactic. (*AAHS Journal*, **15**(4), 25-262). As in the living kingdom, the principles of evolution describe the survival or disappearance of new technological species.
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I also relied heavily on a small but extremely valuable scholarly literature centered on NRL. Long and short works both by professional historians and NRL researchers fall under this category. In addition to these sources, I have consulted many official NRL reports and memoranda available at the NRL library as well as the annual *NRL Reviews*, which provide year-at-a-time snapshots of NRL's research portfolio. Moreover, NRL has published many booklets, pamphlets, press releases, and other special publications that have come in handy. To these, I have added several dozen of my own interviews, and many additional documents, letters, and other items harvested from these contacts via phone, e-mail, and other means.

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Acronym Glossary

ABM—Antiballistic Missile
ACG—Airborne Coordinating Group
AFFF—Aqueous Film Forming Foam
AFOSR—Air Force Office of Scientific Research
APL—Applied Physics Laboratory
ARO—Army Research Office
ARPA—Advanced Research Projects Agency
ASW—Antisubmarine Warfare
ATM—Asynchronous Transfer Mode
BMDO—Ballistic Missile Defense Organization
BuAir—Bureau of Aeronautics
BuEng—Bureau of Engineering
BuOrd—Bureau of Ordnance
Calsphere—Calibration Sphere satellite
Cal Tech—California Institute of Technology
CAMS—Central Atmosphere Measurement System
CFCs—Chlorofluorocarbons
CIA—Central Intelligence Agency
CIW—Carnegie Institution of Washington
CMR—Communication Moon Relay
CNN—Cable News Network
CNO—Chief of Naval Operations
CRADA—Cooperative Research And Development Agreement
CRD—Coordinator of Research and Development
CRG—Combined Research Group
C^4I—Command, Control, Communications, Computers, and Intelligence
DARPA—Defense Advanced Research Projects Agency
DF—Direction Finding
DNA—Defense Nuclear Agency
DoD—Department of Defense
DoE—Department of Energy
DoT—Department of Transportation
ELINT—Electronic Intelligence
EW—Electronic Warfare
FAA—Federal Aviation Administration
FOSS—Fiber Optic Sensor System

GeV—Giga electron volts
GMR—Giant Magnetoresistance
GPS—Global Positioning System
HANE—High Altitude Nuclear Effects
HRTS—High Resolution Telescope and Spectrograph
HTSC—High Transition-temperature Superconductor
IDM—Improved Data Modem
IFF—Identification: Friend or Foe
IGY—International Geophysical Year
IOM—Institute of Medicine
JHU—Johns Hopkins University
JPL—Jet Propulsion Laboratory
km—kilometer
kHz—kilohertz
LASCO—Large Angle and Spectrometric Coronagraph
Laser—Light amplification by the stimulated emission of radiation
LEO—Low-Earth Orbiting Satellite
LIPS—Livly Plume Shield
LLNL—Lawrence Livermore National Laboratory.
LOFTI—Low Frequency Trans-Ionospheric satellite
MAD—Multiple-Wavelength Anomalous Dispersion - also Mutually Assured Destruction
MATT—Multi-mission Advanced Tactical Terminal
MBE—Molecular Beam Epitaxy
Mc—Megacycles
MeV—Mega Electron Volts
MHz—megahertz
MIT—Massachusetts Institute of Technology
NAA—National Aeronautics Association
NACA—National Advisory Committee for Aeronautics
NAREC—Naval Research Computer
NASA—National Aeronautics and Space Administration
NAVSPASUR—Naval Space Surveillance System
NBS—National Bureau of Standards
NCARAI—Navy Center for Applied Research in Artificial Intelligence
NCB—Naval Consulting Board
NCST—Naval Center for Space Technology
NDRC—National Defense Research Committee
NOARL—Naval Oceanographic and Atmospheric Research Laboratory
NORAD—North American Aerospace Defense Command

NORDA—Naval Ocean Research and Development Activity
NRL—Naval Research Laboratory
NRO—National Reconnaissance Office
NSA—National Security Agency
NSWC—Naval Surface Warfare Center
NSF—National Science Foundation
ONR—Office of Naval Research
ORI—Office of Research and Inventions
OSRD—Office of Scientific Research and Development
PAMOR—Passive Moon Relay
PPI—Plan Position Indicator
R&D—Research and Development
RAC—Research Advisory Council
Radar—Radio Detecting and Ranging
RBOC—Rapid-Blooming Offboard Chaff
RRL—Radiation Research Laboratory
SDI—Strategic Defense Initiative
Solrad—Solar Radiation
SOHO—Solar Heliospheric Observatory
SPASUR—Space Surveillance
SUSIM—Solar Ultraviolet Spectral Irradiance Monitor
TEWD—Tactical Electronic Warfare Division
TRAP—Tactical Recovery of Aircraft Personnel
TRE—Tactical Receiver Equipment
UHF—Ultrahigh Frequency
US—United States
UTE—Underwater Tracking Equipment
UV—Ultraviolet
USNC—United States National Committee
U^{235}—Uranium 235 (an isotope of the element)
U^{238}—Uranium 238 (an isotope of the element)
VHF—Very High Frequency
WAVES—Women Accepted for Volunteer Emergency Service
WWI—World War I
WWII—World War II

Appendix

Military Directors and Commanding Officers

RADM William S. Smith	September 13, 1921	September 15, 1921
CAPT Edward L. Bennett	December 21, 1921	August 24, 1924
CAPT Paul Foley	September 2, 1924	July 15, 1926
CAPT David E. Theleen	July 15, 1926	July 22, 1930
CAPT Edward J. Marquart	July 22, 1930	November 17, 1930
CAPT Edgar G. Oberlin	February 18, 1931	March 2, 1932
CDR Edmund D. Almy	March 2, 1932	May 15, 1933
LCDR Wilbur J. Ruble (Acting)	May 15, 1933	June 30, 1933
CDR James B. Will (Acting)	June 30, 1933	September 5, 1933
CAPT Halford R. Greenlee	September 5, 1933	May 14, 1935
CDR James B. Will (Acting)	May 14, 1935	June 17, 1935
CAPT Hollis M. Cooley	June 17, 1935	September 12, 1939
RADM Harold G. Bowen	October 9, 1939	November 5, 1942
RADM Alexander H. Van Keuren	November 23, 1942	November 1, 1945
CAPT Henry A. Schade	November 1, 1945	January 31, 1949
CAPT Frederick R. Furth	February 1, 1949	June 9, 1952
CAPT Willis H. Beltz	June 9, 1952	March 29, 1955
CAPT Samuel M. Tucker	March 29, 1955	May 15, 1956
CAPT Peter H. Horn	May 15, 1956	July 1, 1959
CAPT Arthur E. Krapf	July 1, 1959	May 29, 1963
CAPT Bradley F. Bennett	May 29, 1963	January 29, 1965
CAPT Thomas B. Owen	January 29, 1965	May 29, 1967
CAPT James C. Matheson	May 29, 1967	June 30, 1970
CAPT Earl W. Sapp	June 30, 1970	July 16, 1973

CAPT John T. Geary	July 16, 1973	June 30, 1976
CAPT Lionel M. Noel	June 30, 1976	July 31, 1978
CAPT Edward E. Henifin	July 31, 1978	September 4, 1981
CAPT John A. McMorris, II	September 4, 1981	October 26, 1984
CAPT James P. O' Donovan	October 26, 1984	October 30, 1986
CAPT William C. Miller	October 30, 1986	August 26, 1987
CAPT William G. Clautice	August 26, 1987	June 2, 1989
CAPT John J. Donegan, Jr.	June 2, 1989	February 22, 1991
CAPT Paul G. Gaffney, II	February 22, 1991	April 28, 1994
CAPT Richard Cassidy	April 28, 1994	January 26, 1996
CAPT Bruce W. Buckley	January 26, 1996	Present

Civilian Directors of Research

Edward O. Hulburt	1949 to 1955
Oscar T. Marzke	1956 to 1957
Robert M. Page	1957 to 1966
Alan Berman	1967 to 1982
Timothy Coffey	1982 to present

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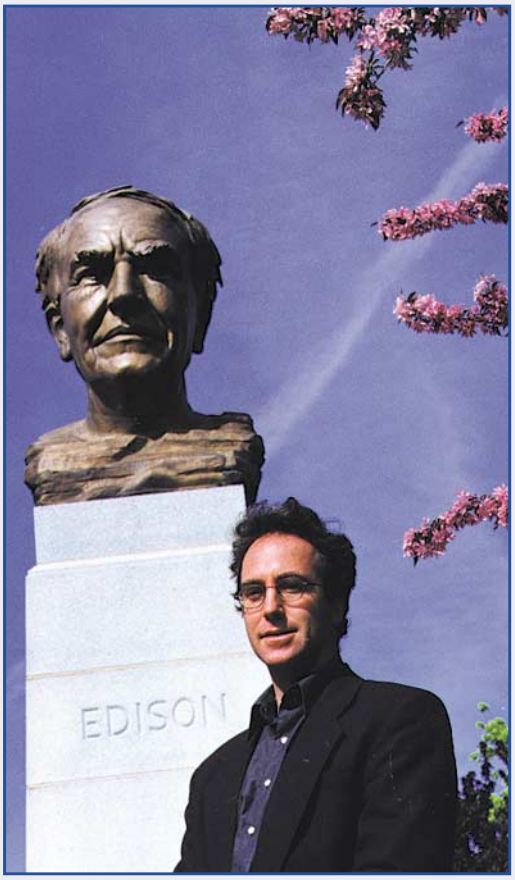

Ivan Amato is an award-winning science writer whose articles have appeared in many newspapers, including the *Washington Post*, *San Francisco Examiner*, *Los Angeles Times*, and *Baltimore Sun*, and in many magazines including *Fortune*, *Time*, *Scientific American*, *Science*, and *Science News*. His work also has been heard on National Public Radio. Amato's first book, *Stuff: The Materials the World is Made of*, came out in 1997. He lives in Silver Spring, Maryland, with his wife and two sons.

Jacket design by Jan Morrow/NRL
Jacket water color by Rob Sprouse/RLS Illustration
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The Naval Research Laboratory in 1923
viewed from the Potomac River

and

the Laboratory in a more recent year
looking toward the Potomac River