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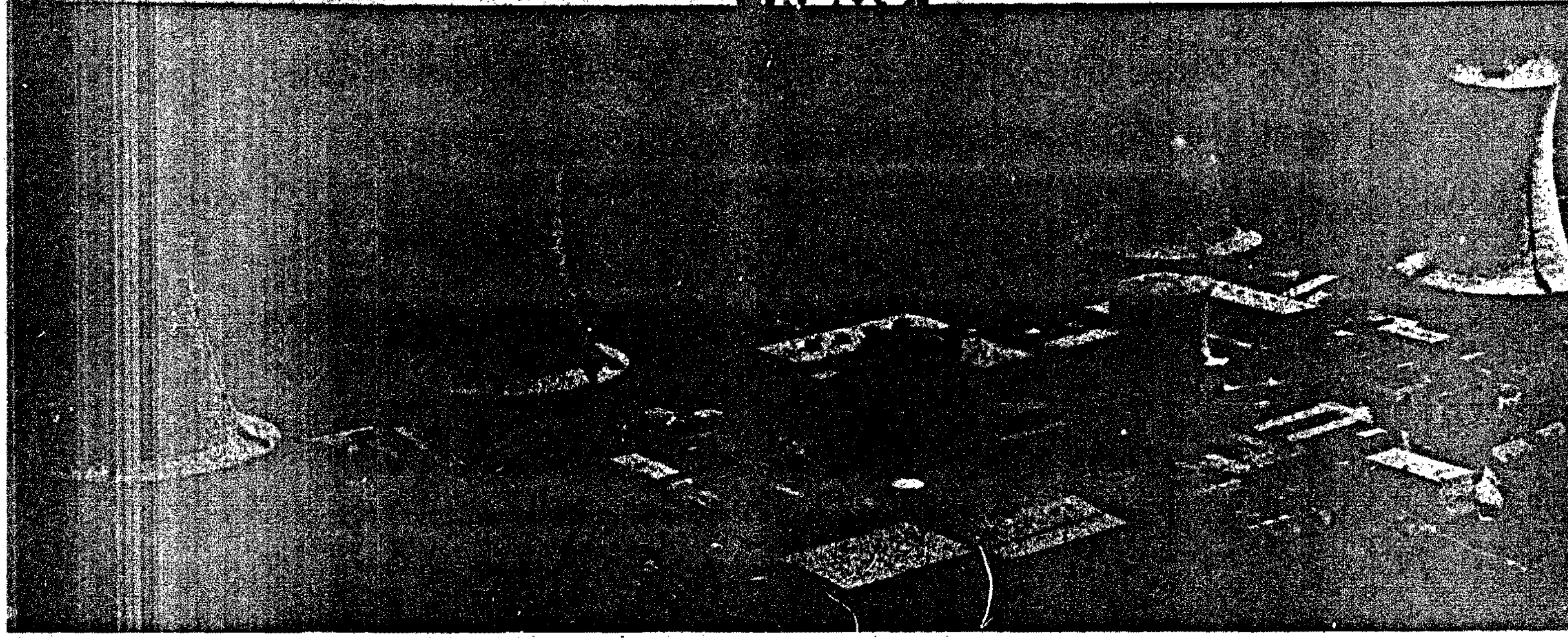

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Examination Results of the Three Mile Island Radiation Detector HP-R-211

Michael B. Murphy
Geoffrey M. Mueller
Frank V. Thome

October 1981

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EXAMINATION RESULTS OF THE THREE MILE ISLAND RADIATION DETECTOR HP-R-211

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ABSTRACT

An area radiation detector, HP-R-211, which was removed from the Three Mile Island containment building on August 15, 1980 has been examined. The detector had failed at some time following the accident and indicated erroneous, low radiation levels from that point on. This report discusses the cause of failure, detector radiation measurement characteristics, our attempts to reconstruct the gamma rate history from detector output stripchart recordings, and our estimates of the total gamma radiation dose received by the detector electronics. We have also identified the radioactive contaiminants present on the detector and explored decontamination methods.

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At Sandia, Lloyd Bonzon, Paul Yarrington, and Dick Damerow provided technical support. Al Asselmeier provided all of the transistor failure analysis. Billy O'Neal of Sandia and Glen Waterbury of Los Alamos National Laboratories did most of the work in gamma spectra and radiochemical analysis. Lloyd Bonzon was responsible for determining the elastomeric materials total dose. Special thanks goes to Gary Romero of Sandia's Health Physics division in supporting all of the radiological work and assisting in the decontamination.

Special thanks goes to Karl West, Oak Ridge National Laboratory, for his enthusiastic support and helpful suggestions. Mel Mathis and Jim Jones at Technology for Energy, Inc. provided all of the on-site test data in a most helpful manner.

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FIGURES & TABLES

I. INTRODUCTION AND SUMMARY FINDINGS

A. Background

On August 15, 1980, during the second manned entry into the Three Mile Island (TMI) Unit 2 containment building, the first piece of electrical equipment was removed for examination and laboratory testing. The instrument that was removed is an area radiation detector having the TMI-2 equipment tag number HP-R-211. This particular instrument was chosen for examination because of its accessibility, its similarity to other instruments found in the containment building, and the desire to replace it with an operable unit. The detector is a gamma radiation monitor manufactured by Victoreen (Model 857-2) and employs a GM tube to detect events. It had operated continuously during and following the accident; however, it had indicated erroneous, low radiation levels both during the accident and at the time of removal some 506 days later. Extensive in situ electrical measurements were made on the instrument from the TMI-2 control room by General Public Utilities (GPU) and Technology for Energy, Inc.[1] the day before removal. The detector was delivered to Sandia National Laboratories on October 7, 1980 for extensive electrical and radiological examination. The radiation detector was removed as a part of the DOE TMI-2 Instrumentation and Electrical Equipment Examination Program administered by the DOE/EG&G Technical Integration Office (TIO) at Three Mile Island.

B. This Report

This report summarizes the results of the Sandia examination of HP-R-211. The specific areas discussed are:

1. the cause of failure,
2. detector characteristics and gamma doserate history,
3. total gamma dose received,
4. contamination nuclides and activity levels, and
5. decontamination methods and efficiencies.

One problem which we have encountered is that of striking a balance between a completely thorough experimental and theoretical examination and one which addresses the most important areas and obtains results for timely release. We believe this report achieves that balance. In the interest of distributing our results as quickly as practicable, some of our experimental data has been omitted from this report and is contained in laboratory notebooks.[2,3,18] Data felt to be most important in understanding or supporting conclusions are included here. This document is an expansion and update of the preliminary findings reported at the TMI-2 Information and Examination Program International Seminar sponsored by the U. S. Department of Energy and held in Washington DC on November 21 and 22, 1980.[4]

C. Findings and Recommendations

1. The mode of failure of HP-R-211 was confirmed to be a low impedance fault between the collector and emitter leads in transistor Q6 in the detector output circuit. The transistor failed because of catastrophic, non-annealing, punch-through from collector to emitter caused by high voltage breakdown and energy deposition. Substantial evidence indicates that this occurred at least partially when the reactor building sprays were initiated some 10 hours into

the accident. Spray and/or steam apparently entered the connector assembly where the detector and cable mate and caused the 600 volt GM tube power line to short, momentarily, to the signal output line. The connector backshell does not look as though it was properly mated to the connector insert. This, and the orientation in which the detector was mounted provided an entryway for the moisture. To prevent this from occurring in the future, we recommend that Victoreen detectors of this and similar types be mounted with the connector below the housing and that the connector backshells be potted. Even more fundamentally we question the need for having anything other than a sensor inside the containment building. Wherever possible, active electronics should be located outside containment.

2. The repaired, but degraded, detector exhibits a radiation level indication which becomes multivalued when it is exposed to radiation levels in the 10^3 to 10^6 R/H range. Instead of remaining pegged at its maximum 10^4 mR/H indication in this range, the readout begins to decrease at 10^3 R/H, reaches a minimum at approximately 50 x 10^3 R/H, and then begins to increase thereafter. This characteristic is caused by detector to cable impedance mismatches and is accentuated by long cable lengths and radiation degradation of detector transistors and the GM tube. This could present a hazardous situation in a reactor LOCA wherein radiation degraded detectors may indicate radiation levels to be significantly lower than they actually are. Changes in circuit design and/or the use of more radiation tolerant transistors can correct this problem.

3. We have been unable to reconstruct the time history of containment building gamma radiation using the HP-R-211 stripchart data at this writing. These data have certain characteristics during

the first several days of the accident which we cannot fully explain. Hopefully, the analysis of other detectors and the Dome monitor will provide information to fill in gaps in our understanding of this detector. A separate report will address this subject.

4. Both transistor and elastomeric data indicate that the electronics inside HP-R-211 received a total gamma radiation dose of approximately 2.5×10^5 rads. This level is appreciably below some earlier estimates.

5. The major radionuclides on the outside of the detector were found to be CS-134, CS-137 and SR-90. The concentration of CS-137 was found to be 0.973 $\mu Ci/cm^2$ on the top horizontal surface and 0.103 $\mu Ci/cm^2$ on the side and bottom surfaces. These findings are higher than those obtained using swipes on floors and walls.[17]

6. The approach used to decontaminate the detector outside was to avoid scrubbing and minimize the use of caustic chemicals. We found that as much as 44% of the contaminants were removed simply by handling during shipment and contaminant characterization. Low-pressure water and detergent sprays were ineffectual. Low-pressure steam and mild phosphoric acid washes (Turkel 4512A) were the most efficient. Even so, only about an order of magnitude reduction was achieved using all of the above steps.

II. DESCRIPTION

A. Detector Channel

HP-R-211 (SN 359) is one of six containment building area radiation monitors. It was mounted on a pillar at the 305' elevation near personnel hatch No. 2, as shown in Figure 1. Similar detectors are mounted at the 305' elevation near the equipment hatch (HP-R-212), the 347' elevation near the incore tubes (HP-R-213), and the 347' elevation fuel handling bridges (HP-R-209 and HP-R-210). In addition, an ion chamber monitor housed within a lead shield is located at the 372' elevation above the elevator (HP-R-214, dome monitor). Separate instrumentation cables connect each detector located inside the containment building to ratemeter readout electronic modules located in the TMI-2 control room. There, a multipoint stripchart recorder (HP-UR-1901) records each readout using a sample interval of 1 minute. Figure 2 shows the cable interconnect diagram for HP-R-211. The detector power and signal cable exits the containment building through penetration R507 and eventually connects to a remote readout and alarm located in the anteroom. From there, signals are distributed to the control room, where the ratemeter (readout electronics and power supply) is located, and back into containment to an alarm. It is noteworthy that the HP-UR-1901 stripchart shows traces for only detectors 211, 213, and 214 at the time of reactor trip. The trace for 212 is unreadable.

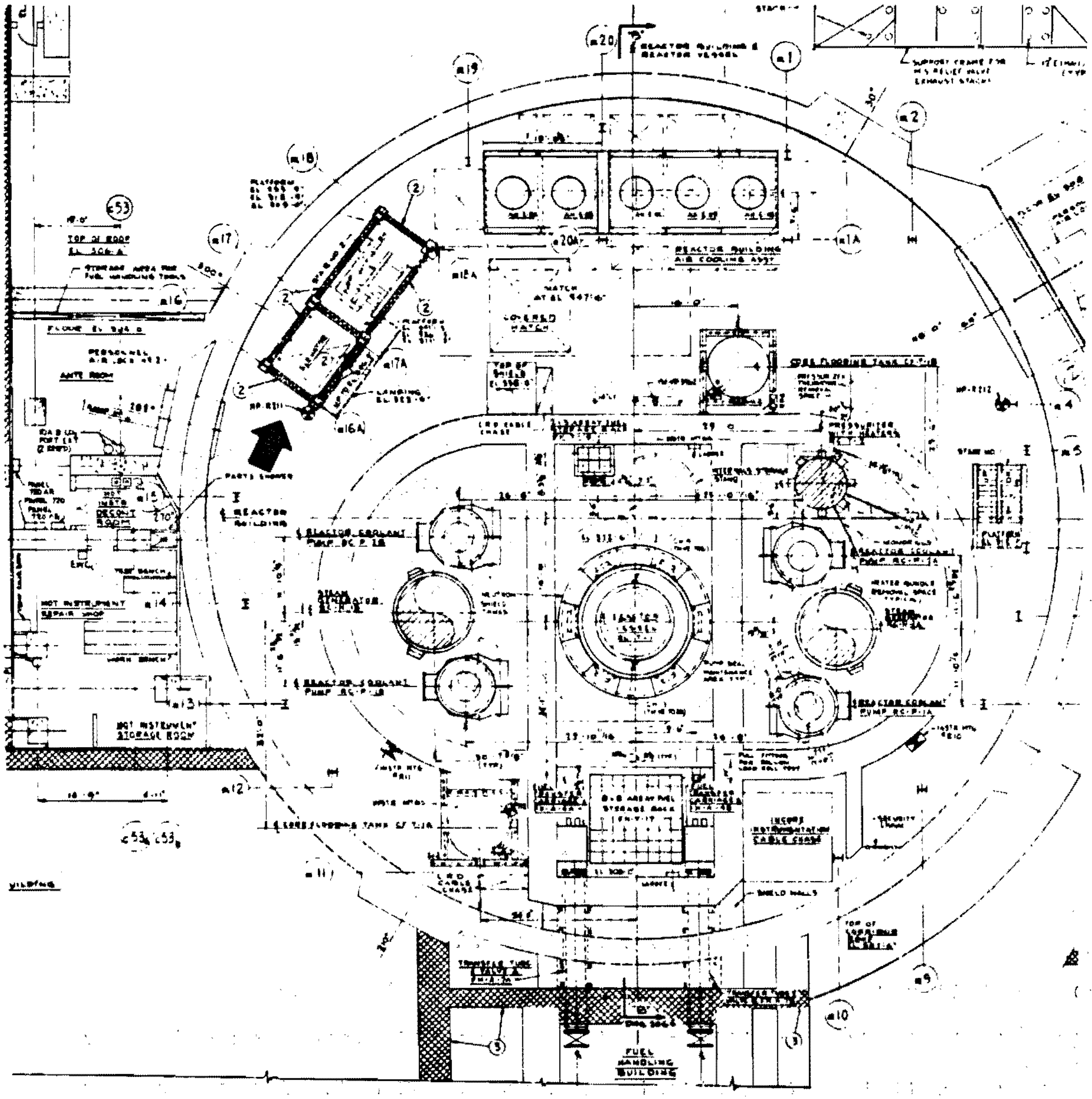

FIGURE 1. TMI Unit 2 305' Plan Layout. Radiation detector HP-R-211 (HP-R211) is located near Personnel Air Lock No. 2.

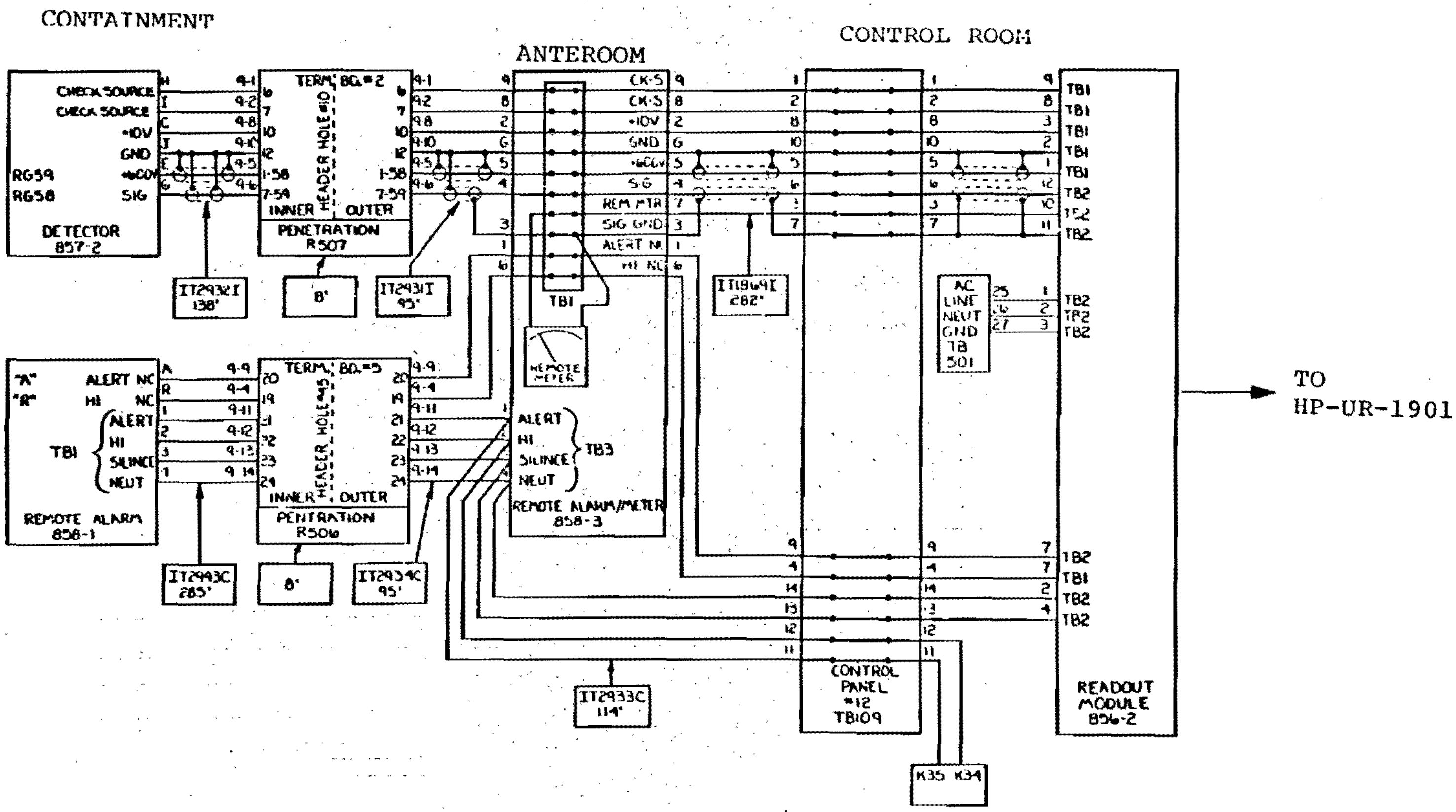

FIGURE 2. Cabling and Interconnect Diagram.
The approximate length in feet of each cable is shown.

B. Removal

Extensive preparations were made prior to removal to minimize the time spent by the GPU staff inside the containment building. This included practice on a full scale mock-up assembled by the TIO staff. The plan was to remove the faulty detector and replace it with a functional one. Unfortunately, during removal (Figures 3 and 4) the cable was detached from the connector backshell at the point where solder connections are made. The result of this was to make it impractical to install the replacement.

C. Detector Description

The Model 857-2[5] detector, shown after removal in Figures 5, 6 and 7, consists of a painted, nominal 5 mm thick aluminum housing, a 64 x 137 mm glass epoxy circuit board with electronics, an O-ring seal, and a waterproof Bendix connector. The detector is connected to the Victoreen Model 856-2 ratemeter (Figure 8) through an estimated 159 m (523 ft.) of cabling. The printed circuit board holds the Geiger-Mueller (GM) tube and signal conditioning electronics. The detector is not loss-of-cooling-accident (LOCA) qualified but does have a good O-ring seal and sturdy housing and is designed to function up to a total accumulated radiation dose of 10^5 rads. This unit was set to indicate radiation rates ranging from 0.1 mR/H to 10^4 mR/H. The ratemeter was adjusted to actuate the alarm at 50 mR/H. A 0.08 µCi Ra-226 check source can be used to indicate operability.

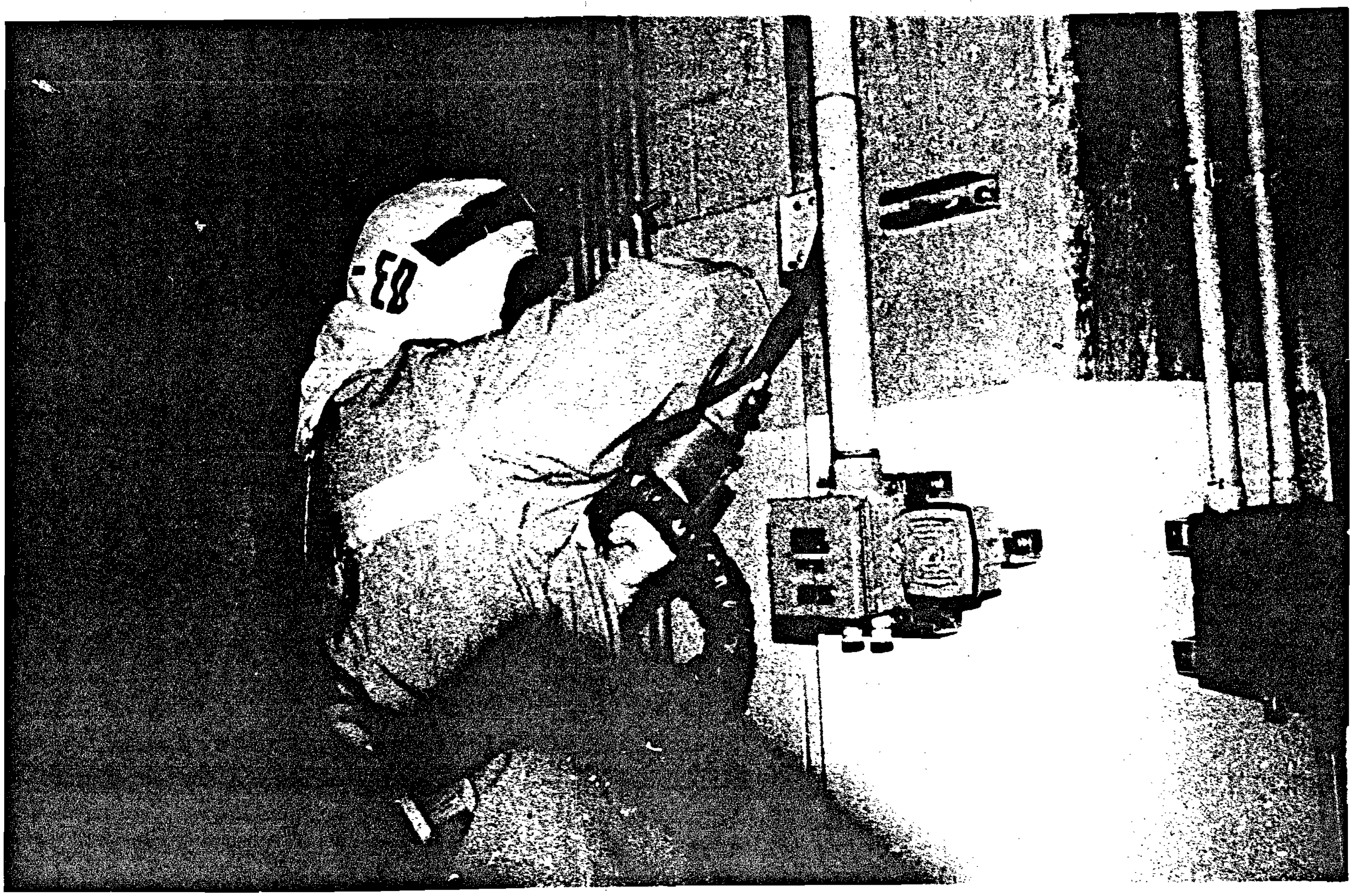

FIGURE 3. Detector Removal. The detector has been removed from the wall slide bracket and the cable is being disconnected.

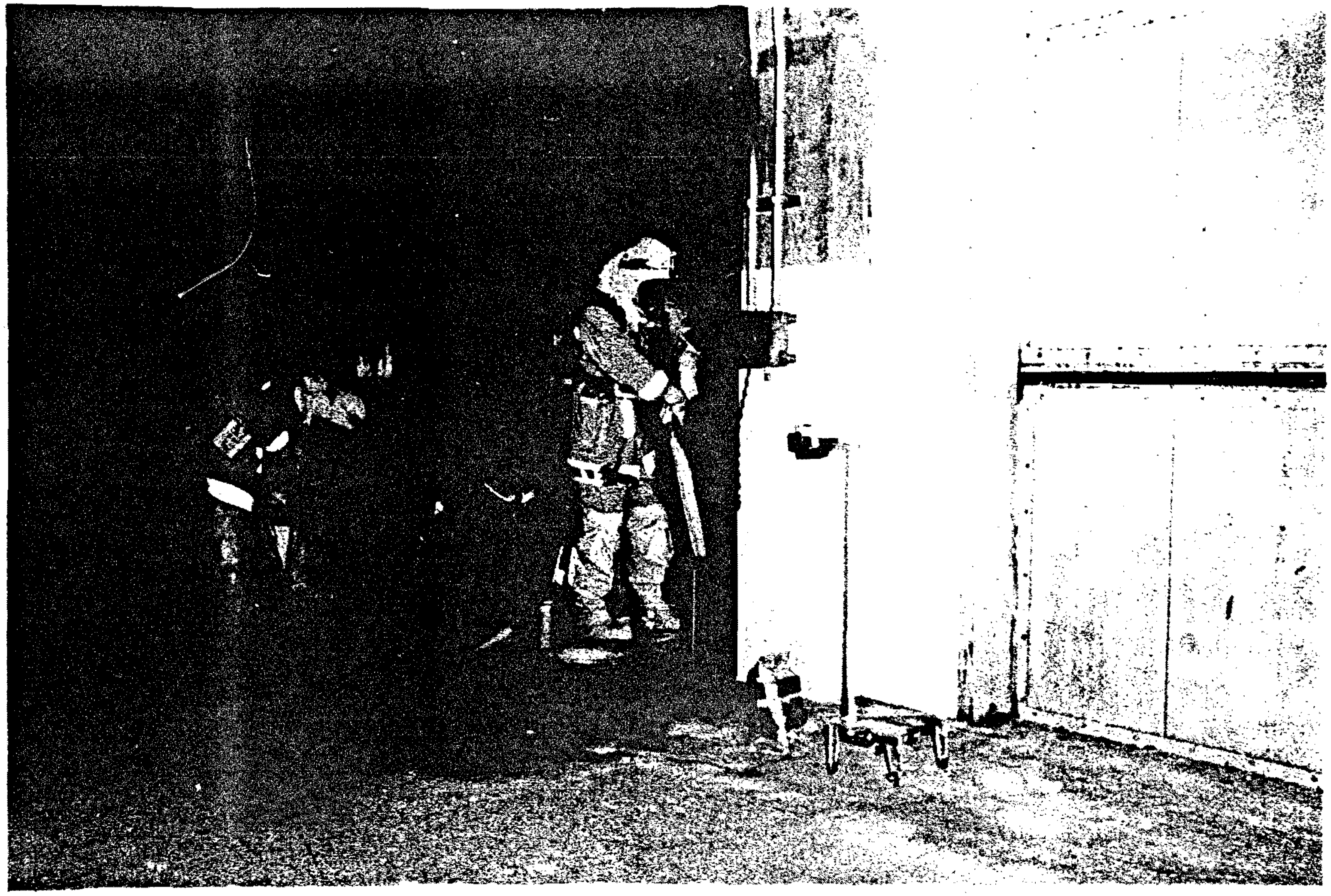

FIGURE 4. Elevator Shaft and Airlock. The detector was located directly in front of the technician in the center of the picture. The personnel airlock entryway is shown.

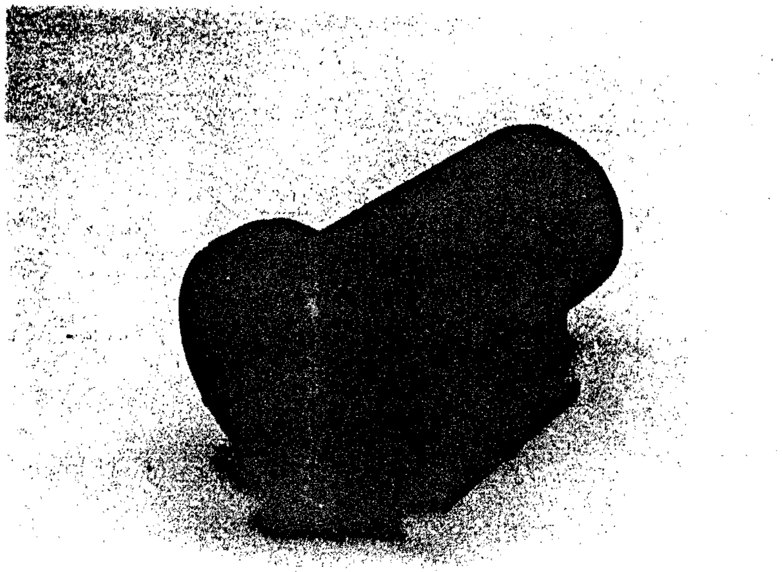

FIGURE 5. Detector Outside Case. The corrosion is apparent on the detector shown approximately as received at Sandia (the nameplate has been removed for isotopic analysis).

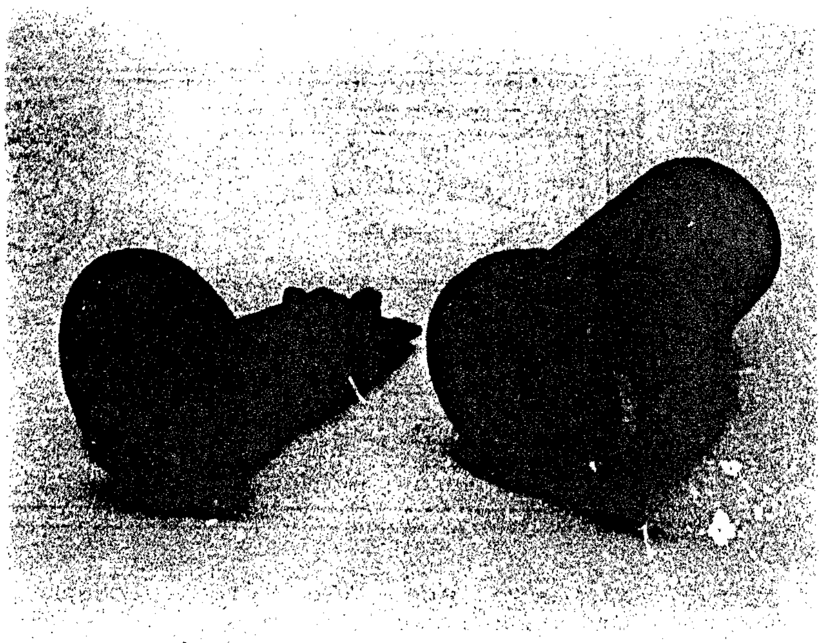

FIGURE 6. Detector Exploded View. The 211 detector circuit board was mounted on a spare front plate for testing. The O-ring seal channel can be seen on the case.

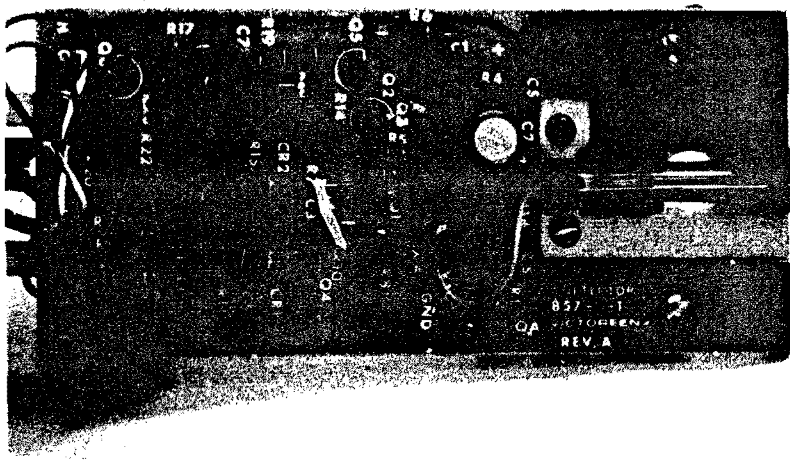

FIGURE 7. HP-R-211 Circuit Board. This picture shows the actual circuit board as removed from the housing. Notice the clean, uncorroded appearance. The GM tube is shown on the right end.

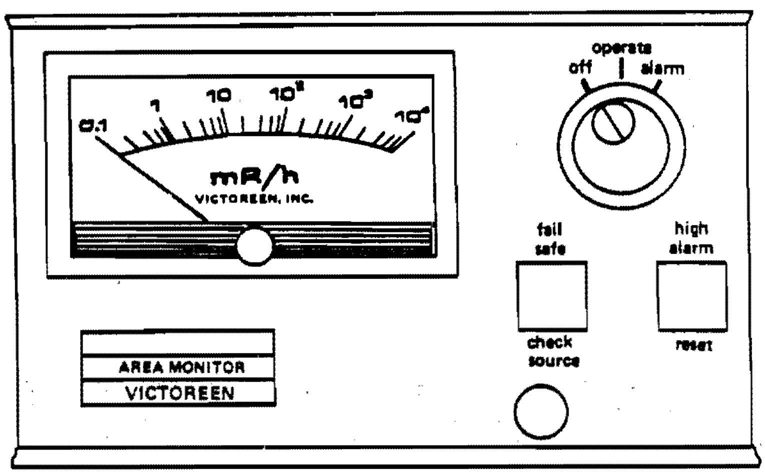

FIGURE 8. Ratemeter Face. The Victoreen channel measures radiation rates of from 0.1 to 10^4 mR/H.

Figure 9 shows a circuit diagram of the detector. The GM tube operates from a 600 volt DC power supply which is current-limited by 2 MΩ resistors both in the detector and in the ratemeter. The signal conditioning electronics of the detector uses a +10 volt DC supply. The Ra-226 check source is switched from behind a lead shield by the application of ground to one of the check source leads at the ratemeter. A DC voltage of 22 volts is used for the driver solenoid. Transistors Q4 and Q5, under normal range operation, form a cross-coupled toggle flip-flop. Each breakdown of the GM tube generates a narrow pulse which is amplified by the Q1 amplifier and routed to the flip-flop. This binary changes state after each pulse. The flip-flop output is buffered by line drivers Q6 and Q7. Thus the detector output is a zero to 10 volt logical signal whose frequency is dependent on the rate of GM pulses. A pulse counter placed on the detector output measures only half the number of actual "event" GM pulses. The Signal Output goes to a log pump circuit in the ratemeter, as shown in Figure 10. A discrete summing amplifier sums all the log pump voltages, amplifies the sum and produces meter and computer outputs. The computer output is a zero to 1V signal which drives the HP-UR-1901 stripchart recorder. The detector is calibrated by first adjusting the +10 and +22 volt sources. The detector is then placed inside a Victoreen field source having three radiation rates (this detector was calibrated with a source of approximately 49, 360, and 1800 mR/H) and "zero" and "gain" pots are alternately adjusted. If the rate that photons arrive at the GM tube exceeds a certain upper limit, the GM tube cannot respond to each individually and tends toward a constant discharge. This high frequency train of pulses or constant discharge current is integrated by C1 in the detector and causes the "antijam" circuit to become functional. Transistor Q3 switches on, and subsequently causes the Q4, Q5 flip-flop to become a freerunning multivibrator, which oscillates at a nearly

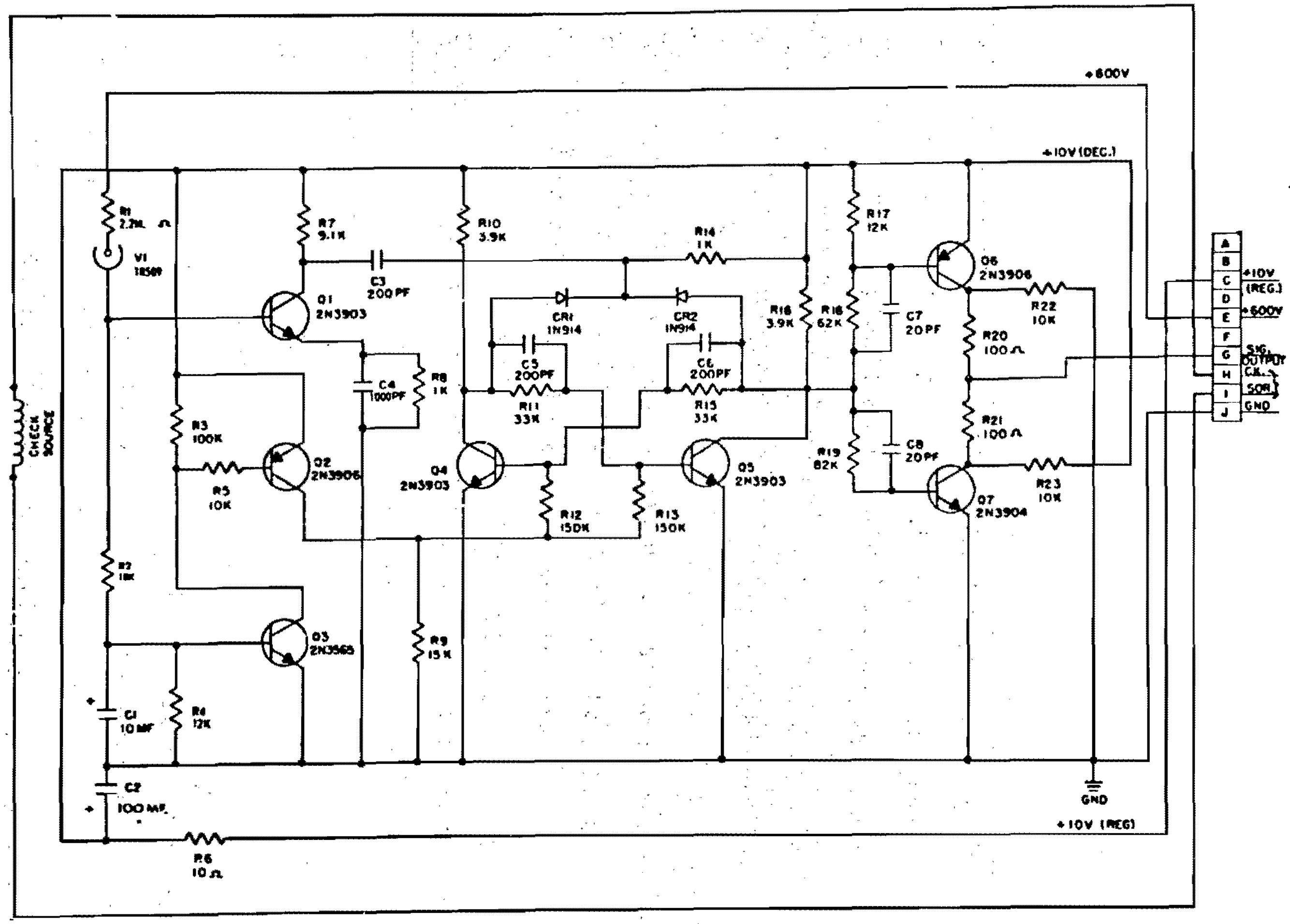

FIGURE 9. Detector Schematic. The GM tube and antijam circuits are on the left, the flip-flop is in the center and the output driver is on the right side of the schematic. Transistor Q6 failed.

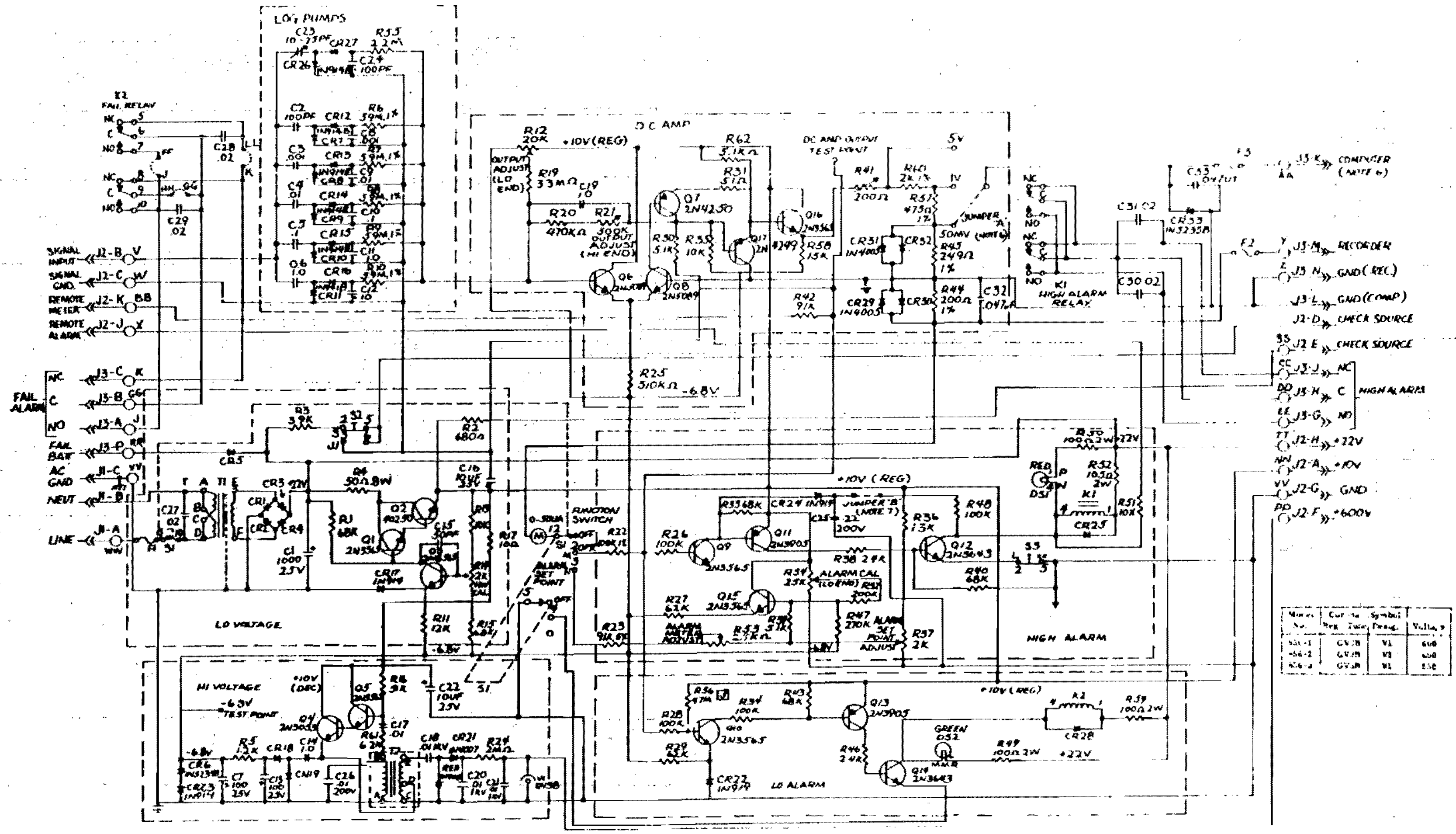

FIGURE 10. Ratemeter Schematic. The detector signal enters the log pump circuit in the upper left. The log pump outputs are then summed and amplified by the differential amplifier. The computer output connection goes to the stripchart recorder. R19 and R21 ("zero" and "gain" adjust) taylor the ratemeter response to each unique detector.

constant 40 kHz. This frequency is high enough to cause the readout meter to peg on the upper limit. This antijam circuit thus should prevent a decrease in the detector output frequency for radiation levels higher than approximately 10^4 mR/H.

D. Specifications

The electrical specifications for the detector are shown in Figure 11.

E. Containment Environment

During the first day of the accident the environment inside containment was one of intense beta and gamma radiation, steam, moderate temperature excursions, a hydrogen burn and the resultant pressure spike, and NaOH/boron spray. No attempt will be made here to quantify these in detail. Generally, the nominal temperature experienced by this detector was probably 54°C (130°F) and peaked at 85°C (185°F).[6] The pressure spike was approximately 1.93×10^5 Pa (28 psi).[6] The building spray was initiated at 1350 Hrs on March 28, some 10 hours after the start of the accident, and lasted for approximately 5 minutes. Other events happening during the first day can be found in reference material.[6,7] High radiation levels and high humidity characterized the building environment over the remainder of the period before removal.

Feature	Specification
Dimensions	3 in. diameter, 7 1/8 in high (7.63 cm, 18.1 cm)
Weight	Approximately 1 lb. (0.45 kg.)
Mounting	Wall Bracket
Radiation detected	Gamma rays
Energy dependence of reading	± 15% from 100 keV to 1.5 MeV
Range of radiation measureable:	
857-10	0.01 to 10^3 mR/hr. (Lo-channel)
857-20	0.1 to 10^4 mR/hr. (Med-channel)
857-30	1.0 to 10^5 mR/hr. (Hi-channel)
Temperature limits	-20 deg. F to 140 deg. F (-29 deg. C to 60 deg. C)
Pressure limits	30 psig.
Detector element life	Exceeds 100 hours at full scale
Electronic exposure life	Approximately 10^5 Rads
Connector required	Bendix #10-72628-18S
Check Source: (Microcuries of radium):	
Det. Model 857-10	0.02
Det. Model 857-20	0.08
Det. Model 857-30	0.16

FIGURE 11. Detector Electrical Characteristics[5]
HP-R-211 was a Model 857-2 and had
serial number 359.

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III. ELECTRICAL/PHYSICAL EXAMINATION AND FAILURE MODE

A. Physical Examination

As shown in Figure 5, the painted aluminum housing of the detector is heavily corroded where pinholes in the paint allowed the underlying aluminum to be attacked. Chemical analyses have been performed on the Victoreen nameplate (top horizontal surface) specifically looking for sodium and boron.[8] Both sodium and boron were found in moderate concentrations (see Table 8). The white granular material on the connector threads was found to be $CaCO_3$ (residue from tap water) by X-ray diffraction analysis. Analysis of the surface around the connector solder pots will be discussed later. These were the only chemical analyses performed with the exception of the radiochemical analyses. The Buna Nitrile O-ring and sealed connecter performed exceptionally well in keeping contaminants out of the inside of the housing. The circuit board is shown in Figure 7 and, under close visual and radiological examination, was found to be clean; no radioactive contamination was found. Except for the corroded housing, no other mechanical defects were observed.

B. Electrical Measurements

<u>Prior to Removal</u>

Before the detector was removed from the containment building, extensive in situ unpowered and powered electrical tests were performed by TEC on the detector channel.[1] These tests showed fairly conclusively that a resistance of approximately 305 ohms existed between the signal output (pin G) and the +10 volt (pin C) detector lines. The observable effect of this shunt resistance was to cause the output signal level to switch between 5.7 and 9.3 volts rather than from 0 to 10 volts. The frequency of the signal looked reasonable (for some, as then unknown, radiation rate).

Unpowered Tests

Similar passive resistance and impedance checks were made on the detector on arrival at Sandia. For comparison, data were also taken on a test detector (Victoreen SN 673), which is the same model as HP-R-211. Table 1 lists the unpowered resistance measurements taken at Sandia and TMI. Probably the only differences in readings are those due to differences in ohmmeters. These tests show a 296 ohm resistance between pins G and C. No other irregularities were observed.

TABLE 1. UNPOWERED 211 MEASUREMENTS

OHMMETER POLARITY/ LINE TO LINE MEAS.		RESISTANCE (OHMS)		
+	-	211 AT TMI	211 AT SANDIA	TEST DETECTOR
+10V	Gnd.	6.47K	5.63K	6.04K
Gnd.	+10V	8.59K	8.50K	11.67K
+10V	Sig.	→ 305	296	7.95K
Sig.	+10V	→ 305	296	5.59K
Gnd.	Sig.	8.62K	8.52K	8.44K
Sig.	Gnd.	6.53K	5.78K	6.98K
+600V	Gnd.	Open	Open	Open
Gnd.	+600V	Open	Open	Open
CS1	CS2	40.2	27.5	24.2
CS2	CS1	40.2	27.5	24.2

Powered Tests

For all powered measurements, whether in the laboratory or at the Co-60 gamma facility, a standard Victoreen Model No. 856-20 ratemeter was used to supply power and process the detector signal output. In addition, a Victoreen Model 857-2 test detector was characterized along with the 211 detector for comparison. There was, however, one problem. In order to obtain accurate ratemeter readings, the ratemeter power supply voltages are normally adjusted to specified limits; then, using the detector and a known radiation source, the zero offset and gain of the ratemeter are set. Unfortunately, because of GM tube differences, the zero and gain must be adjusted for the particular detector being used. Since this was not possible for 211, because it had failed, only the power supply voltages going to it were adjusted. The zero and gain adjustments were left as set at the factory. Later, when 211 was repaired, a calibration factor was determined. Thus, any ratemeter/detector mismatches could be eliminated; and, as will be shown later, this proved to be a good approach.

Table 2 shows the uncorrected voltage and meter readings obtained when 211 was initially powered. Again, the TMI and test detector data are included for comparison.

TABLE 2. POWERED 211 MEASUREMENTS (DC)

QUANTITY MEASURED		MEASUREMENT		
		211 AT TMI	211 AT SANDIA	TEST DETECTOR
+10V	(V)	9.3	10.04	10.06
→ SIG.	(V)	5.7/9.3	6.7/9.9	0.07/10.0
+600V	(V)	605	598.8	599.1
+22V	(V)	13.66	20.75	21.1
CS I	(mA)	-	2.44	2.55
Mtr	(mR/H)	1.5	0.2	0.15
Rec	(mV)	-	0.5/1.0	0.35

The effect of the shunt resistance is apparent in the SIG. voltages in the TMI and Sandia measurements (arrow). The conclusion is that all measurements both at TMI and Sandia point to the same failure mode.

C. Failure Mode

Following tests at the Sandia gamma range facility, the detector was opened, node voltages were measured, and the failure was diagnosed. Transistor Q6, a Motorola 2N-3906, was removed and found to exhibit a 163 ohm collector-to-emitter shunt resistance. No other circuit abnormalities were found. Figure 12 shows several of the more important transistor Q6 characteristics as measured on a curve tracer. The collector current characteristics show the presence of an approximate 160 ohm slope on any given base current curve. The transistor gain and the base-emitter junction characteristics are all proper. The presence of this apparent shunt resistance is consistent with the passive tests due to the nominal 100 ohm current-limiting resistor R20 in series with the collector of Q6. The Motorola 2N-3906 is a general purpose 350 mW, epoxy encapsulated PNP transistor which is designed to operate with a maximum collector current of 200 ma. The collector to emitter breakdown voltage is rated at 40 V. The epoxy case was removed by grinding the surface away until the semiconductor chip cavity was exposed; normal solvents were ineffective. The chip shown in Figure 13 has a large amount of foreign material on the surface (not due to the grinding operation, since an additional coating of RTV-like material had to be removed). The metallization is shown removed in Figure 14, and a punch-through defect exists under the center emitter finger. Probes were in fact made of each finger, and the failure was electrically isolated to the middle finger. This type of failure is typically caused by high voltage breakdown from collector to emitter and a subsequent transient surge current. The energy deposited is enough to destroy the normal lattice structure and actually diffuse aluminum metallization into the lattice to cause a resistive path. Had the transistor been overheated through high power dissipation over a long period of time, much of the metallization would probably have been melted. As it is, however, the defect points to a rapid transient.

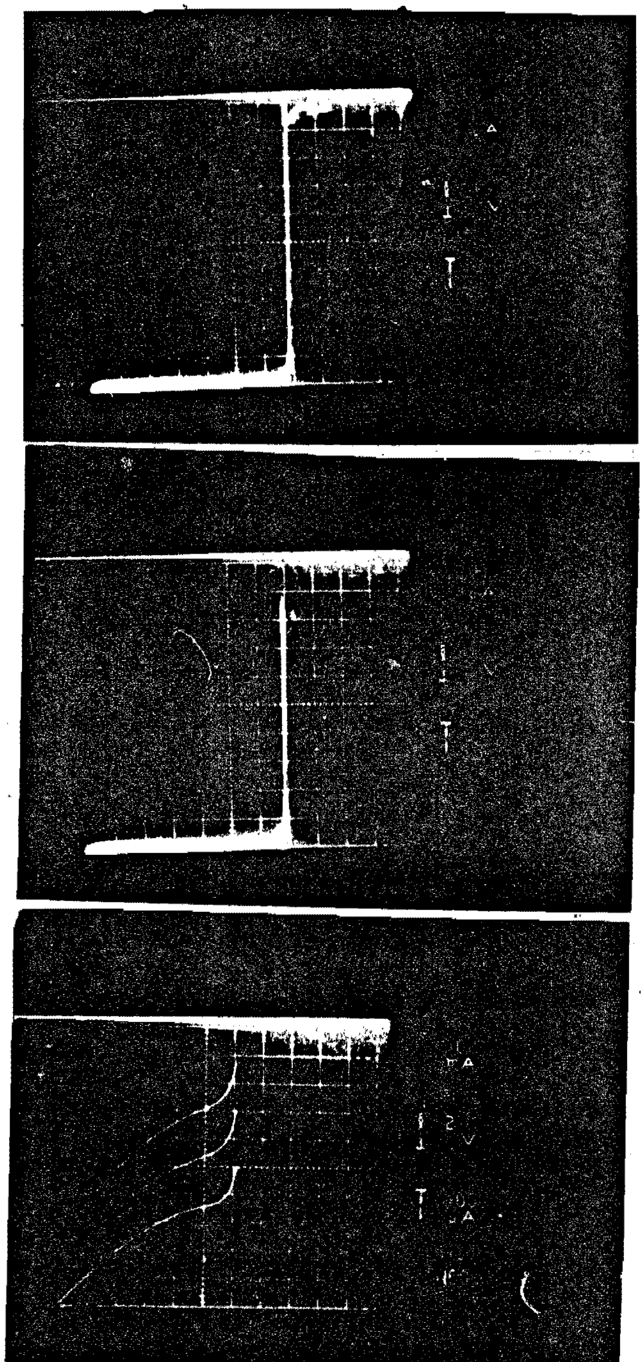


FIGURE 12. Transistor Q6 Characteristics. The top curve is BVCBO, middle curve is BVEBO and lower curve is collector current characteristics. The effect of the 163 ohm anomaly is seen as the slope of the collector current characteristics for any particular base current of the family.

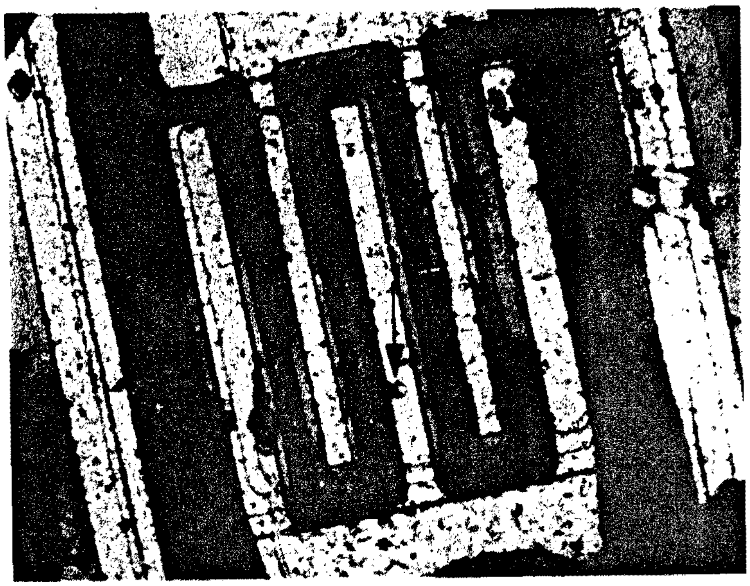


FIGURE 13. Q6 metalization. The punch through defect is apparent even through the emi' 'er metalization (three fingers). This photog1aph was taken after chip probe but before the metalization was stripped. Notice the large amount of foreign material present.

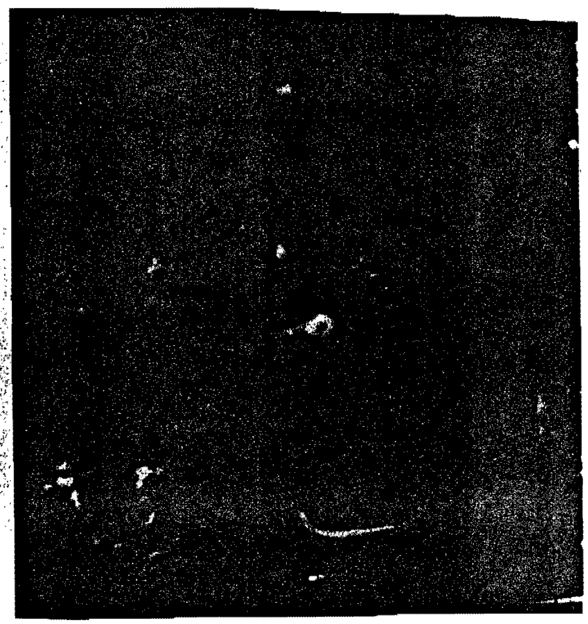


FIGURE 14. SEM Photo of Defect. The metalization was stripped, and a scanning electron microscope was used to examine the chip in detail. The punch-through is noted. Prior to complete metalization removal each emitter finger was individually tested. Only the center finger was defective.

D. Cause of Failure

While we cannot say with absolute certainty how and when transistor Q6 failed, the evidence indicates that the failure was caused either by a transient short in the detector connector backshell, from the 600 Volt GM tube supply pin to the signal output pin, or by a high voltage pulse generated elsewhere, which traveled down the cable on the signal output line. Of these two possibilities, the former appears to be much more probable.

During the removal of the detector from the containment building, the GPU technician was unable to unscrew the connector from the detector, even with the aid of channel-lock pliers. While attempting to loosen the connector, he applied downward pressure on the detector, and it broke free of the cable. The detector, connector first screw-ring assembly, and pin insert were removed as one piece. Figure 15 gives an exploded view of the connector assembly and pin connections. Later examination of the free cable end after its removal revealed the second and third connector screw-ring assemblies to be mated and encased along with the cable end in Raychem WCSF heat-shrink tubing. This tubing was tightly molded to the connector part and covered at least the lower 20 cm of cable. In fact, three layers of heat-shrink tubing were used as shown in Figure 15 to produce what appears to be a good, watertight seal between the connector and cable. Since he did not attempt to rotate the detector to unscrew it when he could not turn the connector, apparently the second screw-ring was not mated or mated by less than one thread to the threaded insert. Corrosion on the connector insert and inside the second connector screw-ring indicates exposure to steam or liquid. Scanning electron microscope (SEM) and energy dispersive spectroscopy (EDS) studies made on the insert around the solder pots were inconclusive in the search for sodium there (because of instrument limitations on the detection of low Z elements).

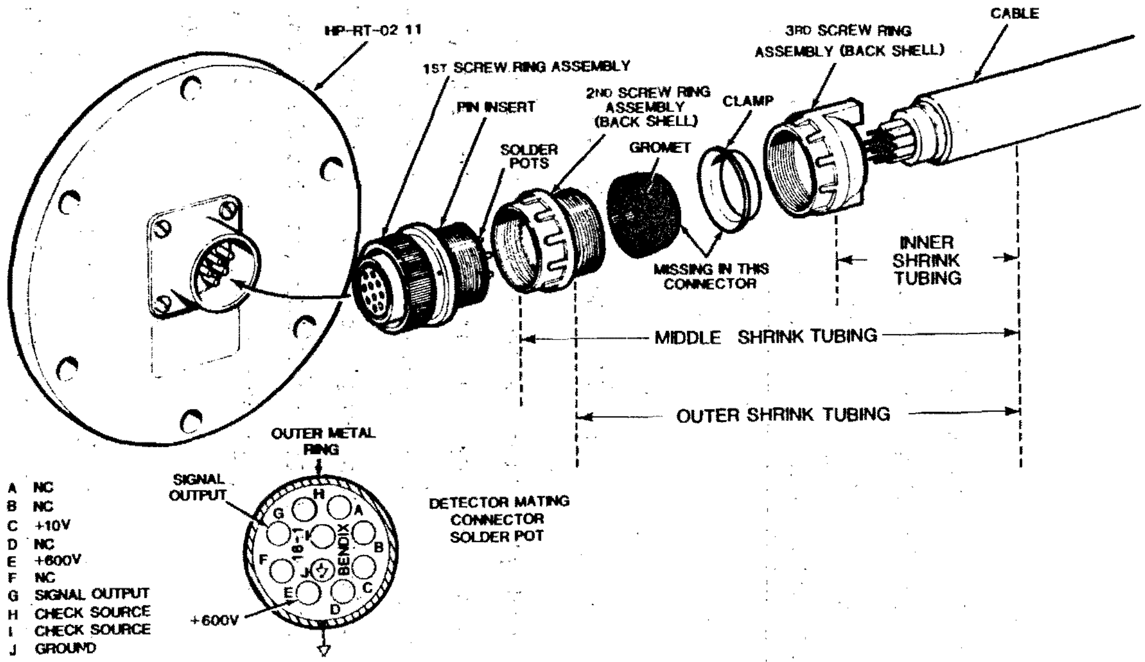


FIGURE 15. HP-R-211 Connector Assembly. The second screw-ring assembly was apparently not screwed onto the pin insert.

A chemical analysis was not performed. We believe that steam and/or NaOH/B spray entered the connector backshell through the loose-fitting insert-to-second screw-ring junction.

To investigate this postulated mode of failure, several laboratory simulations were conducted and will now be discussed. The presence of the 100 ohm current limiting resistors in the signal output line preclude Q6 from being destroyed by a short of the signal line to ground. In fact, DC shorts were made from each connector pin to the next, using the test channel, and a failure could not be induced. The 600 Volt line has a 2 Megohm current limiting resistor at the ratemeter; even though the transistor can break down, the steady-state current is limited to only 300 Microamperes. No discharge paths were found on the circuit board. Recall however, that some 152 M (500 ft.) of cable connects the detector to the power source. We found that the energy stored in the line capacitance was sufficient to cause punch-through. This was found by conducting the following experiment (refer to Figure 16): Capacitors of 0.015 μF and 0.01 μF were connected to the signal output and 600 Volt lines going to the test detector to simulate the charges stored in the 50 Ohm and 75 Ohm cable capacitances. A switch was then thrown to discharge the capacitor on the 600 Volt line into the signal output. This results in a surge current of approximately 6 amperes. The circuit diagram shows a possible current path, I.

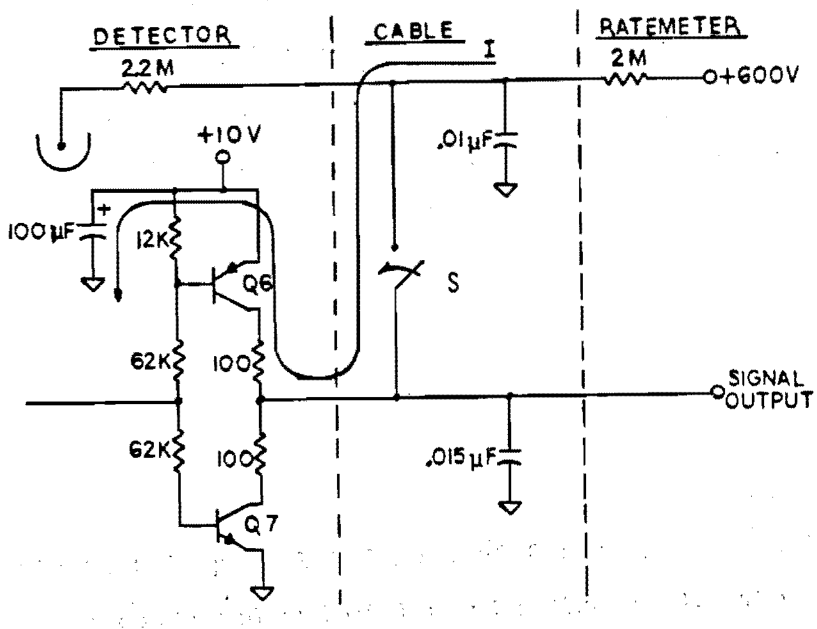


FIGURE 16. Test Circuit Showing Energy Discharge Path

We opened and closed Switch S repeatedly while constantly monitoring the signal output line. After approximately 40 closures the "0" level voltage had increased to 6.65 Volts. After 80 closures, the transistor in slot Q6 was removed, tested and found to exhibit a 96 Ohm collector-to-emitter resistive path, similar to that in the failed detector. No other circuit defects were observed. Tests have been conducted on four other 2N 3906 transistors from a different manufacturer and on two higher current 2N 2904's. All could be made to fail with a single discharge, but only if the 100 Ohm current limiting resistor was decreased. One 2N 3906 failed when the resistor was 72 Ohms, however, all others required lower resistance. The capacitive model of the cable does not simulate exactly the cable characteristic impedance of 75 Ohms and stored charge, since the cable is a transmission line and will appear to have a 75 Ohm source impedance. Since the line is not terminated in 75 Ohms on either end, it will also ring. This will reduce the peak currents somewhat. Nevertheless, we conclude that for a weak device, one having a thin base and geometry sensitive to high current densities, a failure similar to that experienced at TMI can occur in one or more discharges. The following experiments were conducted to determine the detector response to steam and spray introduced to the connector backshell.

Steam and Spray Experiments

The HP-R-211 stripchart recording (Figures 25a and 25b) exhibits only a single observable discontinuity. This occurs at approximately 1350 hours during the time of either the hydrogen burn or five minutes of building spray. The signal first rises, drops to zero for approximately two minutes, and then steps back up abruptly to a level somewhat lower than it was prior to the transient. This five minute perturbation suggests a point in time at which the failure could have occurred.

Several simple experiments were conducted to understand in a macroscopic way the surface conductivity and electrical conduction mechanisms with regard to pin-to-pin conduction in the connector backshell. Surface conductivity and breakdown effects are discussed in some detail by Stuetzer[9] and will not be covered here. Suffice it to say that conductivity is greatly dependent on the surface material, surface contaminants, temperature, humidity and voltage potential difference. The drawing of the connector backshell pin arrangement in Figure 15 shows that the "case" is grounded, and the 600 Volt pin is separated from the signal output pin only by an unused pin. We postulate that something similar to one of the following events occurred during the transient period:

1. The rubber surface of the connector backshell was contaminated. Either steam was forced into the backshell by a pressure differential resulting from the hydrogen explosion, or the hydrogen explosion flattened water droplets which had formed on the surface due to steam condensation. In either case, the 600 volt and signal output pins were momentarily shorted; or,

2. A droplet of NaOH/B spray traveled down the cable, entered the connector backshell through the loose connector fitting and momentarily shorted the two pins.

In either case water entered the connector backshell.

In our experiments, we found the following:

1. Steam condensation on a cool connector surface, contaminated only by normal handling, tends to form constant, long duration, low resistance paths between pins. Small water droplets, initially formed, flow together until the gap between pins is bridged. Once the pins are bridged, conduction takes place until the large droplet evaporates or its ionic contamination is depleted. This could take minutes or hours to occur, and during that time the detector output would be zero. There is no evidence of this on the stripchart records.

2. Steam condensation on a heavily contaminated surface tends to "wet" the surface, resulting in short duration, low resistance conduction. Droplet formation is minimal. Resis-

tive paths between pins can form quite abruptly and disappear as fast. Interestingly, even in the presence of steam, the path can open quickly and remain open. This is illustrated in Figure 17a. Here, using the test detector and its connector, we deposited NaOH of PH 12.7 on the surface and allowed the water to evaporate. We then directed steam onto the surface, and after 100 seconds the signal output dropped to zero indicating a reduction in the 600 Volt to somewhere below 380 Volts. A minute and a half later the detector recovered and did not fail again even in the presence of steam. What happened was that the sodium ions were attracted to a more negative terminal, the surface near the 600 Volt pin was depleted, and conduction terminated. In fact, water ceased to wet this area and even to form droplets there. Figure 17b shows the 600 Volt line in the test where a large droplet of NaOH had been introduced between pins. The 600 Volts decreased abruptly then rapidly increased time-after-time (the 0.01 μF capacitor was used to supply energy). Tiny arcs could be seen around the 600 Volt pin. Each one of these delivered energy to ground or to ground through another pin.

We conclude from these tests that a large droplet of water or spray was not in the connector shell due to the absence in the stripchart recording of any long duration short or repeated signal irregularities. A highly contaminated connector, introduced abruptly to only a small puff of steam, is sufficient to produce the single drop-out noted. The presence of sodium is indicated, and it is possible that even though a single discontinuity was observed other short duration discontinuities could have occurred without being registered on the stripchart recording.

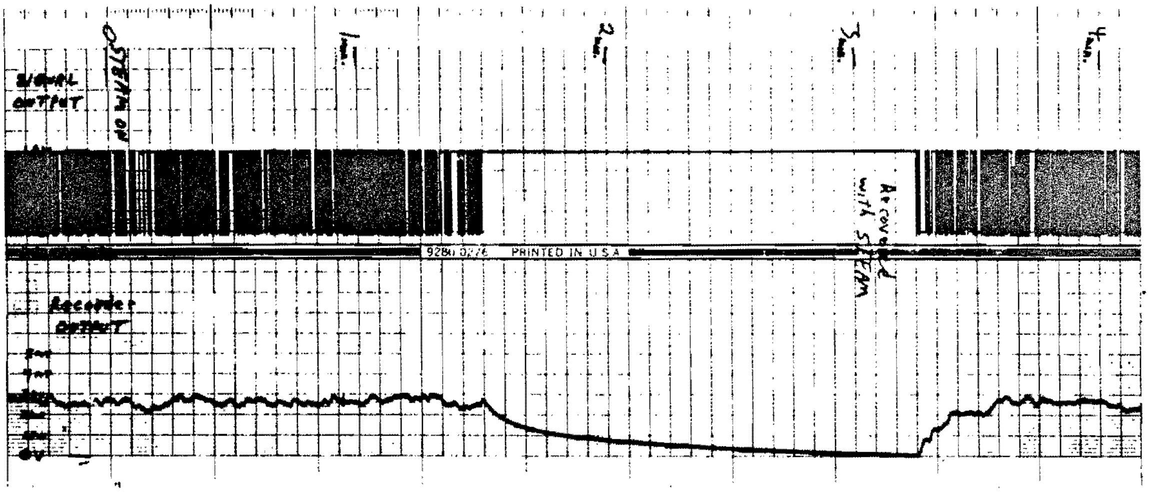


FIGURE 17a. Steam on a Contaminated Backshell. A detector connector backshell was exposed to steam after the backshell was first contaminated with NaOH. NaOH was introduced and then allowed to dry before steam was applied. The top trace is the signal output, and the lower trace is the ratemeter output. The detector failed after about 1.5 minutes of steam, but recovered even though steam was still being applied.

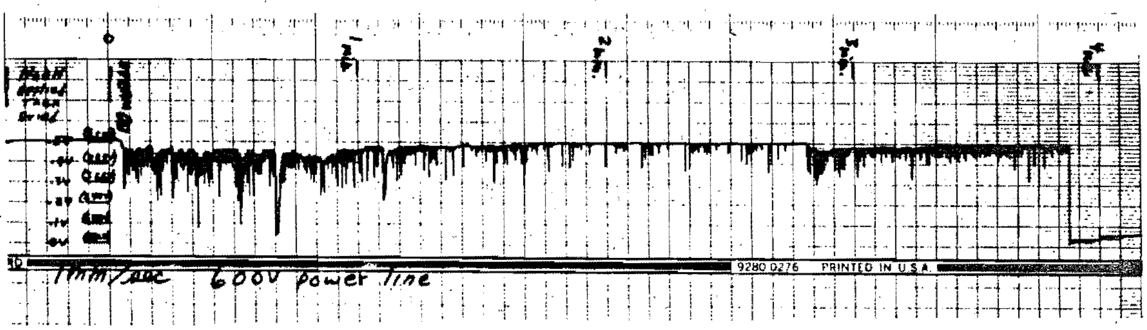


FIGURE 17b. Large Droplet Formation. A similar experiment to that shown in Figure 17a was conducted, except that here all of the detector pins are covered with a water droplet. The 600 Volt power line is plotted versus time. Repeated surges are delivered to a load during each breakdown.

E. Conclusions

The detector was found to operate properly in all respects after the defective transistor Q6 was replaced (except for the multi-valued readout discussed in the next section). The detector environmental seal was good, and no radioactive contaminants were found on the electronics inside the housing. No mechanical damage, or elastomeric material degradation was visible inside the housing or on the connector insert. The housing outside was corroded and pitted.

The failure of transistor Q6 is thought to be due to high voltage breakdown and rapid energy deposition. Although this energy could have been delivered down the cable due to EMP or some such transient, we have found no other evidence of this. Instead, we have been able to cause transistor degradation in laboratory tests where energy stored on the 600 Volt cable is rapidly discharged onto the signal output pin. This has been shown to be possible when the detector connector backshell is subjected to a steam and/or spray environment. The evidence indicates that the connector insert was apparently not properly mated to the connector second screw-ring assembly, thus providing an entryway for steam or spray to make contact with exposed connector pins. Although the manner of failure is fairly clear, the precise time of failure is not. The only stripchart discontinuity occurred at the time of the hydrogen burn, and this point represents the most likely time of failure; however, as will be discussed in the next section, further degradation of transistor Q6 must have occurred after the hydrogen burn with some degradation possibly occurring even before the burn. Our steam and spray tests indicate that a connector backshell insert with no abnormal chemical contamination, when subjected to steam only, would produce an obvious stripchart discontinuity. Once the insert is contaminated with sodium or other similar contaminant, however, it would be possible for transients to occur and not be detectable on the stripchart readout. The most likely scenario, therefore, seems to be one in which major transistor degradation occurred at the time of the hydrogen burn and then further degradation was incurred after the backshell was contaminated with sodium. We have no direct evidence from the stripchart recording that transistor Q6 was degraded before the hydrogen burn, although the possibility exists. All other detectors recorded on the stripchart reacted in the same manner as HP-R-211 at the time of the spray initiation but all did not recover.

IV. DETECTOR CHARACTERISTICS AND RADIATION TIME HISTORY

A. Discussion

Our findings show conclusively that the only failure experienced by HP-R-211 was that of transistor Q6. When this failed transistor was replaced, the detector operated properly up to radiation levels of 500 R/H. At levels higher than this the radiation decreases as the input level is increased. This is caused by detector to cable and cable to readout module impedance mismatches. These cable mismatches cause erroneous, low radiation readings when radiation levels are in the range of 500 R/H to 10^6 R/H. This behavior is hardly noticeable on new, undegraded detectors, but becomes dramatic when transistor gains have been degraded by radiation as in HP-R-211.

Without a doubt the most difficult task has been that of attempting to reconstruct the containment gamma radiation time history as measured by HP-R-211. Of the four radiation detectors normally used to monitor containment radiation, only two, HP-R-211 and HP-R-214, have continuous stripchart outputs both during and since the accident. They, then, represent our best opportunity to supply accurate records of containment gamma radiation. The failed transistor in HP-R-211 caused erroneous, low radiation readings which possibly can be corrected with the use of the proper scale factor.

Studies[10] to date of the dome monitor (HP-R-214) record have uncovered several problems in interpreting its output. Among these is the significant difficulty of transforming radiation levels measured inside a 4 cm lead shield to radiation levels outside. Also complicating the analysis is the probable existence of a 0.3 cm diameter hole in the lead shield. It may never be possible to unravel the HP-R-214 data.

Detector HP-R-213 failed at the time of the hydrogen burn. Unfortunately, much of the time it was pegged at its maximum reading of 10^4 mR/H. HP-R-212 was apparently not recorded until it was switched on 92 days after the accident. It functioned for 128 days thereafter until it also failed. The two fuel handling bridge detectors appear to have been off during the accident, and no records exist for them. Thus, HP-R-211 may represent our best chance to obtain a composite doserate time history.

Knowledge of the radiation environment, if only at one location, is valuable in evaluating the operation of reactor instruments and systems in the quite hostile environment to which they were exposed. Information of this type could also be valuable in assessing the validity of various reactor models relating to radionuclide dispersal following a LOCA.

This section presents measured detector characteristics using both short and long coaxial interconnection cables, stripchart data, and a brief discussion of radiation time history. Radiation time history information will be given in a separate report when this and other investigations have been completed.

B. Detector Characteristics (Short Cables)

The failed detector was mated with the test channel ratemeter using short coaxial cables and exposed at the Sandia Co-60 Vertical Range Facility. Figure 18 shows the ratemeter radiation readings vs known radiation input rates. Three curves are shown. Unfortunately,

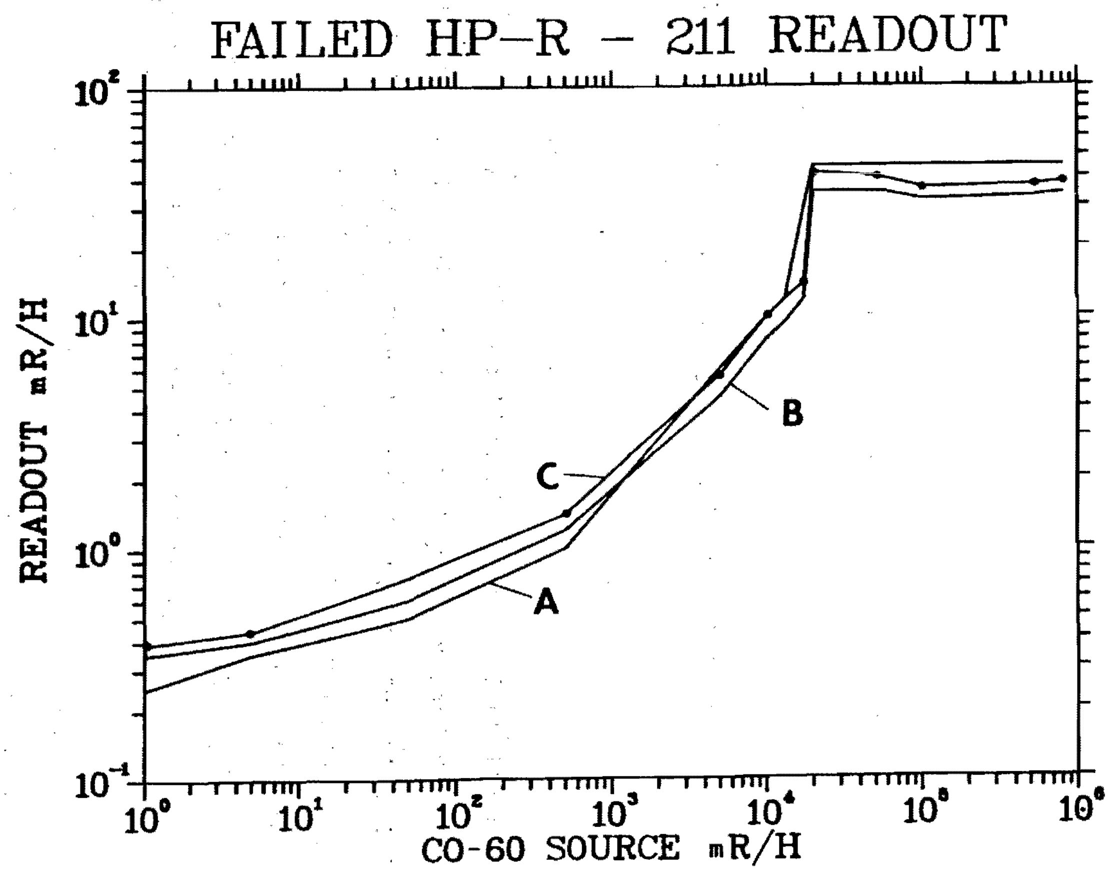


FIGURE 18. HP-R-211 Characteristics. The detector was exposed to a Co-60 source upon arrival at Sandia and produced the output shown. Curve A is for the condition of nominal detector supply voltages, Curve B is for low voltages, and Curve C is low-voltage, ratemeter corrected. These data were taken without 152 m cables or line capacitance equivalents used.

during the TEC measurements on site, we discovered that the +10 V and +22 V power supply voltages going to the detector were +9.3 V and +16 V as a result of a faulty capacitor (C1) in the TMI ratemeter. Therefore, the recorded radiation readings are in error not only because of the faulty transistor but also improper power supply voltages. The length of time this situation existed is not known. Fortunately, this low voltage condition does not have a major effect on our results. Curve A in Figure 18 shows the nominal voltage characteristic. Curve B shows the same characteristic except using the lower supply voltages as measured just prior to removal from containment. Curve C is the final result, using a ratemeter scale factor as described later. The detector level indications are seen to be below the known source levels by up to three orders of magnitude. This is due to the reduced amplitude of the detector output as a result of the failed Q6. Significantly, the anti-jam circuit is seen to cut in at about 20 R/H. Above this level, increases in source level are not followed. Transistor Q6 was replaced with an operable transistor and the detector was exposed again to the Co-60 source (at nominal voltage). Figure 19 shows the result. The detector is seen to function properly, being in error only by a voltage scale factor of 1.05. The test detector is shown for comparison. A Victoreen representative says that the slight offset between HP-R-211 and the ideal curve is normal and is caused by differences in GM tube characteristics.[15] The similarity with the test detector and the ideal curve leads us to the important conclusion that transistor Q6 was the only failure in HP-R-211 and that only minor degradation was experienced. For information, Figure 20 shows detector counts-per-minute versus input radiation level. Counts-per-minute here refers to that measured by a frequency counter which responds only to positive going signal transitions ("events", or photon/GM tube interactions, occur at twice the counter rate).

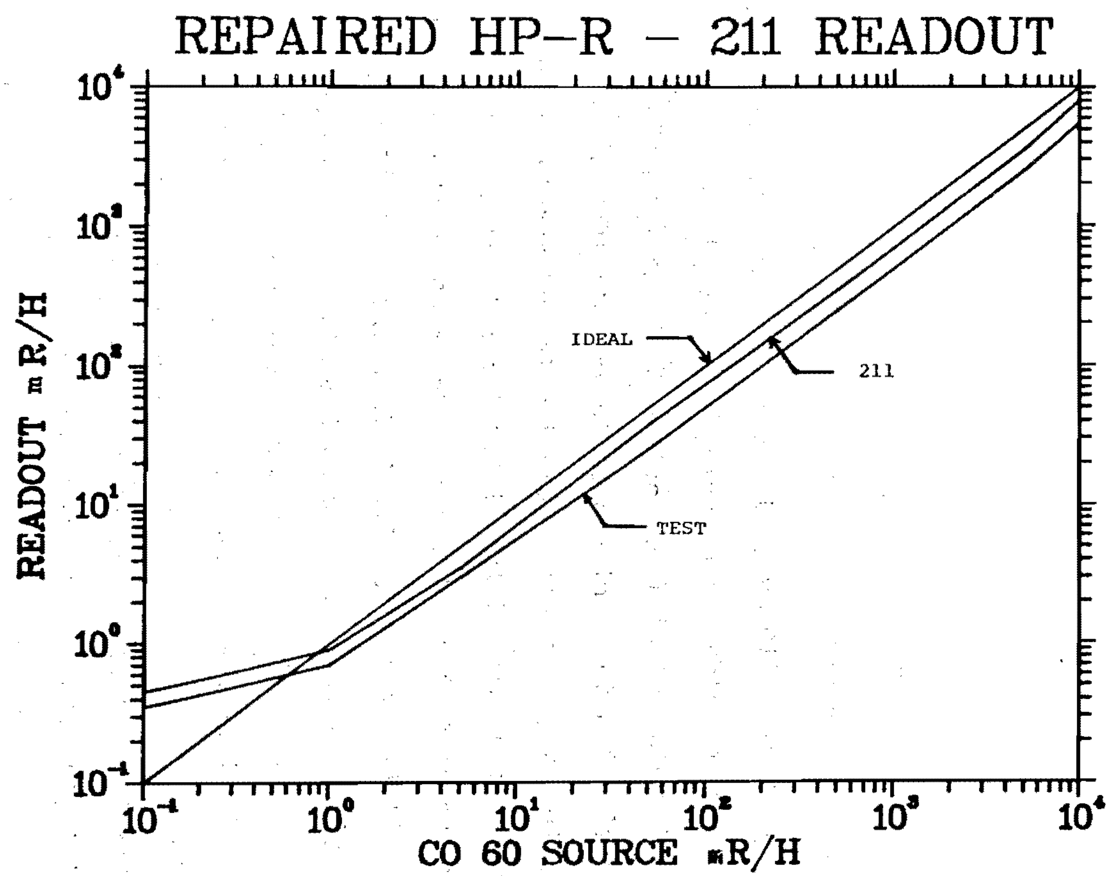


FIGURE 19. Repaired Detector Characteristics. The curve labeled 211 is a plot of the HP-R-211 readout versus Co-60 source level using the test channel ratemeter. The ideal input vs output is shown. The two curves differ by a calibration factor associated with each GM tube. So that there be no mistake that HP-R-211 is operating properly, the test detector is included for comparison. This curve also shows the need for ratemeter calibration. The changes in slope at low radiation levels are due to normal background radiation.

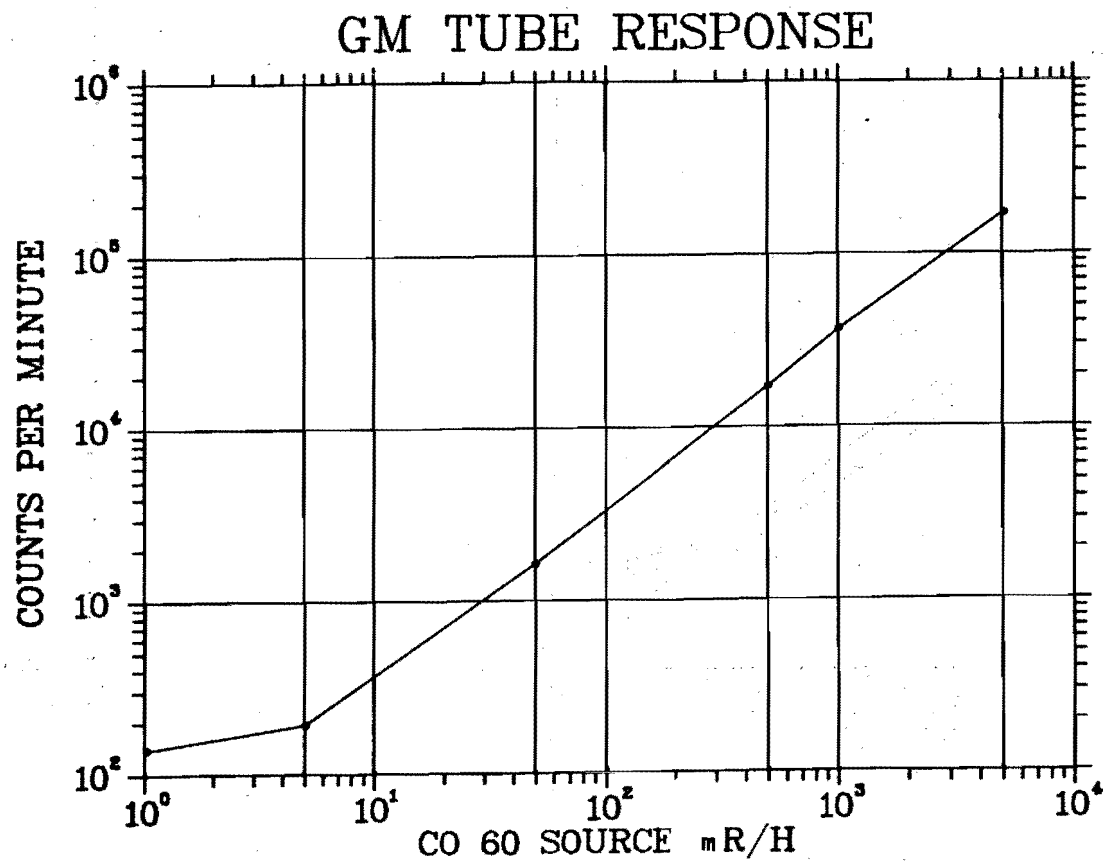


FIGURE 20. GM Tube Characteristics. The detector counts-per-minute are plotted vs gamma source level as measured with a frequency counter. Since the detector was contaminated, the lower end of the curve has a slope change.

Tests were also run to determine the temperature dependence of detector level readings. We found that for an unfailed detector temperatures as high as 60°C had negligible effects. For the failed HP-R-211 detector the readout levels at room temperature are approximately 30% lower than those at 60°C. Because of the difficulty in running tests at various temperature levels, all tests were conducted at room temperature.

C. Detector Characteristics (Long Cables)

During testing at the Sandia Co-60 Gamma Irradiation Facility (GIF), the repaired detector and its associated ratemeter radiation measurement system was observed to indicate erroneous, low radiation levels when in fact the levels were very high. These tests were being conducted to investigate stripchart anomolies, and transistor Q6 had been replaced with a functional one. Also, 152 m (500 ft.) of RG 58 and RG 59 coaxial cable were used to connect the detector Signal Output and 600 Volt lines to the ratemeter. The decrease in radiation level indication began to become noticeable at radiation levels above 500 R/H. This multivalued characteristic was found to be caused by signal reflections in the long Signal Output cable which are set up by cable impedance mismatches on the Signal Output line at both the detector and ratemeter terminations. GM tube pulse interactions above the antijam point combine with the cable reflections to accentuate the problem.

Although this detector was not designed to accurately measure radiation levels above 10 R/H, the antijam feature was added to keep the readout meter "pegged" at full-scale. Radiation degraded detector output drive transistors cause the erroneous indication to become more noticeable; and, in a LOCA induced environment, this multivalued characteristic could potentially be hazardous. The discussion which follows describes this multivalued characteristic in detail. In addition, it was discovered that the presence of the long coaxial cable changes the detector output characteristic somewhat when transistor Q6 is in its failed state at low radiation levels. This subject is also discussed.

Multivalued Output

Figure 21 shows data taken at GIF and the Sandia Vertical Range for three detector conditions. The variable measured and recorded is the ratemeter stripchart output voltage. As stated earlier, this voltage is proportional to radiation levels up to approximately 20 R/H, whereas the ratemeter meter pegs at 10 R/H. The normal, expected output is shown in Curve A. These data were generated using the test detector. The detector to ratemeter interconnection cable was made using a short, unshielded wire bundle. The radiation measurement channel output is proper up to 720,000 R/H. Curve B shows the output of the same channel except that 152 m (500 ft) of 50 ohm, RG 58 coaxial cable was used to transport the detector output signal to the ratemeter. This simulates reactor use conditions. Both the detector and cable were exposed to the source. The ratemeter output voltage begins to dip slightly above 1000 R/H; however, the readout meter is still pegged at 10 R/H. Curve C shows the result when the degraded, but repaired HP-R-211 detector is used with the long cable. Transistor Q6 was a 2N 3906 which had been degraded by exposure to 1×10^6 rads. The curve dips dramatically, reaching a minimum of 150 mR/H at a Co-60 source level of 54,000 R/H. The output recovers significantly as the radiation rate is increased. The degraded detector is seen to have a multivalued radiation indication. Exposure of the cable along with the detector was found to not be significant. Victoreen supplied us with three new detectors for testing in order to obtain some statistical data regarding this multivalued function. In each case, these detectors behaved similarly to the test detector.

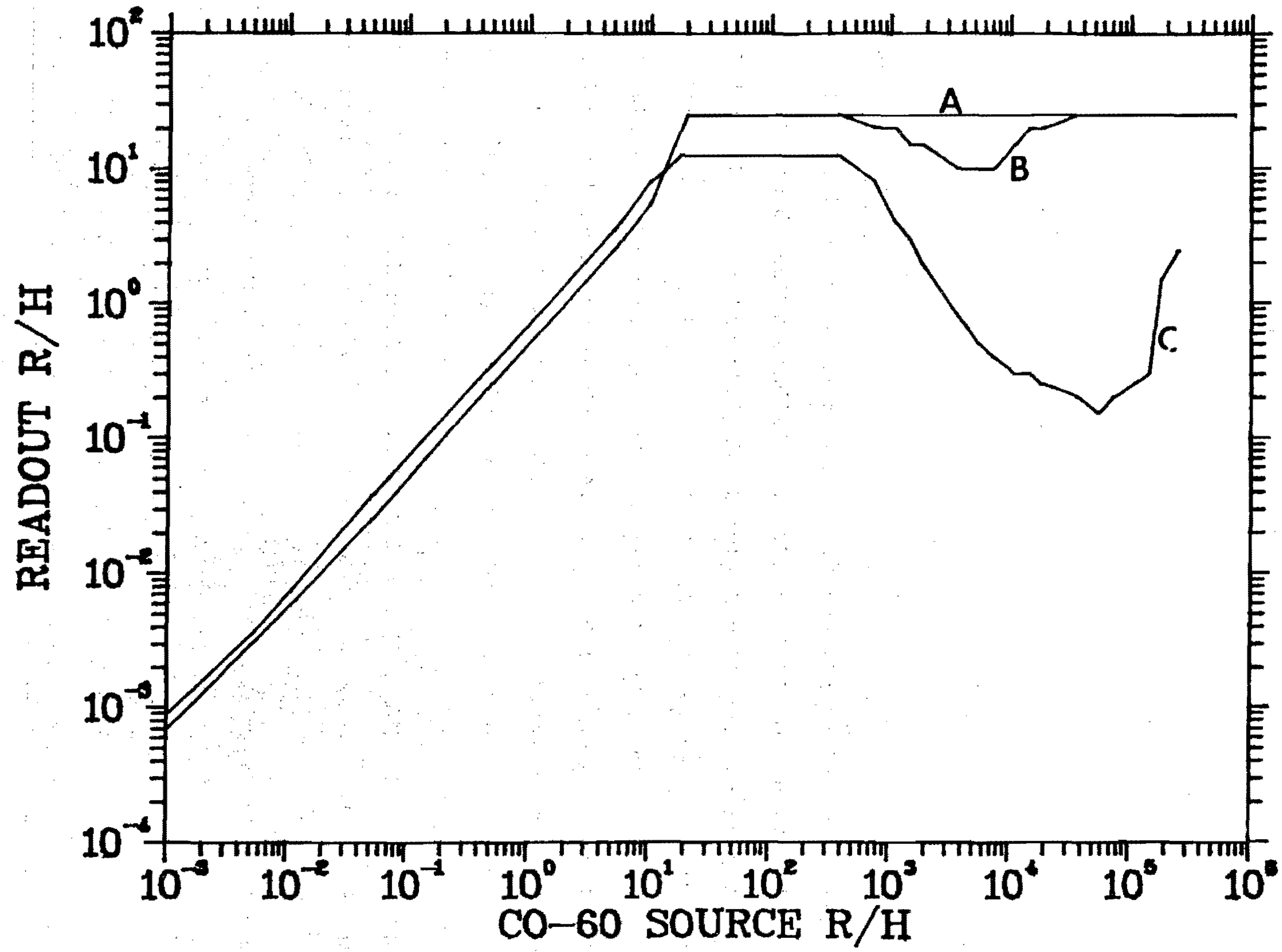


FIGURE 21. Multivalued Readout. Curve A shows the Test detector response to the Co-60 source when a short cable is used to connect the detector to the ratemeter. Curve B gives the response when 152m of coaxial interconnect cable are used. Curve C gives the HP-R-211 response using 152m interconnect cable. The response is seen to be multi-valued when long cables are used, especially for the degraded detector.

Problem Cause -- Several experiments were run in an effort to understand the cause of the detector dip in radiation indication. In order to check the majority of the detector electronics in HP-R-211, we removed the GM tube from circuit interaction. This was done by shorting across it between R1 and R2 of Figure 9. This continuously engages the antijam circuit. The readout was seen to indicate a constant, near maximum, indication regardless of source level even up to 720,000 R/H. This is the proper response for this condition. This indicates that the GM tube pulse output is interacting with the free-running multivibrator at high radiation levels.

The dip has, in fact, been determined to be due to two items: impedance mismatches between the coaxial cable and both the detector and ratemeter circuits, and GM tube circuit interactions above the antijam point. First, and probably most importantly, the detector output circuit is not designed to properly match in impedance the 50 ohm cable attached to it. The normal output impedance of the detector is approximately 100 ohms rather than 50 ohms. Further, the ratemeter input appears as an open circuit for the steady-state signal. This open circuit combined with the mismatched driver sets up reflections in the cable which have the same effect as filtering the signal. Since the ratemeter circuit is a linear log pump, both the amplitude and the frequency of the signal affect readout accuracy. Figure 22 illustrates the effects on the waveform of the mismatch. For a voltage V propagating down a coaxial cable of characteristic impedance Z_o, the voltage across the load impedance Z_L is equal to $(1 + R)V$, where R is the reflection constant. If Z is the termination impedance, R is given by:

$$R = \frac{Z - Z_o}{Z + Z_o}$$

A voltage of RV is reflected back down the cable. With a value of $Z_L = \infty$, R is equal to 1, and V is totally reflected. This voltage travels the

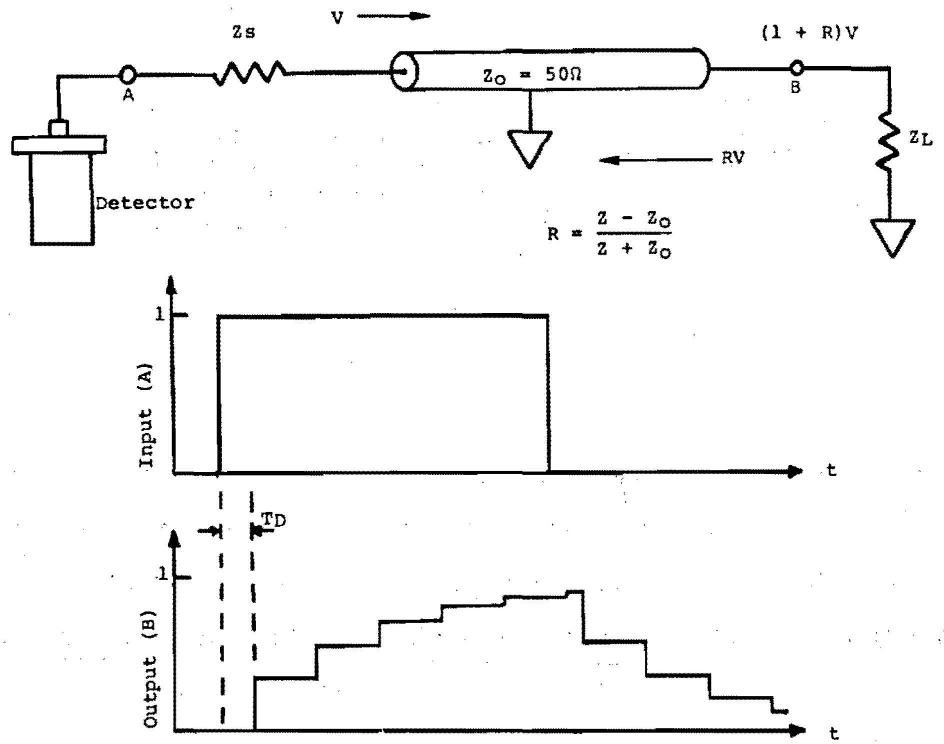
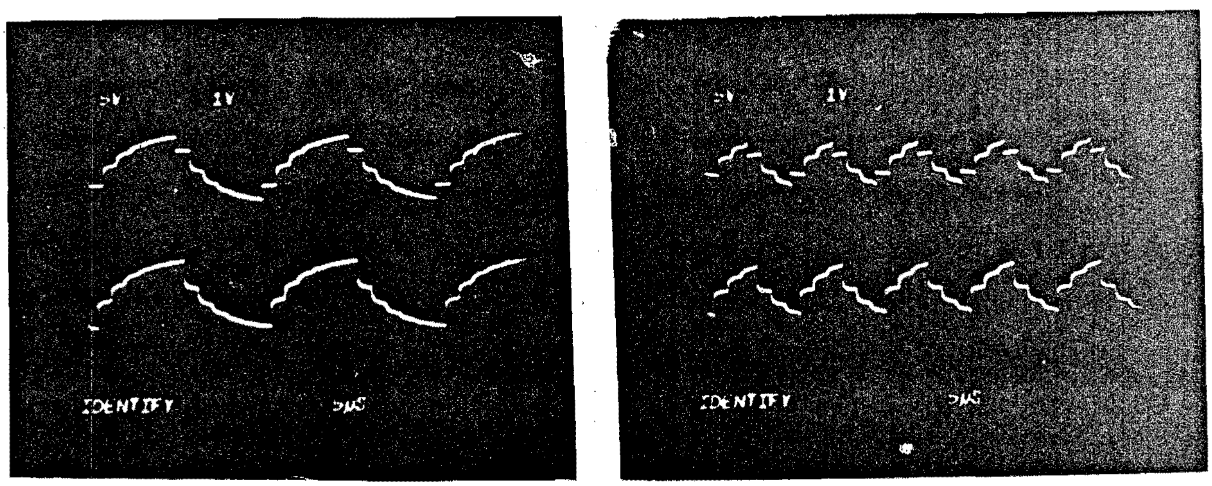


FIGURE 22. Input and Output Waveforms for a Mismatched Transmission Line (Z_S = 250Ω, Z_L = ∞)



50 kHz 100 kHz

FIGURE 23. Mismatch Filtering. For both photographs Zs = 250 ohms and Z_L = ∞ . The top trace is the transmission line input voltage and the bottom trace is the output voltage. The input frequencies for left and right photographs were 50 kHz and 100 kHz respectively.