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**CENTAUR SOLID STATE INVERTER FAILURE DURING SIMULATED
FLIGHT IN AN ENVIRONMENTAL SPACE CHAMBER**

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

A solid state inverter failed during flight simulation testing of a Centaur vehicle in an environmental space chamber. Inspection showed the presence of small metal particles and burrs on the inverter overload sensing shunt. The failure, an electrical short circuit, was analyzed to be due to such a metal particle cutting through the insulation between the shunt and an aluminum heat sink.

While this is a single instance of failure of a key component of a space launch vehicle, we believe that it is a typical example indicating the need for greater attention to detail in the design of components, the preparation of the specifications, the manufacturing process, and the inspection of aerospace components.

In fact, we believe, if more attention to detail were exercised in the production ranging from household appliances to aerospace components the end products would be more trouble free and reliable.

Also, this failure shows the importance of environmental testing under cyclic conditions in uncovering deficient or marginal vehicle components. Such tests should be done extensively at system or sub-system level before testing at vehicle level. In general, such is the case for Centaur vehicle systems.

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SUMMARY

A solid state inverter failed during flight simulation testing of a Centaur vehicle. Analysis of the failure indicates this is an example (Ref. 1) that greater attention to detail must be used during the design, the specification for procurement, the fabrication process, and the inspection of aerospace components. The deficiencies in the above allowed the presence of small metal particles and burrs on the failed inverter overload sensing shunt. The cyclic heating and cooling during repeated testing caused a particle to work through the insulation under the shunt with resulting electrical shorting, burning, and arcing to ground. The arcing caused the failure of the inverter by melting open the shunt.

This investigation also points out the value of repetitive testing of flight equipment in controlled operating environments in uncovering deficient or marginal vehicle components.

INTRODUCTION

As part of the Centaur space vehicle development program, a series of simulated flights was run in 1965 at the Lewis Research Center in a thermal vacuum space simulation chamber (Ref. 2). During one of these simulated flights, a failure occurred in the Centaur solid state inverter. This inverter converts 28 volts direct current to 3-phase 115-volt 400 Hertz alternating current, chiefly for use in the guidance and autopilot systems of the Centaur launch vehicle.

In an actual mission, a similar failure of this component would have resulted in failure of the mission. The faulty performance of the inverter was revealed during ground testing, rather than during an actual flight. This made it possible to pinpoint deficiencies in design, manufacturing procedure and inspection that contributed to the failure and would not have been possible from normal flight data. While this is a single instance of failure in a key component and a subsequent failure

analysis, it is a typical example indicating the need for greater attention to detail in the design, specification, manufacturing, and inspection of aerospace components than now exists.

The Centaur vehicle inverter has since been redesigned for flight use and has eliminated the deficiencies indicated in this report.

TEST PROCEDURE

To simulate the environmental conditions to which Centaur systems are exposed during a space flight, a series of tests were run in a space simulation environmental test chamber. The Centaur vehicle is shown in the environmental test chamber in figure 1. This facility provides test chamber pressures equivalent to 390,000 feet altitude. Liquid nitrogen baffles are used to provide a radiant heat sink, and tungsten quartz-iodine lamps provide the source of solar and earth radiant heating of the vehicle for a simulated flight. This facility is more fully discussed in reference 2. This paragraph defines the procedure during the simulated flight in which the inverter failure occurred. To obtain thermal conditions equivalent to the thermal conditions at the time of liftoff of an actual launch, the airborne inverter was started at "liftoff" (T-0) minus-18 minutes with the guidance system as the inverter's output load. The autopilot system was started at T-0 minus-2 minutes and the autopilot timer was started by guidance command at T-0 ("liftoff"). Two momentary interruptions occurred in inverter output at approximately 13 minutes after simulated liftoff. Because of the interruptions, the autopilot timer was put in a "hold" position; the sequence was stopped. After a 19-minute hold, the timer was again started and the test sequence was resumed. The inverter continued to operate through the hold period and through a subsequent 29 minutes of test at which time it failed causing premature shut-down.

Six special Hall-effect transducers and three voltage phase shifters were used to allow recording of the inverter alternating current output power for each of the three phases. Both active (watts) and reactive (vars) power were measured.

RESULTS AND DISCUSSION

The solid state inverter failed while functioning as part of a Centaur vehicle system in a space thermal environment test. This inverter failure resulted in loss of the simulated mission and end-of-test. Total inverter operating time during the test was 79 minutes. The inverter is shown schematically in figure 2.

Data of output power (fig. 3) show that approximately 31 minutes after inverter start two overloads occurred 25 seconds apart in all 3 phases of inverter output. Also shown in figure 3, the inverter properly shut itself down with inverter output power dropping to zero after each momentary overload. There were no apparent detrimental effects on the inverter operation from these occurrences because the inverter continued to operate normally for an additional 48 minutes before the final failure occurred.

Temperature of a critical inverter transistor (shown in figure 4) indicates that maximum temperature of this transistor was 15° F below the upper operating temperature limit at the end of the run.

Subsequent inspection revealed that the inverter failure was the result of the overload sensing shunt melting open (fig. 5). Further examination of the inverter also revealed that the overload adjustment potentiometer R54 and resistor R55 (fig. 2) were damaged by excessive current. Replacement of these three components restored the inverter to operational condition.

This particular inverter had been previously exposed to numerous tests resulting in many cycles of heating and cooling. Due to the difference in thermal expansion of the manganin shunt and the aluminum heat sink to which the shunt mounts, there is relative motion between the two with each change of temperature.

FAILURE REPORTS AND ANALYSIS

Shunt Failures

Subject test inverter.- The data indicates that at the time of the final malfunction, output power fell to zero (fig. 6) at the same instant that a high input current excursion above 40 amps began (fig. 7). The high input current condition continued for approximately 9 seconds. The input voltage dropped to 14 volts during this period. Referring to inverter power circuit (fig. 2) it should be noted that a short circuit to ground of the overload sensing shunt would draw excess current through the facility metering shunt even with zero inverter output. The input current was limited by facility line resistance to below the 200 amperes required to trip the facility protective breaker. The arcing was sustained for 9 seconds until a section of the shunt material was consumed and input voltage returned to no-load value.

The failed inverter components are shown in figure 5. The mica (3 mil measured thickness) that insulates R53 from electrical

ground is shown with a hole burned through as a result of the arcing.

Metal particles detected on another section of the failed shunt but not directly related to the failure are shown in figure 8 (a) and (b). It is quite likely that such a particle may have been located at the failed area. Due to relative motion between the shunt, the mica, and the heat sink, (caused by cyclic heating and cooling of the inverter in various tests), the particle could have finally worn through the mica, causing shorting and arcing to ground. It was also noted during inspection that the lead at the failed end of shunt R53 was relatively rigid and had been flexed for installation which induced stress at the terminal of the shunt. This heavy, long lead also was unsupported, which would allow stress to be induced by vibration, under some conditions.

Other inverter shunts.- The fact that the foreign matter was common to the shunts of some other inverters is indicated by several additional cases of R53 failures both at LeRC and in the field. During the assembly of the replacement parts into the failed inverter at Lewis, a piece of foreign matter caused a short to ground through a 5-mil-thick mica insulator. Later examination showed this shunt to have burrs around nearly all cutouts. One of the typical burrs is clearly evident in figure 9. Further microscopic investigation showed that very small metal chips are imbedded in the shunt material itself, especially around the mounting holes (fig. 10).

In a field case (failure analysis of inverter serial number 29, on April 9, 1965 at Convair) a burr on the shunt was found to have worked through the 2-mil-thick mica insulator. As a result of this failure, the 2-mil insulator was replaced with a 5-mil insulator on succeeding inverters. This failure is shown still assembled in figure 11.

Subsequently, inverter serial number-30 (with the 5-mil mica) was overheated and went into overload at the Eastern Test Range on July 19, 1965. It was sent to Convair for failure analysis and, during the overload-overheat dropout tests conducted there, R53 burned through at 350 percent overload current (overloads as high as 450 percent were achieved during these tests). Thus, failure of R53 may also possibly result from extended overload conditions when the overload sensing and cutout circuit becomes inoperative due to overheating. Thus, increasing mica thickness may not be the complete solution to the problem since the serial number 30 unit had the 5-mil mica insulator. It must be recognized, however, that this inverter was run under extreme and unrealistic (for flight) conditions and appears to have sufficient margin for the designed use. With regard to the

serial number-30 inverter, it is possible that the mica in this case may also have failed as a result of burrs on the shunt or foreign conductive material between the shunt and mica or the heat sink and the mica instead of just overheating.

Thermal analysis.- The melting temperature of the shunt material (manganin) is 1868° F. If there were no heat transfer, the shunt would melt in a few minutes even at normal inverter loads. However, there is a heat flow through the mica to the heat sink and also out the lead wires (fig. 11). At 350 percent overload less than 0.1 square inches of heat transfer area is required to pass the heat at a temperature differential of 1800° F. The total possible shunt heat transfer area is 2 square inches. Considering only heat conduction out through the leads, a temperature increase rate of only approximately 110° F per hour should result at 350 percent overload. It is concluded that the melting of the shunt was not likely from the heat of normal operation or overload, but by arcing.

Additional Deficiencies

Shunt.- In the failed inverter (serial number-25), R53 had other defects at time of installation (determined during the failure analysis). A crack was noted next to an area which was dented toward the surface facing the mica in one sector of the shunt (figs. 5 and 8 (a) and (b)). The discoloration on the mating mica surface indicates lack of contact between the mica and the shunt near this dented area (the discoloration is caused by condensation of gases from the charred phenolic shunt cover insulator).

Shunt cover.- A nearly uniform charring of the R53 phenolic shunt cover, probably due to sustained overheating during previous tests or by heat conducted along the shunt during the arcing period, is also shown in figure 5. If the heating had resulted only from the final failure, this would probably have resulted in much greater charring toward the end where the shunt melted. The R53 phenolic cover was warped and charred to the degree that non-uniform cooling was effected and the part was not adequately performing its function.

Another Possible Mode of Failure

Another possible mode of failure might result if the substance condensed on the mica from the phenolic cover were to react with the mica. Mica has poor resistance to alkalis and to weak or strong organic and inorganic acids (Ref. 3). Microscopic inspection, however, indicated that the deposits from the phenolic had not attacked the mica in this case.

CONCLUSIONS AND RECOMMENDATIONS

1. It is believed that the cause of this inverter failure was due to an electrical shorting of the shunt which was probably caused by insufficient electrical insulation provided by the 3-mil-thick mica combined with the burrs and foreign conductive chips on the shunt, some of which worked through the mica. The melting of the R53 shunt was likely caused by arcing rather than operational overheating.

Special care must be taken in manufacture and inspection to see that the shunt is free of all burrs, chips, dents, cracks, etc. and that other foreign matter does not get imbedded between the mica insulator and the shunt for the heat sink.

2. The leads to shunt R53 should be more flexible, performed, or supported so no mechanical loads are transmitted to the shunt.

3. The adequacy of the R53 phenolic cover is marginal and should be considered for redesign.

CONCLUDING REMARKS

After these tests were run, the inverter now used on Centaur vehicles has been redesigned to eliminate the deficiencies as indicated in this report.

We believe that if more attention to detail were exercised in the production ranging from household appliances to aerospace components, the end products would be more trouble free or reliable.

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3. Pender, Harold; and DelMar, Willaim A., eds.: Electric Power, Vol. 1 of Electrical Engineers' Handbook. Fourth ed. John Wiley and Sons, Inc., 1949, table 7, pp. 2-62.

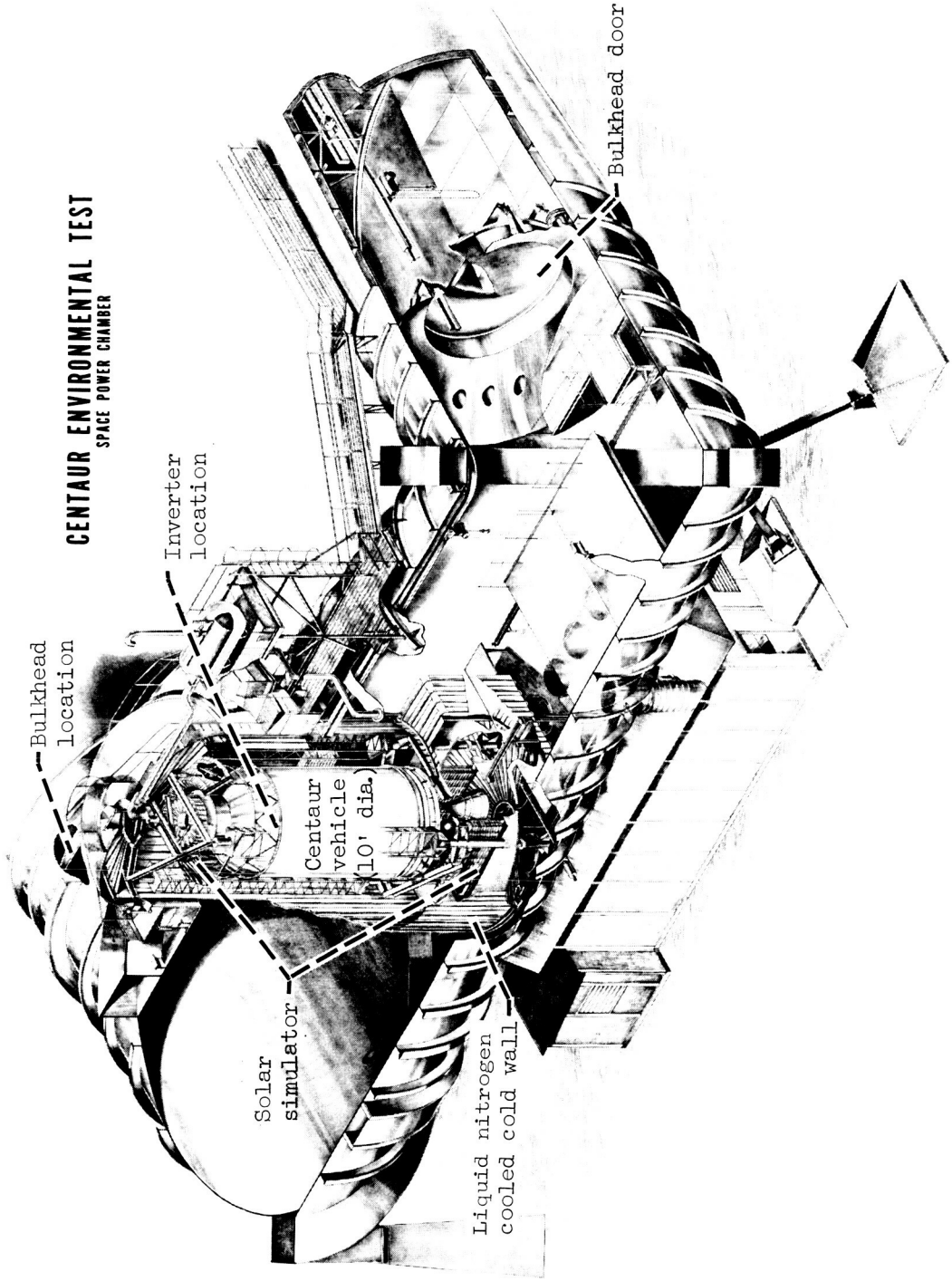


Figure 1. - Centaur vehicle in space simulation environmental test chamber.

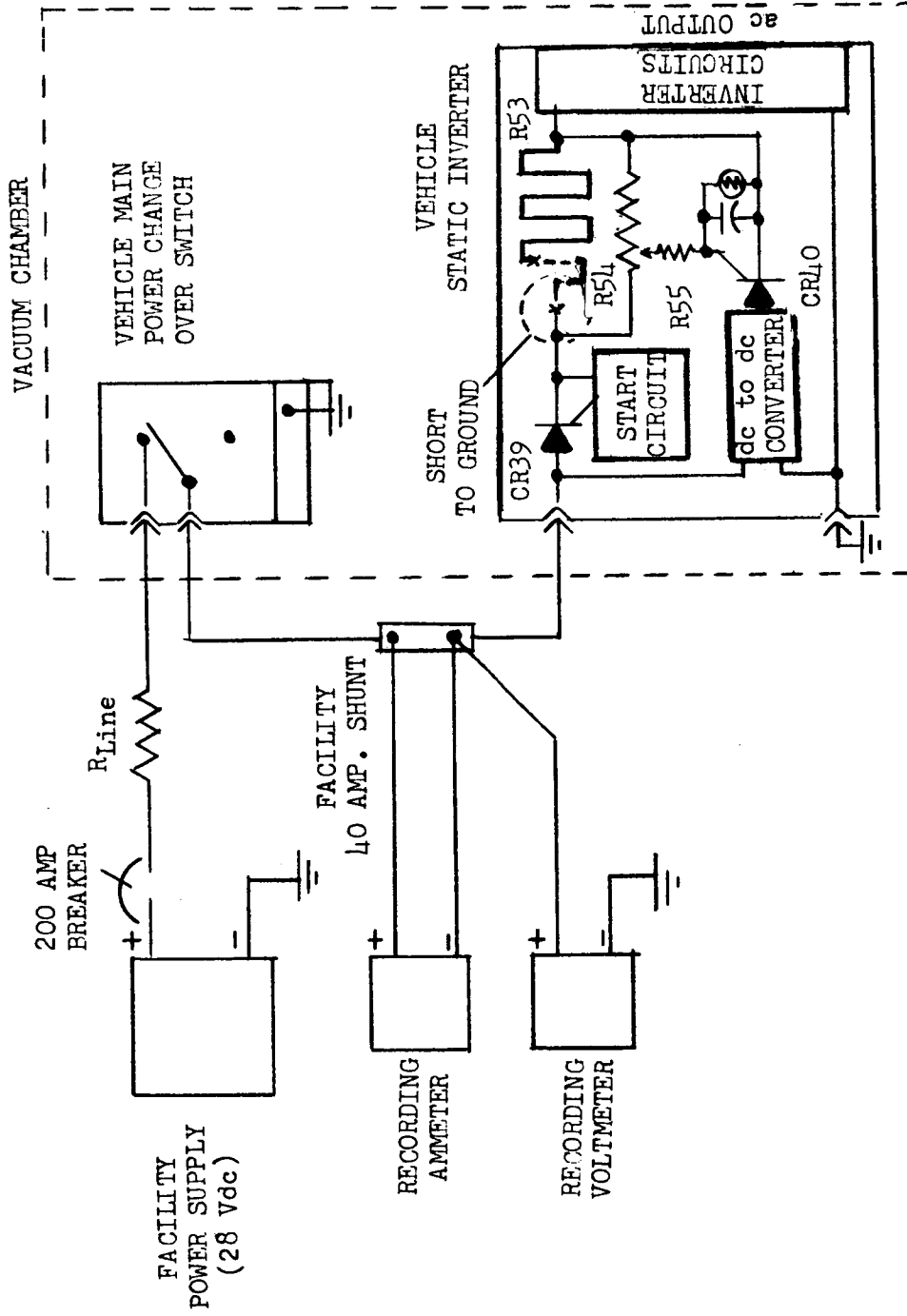


Figure 2. - Simplified circuit diagram of instrumentation and power connections to inverter.

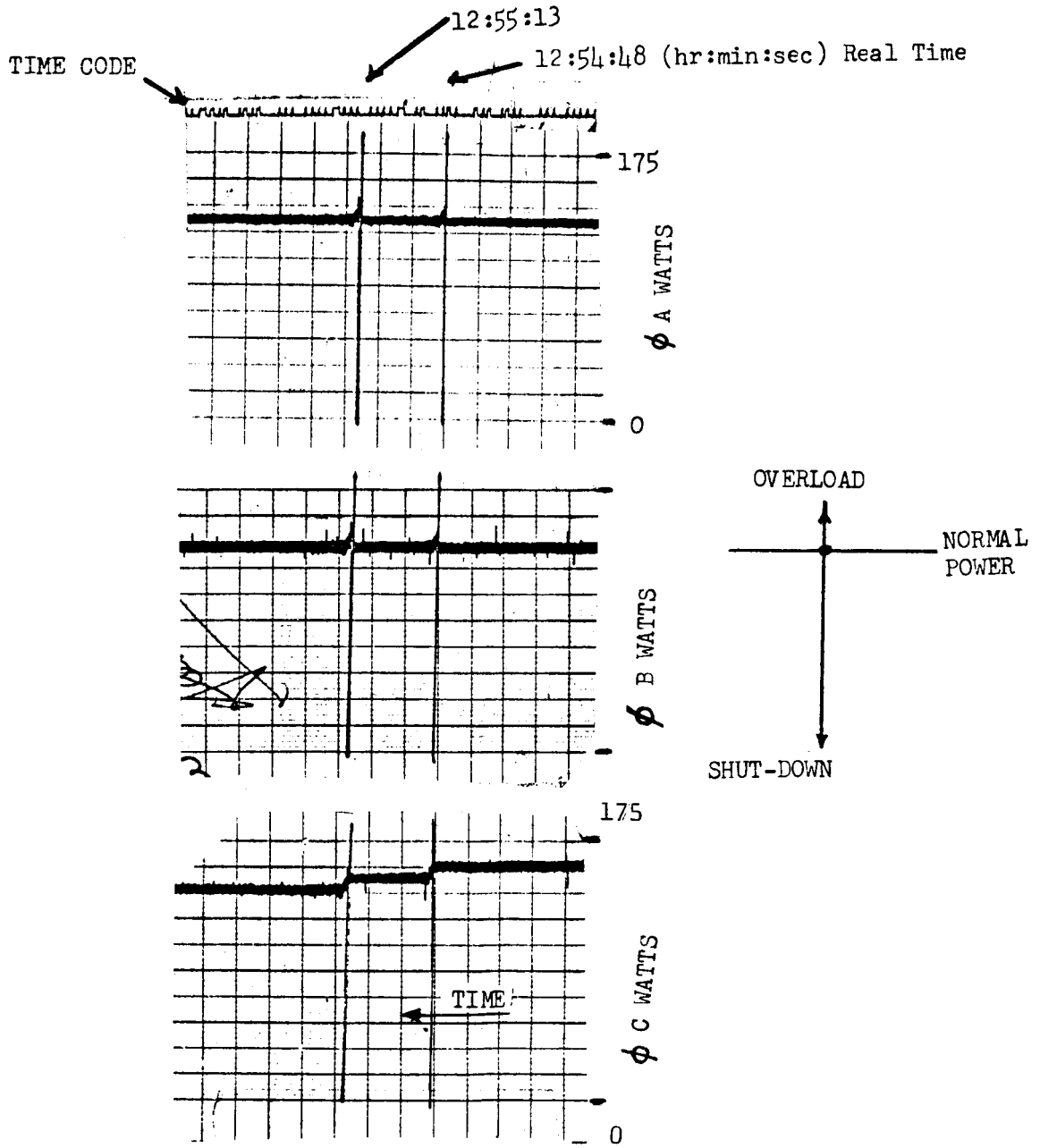
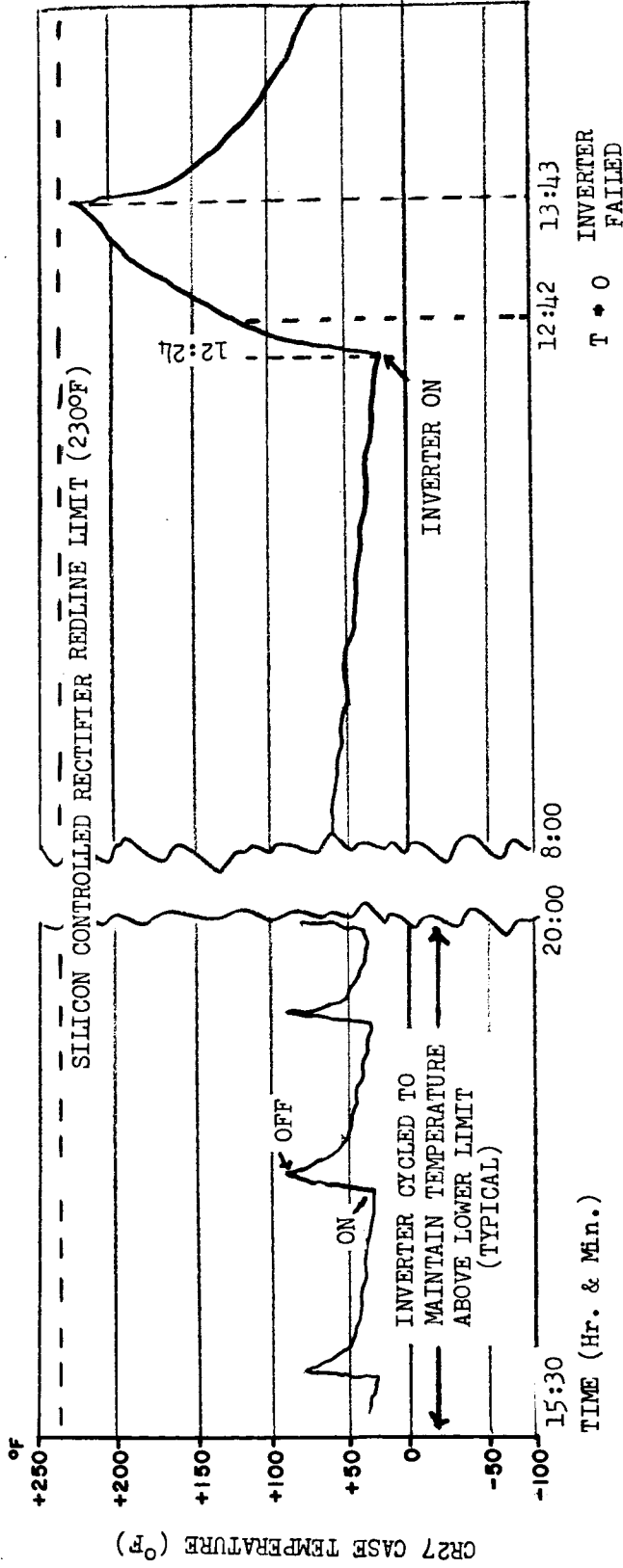


Figure 3. - Inverter output power showing three phase overload and inverter shutdown.



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Figure 4. - Inverter CR27 case temperature vs time.

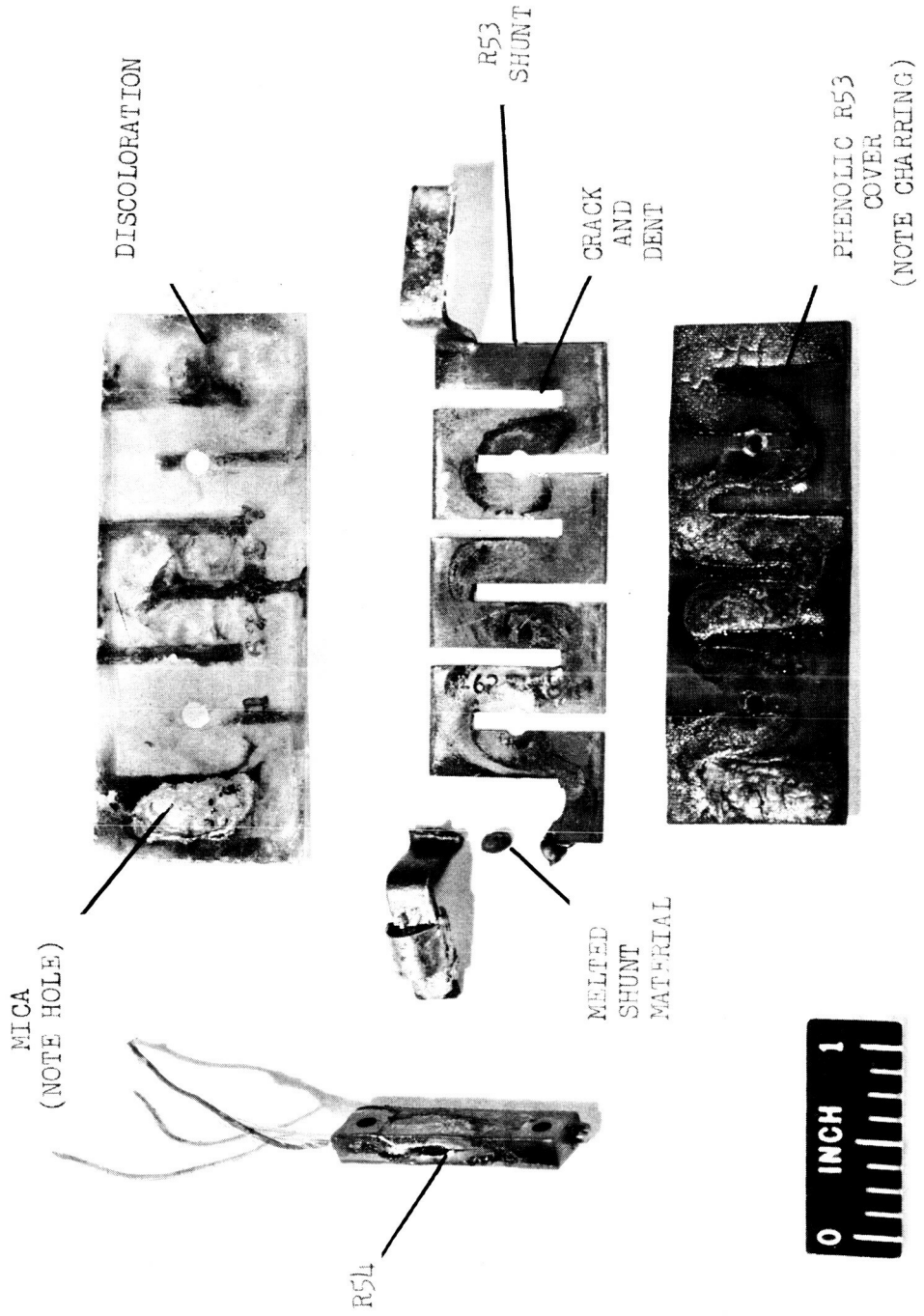


Figure 5. - Inverter failed components.

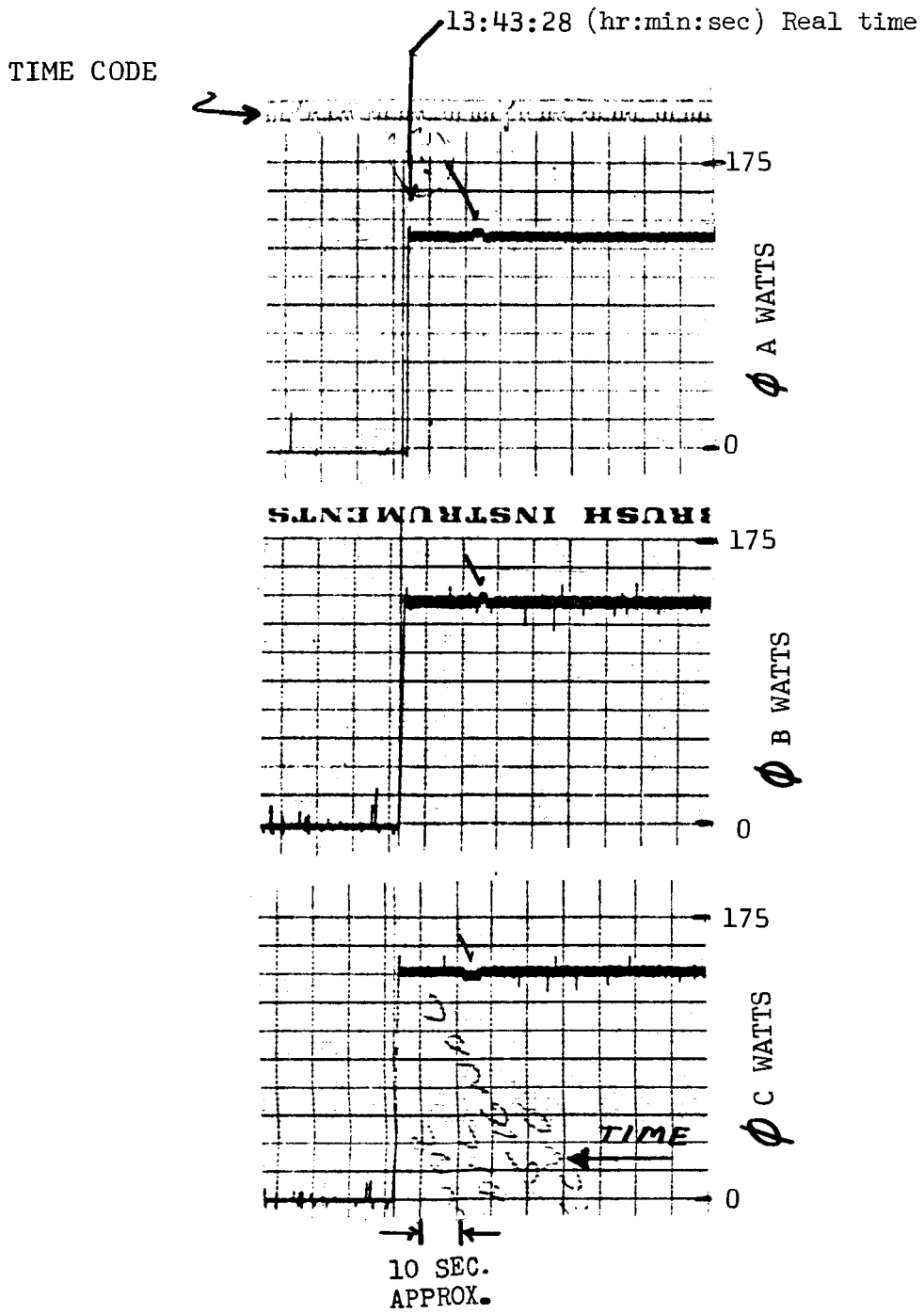


Figure 6. - Three phases, output power at time of inverter failure.

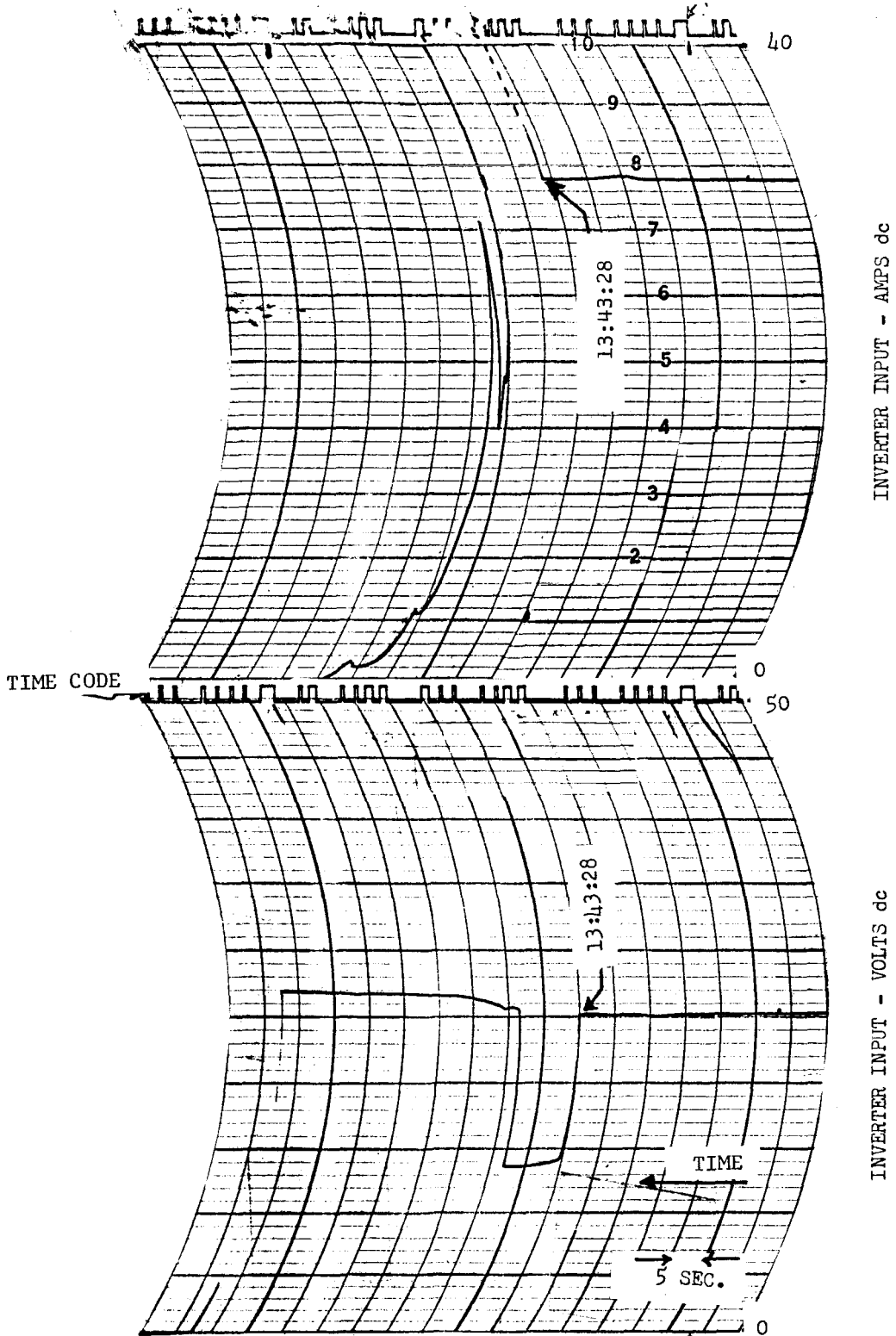


Figure 7. - Input current and voltage of inverter at time of failure.



Figure 8(a). - 10X magnification of R53 showing high point imperfections in shunt material and dented area.

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Figure 8(b). - 15X magnification of same area of figure 8(a) showing cracked area and high point material.



Figure 9. - 10X magnification of R53 showing raised burr along edge of shunt.

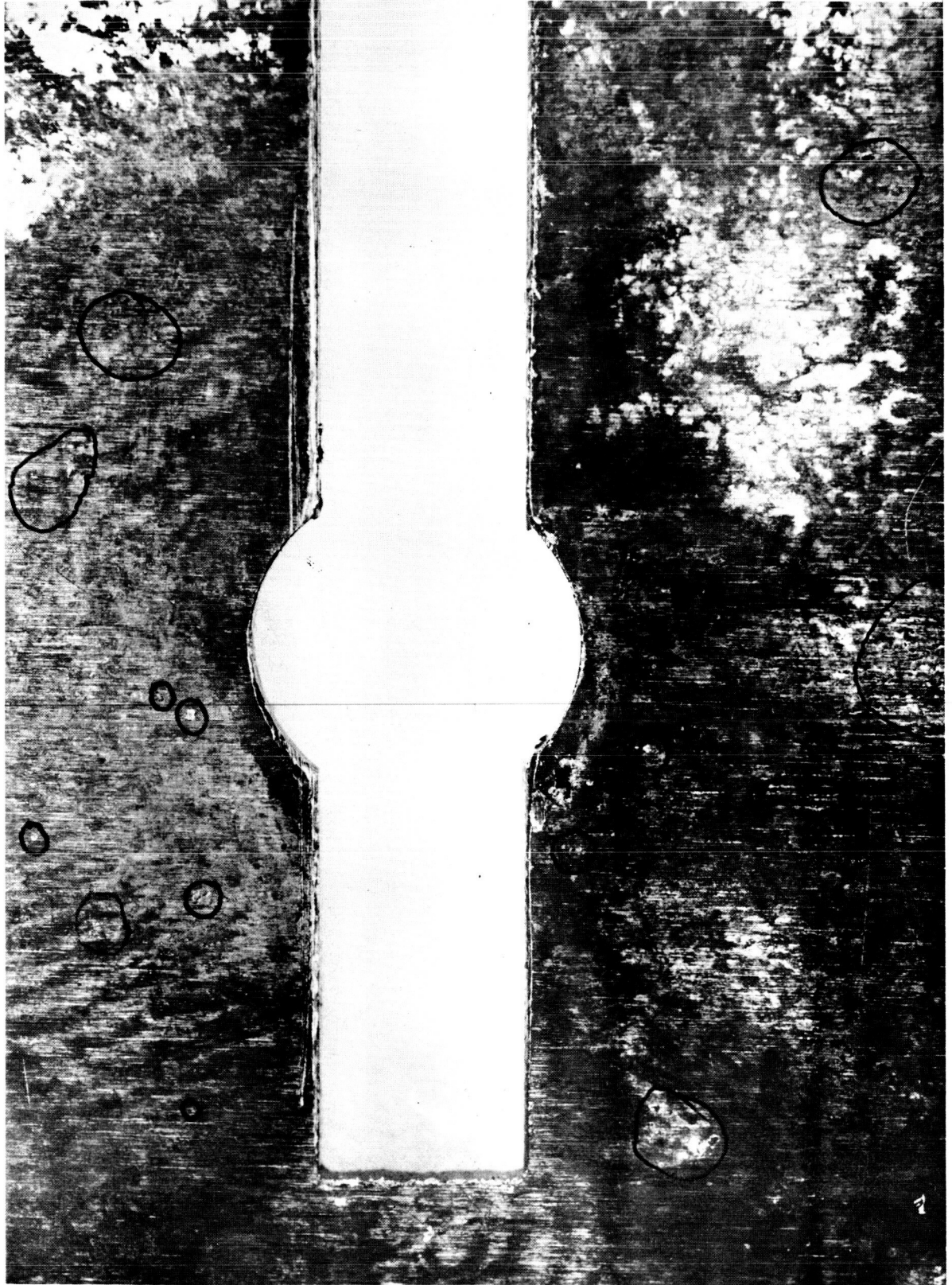


Figure 10. - 10X view of portion of shunt showing small metal chips in area of mounting hole.

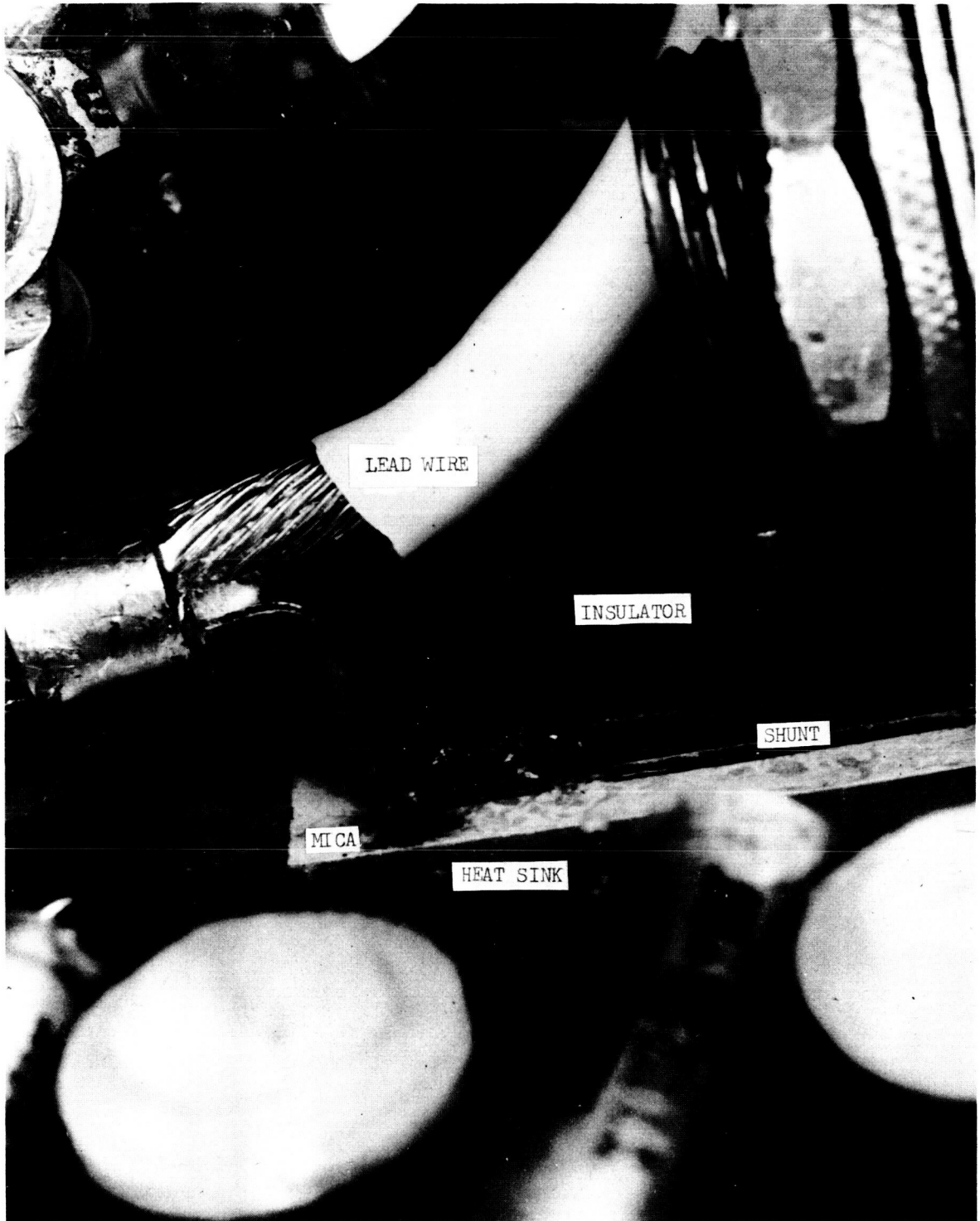


Figure 11. - Failure of inverter shunt by shorting to the heat sink (ground).