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Semiconductor Measurement Technology:

A Reverse-Bias Safe Operating Area Transistor Tester

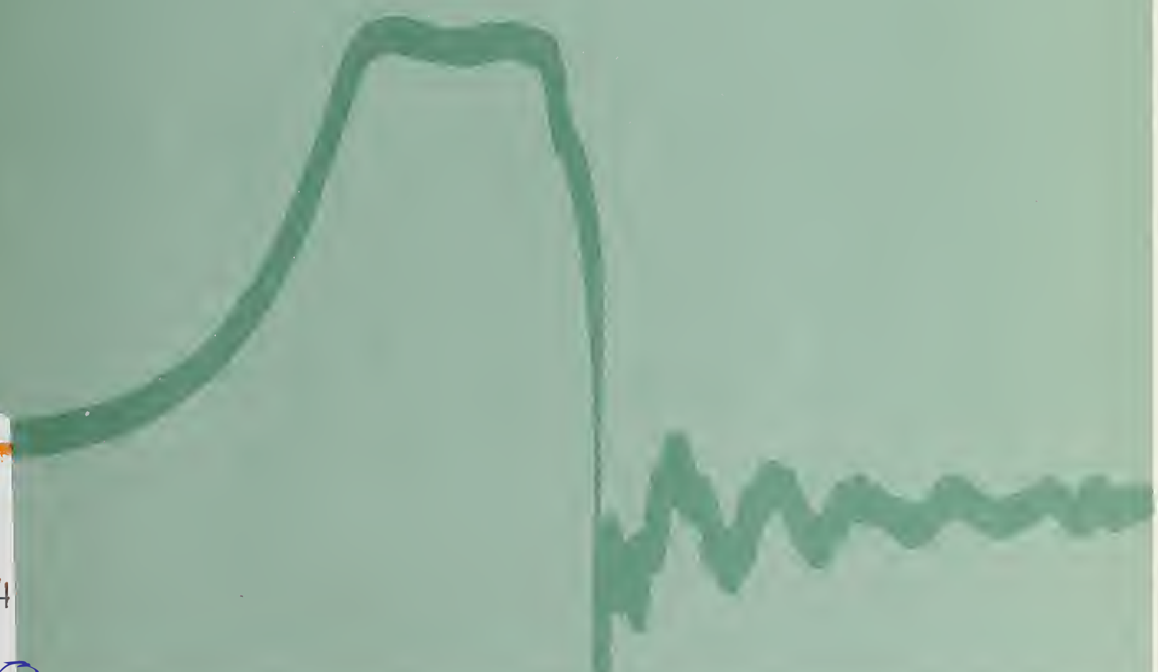

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TABLE OF CONTENTS

LIST OF FIGURES

Disclaimer

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Semiconductor Measurement Technology:
A Reverse-Bias Safe Operating Area
Transistor Tester

by

David W. Berning

Abstract: This is a construction guide for a reverse-bias safe operating area (RBSOA) transistor tester for *npn* switching transistors. Principles of operation for various circuits in the tester are discussed, as well as those of the complete system. System specifications are given. Extensive construction notes are given with hints on chassis layout. Complete circuit schematics are given with additional detail pertaining to power supply and grounding interconnections. Mechanical drawings of the tester enclosure are given. Photographs are included as additional help in building the tester. Special components such as the collector load inductor are described. Finally, a section on the use of the tester includes waveforms generated by a typical test that would be made on a transistor with this equipment.

Key Words: Base drive circuit; electronic circuits; inductive load; nondestructive; protection circuit; reverse bias; safe operating area; second breakdown; switching power transistor; tester; transistor.

1. INTRODUCTION - NEED FOR A REVERSE-BIAS SAFE OPERATING AREA TRANSISTOR TESTER

An increased need for energy-efficient machines and equipment has created a demand for a special type of electronic switching device. The basic approach to designing this new type of equipment involves controlling electrical power in such a way that only the needed power to produce a given output is used by a system that transforms the original electrical energy into whatever form that it is to be used. Examples might include regulating electrical power at different currents and voltages than the original or operating a motor at variable speeds. In constrast, many older design practices required that the system deliver the full amount of power that would be needed under maximum load and dissipate in heat whatever is not needed at a particular time. In the newer equipment, power is applied through an electronic switch which is either on or off, and the time duration of the on-part relative to the off-part of the cycle, or duty factor, determines the amount of power passed through the switch to the load. To fill moderately high speed requirements, the bipolar transistor has been singled out as the most useful switch and has become the most popular. The primary reasons for its success include very low effective on-resistance, good switching speed, and simple drive requirements. Other electronic switching devices, such as SCRs and electron tubes, are deficient in one or more of the above areas but are used in specialized applications where certain advantages can be realized, such as very high power or very high speed.

The bipolar switching power transistor must meet several somewhat conflicting requirements. It must handle high currents, high voltage, and be fast. In actual use, these devices are used most frequently with inductive loads. During turnoff with an inductive load, the transistor experiences very high peak power as the inductor acts to maintain a large current. The voltage reaches a large value on the collector terminal before much change in the collector current occurs. The turnoff portion of the cycle is generally the most difficult for this reason.

The National Bureau of Standards reverse-bias safe operating area (RBSOA) tester was developed to study how various parameters affect transistor switching during the turnoff portion of the switching cycle. Particular transistors differ in their ability to withstand large collector voltages during the turnoff portion of the switching cycle and can go into reverse-bias second breakdown and be destroyed unless some special means is provided to protect the device after it enters second breakdown. A primary goal in developing the RBSOA tester was to be able to take a transistor under test (TUT) into breakdown and save it from destruction in order that repeated measurements could be made. This goal has been met in that the transistors tested to date can be saved for repeated measurements. For this reason, the ability of a given transistor to turn off under reverse bias can be determined for many different drive conditions and collector voltage and current conditions. In addition, by knowing at what voltage a transistor is going to fail with a given collector current and set of drive conditions, it is possible to look for indications of pending failure at a voltage just under that which will cause the device to experience second breakdown. It is not possible to do this by destroying one device and then using a second device from the same manufactured lot, as there tends to be large differences in breakdown voltage from device to device. In addition to comparing different transistors in terms of their breakdown limits, measurements can be made of switching speed and storage time under either clamped or unclamped operating conditions.

This publication has been prepared to serve as a construction guide so that others can duplicate the reverse-bias safe operating area tester developed at NBS. Included in this publication are schematics of the electronics and layout guides. Typical results obtained from measurements on transistors are reported elsewhere [1].

2. SPECIFICATIONS

The following specifications describe the actual performance of the RBSOA tester:

a) Tests *npn* transistors only.

b) Choice of manual one-shot triggering with automatic reset, or electrical triggering for repetitive cycle testing.

c) Choice of forward pulse width covering a range from 1 μs to 100 ms in a 1-2-5-10 sequence.

d) Choice of reverse pulse width is the same as for the forward pulse width.

e) Forward base drive: constant current drive, choice of 0.01 to 15 A. Format includes a 1-2-5-10 coarse amplitude switch and a 1 to 3 continuously variable multiplier. The compliance is 1.5 to 12 V, depending on the multiplier setting.

f) Reverse base drive: same characteristics as forward base drive except the lower current limit is 0.05 A.

g) Choice of TUT (transistor under test) base-emitter clamp voltage -2 to -15 V.

h) TUT base waveform monitor jacks: base voltage jack and base current jack. Current measurement provided by an amplified voltage drop across a small series resistance. One volt per amp of base current appears at the current monitoring jack.

i) Oscilloscope triggering jacks: forward trigger jack provides triggering signal at the beginning of the forward base drive pulse for the TUT; reverse triggering jack provides triggering signal at the beginning of the reverse drive pulse.

j) Voltage clamp for the collector of the TUT: metered and continuously adjustable from 0 to 1000 V.

k) Protection circuit peak power capability: 30-kW (1000-V, 30-A), 40-ns shut-down time.

l) Collector power supply: 0 to 25 V, continuously adjustable; current limited at 30 A; thermal overload protection; gated off and on from the RBSOA tester; series pass type.

3. PRINCIPLES OF OPERATION

The RBSOA tester has a series inductor in the collector circuit and performs the breakdown tests by turning the TUT on and then off. Upon transistor turnoff, the collector voltage rises rapidly until either the voltage reaches a preset clamp voltage and safely remains there until the energy in the coil is dissipated or until the device experiences some form of breakdown with or without the collector voltage reaching the present clamp voltage. When the TUT experiences a potentially destructive breakdown, the collector voltage falls very rapidly, and this fires the protection circuit which very rapidly removes the remaining energy stored in the inductor in time to save the TUT. Because of the inductor, the peak collector current can be changed either by changing the length of the turn-on pulse applied to the TUT or by changing the collector supply voltage.

Figure 1 is a block diagram of the RBSOA tester. The heart of the system is a timing circuit that provides various signal pulses in the correct sequence to the different circuits in the tester. The timing sequence is initiated either by a pulse applied to the trigger input or by pressing the manual "begin test" button. After reception of one of these signals, the clamp voltage supply for the TUT is energized. After a 5-s time delay that gives the clamp supply and collector supply time to stabilize, a rectangular pulse is generated and fed to a variable gain current amplifier. The width of the pulse, determined by switch settings on the front panel, can be varied from 1 μs to 100 ms in 1-2-5-10 intervals. This pulse becomes the forward or turn-on pulse for the base of the TUT. The variable-gain current amplifier feeds the pulse to the TUT as a well-controlled current pulse adjustable in amplitude from 0.01 to 15 A. Two front panel controls together provide a coarse 1-2-5-10 sequence and a continuously variable 1 to 3 multiplier for the forward base current amplitude.

At the termination of the forward pulse, a signal is fed back to the timing circuit and to a second pulse generator and current amplifier. A rectangular pulse is generated to become the reverse base drive pulse or turnoff pulse for the TUT. This pulse is variable in time duration and amplitude in the same manner as the forward pulse except that the minimum current is 0.05 A. There is a variable voltage clamp at the output of the reverse current amplifier which is joined with the forward current amplifier to drive the base of the TUT. The clamp can be adjusted between -2 and -15 V so that a limit can be set as to the maximum reverse voltage applied to the TUT base-emitter junction. The TUT sees a constant current reverse drive only until the base voltage reaches the value equal to the clamp setting, at which time the current is diverted from the TUT base to the clamp. At the termination of the reverse pulse, the high voltage collector clamp supply and the collector supply are turned off unless an additional trigger signal is received by the timing circuit to initiate another test cycle. A jack to monitor the base voltage of the TUT is included on the front panel. The base current is monitored by amplifying the voltage drop across a 10-mΩ base series resistor and displaying it on an oscilloscope.

The TUT is connected in a common emitter configuration with an inductive load in the collector circuit. The 0- to 25-V, 30-A collector power supply is a low voltage supply that can be gated off and on from the RBSOA tester. When the TUT is switched on with the forward bias pulse, the inductor causes the collector current to increase linearly with time at a rate determined by the collector supply voltage V_{CC} and the coil inductance. In the ideal case, the peak current is determined by the length of the forward pulse, the collector supply voltage, and the coil inductance. The TUT saturation voltage and the coil resistance reduce the peak current somewhat from the ideal value.

When the TUT is driven with the turnoff pulse, the collector voltage reaches a high value before there is much reduction in the collector current. A variable-voltage clamp acts to prevent the collector voltage from going above the set point. Once the collector voltage reaches the clamp voltage, the inductor current is diverted from the TUT to the clamp supply. If the clamp voltage is set to a high enough value, the TUT may break down. Usually, the breakdown is characterized by a rapid fall in voltage before the collector current reaches zero. Typically, the collector voltage of the TUT may fall about 500 V in 10 to 20 ns. This rapid fall is detected with a capacitive pickup that triggers the high speed protection circuit. This circuit removes the remainder of the energy stored in the inductor load. This circuit shunts the clamp voltage to a negative power supply. The clamp supply for the TUT has an additional diode-resistor-inductor network that allows the clamp voltage to go negative for a short period of time and then decay to 0. This is done to overcome the inductance in the wire that connects the protection circuit to the TUT. Several power Schottky diodes are put in series with the collector of the TUT to effectively open the collector lead when the clamp voltage is driven negative. Figure 2 is a simplified schematic of the clamping networks surrounding the TUT. Three diodes are used in series for the various clamping functions because no one of these fast switching diodes has the required voltage capability; in addition, parasitic capacitance is reduced by use of the series string. It is of extreme importance to keep the parasitic capacitance at a minimum at the collector node of the TUT. When the protection circuit fires, the clamp supply and the V_{CC} supply are turned off. The capacitor detector that fires the protection circuit is a short length of wire near the base of a sensing transistor. It has a very small value of capacitance and acts as a differentiator to catch only the very rapid fall in collector voltage associated with breakdown. The collector voltage fall associated with the collapsing inductor field after collector voltage clamping for nonbreakdown turnoff is a slower voltage transition (occurring over about 1 µs) and is ignored. The protection circuit typically removes the energy from the TUT in about 40 ns from the time of TUT breakdown and can handle over 1000 V and 30 A simultaneously.

4. CONSTRUCTION

Most of the circuitry required to do reverse-bias testing of *npn* bipolar transistors is packaged in one box. The only additional item, other than measuring equipment, is the collector supply, which was built on a separate chassis. Figure 3 is a photograph of the complete experimental setup used for reverse-bias safe operating area testing. In the photograph is the main RBSOA unit which includes the base drive and timing circuits, the protection circuit, and operating power supplies. To the right are a current probe amplifier, pulse generator for repetitive pulse testing, the collector power supply, a small box that is used to turn off the collector supply in the event of excessive continuous current drain, and a storage oscilloscope. The construction of the various subassemblies that make up this system is described in the following pages. The description begins with drawings of the box housing and proceeds through the circuit schematics, with notes of caution on critical areas. The section closes with a description of the collector load inductor that was fabricated at the National Bureau of Standards.

4.1 Mechanical Assembly

Drawings of the basic housing for the RBSOA transistor tester are given in figures 4 through 7. Dimensions are given in centimeters. The material used for construction is 0.163-cm (0.064-in.) aluminum.

Figure 4 is an overall view showing the completed assembly. Figure 5 gives the dimensions of the part of the assembly that holds the base-drive amplifiers and control circuitry. Figure 6 gives the dimensions of the ground plate that holds the protection circuitry. This plate is supported by two rails and can fold down by removing the screws holding the top rail and allowing the plate to pivot on the bottom rail. The 16 holes are for mounting the tube sockets. Figure 7 gives the dimensions of the part of the housing that contains the protection circuitry and the power supply for the protection circuit. The chassis for the base drive and control circuitry is an off-the-shelf item of dimensions 42.5 by 20 by 7.5 cm (17.0 by 8.0 by 3.0 in.). A 13.13-cm (5.25-in.) high rack panel is used for the face plate of the base drive and control unit. There is space for an additional chassis with a front panel of the same size for future expansion of the RBSOA transistor tester if desired. Such expansion might include a temperature controller for controlling heat sink temperature, for example.

4.2 Base Drive and Control

The base-drive chassis contains the control circuits for the RBSOA tester including timing, logic, pulse generators and amplifiers, base current measuring amplifier, low voltage power supplies, and the gated high voltage clamp supply. Figure 8 is a schematic diagram of the base-drive chassis. The layout for the base-drive chassis requires that careful attention be paid to lead lengths and inductances, particularly in the base-drive section. Parallel switch contacts were used for the forward and reverse pulse amplitude switches for improved reliability. Noninductive power resistors were used on these switches. Some of the circuit configurations for the base drive were taken from earlier work [2]. A special kind of audio speaker cable* was used to carry the base-drive signal from the pulse amplifier chassis to a pair of binding posts mounted on top of the RBSOA tester where the TUT is located. This cable consists of two woven, stranded conductors and is designed to have very low inductance. A second pair of binding posts mounted on the base-drive chassis for the base-drive signal permits easy removal of this chassis for servicing. An 11-pin socket and plug allow connection of other signals and power between the base-drive chassis and the mainframe of the RBSOA tester.

The power supply for the base-drive amplifiers is not adequate for high duty factor testing at large currents. It was felt that the highest power tests that would be made (forward base current $I_{BF} > 5$ A) would be done as one-shot tests rather than repetitive tests. Going to

*This cable is distributed under the name Polk Audio in audio stores; however, any similar cable should work satisfactorily.

a higher average power capability would require not only a more substantial power supply but a heavier duty and perhaps slower base-drive amplifier.

Figure 9 is a photograph of an oscilloscope display of the output of the base-drive amplifier as measured with a current probe. The forward and reverse amplitude switches were set to 2 A, and both forward and reverse pulse width switches were set at 2 μs. A transistor served as the load and the reverse voltage clamp was set to 15 V, allowing the base emitter junction to avalanche, which occurred at 11 V. It can be seen that the transition time in going from forward drive to reverse drive is on the order of 100 ns.

A gated dc-dc converter driving the screen grid of a vacuum tube was used to switch the collector clamp supply. This circuit was decided upon after several attempts to use relays in the primary of the power transformer for the clamp supply. Mechanical contacts emit too much radiation and cause noise that results in erratic circuit operation.

Figures 10 and 11 are photographs of the top and under side of the base-drive, respectively. Referring to figure 10 (top view), the transformer for the clamp supply is on the far left with the gated oscillator and tube just to the right. Some NOR logic transistor gates are in front of the gated oscillator. Integrated circuits for timing and variable pulse width generation are to the right of the NOR logic. Power supply regulation circuitry is to the right of the ICs, and the pulse amplifier and variable base-emitter clamp circuits are to the rear of the chassis. Referring to figure 11 (bottom view), the current amplitude switches are on the left. The resistors used are parallel and series combinations of noninductive wirewound and carbon units. The switches are connected to the circuits by bundles of silver-plated hookup wire in parallel to reduce the inductance. These wires are just long enough to permit switch removal, as the voltage regulation circuitry is located under the switches and may require servicing. The base current monitoring circuit is located on the small shelf in the rear of the chassis behind the current switches. This circuit was found to be less accurate than a current probe placed near the TUT because of stray circuit reactances and the inductance of the detection resistor. The large power supply components for the base drive circuitry are to the right of the current monitoring circuit.

4.3 High Speed Protection Circuit

The high speed protection circuit is a shunt that diverts the collector current of the transistor under test (TUT) to a negative voltage supply upon being fired. The circuit is fired by a rapid drop in voltage at the collector of the TUT which is sensed by a small capacitor differentiator consisting of a short piece of wire near the base of a transistor at the input of the protection circuit. The protection circuit is essentially a 30-kW peak power amplifier in which transistors and tubes are biased in their active regions to increase the speed as much as possible. The circuit can divert 1000 V and 30 A from the TUT within about

40 ns after TUT breakdown. Some additional features of the circuit include a latch and automatic reset that causes the shunting circuit to latch on for 0.5 s and then to switch off again in readiness for additional tests on the TUT. There is also an output that is sent to the timing circuits associated with the TUT base drive. This signal is used to gate off both the collector power supply and the clamp supply for the TUT. This output is reset when the protection circuit is reset.

The protection circuit essentially consists of an input stage that is branched into 16 parallel output stages to give the circuit the required current handling capability. The schematic for the protection circuit is given in figure 12; the schematic for the associated power supply is given in figure 13. Also given in figure 13 is the circuitry surrounding the TUT. The protection circuit is built on a ground plate that can fold down (refer to the description of mechanical assembly of the chassis in sec. 4.1). The circuit is arranged with circular symmetry in which the input transistor is at the center of the plate and 16 output tubes are arranged in a circle so that they are located equal distances from the input.

Five dc power supplies are used to operate the protection circuit. The important requirement for these supplies is that they have substantial energy storage so that they can deliver a large peak current. Regulation of these supplies was found not to be necessary. Four of these supplies are referenced to the remaining one which is a -140-V supply for the cathodes of the tubes. When the TUT breaks down and the protection circuit acts, it is to this -140-V supply that the energy in the collector inductor is dumped. Two 8300-μF capacitors charged to 70 V each provide a total of 40 J of energy that can be used to act on the energy remaining in the collector coil and the collector power supply. This cathode supply and the other four supplies are installed in the RBSOA tester box but not on the ground plate that holds the protection circuit itself. All five of the supplies are capacitively bypassed to ground and in certain cases to each other. This is done at multiple points for each supply on the ground plate where the supplies are used.

Sixteen separate wires connect the -140-V cathode supply to the cathodes. These wires all join together at a terminal post in the tester box where the other power supplies are connected; this is shown in figure 13 as a connection marked "80." The other four supplies are brought to the ground plate via a single wire for each and then distributed to terminal posts on the ground plate for convenient usage. Sixteen sets of terminal posts equally spaced around a circle serve as distribution points for these four supplies. The sequence of distribution is indicated in figure 12. The physical locations of some of the distribution points are indicated in figure 18. Whereas the cathode supply is used as an energy dump, the other four dc supplies are needed to operate the protection circuit. There is a -68-V supply (referenced to the cathodes) used for a collector supply for the driver transistors and grid bias. This supply is connected to point "51." While regulation of this supply was not done in the present RBSOA tester, this voltage is somewhat critical as it is a compromise between being large enough to keep the tubes turned off with a high clamp voltage applied and small enough so as not to exceed the transistor voltage capabilities. This voltage should be regulated if the power line voltage is uncertain or noisy. The supply to point "31" is a -17-V source that is fed to the collectors of Q 1 through Q 32. This is a large group of emitter followers that is used for current gain and for branching the input into 16 parallel signals for the driver transistors Q 33 through Q 48. A +8-V source fed to point "12" is an emitter supply for Q 1 through Q 48. This supply has a large amount of energy storage associated with it because it powers the driver stage. The last dc supply is a +150-V supply for the screens of the tubes. This is fed to point "71" on the ground plate that holds the protection circuit and also to a resistor-diode network that guarantees sufficient tube plate voltage to prevent excessive screen current.

A group of four 6-V transformers provides the heaters of the 16 output tubes with their required power. All of the above supplies, including the heater supplies, float up and down with the cathode supply. There is a 150-W lamp in series with the primaries of the transformers for this supply to limit the current. The lamp serves as a ballast and lights when the energy is exhausted in the cathode supply. This lamp also gives a rather dramatic indication that the protection circuit has fired.

Referring to the protection circuit shown in figure 12, a return that is marked "0" from the cathode power supply is connected to a terminal, and from there it is grounded to the protection circuit ground plate through eight equal lengths of wire. These eight points are ground posts of terminal strips equally spaced in a circle about the input.

Figures 14 to 18 are photographs of the back of the RBSOA tester showing the components of the protection circuit and of the power supply. Figure 14 is an overall view showing the location of power supply components and the protection circuit which is mounted on the vertical ground plate. Figure 15 gives a view with the plate folded down. Connection of the input of the protection circuit to the TUT is made through a coaxial connector that provides a short signal path from the TUT collector to the protection circuit. The outside conductor is connected to the ground plate at one end and to the TUT emitter at the other end. This connector and other key parts are identified in figure 15. The output of the protection circuit, which is collectively taken from all of the electron tube plates (the cap connections on the tubes), is connected to a post which accepts a spring clip so that the current being diverted from the TUT travels only a short distance. Bypass capacitors for the clamp supply can be seen mounted just under the coaxial connector so that they are as close as possible to the clamping diodes. Figures 16, 17, and 18 are close-up photographs of the protection circuit. As can be seen, there is much symmetry in the construction of this circuit. Figures 17 shows most clearly the input to the protection circuit and the small loop of wire that acts as a differentiator because of its close proximity to the base of the input transistor. This wire can be moved to change the sensitivity of the circuit; however, once positioned properly, it had the correct sensitivity for all of the transistors tested to date. If there is too much coupling, the protection circuit will fire when the field in the inductor load for the TUT collapses. Transistors were installed in sockets throughout the RBSOA tester. The sockets make point-to-point wiring easier and allow easy replacement of transistors. The driver transistors Q 33 to Q 48 for the tubes were selected for a 80-V-at-5-mA minimum breakdown voltage using a curve tracer oscilloscope.

Figure 19 is a photograph that shows the TUT and surrounding components. The chain of five power Schottky diodes (only four visible) is located near the TUT which is on the left. The pair of binding posts delivers the base drive from the base-drive circuitry located below. A 2-μF Mylar capacitor serves as a collector power supply bypass to ground. A damping resistor with a value of 2.2 kΩ is in parallel with the inductor, which will be described in a later section of this report. Probes for measuring V_C and I_C can be seen in the photograph also. The TUT and some of the above-mentioned circuit elements are mounted in the clamping circuit through a path which is as short as possible. The small shielded box to the right of the clamp voltage meter contains clamping diodes and some other components arranged to reduce high frequency coupling when these diodes are reverse biased. If this were not done, the protection circuit would oscillate, as it is an amplifier with an extremely high gain-bandwidth product, and any coupling through these diodes is positive feedback. The knob behind the inductor controls the clamp voltage by means of a variable autotransformer which is connected to the primary circuit of a power transformer located on the base-drive chassis.

4.4 Collector Power Supply

The collector supply was built on a separate chassis because of its size and weight. A brute force approach was used in designing and building this supply. The most important feature of the supply is the gating capability that permits it to be turned off and on via a signal from the main chassis of the RBSOA tester. The supply is a linear type and can deliver 0 to 25 V at up to 30 A. It is current-limited at 30 A. In addition to the gating feature, it has thermal shutdown protection. The supply also has diodes on the output terminals to prevent destruction if voltage is fed back into the supply from some other source. Figure 20 is a schematic of the circuit. The driver and output transistors all have their collectors grounded and do not require insulating washers for mounting.

4.5 Accessories

A. Auxiliary Collector Current Limiter

This unit is an add-on box to prevent high collector supply current from destroying the Schottky diodes that are in series with the collector of the transistor being tested in the event of a failure of this transistor. The limiter turns off the collector supply if the collector current exceeds 3 A for 250 ms. The unit is placed in series with the output of the collector supply, and, in addition, the gating signal from the RBSOA tester for the collector supply is passed through the unit. The limiter measures the collector current and uses a timer to time that current that exceeds 3 A and interrupts the gating signal if the level of current exceeds 3 A for 250 ms. The gating signal from the RBSOA tester has to be interrupted (a logic zero-output) to reset the current limiter. Such a zero-output is given by the RBSOA tester normally except during a test cycle. Figure 21 is a schematic of the circuit for the auxiliary collector current limiter. The unit operates using the control (gating) signal from the RBSOA tester as operating power and shorts out this line with a transistor configuration that has characteristics similar to those of an SCR when the measured current exceeds the desired level.

B. Pulse Generator

The RBSOA tester can accept trigger pulses for repetitive cycle testing. This is most useful for setting up the oscilloscope to observe the turnoff transition for the TUT. A commercial signal generator was used to provide the trigger pulses. A positive going 2-V square wave from the generator at any desired repetition rate can be used.

4.6 Collector Series Inductor

To date, most of the tests made on transistors using the RBSOA tester have been done with a large 1-mH choke that was made with ferrite I cores. Several smaller ferrite core chokes with approximate values of 2.5 mH and a 4-mH air-core choke was tried with satisfactory results at low collector current. Most of the small ferrite chokes saturated at collector currents of 2 to 4 A, and the particular air-core choke used had too much resistance to allow tests to be made above several amperes. A wound steel laminate core inductor was tried but found to be too lossy to work satisfactorily.

The 1-mH choke that was made with I cores used 12 ferrite cores with dimensions 10 cm by 2.5 cm by 2.5 cm of material type 3C6. The cores were arranged to form a rectangle with an open area in the center and were stacked three deep on each of the four sides of the rectangle. A coil consisting of 26 turns of number 10 magnet wire was wound on a form 8.5 cm by 2.5 cm. The coil was slipped off the form and three of the I cores that made up one of the long sides of the rectangle were inserted into the coil and the ferrite cores with the coil inserted back into the rectangle. A number of nonmagnetic restraining blocks were mounted on a block of wood to hold the cores rigidly in place, and a cutout was made in the block of wood for the part of the coil that extended below the cores. Some pieces of paper were inserted where the cores touched at the corners of the rectangular array to provide a small air gap, and additional pieces of paper can be used to reduce the inductance of the inductor. A resistor with a value of 2.2 kΩ was added in parallel with the inductor to reduce the tendency for it to ring. The inductor and some of the other components surrounding the TUT can be seen in the photograph in figure 19.

5. USING THE RBSOA TESTER

The RBSOA tester has been designed to be easy to use. It has been made as automatic as possible. For example, the collector and clamp power supplies are electronically disabled after the test cycle except when additional triggering signals (manual or electrical) have been received. This not only makes the equipment safer for the operator but makes it possible to change the TUT without disturbing any voltage settings or turning any equipment off. The protection circuit automatically resets itself after it has fired, thus eliminating the usual reset button. If the TUT does not go into reverse-bias second breakdown, the protection circuit does not fire. Various parameters such as base currents, pulse widths, and clamp voltages can be selected with front panel controls.

5.1 Hookup

Figure 22 is a diagram showing how the various pieces of equipment described in section 4 are interconnected. For simplicity, the clamping- and protection-related components around the TUT are not shown. The inductor is located physically as close as possible to the TUT. The current limiter accessory can be omitted, but this introduces the risk of destroying the Schottky diodes in the collector circuit of the TUT should the TUT fail.

5.2 Oscilloscope Interfacing

Triggering outputs for an oscilloscope are provided by the RBSOA tester from the forward base-drive pulse for the TUT and also from the reverse base-drive pulse. A 100X probe can be used for monitoring the collector voltage of the TUT. A 470-Ω resistor in series with the probe can be used to reduce ringing. A current probe can be used to monitor the collector current or other currents as desired.

5.3 Triggering the Test

The RBSOA tester allows one to perform one-shot measurements as well as repetitive pulse measurements; the only difference between the two is the mode of triggering. A signal generator can be used to trigger the tester at any rate as long as the sum of the forward and reverse pulse widths used for the test does not exceed the signal generator cycle time. A manual trigger button can be used to trigger one-shot tests. The test will execute 5 s after the manual trigger button has been released. Depression of the button any time before the test cycle has executed will abort the cycle until 5 s after the button has been released. The TUT is subjected to one additional test cycle 5 s after an electrical triggering signal has been received.

5.4 Test Example

An easy method of setting up the equipment to observe and measure transistor breakdown is given in this section of the report. The collector clamp voltage is set to a low enough value that it is unlikely that the TUT will break down. A signal generator is then connected to the triggered input. A storage oscilloscope monitors the collector voltage or current of the TUT. The scope is triggered from the reverse pulse trigger output of the RBSOA tester. The sweep rate and sweep delay time are adjusted to give the desired display. The delayed sweep must be used because of the storage time of the TUT. The storage time, however, allows the entire turnoff cycle to be observed, including initial current and voltage conditions. Once the time base of the oscilloscope is properly set, the signal generator can be removed and one-shot tests can be made on the TUT. By raising the clamp voltage to a high enough value, a breakdown event can be captured on the storage oscilloscope.

Figure 23 is a photograph of the storage oscilloscope display showing typical results that can be obtained from the RBSOA tester. The following conditions were used to obtain these data.

Forward pulse width	1 ms
Reverse pulse width	0.2 ms
Reverse base-emitter voltage clamp	-5 V
Forward base current	2 A
Reverse base current	2 A
Collector voltage	10 V
Inductor size	1 mH

The collector currents depicted in this figure are offset for clarity; the current is approximately zero at the ends of both traces. Traces 3 and 4 are the collector voltage, and the voltage is near zero at the beginning of these traces. Trace 1 is the current fall with normal transistor turnoff (no breakdown). Trace 3 is the voltage rise with the clamp set at 350 V for the same conditions that produced trace 1. Traces 2 and 4 are current and voltage, respectively, for transistor breakdown. The collector clamp voltage was raised from 350 to 800 V to obtain these traces. The transistor had to be driven into breakdown twice, once to capture the voltage on the scope and once to capture the current. The protection circuit in the RBSOA tester makes it possible to make many breakdown measurements on the same transistor. Trace 4 shows the collector voltage going below 0 V. This is because the probe was not actually monitoring the collector voltage but the voltage on the anode side of the Schottky diode chain. The power Schottky diodes placed in series with the collector of the TUT become reverse biased when the protection circuit diverts the power away from the TUT, forcing the collector current to go to zero.

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1. Blackburn, D. L., and Berning, D. W., Some Effects of Base Current on Transistor Switching and Reverse-Bias Second Breakdown, *Technical Digest, 1978 Int. Electron Devices Meeting*, Washington, D.C., December 4-6, 1978.

2. Jahns, T. M., Investigation of Reverse-Bias Second Breakdown in Power Transistors, Massachusetts Institute of Technology MS Thesis, Dept. of Electrical Engineering, May 1974.

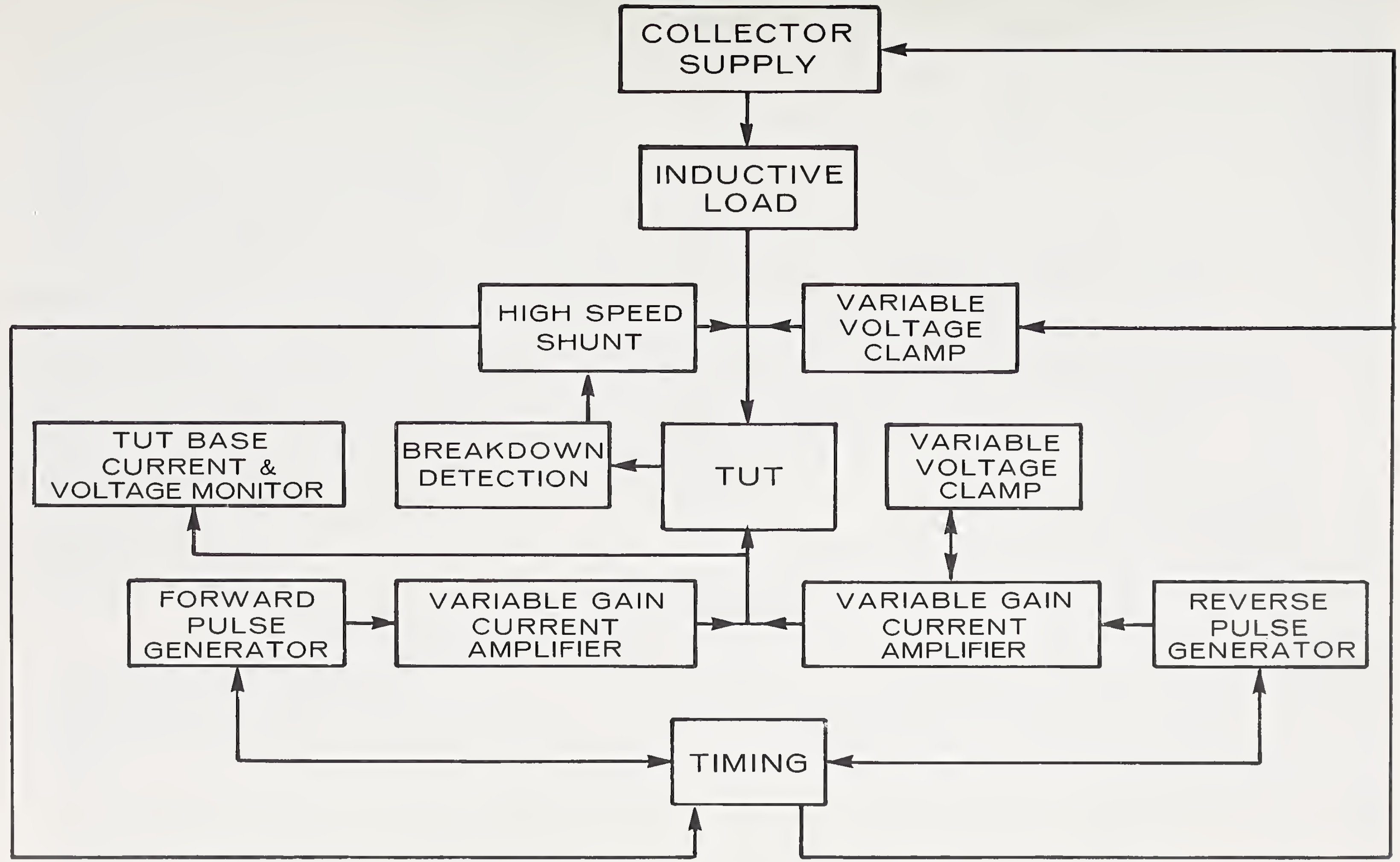

Figure 1. Block diagram of the reverse-bias safe operating area testing system.

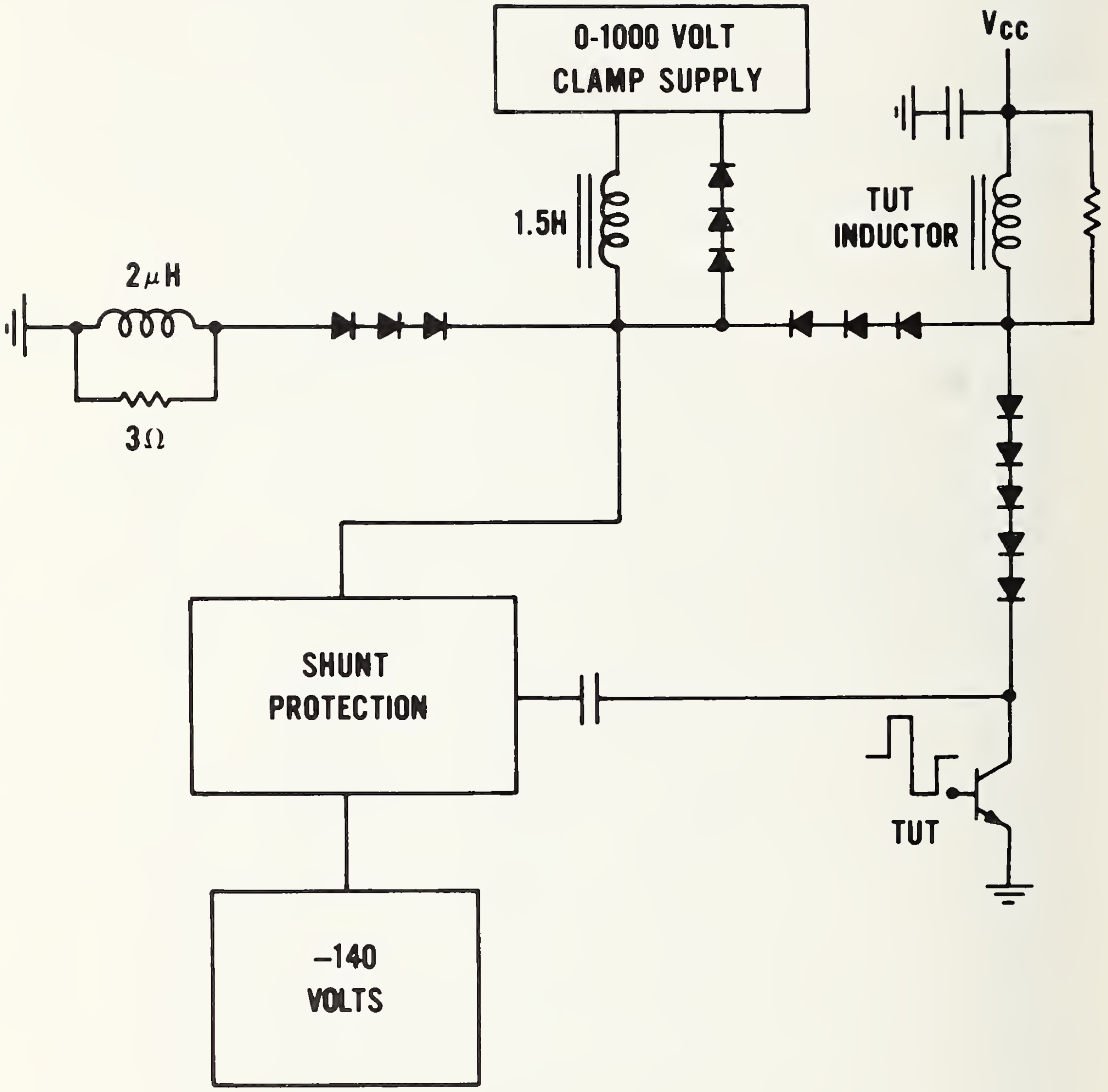

Figure 2. Key components surrounding the TUT.

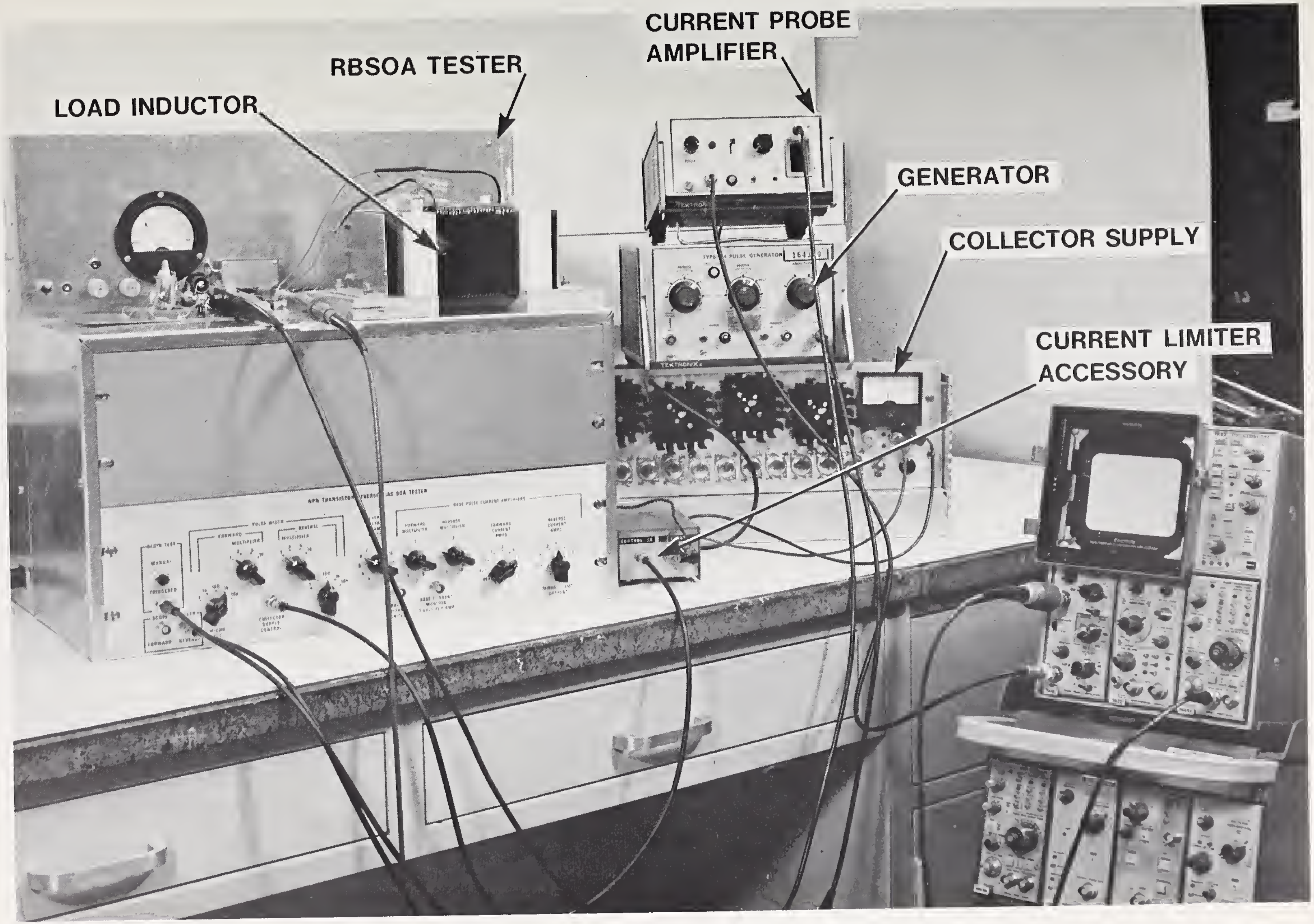

Figure 3. Photograph of the RBSOA testing system.

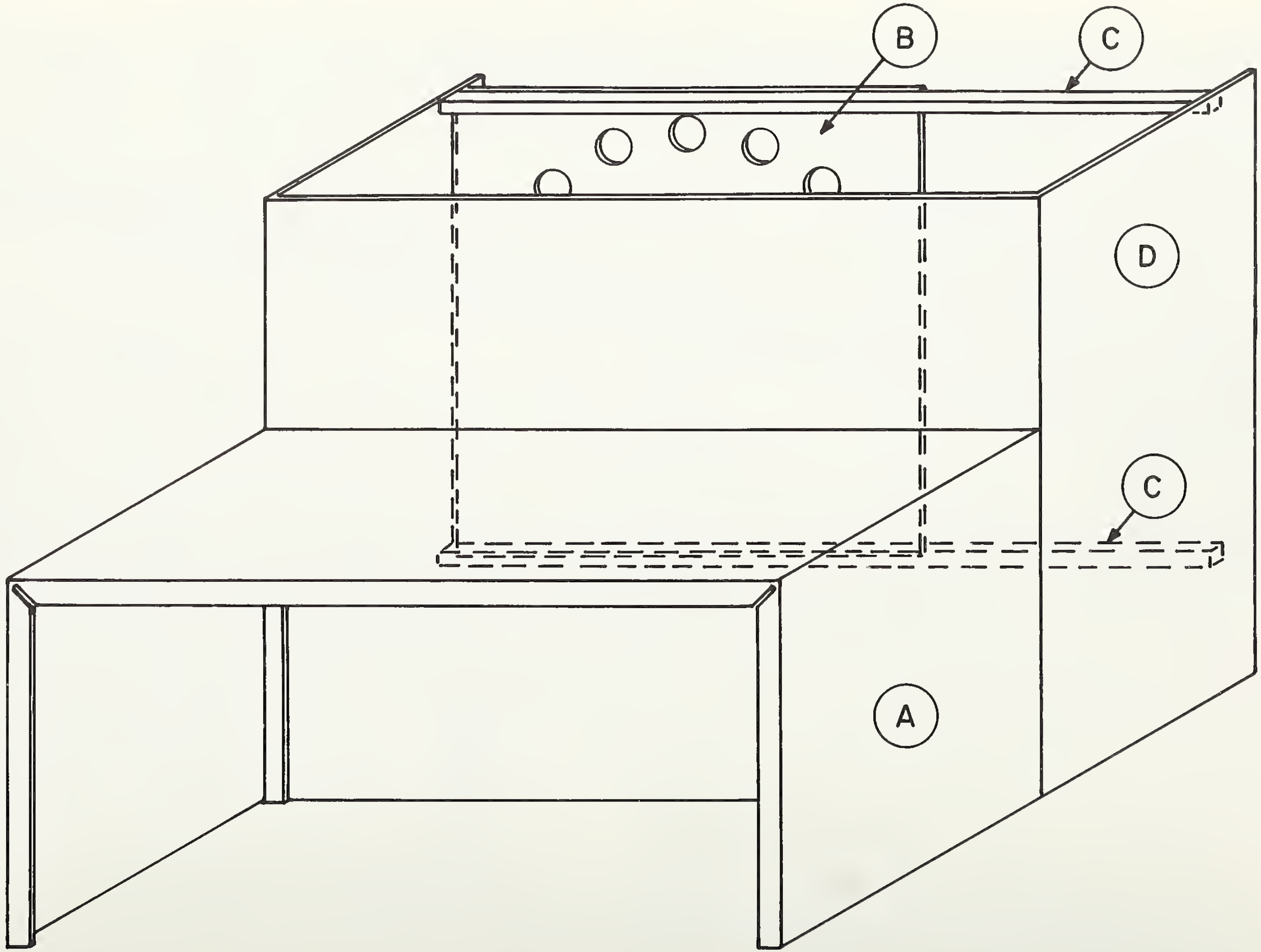

Figure 4. Sketch of the mechanical assembly of the main enclosure.

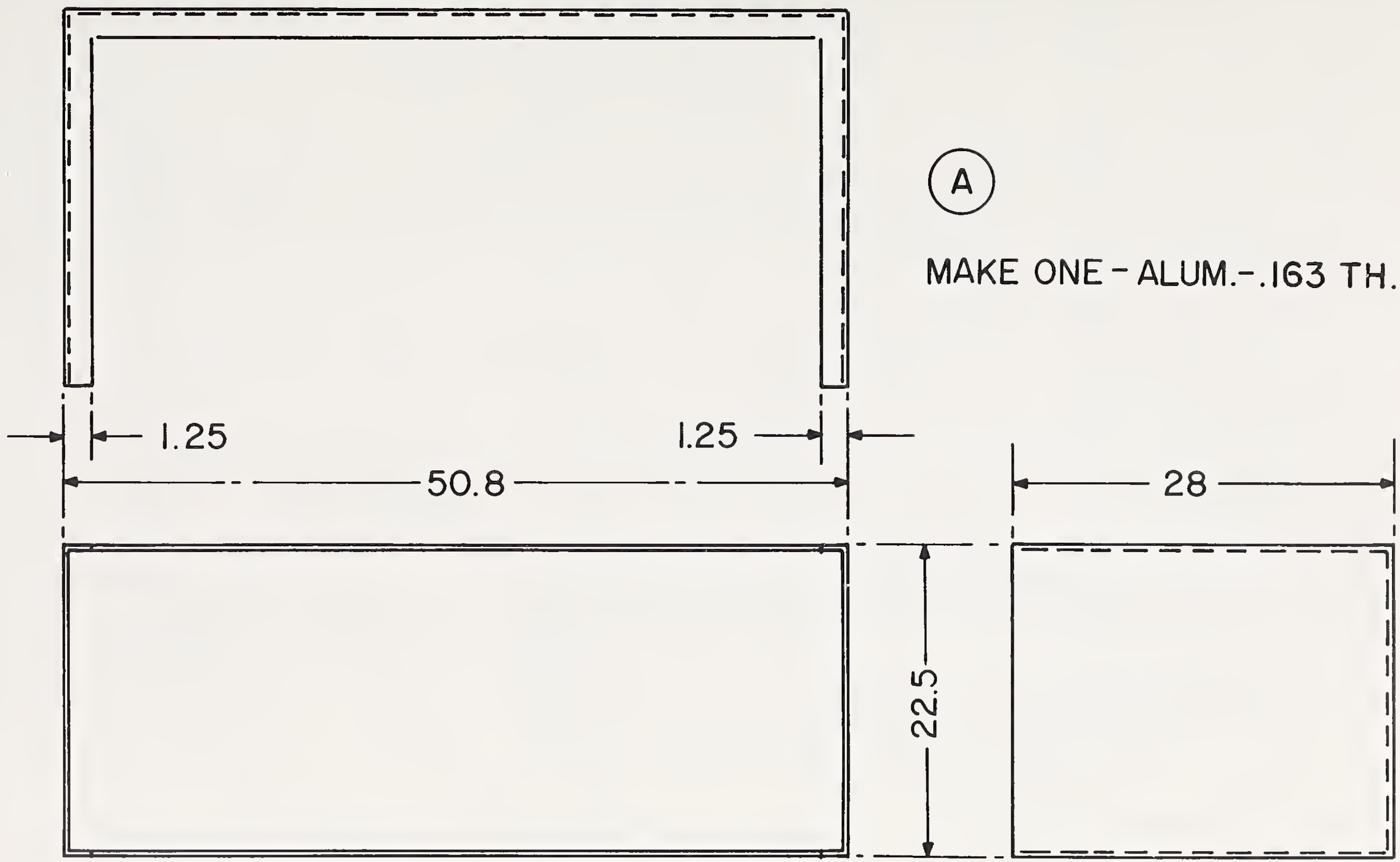

Figure 5. Drawing detail of the portion of the housing that contains the base drive and control chassis. Dimensions are given in centimeters.

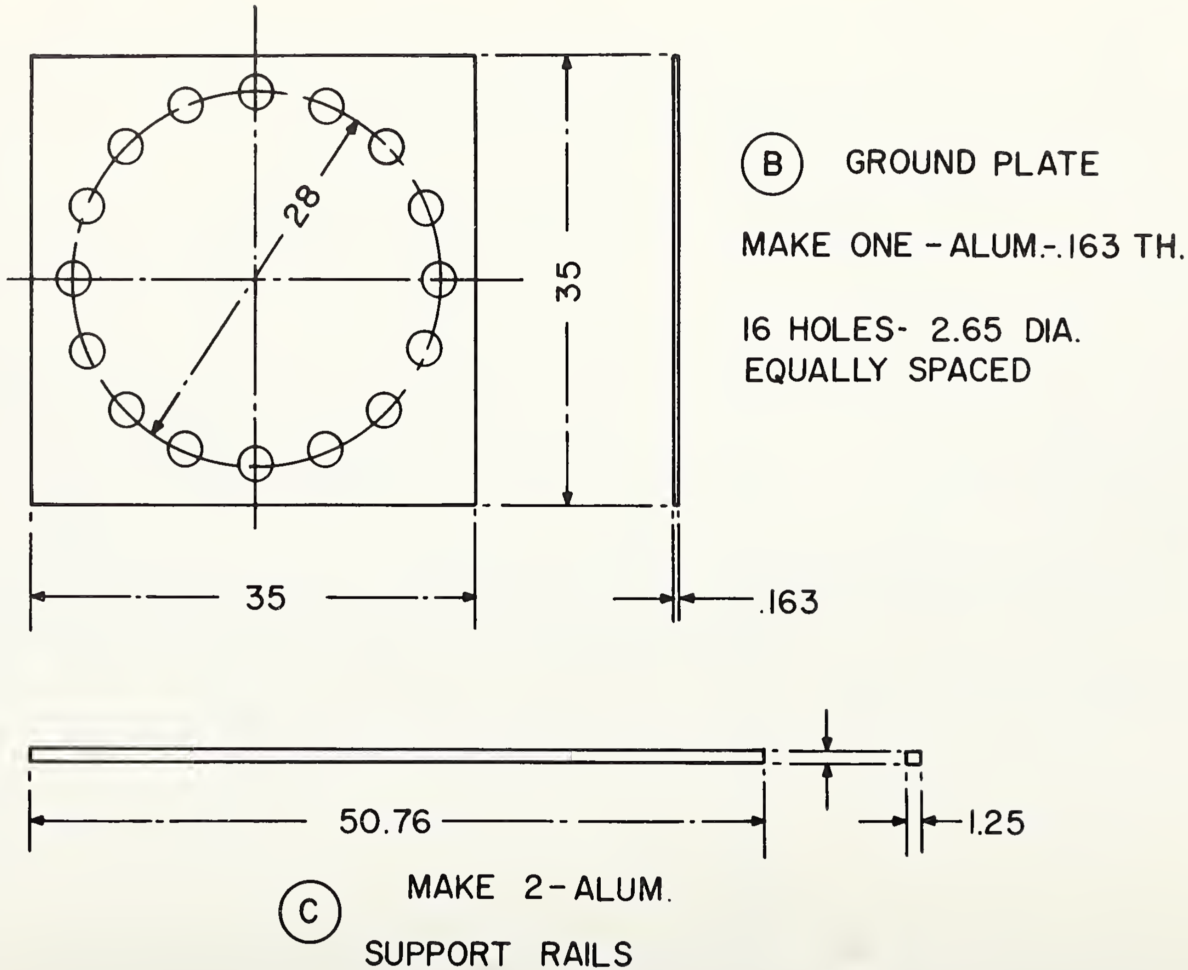

Figure 6. Drawing detail of the ground plate that holds the protection circuit. Dimensions are given in centimeters.

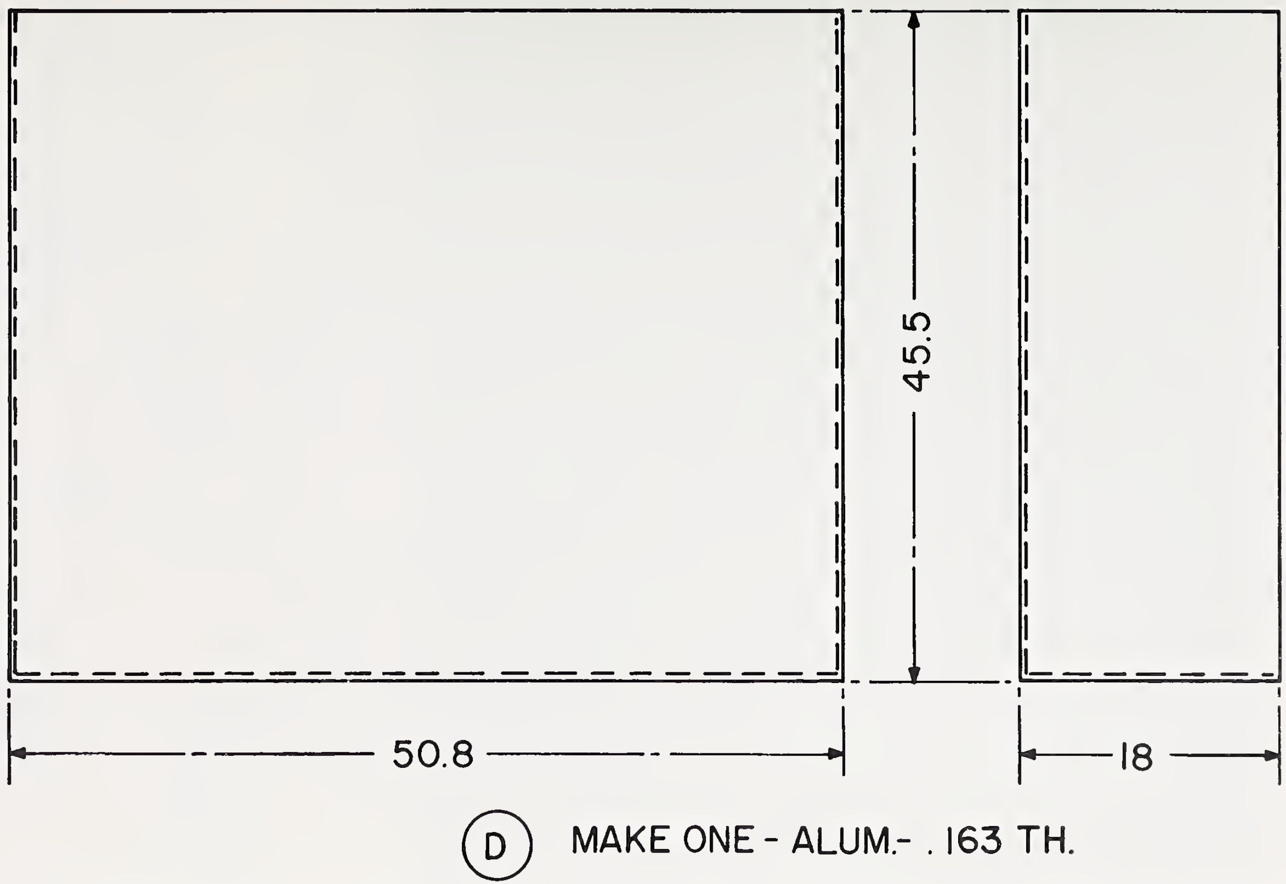

Figure 7. Drawing detail of the housing for the protection circuit. Dimensions are given in centimeters.

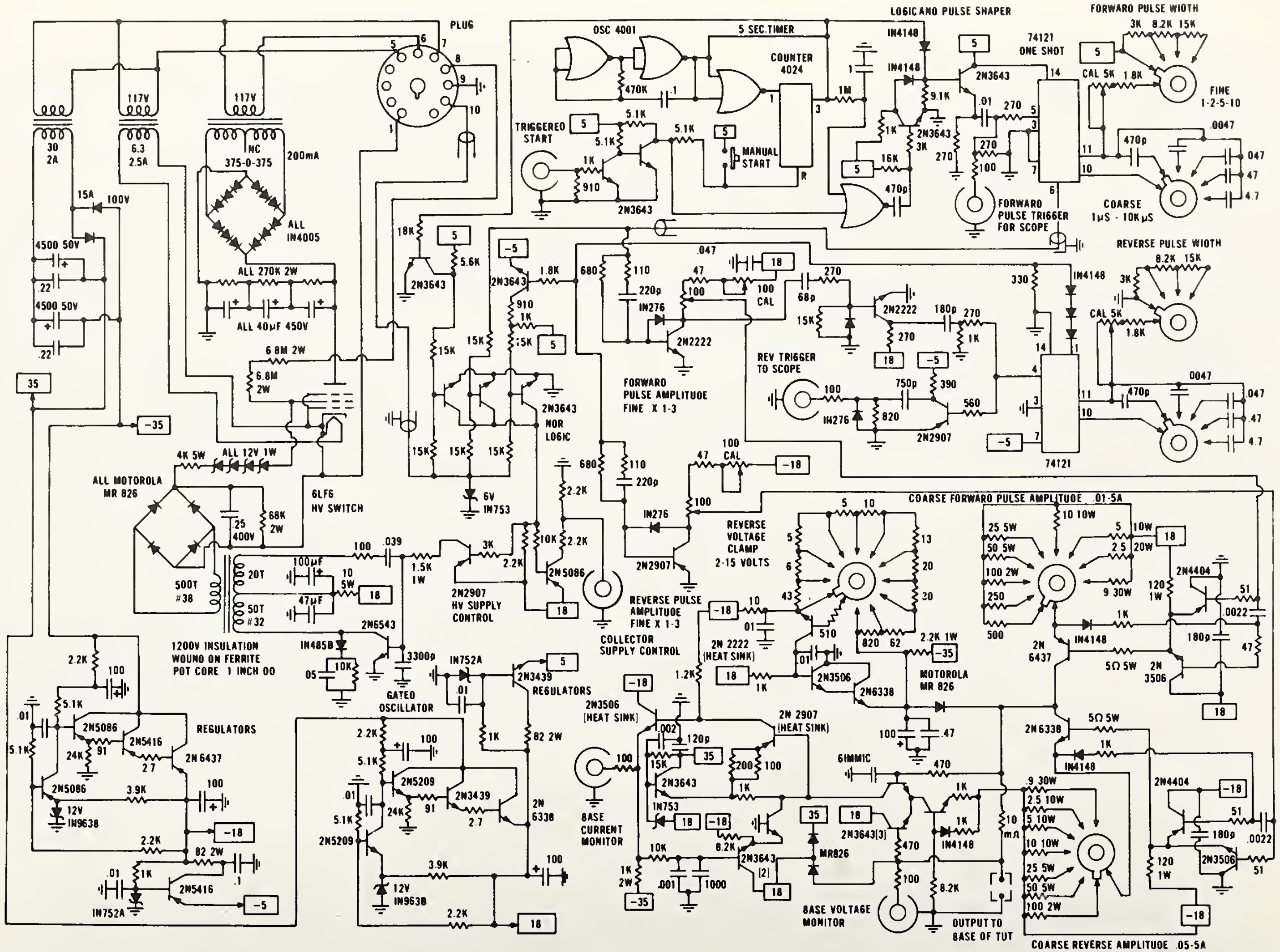

Figure 8. Schematic diagram for the base drive and control circuit.

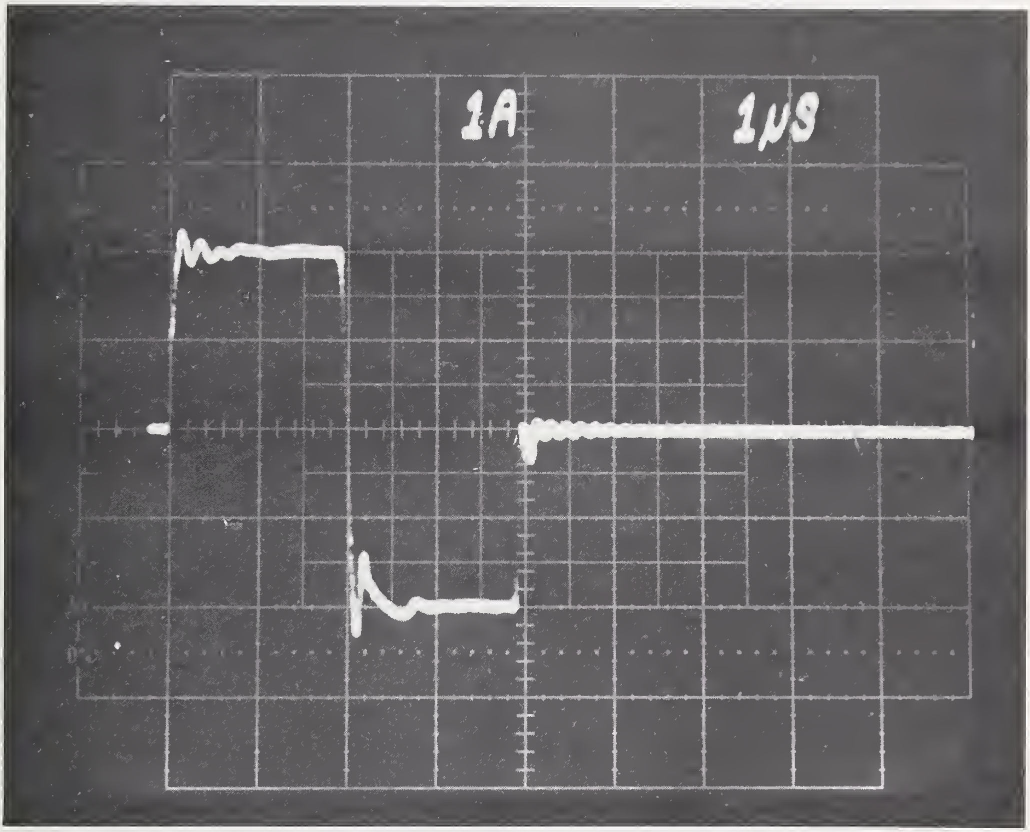

Figure 9. Base drive circuit output waveform with transistor load.

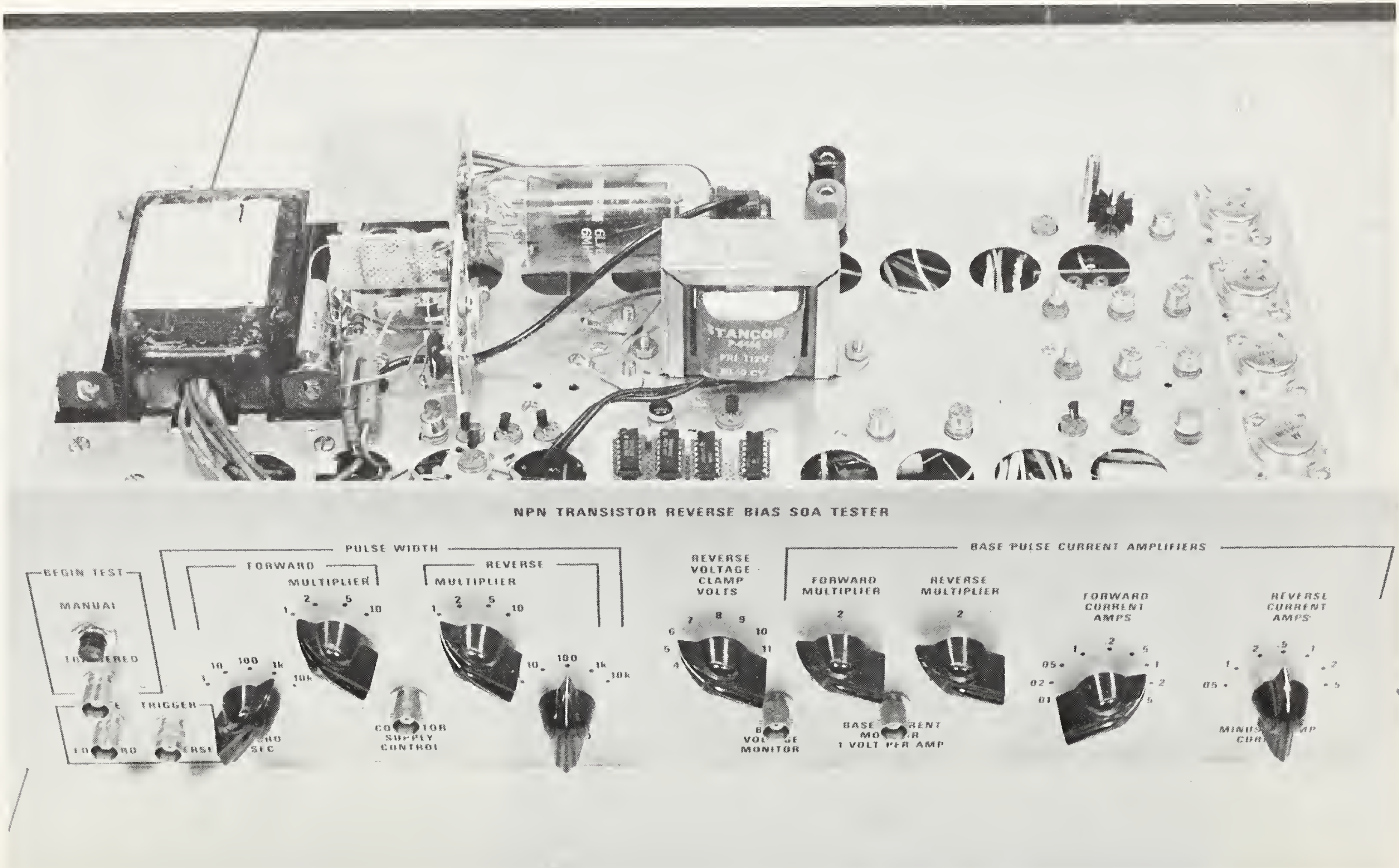

Figure 10. Photograph showing the top of the base driver chassis.

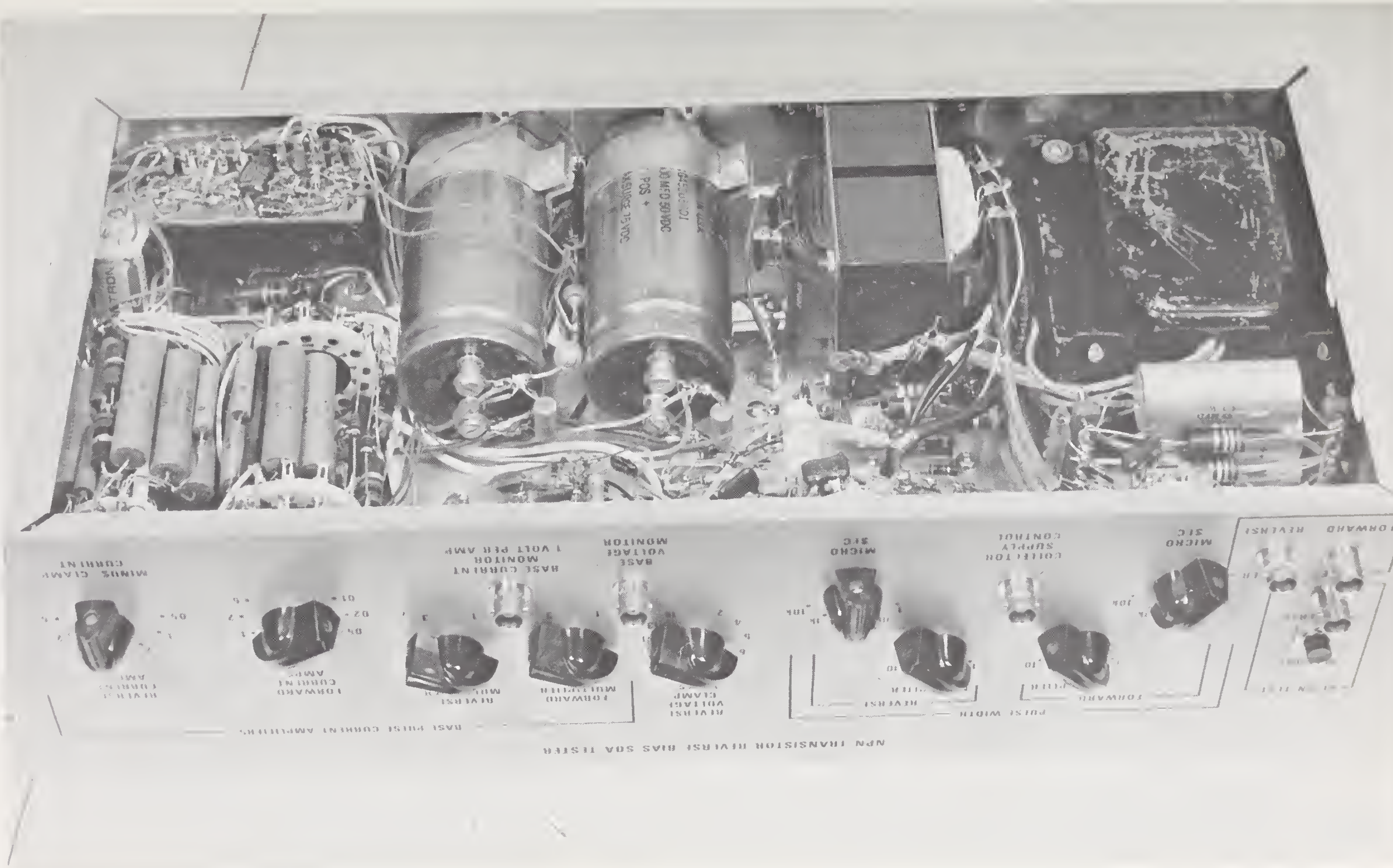

Figure 11. Photograph showing the under side of the base driver chassis.

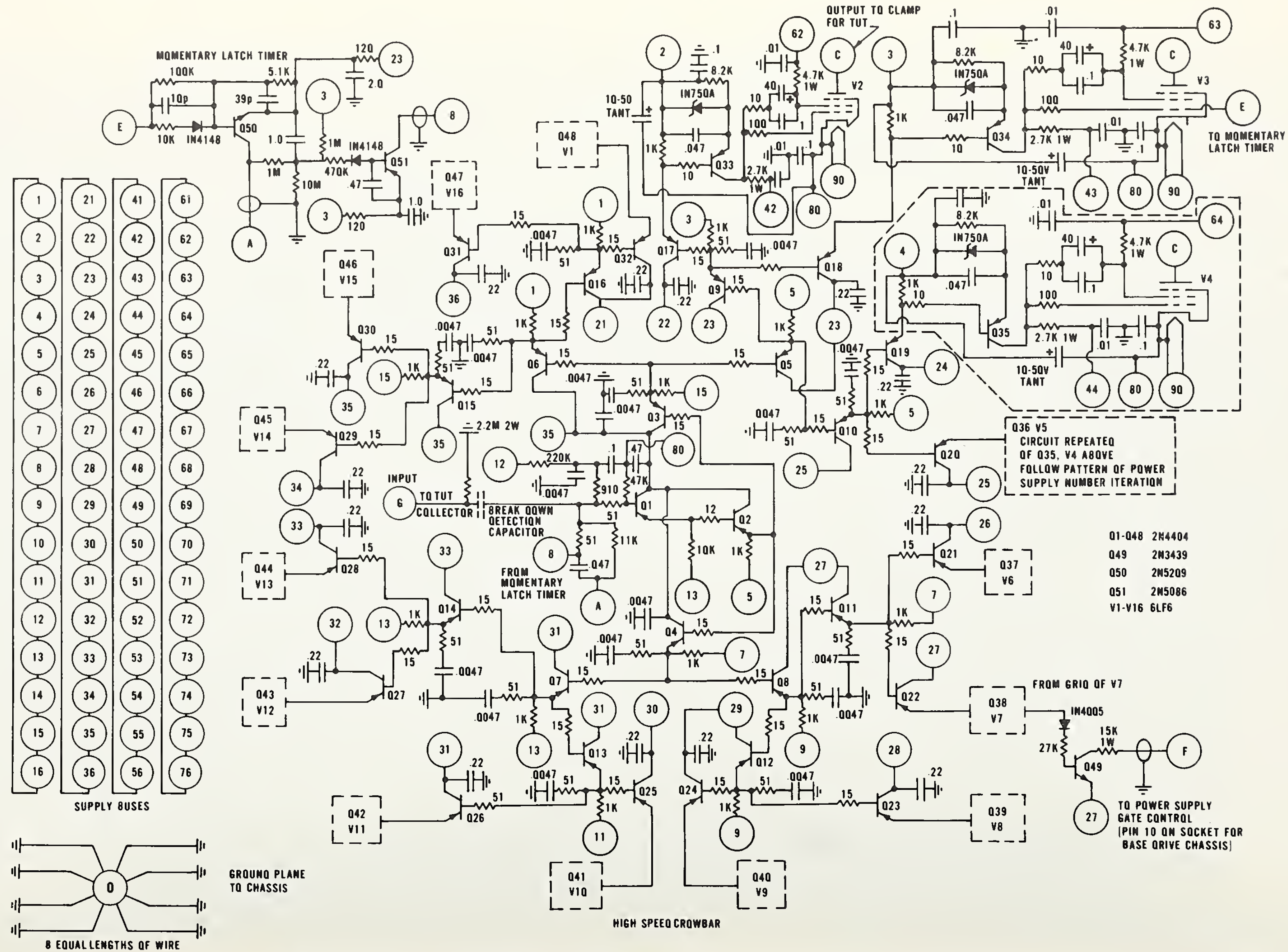

Figure 12. Schematic diagram of the protection circuit.

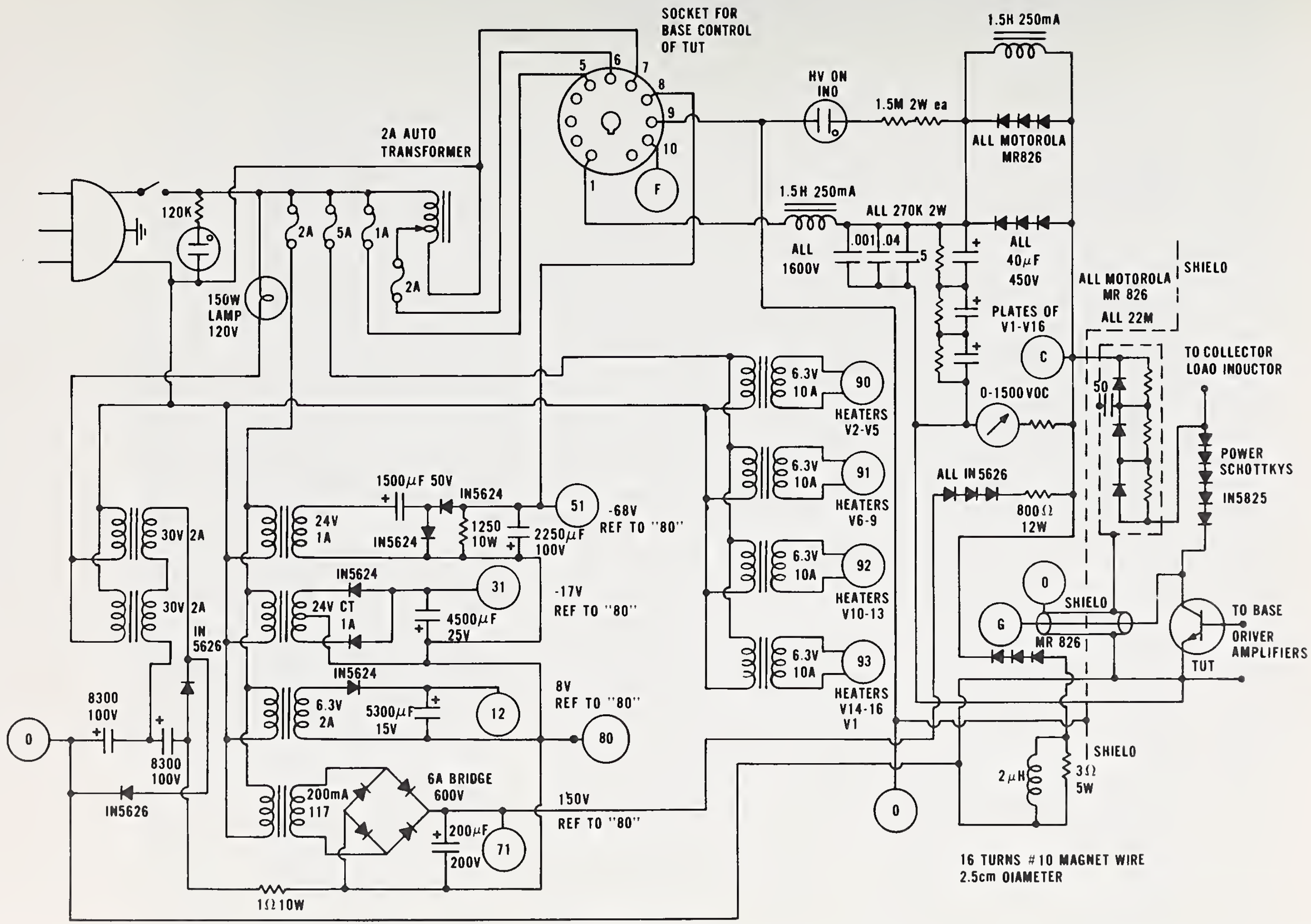

Figure 13. Schematic diagram of the power supply portions of the protection current and the circuitry surrounding the TUT.

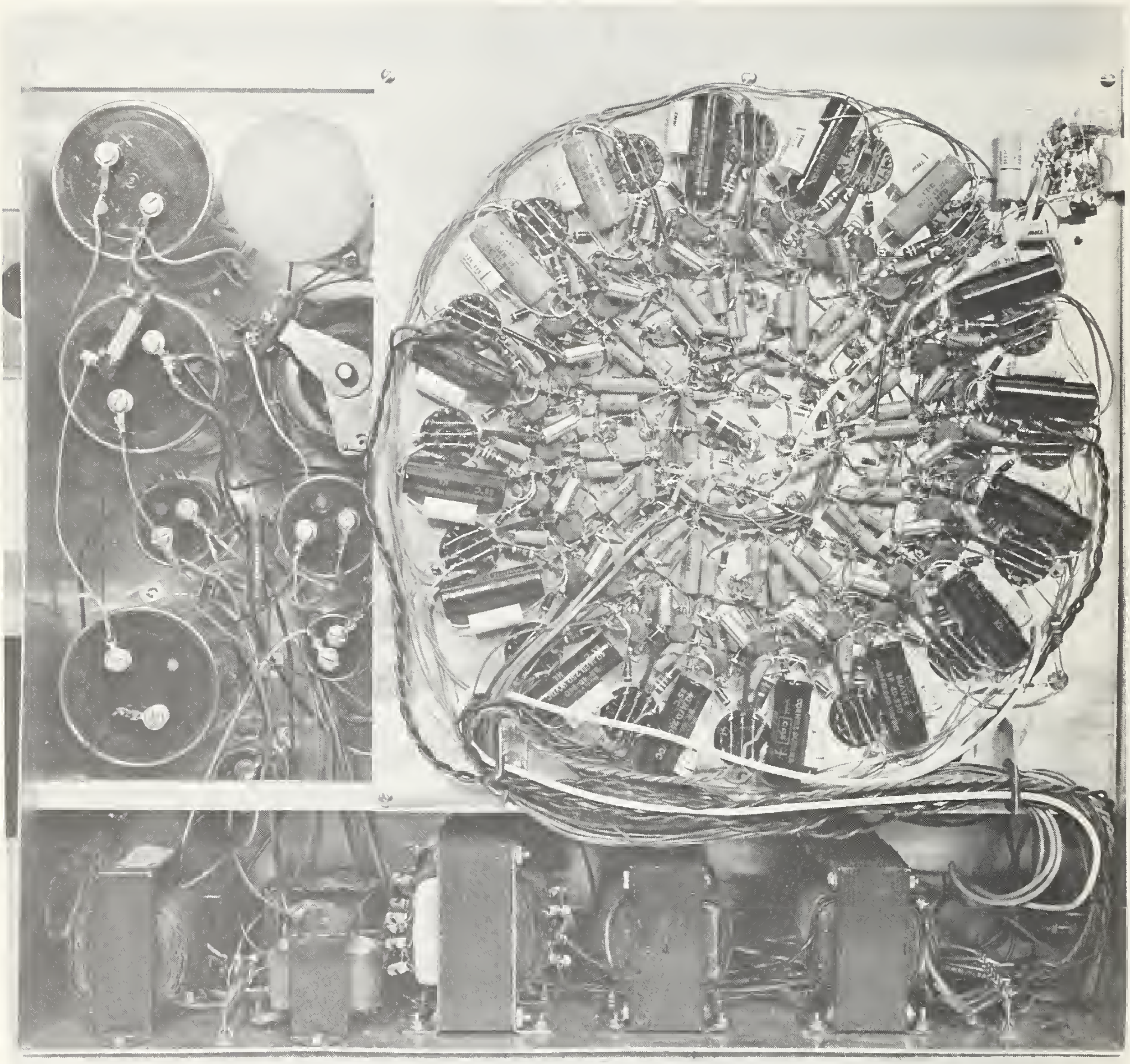

Figure 14. Photograph of the rear of the RBSOA tester.

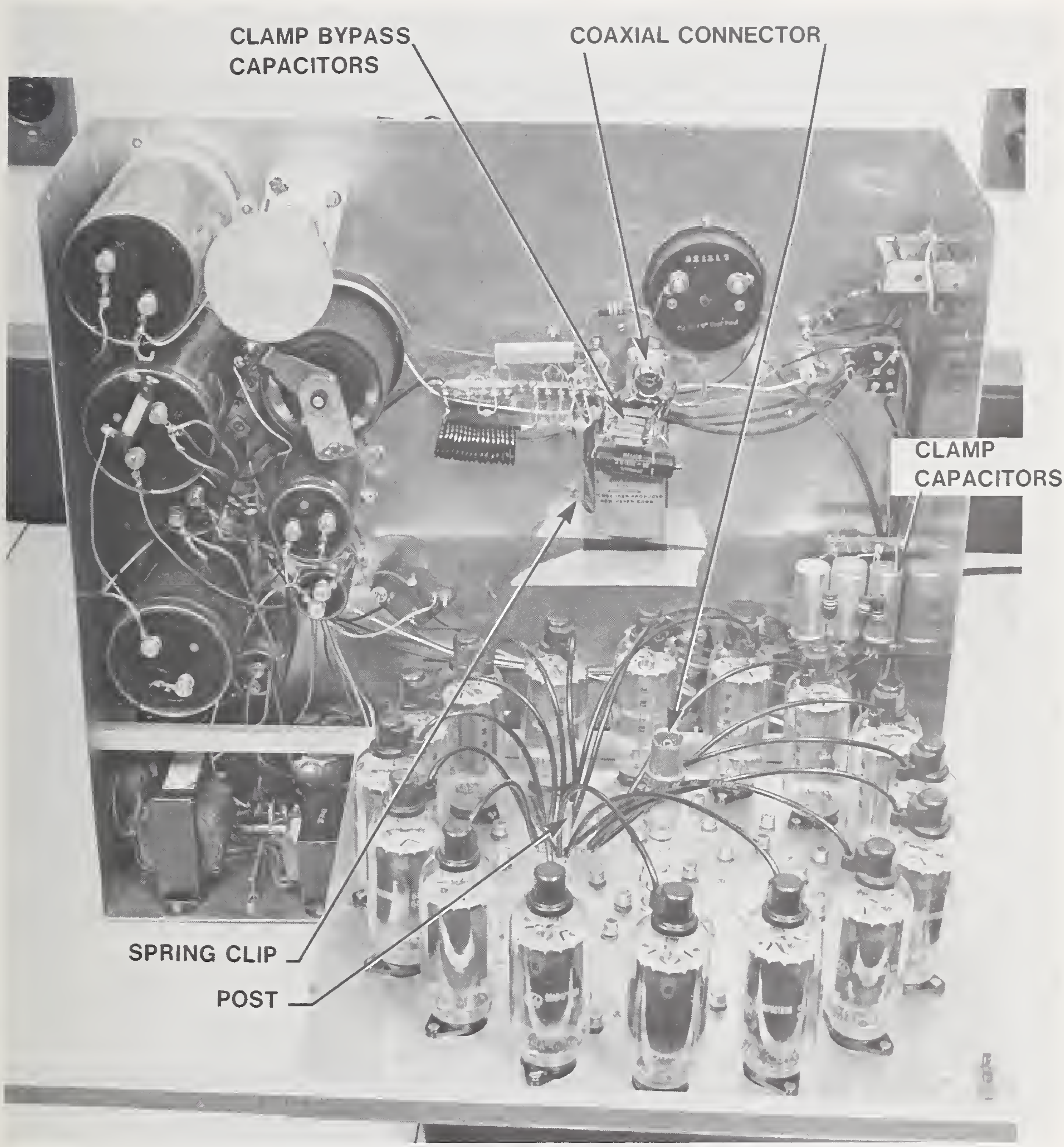

Figure 15. Photograph of the protection circuitry with the ground plate folded down.

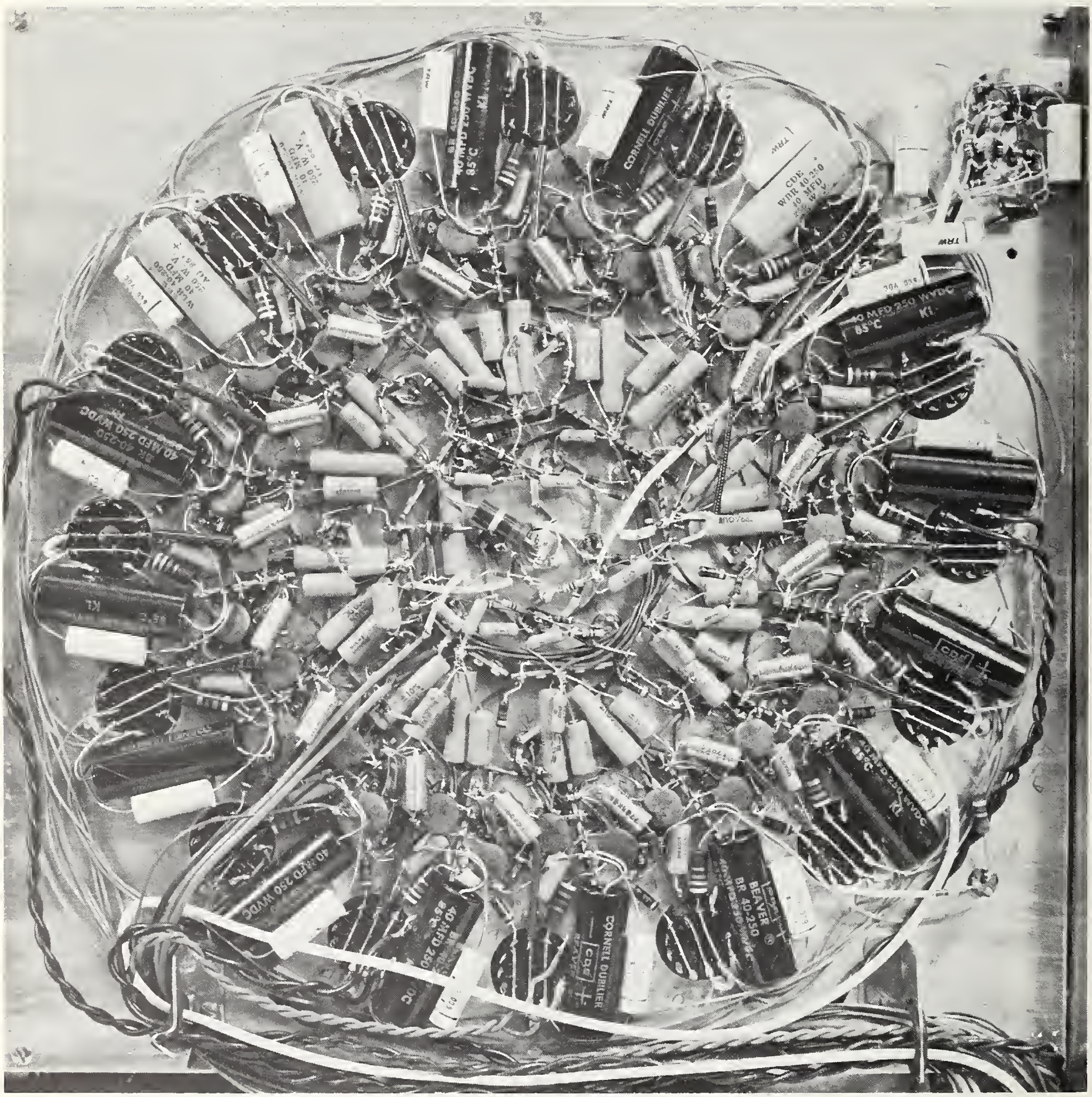

Figure 16. Photograph of the ground plate that holds the protection circuit.

Figure 17. Close-up photograph of the components surrounding the input to the protection circuit.

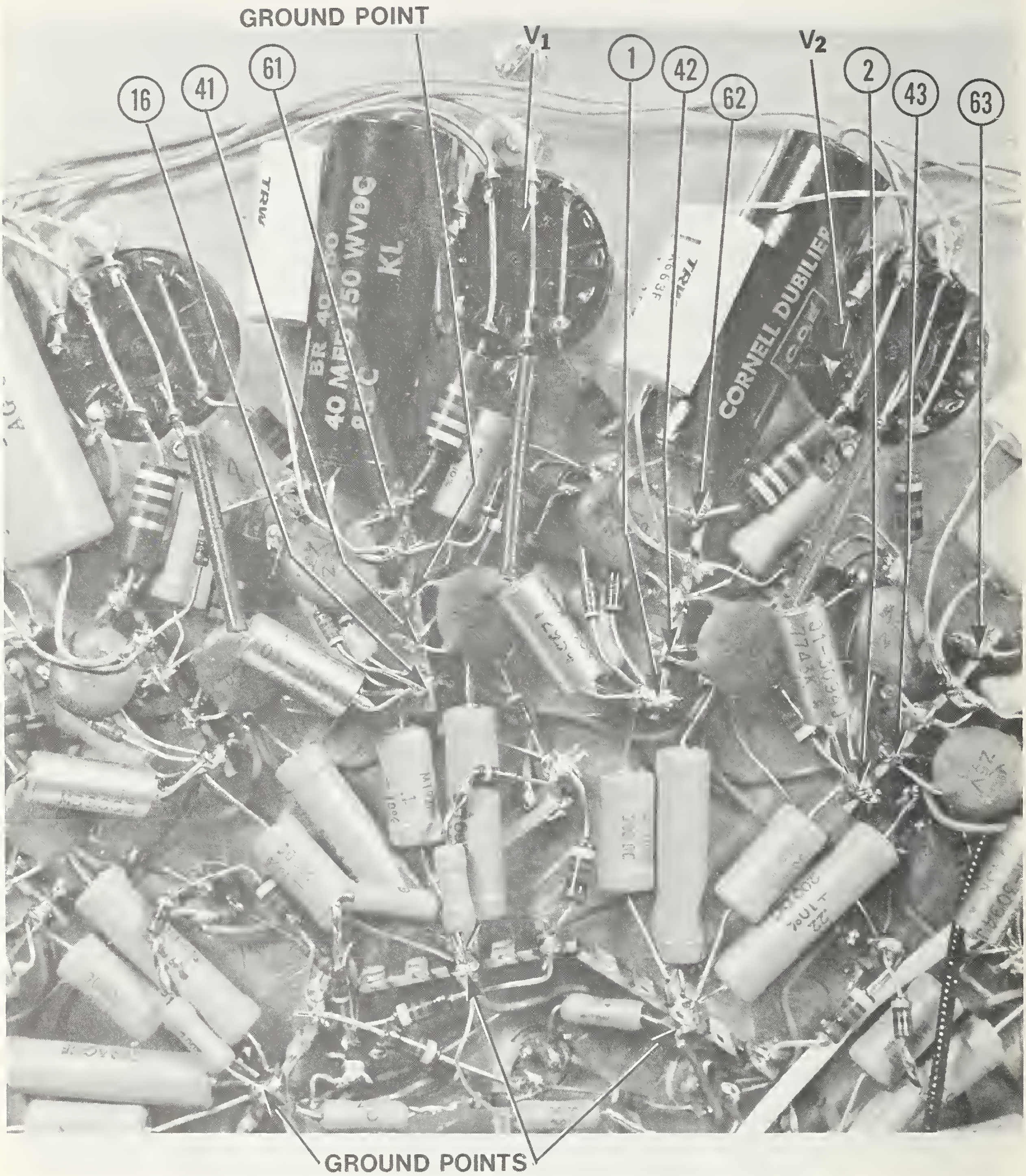

Figure 18. Close-up photograph of a portion of the protection circuit.

Figure 19. Photograph of the top of the RBSOA tester showing the TUT and load inductor.

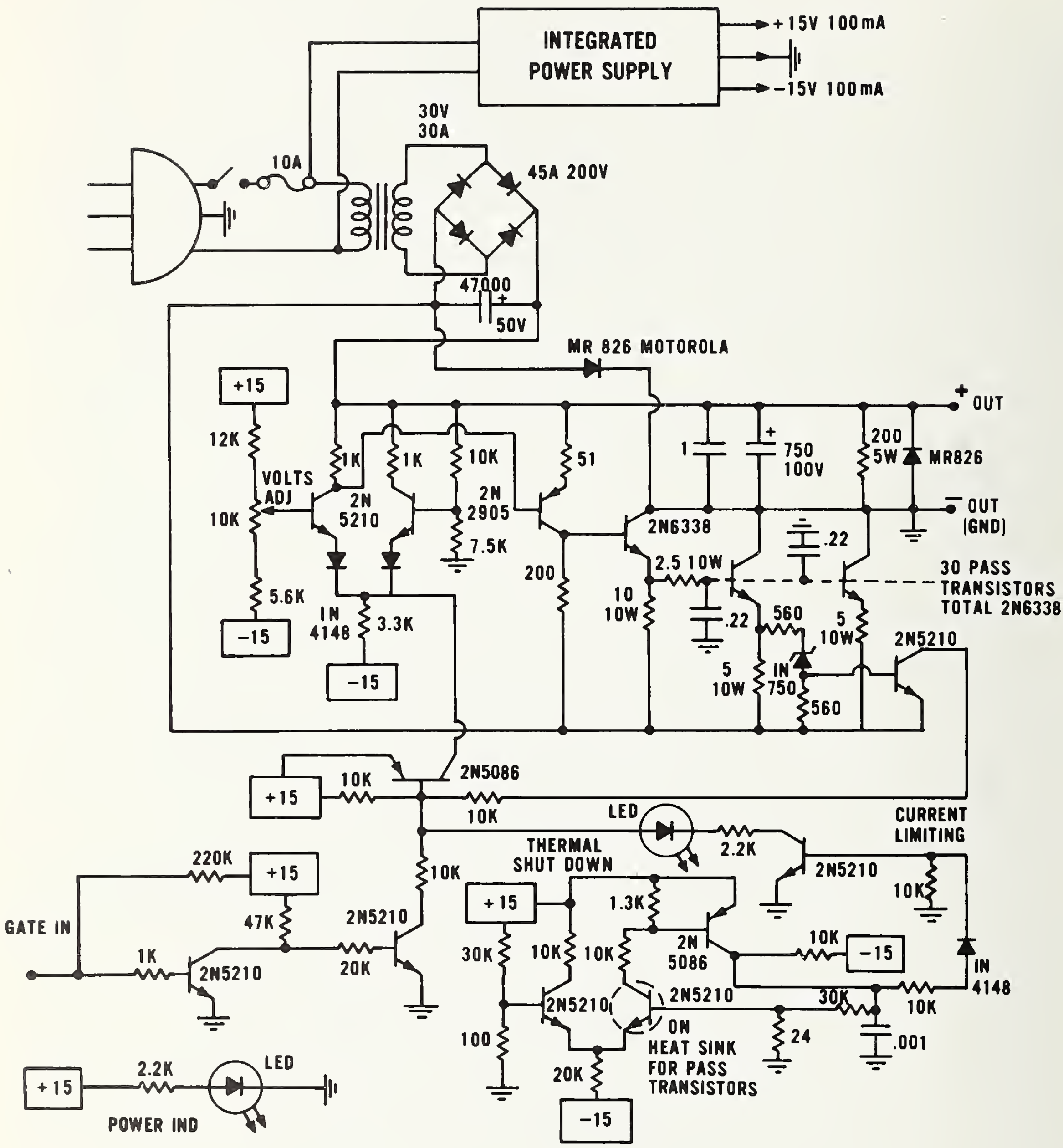

Figure 20. Schematic diagram of the collector power supply.

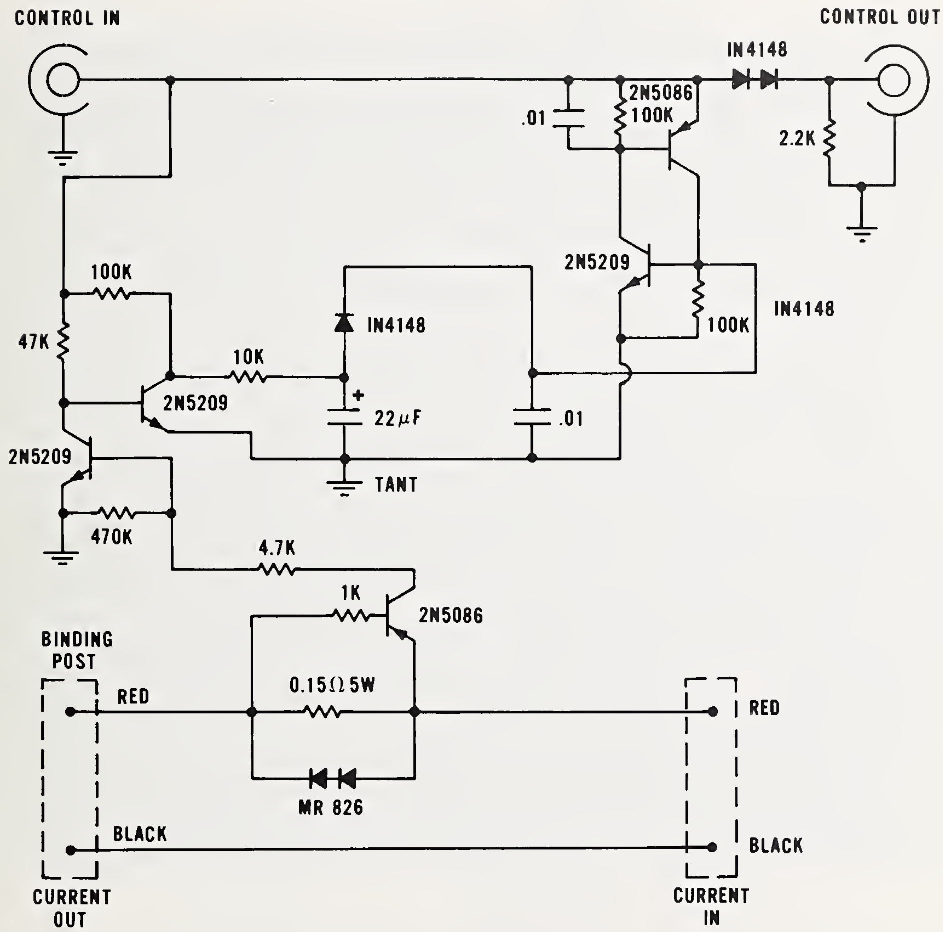

Figure 21. Schematic diagram of the current limiter accessory.

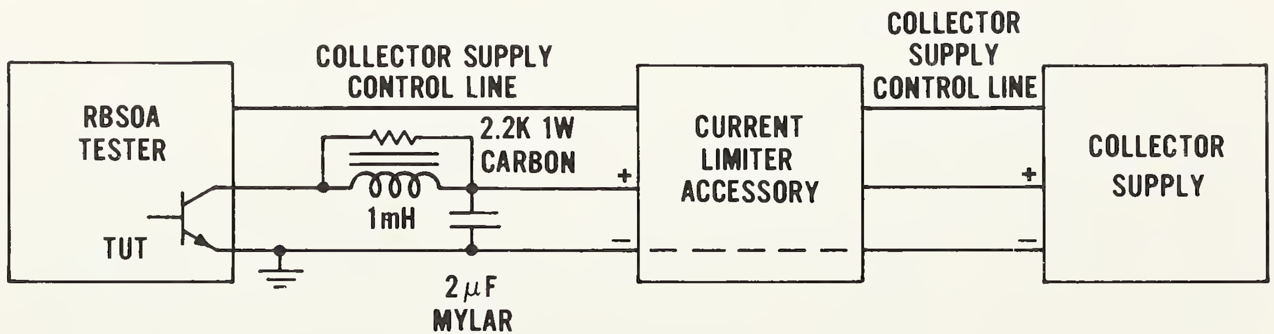

Figure 22. Block diagram of component interconnection.

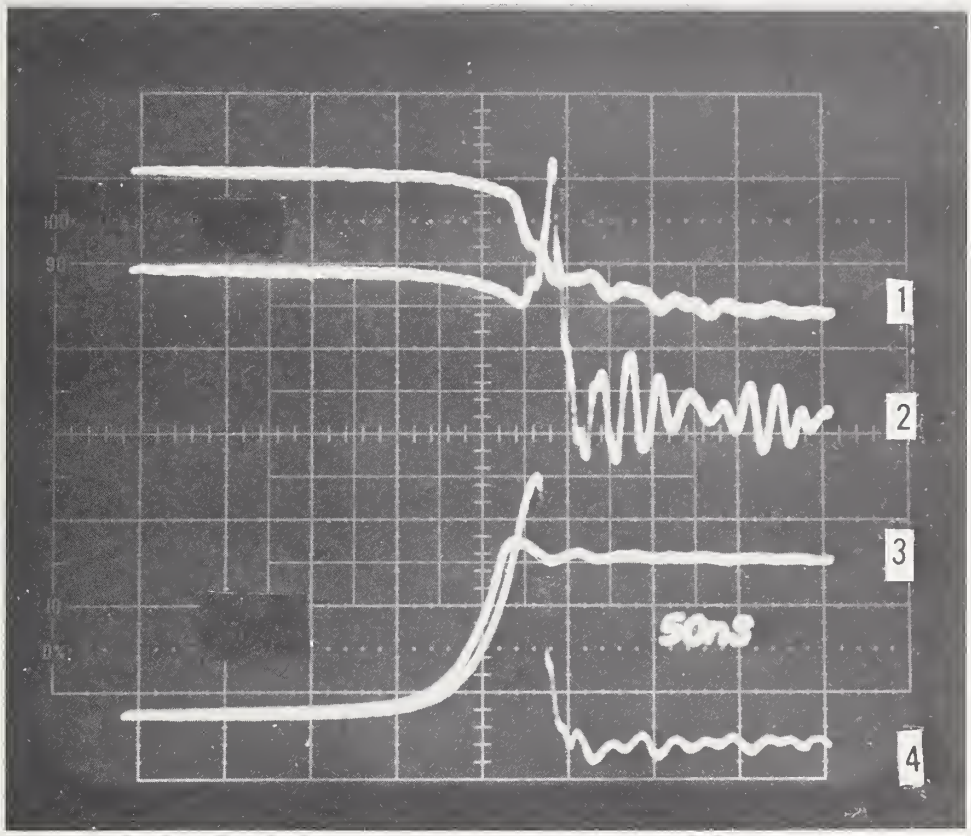

Figure 23. Waveforms obtained using the RBSOA tester to test a transistor. Trace 1: collector current without breakdown, 2 amps per small square; Trace 2: collector current with breakdown; Trace 3: collector voltage without breakdown, 100 volts per small square; Trace 4: collector voltage with breakdown. Current and voltage diverted from the TUT upon breakdown by the protection circuit.

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☐ 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 construction guide for a reverse-bias safe operating area (RBSOA) transistor tester for *npn* switching transistors. Principles of operation for various circuits in the tester are discussed, as well as those of the complete system. System specifications are given. Extensive construction notes are given with hints on chassis layout. Complete circuit schematics are given with additional detail pertaining to power supply and grounding interconnections. Mechanical drawings of the tester enclosure are given. Photographs are included as additional help in building the tester. Special components such as the collector load inductor are described. Finally, a section on the use of the tester includes waveforms generated by a typical test that would be made on a transistor with this equipment.

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*)

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