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A Report on the Relevance of the Second Law of Thermodynamics to Energy Conservation

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ABSTRACT

This is a study of the relevance to Federal energy conservation programs of the use of the concept of energy efficiency as being the ratio of the minimum available work necessary for accomplishing a given task to the available work in the actual fuel used to accomplish this task. Included within the study is a review of selected elements of thermodynamics and efficiency concepts, and identification of the technology pertinent to energy conservation programs. The study examines the potential benefits, if any, that would accrue from the application of Second Law of Thermodynamics principles to these technologies. Results indicate the positive value of the Second Law analytical techniques in the planning and design stages of system development, and the rather limited value of its use during the performance monitoring stage. Needs for advancing the acceptance and use of the Second Law analytical techniques are identified.

Key words: Availability analysis; energy conservation; energy; process efficiency, Second Law of Thermodynamics; system efficiency

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I. INTRODUCTION

Section 683 of the National Energy Conservation Policy Act (NECPA), Pub. L. 95-619, directed the Secretary of Energy to conduct a study of the "relevance to energy conservation programs of the use of the concept of energy efficiency as being the ratio of the minimum available work necessary for accomplishing a given task to the available work in the actual fuel used to accomplish that task" (hereinafter referred to as the "study" or the "Second Law Study"). This concept of energy efficiency is based on the First and Second Laws of Thermodynamics.

The National Bureau of Standards (NBS) conducted this study for the Department of Energy (DoE). Staff members at NBS carried out a qualitative assessment of the benefits of applying the Second Law of Thermodynamics concepts to the various energy technologies which comprise the energy conservation programs that are specified in Section 683 of NECPA. The discussion and results of this effort are covered in Volume 1 of the the DoE report to Congress (DoE/CS/40178.000-01) of January 1980. NBS also contracted with a private firm specializing in Second Law analyses to conduct detailed technical analyses. The contractor's report consisting of a quantitative analyses of selected technology systems and generalized conclusions are presented in Volume 2 of the same DoE report. This NBS report is a rewrite of Volume 1. It contains a modest elaboration of the thermodynamics background and is oriented towards a slightly more technical audience. Although the conclusions are generally identical to those in the DoE report, it is hoped that the technical discussion is more precise and explicit. (A format identical to Volume 1 has been maintained for ease of comparison.)

The energy conservation programs addressed in this study include (1) those authorized in the Energy Policy and Conservation Act (EPCA), Pub. L. 94-163; the Energy Conservation and Production Act (ECPA), Pub. L. 94-385; and NECPA;

and (2) appropriate Federal programs in energy research, development and demonstration.

The process of establishing the relevance of the Second Law of Thermodynamics to these energy conservation programs includes reviewing the elements of thermodynamics and efficiency concepts, identifying the technologies pertinent to energy conservation programs* and finally establishing what particular benefits, if any, would accrue from application of Second Law principles to these technologies.

In particular, consideration has been given as to how the analytical techniques based on the Second Law of Thermodynamics might be useful in:

(1) planning and setting of research priorities (i.e. the assessment of technologies for investment, management, regulatory, or policy purposes)

(2) design, analysis and testing of components or systems

(3) monitoring or rating of operating systems

With reference to each of these questions, sample energy systems from the following five major energy technology groups were considered:

(1) industrial processes which involve the generation of process steam as applied to the manufacture of chemical products, paper, and allied products, food products, transportation equipment, machinery and textiles;

(2) industrial systems which involve direct heating as applied to the processing of primary metals, fabricated metals, stone, glass and clay products, petroleum and coal products;

(3) transportation;

(4) generation of electrical power; and

(5) building, heating, ventilating and air conditioning systems.

* Only those aspects of energy conservation programs that deal with "more efficient use" have been considered. The curtailment aspects of the programs were not considered relevant to this study.

The methodology utilized in conducting this study is presented in Section 2. Section 3 presents the technical background of the pertinent elements of thermodynamics and the legislative background of Federal energy conservation programs. The analyses and conclusions of the study are the topics of Sections 4 and 5.

II. METHODOLOGY

This section addresses the methodology employed in assessing the relevance of Second Law analyses to the research, development and demonstration programs of the Federal Government that are related to energy conservation. The study methodology involved examining actual examples of the use of Second Law analysis and hypothetical applications of its use in Federal energy conservation programs. Its relevance was assessed using a simple evaluation scheme.
In principle, analyses based on the Laws of Thermodynamics are relevant to all systems in which energy is an important factor. But this does not mean that those analyses always will be useful. Relevance must be defined in a more limited sense for the purpose of this study.

Typically, the criterion used to establish the relevance of an analytical tool to application in a particular area is that its benefit-cost ratio is favorable relative to other available tools. This may mean providing the same information that other tools do but more quickly, with less effort or at a lower cost; or, it may mean the tool in question provides new or additional information, the value of which is greater than the costs associated with its use. Energy analyses based on the Second Law of Thermodynamics clearly must fall within the latter of these categories if they are to be practical. (This assertion will become clearer on review of the next section of this report.) Therefore, the criterion used in this study for assessing the relevance of Second Law analyses to energy conservation programs is the following:

> Will Second Law analysis provide data, information, or insights of sufficient value or benefit beyond those obtained using "conventional" energy analysis techniques in relation to its cost to warrant its use?

This general question is answered and the rationale for the different answers for various energy conservation programs and generic classes of potential use is presented. In each case, one of three alternative levels of relevancy is given; i.e., Second Law analysis is useful, or is of limited applicability, or is not beneficial when considered in light of the above question.

As part of this study, an advisory team[1] of in-house thermodynamicists was formed of which the authors of this report were a part. A literature survey was conducted to obtain a cross-section of the various applications of these analytical techniques. Close liaison was maintained with the staff of General Energy Associates who conducted the study presented in Volume 2 of the DoE report. NBS staff members also discussed the subject with several authorities on the application of the Second Law and with representatives of various sectors of industry including an ad hoc technical committee of the Chemical Manufacturers Association. During the period this study was conducted, two professional meetings specifically oriented toward Second Law analytical techniques were held. In December 1978, one of the team members organized and chaired a panel of experts from industry and the university sector to discuss the practical value of using Second Law techniques. This discussion was conducted at the Winter Annual Meeting of the American Society of Mechanical Engineers. In August 1979, several team members attended a Workshop on the Second Law of Thermodynamics held at George Washington University in Washington, D.C. Over twenty-five experts from the United States and Europe presented technical papers of various systems analyses based on Second Law techniques[2]. Dr. Frederick Costello, a private consultant who had previously conducted a study using Second Law

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1. Dr. Max Klein, Senior Scientist of the Thermophysics Division, Dr. Kenneth Kreider, Chief of the Thermal Processes Division, Dr. Preston McNall, Chief of the Building Thermal Performance Division, and the authors.

2. The proceedings of that meeting may be obtained from Dr. Ali Cambel, School of Engineering, George Washington University, Washington, D.C.

analysis for the American Gas Association, participated in the early stages of this study. Professor Richard A. Gaggioli, Marquette University made a detailed review of a draft of this report and offered many useful suggestions.

III. BACKGROUND

A. Technical

In this section several terms used throughout the report are described. The first few are technology terms: energy conservation, energy consumption, sources of energy and feedstocks. These apply to conventional materials used in industrial systems. Then, the thermodynamic basis for quantifying the use of energy sources is explained in terms of internal energy, useful work (availability) and entropy. Next, measures of efficiency are described. Finally, the scope, application and limitations of energy analysis are treated in the context of what is practical and the broader analysis that includes cost, limitations imposed by materials and social factors.

A.1 Energy Sources

Energy conservation, as the term is commonly used and as it is used in this report, has as its goal the more efficient use of sources of energy. This means (a) using less of a source of energy to do a particular job, (b) doing several tasks (concurrently or sequentially) with the same portion of the source, or, (c) using a different source, one more closely matched to the task. An example of (a) is savings resulting from the use of better insulation. Use of process steam both for the generation of electricity or work and then for heating illustrates (b). Use of a low temperature heat source for space heating is an example of (c).

Energy consumption means using the energy stored in a source. More correctly, it means converting the stored energy (chemical, gravitational, magnetic, etc.) to some other, desired form (often heat or work). Neither of these definitions of conservation or consumption should be confused with thermodynamic statements about the conservation of energy, discussed below.

The sources of energy of principal concern here are fossil fuels, biomass, nuclear reactions, geothermal reservoirs, falling water, wind and solar radiation. Sources of energy are rated (and bought and sold) in terms of the energy released by them in certain common standardized processes, for example, the heat released during the combustion of fossil fuels when burned in a constant volume calorimeter at 25°C. Most of the energy from these sources is provided indirectly through conversion to provide heat (thermal energy), work (mechanical energy) or electricity. The nearly direct production of electricity is a special case (fuel cells, photoelectric cells); most electrical generation is done in a secondary process by application of heat to a fluid that produces work (as in a turbine) to drive a generator.

Feedstocks are the raw materials converted to desired products by the processing industries. Often they are distinct from fuels, as for example, iron ore used to make steel. But occasionally they are not, as in coal gasification where part of the coal is reacted with water to produce low BTU gas at a high temperature maintained by burning the rest of the coal. The petrochemical industry is based on converting a fuel, oil, to a variety of chemicals.

A.2 Thermodynamic Quantities

The science of thermodynamics is a rigorous, mathematically consistent treatment of energy changes. It is the technical field which encompasses the laws that describe the nature of energy, its behavior and its associated properties of materials. Two thermodynamic properties of materials, internal energy and entropy, are essential to the understanding of energy analyses. Only changes in these properties are pertinent to energy analysis. Changes in internal energy of a system are directly related to the heat and work produced or absorbed. Internal energy changes are specified by the First Law of Thermodynamics. Changes in the entropy are directly related to the extent to which a process will run under specified external constraints.

Entropy is defined by the Second Law of Thermodynamics. Measures of useful work are obtained when the changes in internal energy and entropy are combined. These combinations are meant when the term "second law analysis" is used.

The <u>energy</u>, or more precisely the internal energy of a system is a thermodynamic property upon which all analyses discussed later depend. This property cannot be measured. However, changes in the energy of a system are measurable. (A system is any microcosm of interest, ranging from a simple laboratory experiment to an industrial plant to the universe.) The change in energy of a system, ΔU, when that system goes from one physical state to another is defined by the <u>First Law of Thermodynamics</u> as

$$\underbrace{\Delta U}_{\text{change in energy}} = \underbrace{Q}_{\text{heat absorbed}} - \underbrace{W}_{\text{work done}}$$

Energy has two important properties. First, the energy of a system is a function of the present state of the system and does not depend upon how the system got there. If the temperature, pressure, material composition and, if need be, gravitational potential, etc., are specified, then the internal energy is fixed. This means that the change of energy of a system accompanying a process can be determined without knowing the details of the process. Only the properties of the system before and after the process need to be known. For example, the change in internal energy of one kilogram of water when heated from 20°C and one atmosphere pressure to 350°C and 165 atmospheres (where it is steam) depends only on the properties of the initial water and the final steam. This change can then be compared to the amount of an energy source used to produce the change, in order to calculate the efficiency of the actual process.

The second important property of energy is that it can be converted from one form (chemical, mechanical, thermal, etc.) to another but it cannot be destroyed. This is the thermodynamic statement of conservation of energy. This leads to an accounting principle used in energy analysis. The total energy in a system before a process begins is equal to the total energy present afterwards. Energy conservation measures aim at maximizing the energy in useful products of the process. Consider the production of electricity. Fossil fuel is burned to produce hot gases which convert water to steam at high temperature and pressure. The steam drives a turbine (mechanical work) coupled to a generator that produces electricity. The initial store of energy that was in the fuel is present afterwards in the electricity, waste heat and the combustion products. Contrast this statement to the energy conservation question: how much fuel must be burned to produce a certain amount of electricity? This question implies that the only useful output of the process is the electricity, which, of course, is correct if electricity is the only <u>desired</u> output. The electricity is only a fraction ($\approx$35%) of the input energy and thus the efficiency of the process is less than 100 percent.

<u>Heat</u> and <u>work</u> are energy in transit from one material to another. Heat flows from a hotter body to a cooler one, raising the internal energy of the latter. Work causes a mechanical change, seen most easily in the raising of a weight, winding of a spring, or deformation of a material.

<u>Useful work</u>. An accounting of the energy changes accompanying a process does not reveal the maximum useful work that can be done by a system. This can be appreciably smaller than the total energy change, particularly if there are steps in the process driven by the application of heat. The thermodynamic limiting value for the maximum useful work is controlled jointly by energy and entropy changes. (Entropy is further described below. It, like energy is a function of only the present state of the system. But, unlike energy, the total entropy is not conserved in natural processes. It tends to increase).

Various terms are used in engineering practice to describe this maximum useful work concept and to calculate a value. Common ones are availability, exergy, essergy, lost work, potential work and potential energy (1, 2). Their definitions differ but their essential content is the same. Availability is the term used in this report. It is defined as the maximum work that can be done by a system when it changes from its initial state to complete equilibrium with the terrestrial environment. In terms of thermodynamic quantities the availability of a system, B, is defined as

$$B = (U_i - U_f) + P_o(V_i - V_f) - T_o(S_i - S_f)$$

where U, V, and S are the internal energy, volume and entropy of the system in the initial and final states. T_o and P_o are the temperature and pressure of some standardized terrestrial environment, as for example, 25°C and one atmosphere pressure. Unlike energy, the availability is not conserved. It decreases in any natural process.

The importance of this thermodynamic property, B, is that the thermodynamic limiting value for the work that a system could do can be calculated from the properties of the system itself. Because B involves entropy and because entropy is defined by the Second Law of Thermodynamics (see below), it provides a recipe for the quantitative application of the Second Law of Thermodynamics to industrial systems.

Although this discussion is in the context of the maximum work that a system could do, exactly the same limit is reached when one calculates the minimum work required to produce the reverse of the process considered. This is the basis of the statement in the Introduction quoted from the National Energy Conservation Policy Act.

Entropy is a property that specifies the feasibility of a process: the direction in which it will run spontaneously and how far it will run before reaching equilibrium. It is a quantitative statement about the tendency of liquids to mix, solids to dissolve, gases to expand and fill the available volume. In a very general sense, the change of entropy measures the change of randomness in the system--both mixing of materials and spreading of thermal energy. For a natural, spontaneous process in a closed system, entropy and randomness increase.

Entropy is defined by the Second Law of Thermodynamics as being a function of the state of the system. Entropy change is defined in terms of the most efficient, reversible process as $dS = (dq/T)_{rev.}$ here dq is the infinitesimal absorption of heat at temperature T in the process. When no heat is absorbed, dS is zero for a reversible process and is greater than zero in a natural process (as for a chemical reaction occuring in an insulated bottle).

There are two classical statements of the Second Law of Thermodynamics which are a generalization of experiences with the heat engine and its exact opposite the refrigeration machine (i.e. heat pump). These statements may be written as:

(1) It is impossible to construct a machine, operating in cycles, which will produce no effect other than the absorption of heat from a reservoir and the conversion of that heat to an equivalent amount of work.

(2) It is impossible to construct a machine, operating in cycles, which will produce no effect other than the transfer of heat from a cooler to a hotter body.

A.3 Measures of Efficiency

The energy efficiency based on the First Law of Thermodynamics, η, is the ratio of the energy transferred to the desired products to the energy applied. For example:

$$\eta = \frac{\text{heat transferred to a material}}{\text{change in internal energy in the fuel}}$$

$$\eta = \frac{\text{work done}}{\text{change in internal energy}}$$

or, more generally, with a very broad interpretation of the terms

$$\eta = \frac{\text{useful energy in the desired products}}{\text{energy applied to do the task.}}$$

For example, η answers the question: what fraction of the heat released by burning a known quantity of coal is transferred to the steam produced in a boiler.

Energy efficiencies based on the Second Law of Thermodynamics take two forms. The first answers the question: what is the maximum achievable value of η for a specified process. This question is most pertinent to a component of an industrial process. The answers are particularly simple for the large class of processes that can be considered to be either heat engines or heat pumps (steam and gas driven turbines, diesel and gasoline engines, air conditioners, refrigerators, etc.). For the case of high pressure steam at a temperature T_1, driving an engine producing work with the waste steam being exhausted to the atmosphere at a temperature T_2, the maximum or Carnot efficiency is

$$\eta_{max} = (T_1 - T_2)/T_1.$$

This maximum efficiency is necessarily less than unity.

Similarily, for a refrigerator operating between temperatures T_2 and T_3 the maximum efficiency is

$$\eta_{max} = T_3/(T_3 - T_2)$$

The numerical value for this ideal heat pump efficiency (usually called coefficienct of performance) is necessarily greater than 1. Thus, $\eta = 1$ is not the measure of 100% efficiency for either of these traditional efficiency scales. A comparison of η_{actual} with η_{max} is a comparison of what has been achieved to what is achievable in a particular type of system. It shows how much room there is for improvement. An effective comparison for nine types of such heat and work systems is given in reference (13).

The second question answered by application of Second Law analysis is more general. It is: how does the theoretical least work required to accomplish the task compare with the maximum work that could have been extracted from the input energies. This comparison, often called effectiveness, ξ, is

$$\xi = \frac{\text{minimum work required to do the task}}{\text{potential work available in the inputs}}$$

or, for simple heating of a material

$$\xi = \frac{\text{minimum heat required to do the task}}{\text{heat available from the inputs}} .$$

This measure, effectiveness, is the one of primary concern in this report. Two features should be noted. First, effectiveness is independent of the way the task is actually done. Second, the inputs are rated in terms of the maximum effect they could produce, not what they could produce in the actual process were it to be run with maximum efficiency. At times this generalization leads to different answers than does η_{max}, particularly for complex systems.

In short, effectiveness is task oriented. The other measures are process oriented. Because effectiveness gives the ultimate thermodynamic limit, it has been recommended as a rational approach to the measurement of the utilization of sources of energy (4, 13). The thermodynamic function, availability, B, defined earlier, can be used to determine both the numerator and denominator of the expressions for

$$\xi = \frac{B_{min}}{B_{actual}}.$$

This general formulation is applicable to any process (13). It is particularly appropriate for complex systems that have several inputs and outputs.

Variations on this definition of effectiveness do exist and are often used for system analysis, depending on what information is desired. For example, the fact that in the theoretical limit the availability associated with the total input can be completely transferred to the total output can also be used to define an effectiveness measure (4):

$$\varepsilon = \frac{\text{available energy in useful products}}{\text{available energy supplied}}.$$

This definition relates to the actual process specifically in that both the numerator and the denominator refer to the actual system's properties and not to an idealized system. The denominator exceeds the numerator in value by the amount of availability consumed in the conversion. This definition, therefore, is particularly convenient for a basis of determining operating costs, as will be discussed later.

A.4 Energy Analysis

Energy analysis utilizing measures such as those found above treats the changes of energy and entropy in a process. It is a study of efficiency and is a major tool in developing energy conservation strategies.

The analysis of energy and materials processing is carried out on several levels of complexity in engineering practice and is used at various stages of operation in industry. Typical complexity levels are:

(a) Energy accounting based on the First Law of Thermodynamics,

(b) First Law energy accounting supplemented with a qualitative, intuitive application of the Second Law,

(c) Quantitative analysis of the availability (potential work) based on a combination of the principles of the First and Second Laws of Thermodynamics,

(d) Analysis of the dynamics of a system, combining principles of equilibrium thermodynamics, irreversible thermodynamics, physical and chemical kinetics and fluid mechanics,

(e) Any or all of the above combined with other technical considerations (e.g. reliability, safety, etc.), economic analysis and consideration of social impacts.

The first three items are of principal concern here. These energy analyses may be applied at the following stages of an energy system's life:

(a) Research and development on a new concept,

(b) Selection between different conceptual methods for performing a task,

(c) Design of an operating system to perform the task,

(d) Optimization of new or existing equipment - usually applied to specific components,

(e) Operation and control of existing systems

(f) Monitoring of performance, and

(g) Reporting of energy utilization.

All of these stages are of interest when methods of energy analysis are being compared; but the value of a specific analysis method may vary for the different stages as well as for different systems.

Many efficiency analyses conducted today are done on a First Law basis with a qualitative awareness of the Second Law concepts. This awareness means that it is understood not only the quantity of energy but also its quality (potential level) are important. For instance, in order to achieve high Second Law efficiency one should match the temperature of heat source to that of the heated material as closely as possible. Also, one should arrange that the inevitable heat rejection from the system should be done at a temperature as close to ambient as possible. Lack of an understanding of this principle is responsible for some of the misconceptions held by the general public about the everyday energy systems. For example, it is commonly believed that home heating is an efficient use of fossil fuel combustion and that fossil fuel fired electric power plants are relatively wasteful because they reject large amounts of energy to the atmosphere. In the first case, the large difference between the furnace combustion temperature (≈3500°F) and the temperature of the hot air (≈120°F) means that there is an ineffective use of the fuel since the energy of the high temperature of combustion could be used to produce some mechanical work before delivering the heat (cogeneration). In the latter case, the fact that power plants reject large amounts of heat is inevitable because they are producing large amounts of electric power from a high temperature heat source. What is important is that the temperature level at which the heat is rejected is relatively low and therefore the heat is virtually useless except for applications at even lower temperatures (e.g. space heating). The inefficiency that the power plant does have is again a result of the large difference (although not as large as the home furnace) between the combustion and utilization (steam) temperatures.

Availability analysis, which is based on both the first and second laws, is a formal energy accounting procedure which considers the potential level of each energy stream as well as the quantity. It is concerned with the work that can be done by a perfectly efficient process. For every system there is a maximum fraction of the input energy that can be converted theoretically to work. Anytime there is a decrease in the quality of thermal energy (e.g. that due to the difference between a furnace's combustion temperature and the house heating system's supply air temperature) without an extraction of useful work there is a net loss of availability for the system. Whereas energy is always conserved, availability is destroyed in a natural process. The amount of availability destruction is used as a basis for measuring the processes efficiency.

A.5 Applicability and Limitations of Energy Analysis Methods

Both simple energy accounting and availability analysis can be applied to a complex process, treating the process as a "black box" and considering only inputs and outputs. Thus both can be used for monitoring at a plant or industry level. Both methods can be applied to individual steps in a complex process. Availability analysis gives a better guide to where improvements are possible. It is particularly applicable to the design (or redesign) phase of an industrial process. However, for some cases both methods give substantially the same result. This must be determined by detailed analyses of typical processes. When this has been determined for test cases the simplicity of First Law analysis is to be preferred. Although both methods can be used to assess the needs for developing new processes or to select among possibilities, the Second Law approach provides a better comparison in this application. In one form or another it is essential to understand the Second Law implications in planning stage of an industrial system [3, 4].

When applying any of the energy analysis techniques it is imperative that the system be well defined and the thermodynamic properties of the inputs and outputs be known. For application of a First Law analysis this means that the thermodynamic property, internal energy, must be known for the fuels, feedstocks and products. For the Second Law application another property, entropy, must be known. This property is more difficult to obtain. There are larger gaps in the data bank of this property than for internal energy. This is a practical limitation, one that should become less important in the future. This is not a limitation today for the most significant industrial case, the generation and use of steam, simply because an immense amount of careful work has been done to establish the properties of steam [5]. There also is a large body of data for metallurgical systems. However, for many chemicals neither of these properties is known and for others the energy is known but the entropy is not. Where these essential properties are not known the technique either can not be applied or estimates of their values must be made. There is a need for better methodologies for predicting thermochemical properties and an even greater need for making them widely known in the engineering community.

Efficiency analysis, based on the First Law only, may usually be used for comparing the relative performance of similar systems that are producing an identical product or energy output. Energy analyses of different systems, which are producing different products, are more difficult to intercompare [6]. Usually a Second Law analysis of some form must be used to establish a maximum performance limit. It is then possible to compare the respective ratios of theoretical to actual performance for each system and determine which is closer to ideal performance.

However, comparison of different systems on the basis of energy efficiency can be misleading. Energy efficiency is only part of the story. Improving the performance of a comparatively poor system may be impractical for various technical reasons: process technology, strength of materials, requirements for high rates of production, inability to control combustion temperatures, corrosion, pollution, etc. In addition, energy performance is often subordinate to economic and social considerations [7].

Much of what has been said above can be understood fairly easily if one restricts consideration to power generation systems: work out, thermal energy in. But it is much more difficult to develop a feeling for the idea of efficiency in systems where several things are happening at the same time. A case in point is materials processing. Aluminum is made from bauxite. During this process there are two streams that suffer changes in availability. The feedstock stream changes (bauxite to aluminum), with the product having a higher availability than the raw materials. At the same time the source of energy applied to the task suffers a decrease in availability. Over all, availability decreases for the combined streams. The efficiency of the process can be calculated. However, there are procedural questions that are very difficult to answer. It is possible that they can be settled only by agreement. For example, from a strict energy conservation point of view it may be immaterial that aluminum metal has a high availability that could be released by reacting it with acid to produce hydrogen. How should this availability be counted? Another ultimate disposal of fabricated aluminum is recycling it - back to the melting pot. How should account of this preservation of availability be counted in assessing the original processing? These conceptual difficulties abound, particularly for cross-industry comparisons.

In spite of these caveats, availability analysis remains important. It is availability (potential energy) not energy for which we pay. Availability is consumed in the combustion of a fuel, not energy. Therefore, everywhere that availability is destroyed in a system, due to inefficiency, the decrease in availability is a measure of what that particular inefficiency, costs the operator of the system.

An important use of availability analysis techniques has been in the quantification of life cycle costs for a system (capital and operating costs) [8, 9]. At least two types of costing applications are becoming more prevalent in engineering studies. The first is the prorating of charges for different types of energy or different potential levels of energy [14]. For example, a total energy plant, whose primary product is electric power, but also sells "waste" steam for industrial processes or building heating, has to determine the relative costs of fuel consumption and equipment amortization. One advantage (increased fairness in pricing) to using availability, as opposed to energy, is that it takes into account the by-product's temperature and pressure level. Clearly the higher these are the potentially more useful the steam is. That is, it is either able to produce more work or be used to create a higher temperature environment.

In Figure 1 (from reference [14]), the results of an analysis of a total energy plant are presented. Here "waste" steam is available at various temperatures and pressures. The energy costing line shows a price for 100°F saturated steam that is 80% of the price for steam at 250°F. In contrast the available energy costing shows that 100°F steam is worth less than 1/3 that at 250°F. Available energy costing shows the customer the value of what he is buying even if all of this value cannot be used in the immediate application.

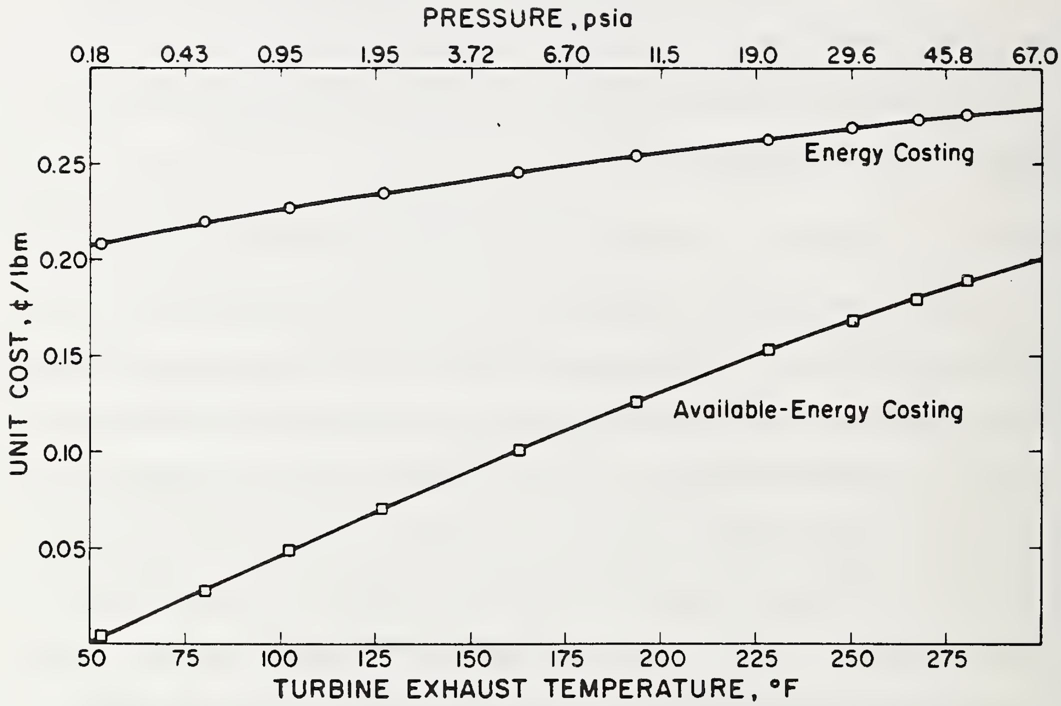

Figure 1. Cost of Cogenerated Steam
(as presented in reference [14])

Another costing application is one that may be utilized during the design phase of most any complex manufacturing system. Typically a trade-off between first cost expenditures and operating costs may be optimized so that minimum life cycle costs result. Attempts to utilize operations research techniques in conjunction with availability analysis are presently under development [10]. This combined analysis of the availability of an energy stream and its cost (in dollars) may well prove to be the most valuable contribution of the Second Law techniques.

B. Energy Conservation Programs

The purpose of this section is to describe briefly the energy conservation programs covered by this study and to note in each case the aspect of the program, if any, for which the concept of energy efficiency deriving from the second law of thermodynamics may be relevant. Section 683 of P.L. 95-619, the National Energy Conservation Policy Act, requires specifically that the following energy conservation programs be considered:

1. Those authorized in . . .
   a. Pub.L. 94-163, the 1975 Energy Policy and Conservation Act (EPCA):
   b. Pub.L. 94-385, the 1976 Energy Conservation and Production Act (ECPA);
   c. Pub.L. 95-619, the 1978 National Energy Conservation Policy Act (NECPA); and
2. Appropriate Federal programs in energy research, development and demonstration. (Principal authority in this area is Pub.L. 93-577 the 1974 Federal Nonnuclear Energy Research and Development Act.)

In general, all of these programs fall under the responsibility of the Assistant Secretary, Conservation and Solar Energy, Department of Energy, with important related roles played by other offices in DOE, other government agencies including State and local governments, and private sector organizations as well.

A number of the programs authorized by these statutes are concerned with related aspects of the same technologies within the various sectors of the energy economy. This is particularly true for DOE research, development and demonstration programs. Therefore, in the analysis (Section IV) the principal techniques associated with each sector are discussed instead of the individual programs. For example, in the area of building energy conservation, the technologies of appliances; building heating, ventilating and air conditioning systems; and total energy or cogeneration are considered instead of each of the numerous specific programs described below.

Finally, the general topic of solar energy is not explicitly addressed in this study although it is mentioned in a number of these statutes. Solar is not usually considered as an energy conservation technology, but as an alternative source. Also, as yet, no clear advantage for applying Second Law techniques to solar systems has been established. Furthermore, difficulties exist in defining an appropriate solar source temperature that will provide an equitable comparison with fossil fuel systems.

Since the technologies involved in the DOE energy conservation research, development and demonstration (RD&D) programs are essentially the same as those affected by the mandated programs, the RD&D programs are not described in the following paragraphs. What follows is a brief summary of Federal energy conservation programs by major energy-using sectors of the economy (buildings, industry, transportation, and utilities).

B.1 Energy Conservation in Buildings

Buildings account for approximately 1/3 of energy use. Thus, programs and technologies aimed at improving efficiency of energy use in new and existing buildings and associated appliances and equipment offer important contributions to the total national energy conservation effort. Legislated programs in this area include the following:

° Energy Conservation Standards for New Buildings (Pub.L. 94-385 sections 301-311). This program involves the development and implementation, "as soon as practicable, of performance standards to which new residential and commercial buildings will be designed to achieve the maximum practicable. improvements in energy efficiency and increases in the use of nondepletable sources of energy." DOE's proposed standards were issued for public comment on November 14, 1979 (44 FR 68120 [November 28, 1979]). The standards will require new buildings to meet specific design energy budget levels measured in terms of thousands of Btu's per square foot per year. Because they are performance, instead of component standards, designers and builders will retain flexibility in choosing designs which achieve significant energy savings. In developing these standards, DOE is carrying out extensive research and technology development efforts which will significantly advance the state-of-the art for the energy efficient design of new buildings.

° State Energy Conservation Plans (Pub.L. 94-163, sections 361-366; Pub.L. 94-385, sections 431-432; Pub.L. 95-619, sections 621-623). This program lays out the requirements that State energy conservation plans must meet to be eligible for Federal assistance. They include mandatory lighting efficiency standards for public buildings, mandatory standards and policies relating to energy efficiency in procurement practices, and mandatory thermal efficiency standards and insulation requirements for new and renovated buildings. The mandatory lighting efficiency standards which have been developed by DOE are expressed in terms of illumination requirements for various types of activities within buildings. Thermal efficiency standards and insulation requirements are expressed in engineering units in a form consistent with the building energy conservation standards described above and other standards widely used in current practice (for example, the American Society for Heating, Refrigerating and Air-Conditioning Engineers' Standard 90-75).

° Weatherization Assistance for Low-Income Persons/Families (Pub.L. 94-385 sections 411-422; Pub.L. 95-619, sections 231-233). The purpose of this program is to develop and implement procedures to assist low-income persons in achieving the prescribed level of insulation in the dwellings. This is a financial assistance program. DoE's regulations for this program are required "to achieve a balance of a healthy dwelling environment and maximum practicable energy conservation." The weatherization materials eligible under this program include, for example, caulking and weather-stripping, certain furnace modifications, clock thermostats, ceiling/attic/wall/floor/duct insulation, and "such other insulating or energy-conserving devices or technologies as the Administrator may determine by rule." DoE and others have conducted a series of analyses to determine the energy conservation effects of such weatherization measures.

° Residential Conservation Service Program (Pub.L. 95-619, sections 210-225, 10 CFR Part 456 [1979]). This program requires large electric and gas utilities and, on a voluntary basis, urges oil dealers to inform customers of suggested measures for energy conservation and uses of renewable resources and to provide estimates of the energy savings and costs of such measures. These measures include insulation, storm windows and doors, caulking and weatherstripping, replacement air conditioners, furnace efficiency modifications, clock thermostats, solar hot water heaters, and solar space heating systems. These programs are to be initiated in 1980. Here again, the principal technical issues include identifying the appropriate standards necessary for safe and effective installation of the program measures and determining which measures are appropriate for use for a given location and category of building.

° Energy Conservation in Schools and Hospitals (Pub.L. 95-619, sections 301-312). This program involves grants "to States and to public and non-profit schools and hospitals to assist them in identifying and implementing energy conservation maintenance and operating procedures and in evaluating, acquiring, and installing energy conservation measures to reduce the energy use and anticipated energy costs of schools and hospitals." As with the Residential Conservation Service, this program involves explicitly defined energy conservation measures. These include insulation, storm windows and doors, automatic energy control systems, furnace or utility plant and distribution system modifications, energy recovery systems, cogeneration systems, "such other measures as the Secretary identifies by rule," and "such other measures as a grant applicant shows will save a substantial amount of energy and are identified in an energy audit."

° Energy Conservation and Measurement in Federal Buildings (Pub.L. 94-163, section 318, Pub.L. 95-619, sections 501-551). These programs involve efforts to improve efficiency of energy use in new and existing Federal buildings and facilities and to encourage the use of renewable resource systems in them. In particular, it is the purpose of these programs to promote the use of commonly accepted methods to establish and compare the life-cycle costs of operating Federal buildings and the life-cycle fuel and energy requirements of such buildings with and without special features for energy conservation and " . . . the use of solar heating and cooling and other renewable energy sources in Federal buildings."

° Appliance Labeling and Minimum Efficiency Standards (Pub.L. 94-163 sections 321-339; Pub.L. 95-619, sections 421-427). This program is aimed at improving the efficiency of a variety of home appliances including refrigerators and refrigerator-freezers, freezers, dishwashers, clothes dryers, water heaters, room air conditioners, home heating equipment, kitchen ranges and ovens, clothes washers, central air conditioners, furnaces, etc. DOE has developed test methods presently used for the energy efficiency labeling of appliances under regulations of the Federal Trade Commission. "Energy efficiency" is defined in terms of the "ratio of the useful output of services from a consumer product to the energy use of such product." DOE, prior to NECPA enactment, developed efficiency improvement targets for these appliances. The National Energy Conservation Policy Act presently requires the development of energy efficiency standards for 13 categories of appliances. Further, the Department of Energy has the authority to expand the list to cover other major appliances meeting statutory criteria.

B.2 Industrial Energy Conservation

Industry accounts for over 40 percent of energy used in the U.S. The effect of increased fuel prices and altered patterns of fuel availability has stimulated many commercial and industrial firms to improve the efficiency with which they use energy. Mandated programs in this area include the following:

° Industrial Energy Conservation (Pub.L. 94-163, sections 371-376: Pub.L. 95-619, section 601). This program is designed to "promote increased energy efficiency by American industry." This program requires each corporation which consumes at least 1 trillion British Thermal Units (one terajoule) of energy per year and is within one of the twenty major energy-consuming industries identified by DoE to report annually to the Secretary of Energy on the progress made by that corporation in improving its energy efficiency. Further, this program requires the Secretary to establish energy efficiency improvement targets for at least the most energy-consuming industries and to apprise the Congress of the progress made toward meeting such targets.

° Industrial Equipment Energy Efficiency Pub.L. 95-619, section 441), quoted as "The purpose of this part is to improve the efficiency of electric motors and pumps and certain other industrial equipment in order to conserve the energy resources of the Nation." The types of equipment covered include compressors, fans, blowers, air conditioning and refrigeration equipment, electrolytic and electric arc equipment, steam boilers, ovens, furnaces, kilns, evaporators and dryers. This program authorizes a study to determine the practicability of requiring electric motors and pumps to meet performance standards establishing minimum levels of energy efficiency. Further, it authorizes the Secretary of Energy to conduct similar evaluations of other types of industrial equipment. It further authorizes DOE to propose test procedures and labeling requirements for any equipment for which such standards are determined to be practicable.

° Recovered Materials (Pub.L. 95-619, section 461). The purpose of this program is to conserve valuable energy in scarce natural resources by establishing targets for increased industrial utilization of recovered materials and to establish voluntary goals and incentives for this purpose. Materials explicitly covered by this program as energy-saving recovered materials include aluminum, lead, copper, zinc, iron, steel, paper and allied paper products, textiles, and rubber. In establishing these voluntary goals or targets, the technological and economic ability of each affected industry to increase progressively use of energy-saving recovered materials is to be considered.

B.3 Transportation

Transportation accounts for approximately 25 percent of energy end use. A major energy conservation program of interest in this study in this area involves:

° Automotive Fuel Economy (Pub.L. 94-163, section 301; Pub.L. 95-619, sections 401-404). This program involves the establishment of average fuel economy standards applicable to each of a number of designated automobile manufacturers. Average fuel economy is defined in terms of a fleet-weighted average for all the vehicles produced by a manufacturer in a given model year. The standards range from an average fuel economy standard in miles per gallon of 18 in 1979 to 27.5 in 1985 and thereafter.

B.4 Utilities

Efficiency of energy use in energy utilities, particularly electric power generation, but also in those producing and selling heat, is also an important element of the national energy conservation effort. A major mandated program in this area involves:

° Rate Designed Initiatives for Electric Utilities (Pub.L. 94-385, section 204). The purpose of this program is to fund regulatory rate reform initiatives. In addition, under the Public Utility Regulatory Policies Act of 1978, Pub.L. 95-617, State regulatory bodies and nonregulated utilities are required to consider 11 ratemaking and regulatory policy standards with respect to, among other things, the conservation and efficient use of resources.

IV. RELEVANCE OF SECOND LAW ANALYSIS TO ENERGY CONSERVATION PROGRAMS

The purpose of this section is to present an analysis of the relevance of analytical techniques based on the Second Law of Thermodynamics to energy conservation programs. This analysis was carried out using the methodology described in Section II, draws on the materials presented in the previous sections, on the results of the contract study carried out by General Energy Associates (Vol. 2 of DoE's report to Congress), the state-of-the art as reflected in the literature, and the judgment of the NBS reviewers. This analysis has of necessity been limited both in scope and depth by the resources available for this study. Nonetheless, it is believed that the most important and potentially relevant applications of Second Law analysis have been considered in this process. Since availability analysis and other forms of application of Second Law principles are constantly evolving and finding broader use, it should be expected that new techniques and applications will emerge in the future.

Before describing the results of the study they must be put into context. Energy analyses based on the Second Law of Thermodynamics are relevant, in principle, to the understanding, designing and optimizations for all systems in which the use of energy is important. However for some applications they may not be sufficient, for others they may be irrelevant and in some cases they may be impractical today.

Capital costs and social goals may be overriding factors. Energy analysis may be only tenuously connected to programs emphasizing financial assistance. Current technology and the lack of thermodynamic properties data may inhibit the use of Second Law based analyses. All of these factors are reflected in the judgments presented below.

A summary of the results of the analysis of the relevance to energy conservation programs of the Second Law of Thermodynamics is presented on Table 1. An account of the basis for this assessment constitutes the balance of this section. The rows of Table 1 represent the various groups of Federal energy conservation programs outlined in Section III. The titles of the various elements of each of these programs are also presented in Column 1. The second column of this table identifies potentially relevant existing energy technologies or systems considered in examining each of the major energy conservation program areas. Major technical systems or components not particularly affected by Second Law analysis are not shown. (For example, consider the area of building energy conservation. The thermal resistance of a building envelope and its design are largely functions of weather, indoor-outdoor temperature differentials, and materials properties. In this instance, Second Law analysis is of little relevance since it provides no additional useful information. Similarly, in the transportation area, transportation network configuration, traffic generation and density distributions are affected by a wide range of socioeconomic as well as technical factors and are beyond the scope of Second Law analysis techniques).

The third column of Table 1 presents the principal results of this study. This column contains three subcolumns representing the three generic situations for which the potential relevance of Second Law analysis has been considered; that is, in general planning or establishing research priorities; as a tool for system or component design, analysis, evaluation, or testing; and, finally, in the monitoring and/or reporting of system operational performance. The first of these subcolumns is analogous to the general planning stage during which background research on various technologies might be conducted to determine whether a commitment for investing in a particular technology should be made.

It also represents the type of activity in which research priorities are established for overcoming existing barriers to further development of a given technology. The second subcolumn represents situations analogous to the detailed design process which generally follows conceptual design. It includes analyses, evaluation, and testing of new or existing systems where energy optimization is one of the major criteria of a successful design. It also includes assessment of the effect of improvement of components on the overall performance of a system. The third subcolumn is concerned with existing functioning systems and their operation performance and control. Obviously, information gathered from monitoring or reporting on operating systems is used by decision makers in the other two subgroups as well as by system operators, technicians, etc. Also, measures of system operational performance generally involve a number of parameters in addition to efficiency of energy use.

The symbols inserted under each of these three headings represent judgments on the potential relevance of Second Law analyses to the general types of Federal energy conservation programs indicated. Obviously, there are many aspects of each of these energy conservation program areas for which Second Law analysis is of little or no immediate relevance--for example, in developing State energy conservation plans or in developing innovative utility rates. (In the long run there may be relevance in these areas). The energy conservation programs involving technologies of potential interest here are highlighted with an asterisk in column 1 on Table 1. The symbols shown on Table 1 relate only to those technologies such as the examples listed in column 2 for which it is appropriate to consider Second Law analysis.

Three symbols are used in this table. They are defined as follows: The Second Law analysis is . . .

△: useful. It is effective for the general purpose indicated and merits consideration for use.

☐, ☒: of limited applicability. It is generally useful and could provide some new information, but may not be practicable or practical problems may now exist in implementing the Second Law technique. (These may include institutional political, economic, or technological constraints.) Two cases are distinguished. ☒ means that Second Law analysis is applicable in a limited number of particular cases; whereas ☐ means there may be a broad range of cases where Second Law analysis is useful but for which it offers at best marginal benefits.

○: not beneficial. It would reveal no new information of practical value beyond what is revealed from conventional analysis.

Rationale

The methodology outlined in Section II was used in assigning the symbols in column 3 of Table 1. This involved first identifying the potentially relevant existing energy technologies or systems arising in the context of the various energy conservation programs listed in column 1. This produced the list of technologies or systems which follows: *

- Household appliances
- Building heating, ventilating and air conditioning systems

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* The general topic of solar has not been explicitly addressed. Solar is generally not considered an energy conservation technology. Also, lack of agreement on a definition of a meaningful reference temperature for the solar source makes availability analysis difficult to apply in a manner possible to make performance comparisons with fossil fuel systems.

- Total energy or cogeneration systems
- The automobile
- Generation and use of process steam
- Direct heating of materials in industrial manufacturing processes
- Materials processing, including extractive, recovery, refining, chemical, reforming, and fabrication, etc.
- Generation of electric power.

The potential relevance of Second Law analysis to each of these technologies as they arise in the context of the Federal energy conservation programs was reviewed in light of the contractor study report (DoE report to Congress, Vol. 2) and other relevant information as discussed in the following paragraphs. It may be apparent from Table 1 that the rationale for the potential relevance of Second Law analyses to energy conservation programs is similar for each of the technologies listed under the three subheadings of column 3. For this reason, and to avoid needless repetition, the bases for the assignment of the symbols on Table 1 is discussed in terms of each subcolumn.

Planning and Setting Research Priorities

General planning and research priority setting involve generalized analyses and decisions relating to choice of technologies, to conceptual approaches and to basic decisions affecting resource allocation. Formalized availability analyses appear to be most useful in this context. Vol. 2 of the DoE report to Congress and literature surveys have identified a number of specific examples of appropriate and effective use of Second Law analyses in conceptual design of industrial processes. For example, analytical studies have been made of the application of availability analysis to residential water heating, automobile performance, coal gasification, petroleum refining, polymerization, paper making, the glass industry, aluminum production, steel production, total energy systems, heating and air conditioning, electric power. Various authors have provided summary tables showing approximate efficiencies for industries and technologies. One study uses the results of Second Law anslyses in the formulation of energy conservation policy proposals. Also, the Office of Industrial Energy Conservation, DoE, has made use of Second Law analyses in establishing its research program priorities and in identifying areas of particular promise for potential efficiency improvement in the ten most energy-intensive industries. Historically, Second Law analysis has found its most widespread use in the system conceptual design stage. Principal examples arise in the context of total energy or cogeneration strategies which make effective use of the rather large amounts of heat that are rejected. Second Law analyses are also particularly useful in analyzing industrial heating and materials processing technologies. Chemical processing industries have utilized Second Law analyses in this context for many years.

Obviously, this is but one of a number of tools used in the planning stage, but with increasing energy prices and with looming constraints on available supplies of energy, it is one that will only increase in importance. One practical constraint on more widespread use of availability analyses in this context is the lack of thermodynamic data directly applicable to the actual conditions used in materials processing. Another is a lack of agreement on the reference states that should be used in the analysis of various types of processes. Also, it is not clear how the changes of availability in feedstocks should be handled in analyses that are concerned with the conservation of energy sources, that is, how narrowly the systems should be defined.

Also, it should be obvious that all heat rejected in one process is not equally useful in others. In many industrial systems, particularly those involving complex processes with many different energy requirements, tools such as Second Law analysis are virtually essential in achieving optimization of natural resource use.

Although Second Law analysis is somewhat less directly relevant to residential appliances and heating, ventilating and air conditioning systems, it is useful in identifying areas for potential improvement in these systems and for identifying possible practical combinations of traditionally independent functions. Current developments in heat pump technology and applications are a good case in point. Potentially beneficial technology combinations include solar energy heat pumps, ground water heat pumps, hot water heater heat pumps, and heat recovery from refrigeration for water pre-heating. Second Law analysis of overall building energy use will, in fact, point out the relative importance of the energy conversion equipment inefficiency (typically $\varepsilon < 10\%$) as compared to the more popular area of reducing building loads [13, 14].

Obviously, improved automobile efficiency is an important national goal. Considerable Federal as well as industry effort is being directed toward identification of potentially more efficient forms of automotive transport than that provided by state-of-the-art internal combustion engines. Economy in the use of transportable fuels is just one factor of concern in personal transport system design. Second Law analysis appears to be limited usefulness in pinpointing immediate targets of opportunity in various areas of automotive engine research, but could easily become more important in the future. On this basis, all areas have been assigned the symbol Δ except for automotive which has been labeled $\boxed{X}$.

Design, Analysis, and Testing of Components or Systems

Assessments of the potential relevance of Second Law analyses to design analysis or testing of energy systems and their components range from useful (i.e., $\triangle$) to limited applicability (i.e., $\square$) for the technologies and programs considered.

These assessments are consistent with the findings of the contractor's study. The contractor notes that "the second law is most appropriate in the process and system design and modification area and for component design." Detailed examples are presented in Volume 2 of DoE's report to Congress which address heat exchangers, petroleum heaters, multi-effect evaporators, and distillation processes. Examples in the area of process design include pulp mills (the Kraft process), processes for producing alkalies and chlorine, ethylene production, a number of petroleum refining processes, and primary aluminum productions are also presented. Further, the use of Second Law concepts by engineers in process design and modification has been widespread in industry for years. Thus, a $\triangle$ is assigned for the industry programs.

The potential relevance of application in the areas of building mechanical systems, appliances, and automobiles is somewhat limited because of the often overriding importance of user requirements vis-a-vis energy efficiency in the design of such systems. Also once the user requirement are defined many of the First Law figures of merit serve quite adequately for determining the relative efficiency of a component or system (i.e. miles per gallon, energy efficiency ratio). Therefore, the limited applicability symbol, $\boxed{X}$, is assigned.

As with any analytical tool, the applicability of Second Law analysis is highly situation-specific. Thus, it is difficult to generalize and, indeed, it would be inappropriate to specify its use industry-wide. The potential benefits derivable from its application depend in large part on the state of development and quality of the analytical or computerized models and basic data available to the system or component design engineer and, of course, his ability to use these tools. Indeed, increased efforts on the part of the Federal Government to help industry produce needed data and models and to develop appropriate training materials may be most effective in stimulating more widespread use of this important analytical tool.

Monitoring or Rating of Operating Systems

The essential requirement in monitoring or rating of operating system performance is to characterize performance in useful terms. The principal use of such information is in tracking the overall performance of a system or in providing essential feedback on the operation and maintenance costs of an existing system to designers of new and retrofit systems.

For a particular plant this can be done on the basis of measurements of energy consumption, products produced and operating variables. The optimum conditions can be set partially on the basis of Second Law analyses made during the design phase, but they must also consider pilot plant performance and studies made during the run-in phase of the actual system. This means that currently used measures of energy efficiency often can be considered adequate for comparing performance now with that achieved in the past for the same system. A switch to Second Law based methods would not be warranted for the purposes described above, unless more useful or important new information resulted.

When the broader picture was considered, comparison of similar systems, the conclusion in Volume 2 of DoE's report to Congress was "where the product or function is the same, present efficiency measures are adequate." In addition a warning was given that "it is inappropriate to use an availability measure to compare products or systems whose products or end functions are different." This is because more than energy efficiency is involved in such comparisons. It should be noted that these conclusions apply only to existing systems and that an entirely different conclusion has been reached for the conceptual and design phases.

Some of the diverse, situation specific efficiency measures now being used include, for example, miles per gallon for automobiles, energy efficiency ratio for appliances, measures such as Btu's per hour for HVAC systems, Btu's per pound of product in a number of industrial processes, etc. The study in Volume 2 of the DoE report to Congress reviewed 20 diverse industrial processes to examine various availability measures. The conclusion was, "We have been unable to distinguish any inherent advantages afforded by any of these measures relative to others and have been unable to observe any intrinsic insights these measures afforded in comparing different processes. As a result, the not beneficial symbol, O, usually has been assigned.

The exceptions in Table 1 all involve the case of multiple output systems. Total energy and cogeneration systems are examples of this class. In this case, system output is partly thermal and partly mechanical or electrical. Here, Second Law efficiency is useful, particularly for pricing the various outputs. A strong argument has been presented for the need to use Second Law based energy price schemes for steam and electricity from the same plant [15] for customer equity. It is even suggested [14] that the inequities of First Law based energy pricing schemes have been a principal factor in the continuing unsuccessful attempts to make total energy plants viable in the

U.S.A. Thus, it is noted in column 3 of Table 1 that Second Law analyses may offer some benefit in programs involving analyses of cogeneration and similar energy systems. Thus, the symbol, $\square$, has been assigned.

POTENTIAL RELEVANCE OF SECOND LAW TO ENERGY CONSERVATION PROGRAMS

(Column 1) ENERGY CONSERVATION PROGRAMS (*denotes programs involving technologies in column 2)	(Column 2) POTENTIALLY RELEVANT EXISTING ENERGY TECHNOLOGIES OR SYSTEMS	(Column 3) EXTENT TO WHICH 2ND LAW ANALYSIS MAY BE RELEVANT IN . . . Planning & Setting Research Priorities	Design Analysis & Testing of Component Systems	Monitoring or Rating of Operating Systems
<u>Buildings Energy Conservation</u>: *Energy conservation standards for new buildings °State energy conservation plans °Weatherization assistance °Residential Conservation Service °Energy conservation & renewable resource demonstration *Energy conservation in schools & hospitals °Energy conservation & solar energy in Federal buildings *Appliance labeling, efficiency improvement targets, & minimum efficiency standards	Heating, ventilation, & air conditioning systems Appliances Total energy or cogeneration	△ △	☒ △	○ □
<u>Industrial Energy Conservation</u>: *Industrial reporting *Industrial equipment efficiency *Recovered materials *RD&D programs	Total energy or cogeneration Process steam Direct heating of materials Materials processing	△ △	△ △	□ ○
<u>Transportation</u>: *Automotive fuel economy *RD&D programs	Automobiles	☒	☒	○
<u>Utilities</u>: °Rate design initiatives *RD&D programs	Process steam Generation of electric power	△ △	△ △	□ ○

KEY:[1] Second law analysis is . . .

△ useful

☒ means applicable in a limited number of cases,

□ means potentially of some benefit

○ not beneficial

[1] A detailed explanation of symbolism is discussed in text.

V. CONCLUSIONS AND RECOMMENDATIONS

This study has presented an analysis of the potential relevance of the use of analytical tools based on the Second Law of thermodynamics to existing Federal energy conservation programs. It is believed to have addressed the most significant of potential applications and programs. However, this is a rapidly developing field with new applications continually arising that could change in detail the assessment provided herein. Despite this, it is not expected that foreseeable developments will alter substantially the major conclusions of this effort.

The principal conclusions of this study are the following:

General

- Energy analysis techniques are commonly used in current engineering practice. Both First Law and Second Law analysis techniques are used.
- Second Law availability analysis is a useful tool, but only one of a number of directly pertinent planning and analysis tools.
- Second Law analyses provide useful information and insights about energy systems, i.e., where various energy losses of different types may occur, but do not determine what to do about such losses. The latter requires insight and invention.
- In engineering analysis, the relative importance of Second Law analysis varies considerably between applications.

Application

Planning:

- Second Law analysis is highly pertinent to planning and research priority setting and is already being used widely in this context.

° Second Law analysis very often is appropriate for conceptual design and assessment of new ideas.

Design:

° Energy analysis is only one of a number of performance measures that can be used in designing or evaluating energy conservation programs.

° Second Law analysis can be useful in the detailed design of a system. The more complex a system, the greater chance that it will be useful.

Monitoring:

° In most cases, both First and Second Law analyses are not sufficient to establish practical efficiency goals. Other technical factors such as strength of materials, speeds of chemical reaction, needed rates of production, corrosion and pollution control must be considered.

° There is little or no advantage to using Second Law analyses as opposed to energy accounting in monitoring the performance of an existing plant or system.

° In most cases examined, including those involving intra-industry comparisons, existing monitoring and reporting measures appear adequate. Exceptions involve complex processes with multiple energy streams. Second Law analysis does not resolve difficulties in making inter-industry comparisons; for example, comparing the efficiency of aluminum with steel-making processes.

° In cases where different energy streams (i.e. steam and electricity) are being sold to the public, an availability based pricing structure should be considered for customer equity purposes.

Needs:

° The potential applicability of Second Law analysis to the long-term policy realm of optimal resource allocation remains to be established. Research on this point is desirable.

° Increased use of Second Law analysis, where appropriate, is dependent upon development of better data, models, and further generalized education and training.

-Appropriate intercomparisons require data for common reference states to be developed and defined.

-Fundamental research and applications are needed to further develop Second Law-based analytical tools and computer models. There will be some need to expand the data base of thermodynamic properties of materials widely used in commerce and industry.

-Specialized reference and course materials are required for education and training in many engineering disciplines particularly on

(a) fundamentals of thermodynamics

(b) calculation of thermodynamic properties applicable to conditions found in industrial processes

(c) estimation of thermodynamic properties, and

(d) application of availability analysis.

In the final analysis, Second Law analysis techniques must be viewed in the context of a broader range of engineering tools and along with economic, institutional, political, and social factors in making important decisions in the energy conservation arena. The above conclusions establish no basis for requiring Second Law efficiency analysis as a mandatory factor in controlling any particular facet of government or industrial activities in energy conservation. This report has pointed out in a general way the potential relevance of Second Law analyses. These are neither simple nor routinely used techniques. It is characteristic of the state-of-the-art of development of these tools that the relative benefit/cost of their use should be considered on a case-by-case basis.

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15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This is a study of the relevance to Federal energy conservation programs of the use of the concept of energy efficiency as being the ratio of the minimum available work necessary for accomplishing a given task to the available work in the actual fuel used to accomplish this task. Included within the study is a review of selected elements of thermodynamics and efficiency concepts, and identification of the technology pertinent to energy conservation programs. The study examines the potential benefits, if any, that would accrue from the application of Second Law of Thermodynamics principles to these technologies. Results indicate the positive value of the Second Law analytical techniques in the planning and design stages of system development, and the rather limited value of its use during the performance monitoring stage. Needs for advancing the acceptance and use of the Second Law analytical techniques are identified.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Availability analysis; energy, energy conservation; process efficiency, Second Law of Thermodynamics; system efficiency

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