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EXAMINATION RESULTS ON TMI-2 LPM CHARGE CONVERTERS YM-AMP-70 3 AND YM-AMP-7025

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ABSTRACT

During, and for several months after the Three Mile Island Unit 2 accident, the reactor vessel and two steam generators were closely monitored for the existence of coolant system loose parts. We have examined two Endevco charge converters removed from the loose parts monitoring system inside containment and found the devices to be severely degraded by gamma radiation. Because of this, it is likely that the loose parts readings made during the accident were lower than actual levels. This report discusses the cause of failure, our estimates of the total gamma radiation doses received by the charge converters, and our recommendations for changes in U.S. Nuclear Regulatory Guide 1.133.

ACKNOWLEDGEMENTS

This examination was administered by the Technical Integration Office at Three Mile Island. Jim Mock and Florante Soberano of that office were helpful in coordinating the removal and shipment of the charge converters.

At Sandia National Laboratories, Lee Pickard performed the initial testing of the charge converters, and Al Asselmeier and Don Holck performed the transistor gamma dose testing.

CONTENTS

FIGURES AND TABLES

I. INTRODUCTION AND SUMMARY FINDINGS

This report contains the results of our laboratory examinations of two Endevco Model 2652M4 Remote Charge Converters which were removed from the Three Mile Island Unit 2 (TMI-2) containment building in November 1980. In situ testing done in September 1980 indicated that both charge converters, having TMI-2 tag numbers YM-AMP-7023 and YM-AMP-7025, were inoperable at the time of the measurements.[1] Records obtained in the accident time frame indicate that all eight Rockwell steam generator loose parts monitoring (LPM) channels, each containing Endevco charge converters, may have failed, or were close to failure, during the first few days of the TMI-2 accident.[2,3] This is indicated by the need on April 2, 1979 to increase channel gains and, a few weeks later, the measurement of inappropriately high bias voltages.

The charge converters were mounted inside protective boxes on the outside of the "D" ring wall on the 305 foot elevation near the personnel hatch of the TMI-2 containment building (see Appendix A). They were removed for laboratory examination because they had failed, they contain radiation sensitive MOS transistors known to be useful as radiation dosimeters, and they were easily accessible. This report is not meant to evaluate the entire LPM system. Here, we discuss the cause of failure of the charge converters and the implications of this on loose parts monitoring. We also make estimates of the total gamma radiation doses received by each charge converter.

A. Findings and Recommendations

1. Both charge converters were degraded by radiation, probably in the first few days of the accident, to the extent that YM-AMP-7025 was non-functional and YM-AMP-7023 was marginally functional. The degradation in both cases was caused by a large upward shift in the gate-to-source threshold voltage of the MEM 511 transistor used in the Q2 slot. This can result in an indication of lower vibration levels than are actually there. The MEM 511 is an MOS field effect transistor; and, like all non-hardened MOS transistors, it is quite sensitive to radiation dose. Our tests indicate that, because of this transistor, these charge converters are usable up to only approximately 1×10^5 rads.

2. The failure mode observed in these charge converters is especially insidious since the LPM channel can appear to operate properly even after severe

degradation has occurred. The only normal indication of this condition is that the usual background vibration levels would appear to decrease. Fortunately, the condition can be detected remotely by measuring the charge converter DC bias voltage and looking for a higher than normal level. The normal bias voltage is about 13.5 volts. This voltage will shift upwards as radiation dose is accumulated until, in the limit, the power supply rail (normally 30 volts) is reached. We recommend that all power plant operators using this and similar model Endevco charge converters perform the above measurements to determine the state-of-health of their LPM systems. This same problem has been observed in operating plants where the charge converters are located in high radiation fields.[3]

3. We recommend that Endevco Model 2652M4 charge converters, other similar Endevco models, and other manufacturer's models which cannot survive low radiation exposure be removed from nuclear power plants and replaced with more radiation tolerant designs. MOS transistors should not be used in any application where inherent or potential radiation exposure is possible.

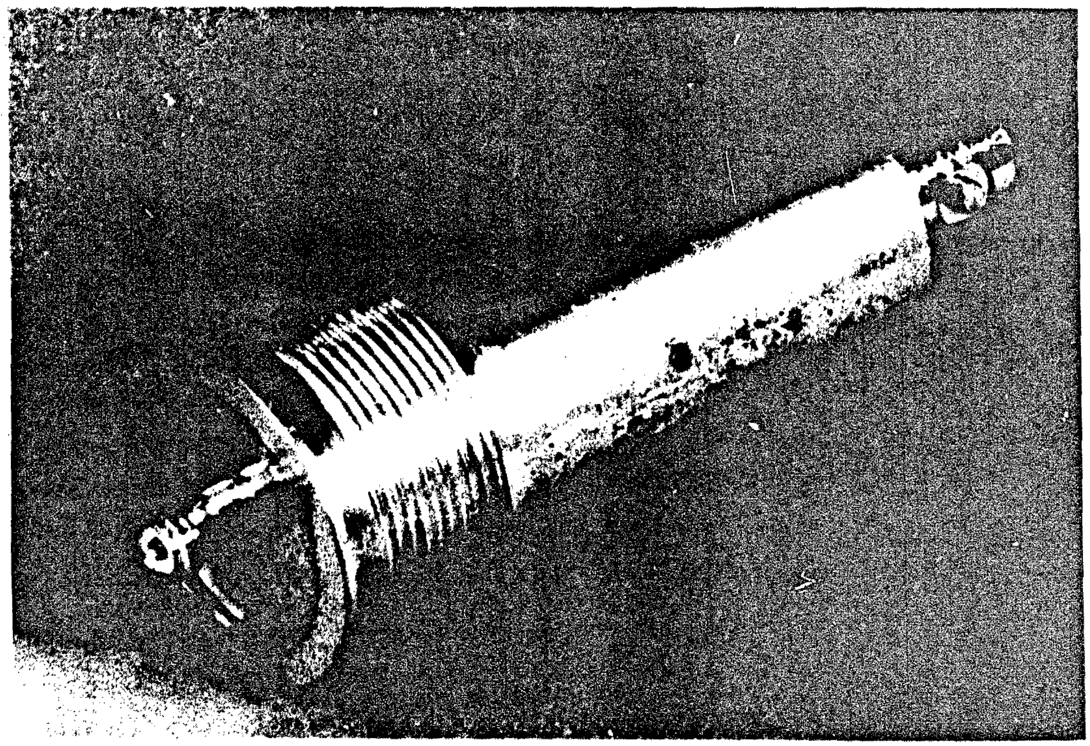
4. We recommend that U. S. Nuclear Regulatory Guide 1.133 be modified to strongly encourage the use of radiation resistant LPM systems. The May 1981, Revision 1 guide states "Early detection (of loose parts) can provide the time required to avoid or mitigate safety-related damage to or malfunctions of primary system components".[4] This statement is actually relevant for a power plant operating normally as well as during an accident. During an accident, where operators do not have access to the containment building, the LPM system can potentially provide a much needed indication of vibration and/or impact levels. Operators can use this information to possibly mitigate further damage. The Guide should specify design goal radiation levels which are consistent with those required for Class 1E equipment.

5. The degradation in $V_{GS(th)}$ of the MOS transistors indicates that YM-AMP-7023 and YM-AMP-7025 received total gamma doses of 1.8×10^5 and 5.4×10^5 Rads respectively. These levels correlate well with the estimate of 2.5×10^5 rads received by radiation detector HP-R-211 located near-by.

II. DESCRIPTION

A. Rockwell LPM System at TMI-2

The Rockwell LPM System at TMI-2 uses a total of eight channels to monitor the upper and lower tube sheets of the two steam generators. Signals from these channels are processed in a Rockwell electronics cabinet located in the cable spreading room. Alarms and a channel selectable audio output are located in the control room. Each channel consists of an Endevco Model 2276 accelerometer mounted on the tube sheet and an Endevco Model 2652M4 charge converter mounted outside the D-ring. A photograph of the charge converter is shown in Figure 1. The accelerometers are exposed to high temperatures and radiation, while the charge converters are in much less severe environments. The normal radiation field around the charge converters is on the order of 1 to 10 mRad/hr. YM-AMP-7023 and YM-AMP-7025 are used to monitor opposite sides of steam generator B upper tube sheets. These are connected to the Rockwell cabinet by approximately 110 meters and 200 meters of coaxial cable respectively.



1. YM-AMP-7025 Remote Charge Converter. Actual size is 5.7 cm x 2.22 cm. Signal input connector shown.

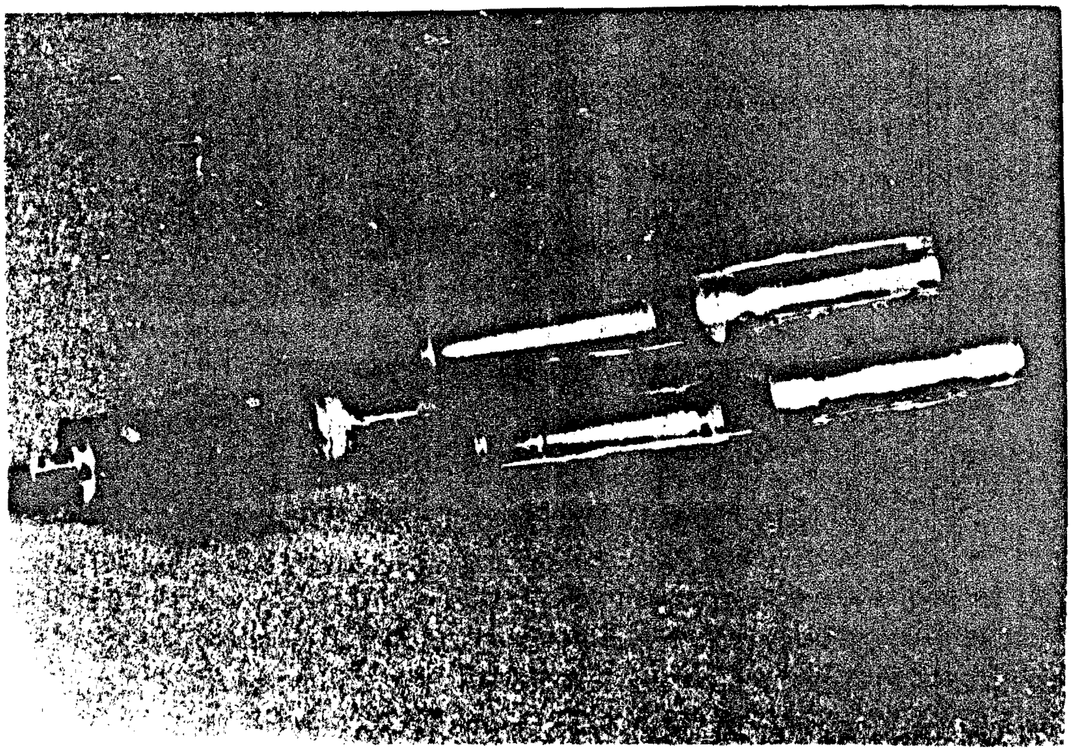
B. Operational History

We have not attempted to piece together a precise operational history of the LPM channels; however, we will provide a sketch of information given to us.[2,3,5] The LPM system, as described above, was calibrated and operational at the time of the accident. The day after the accident a team of Babcock and Wilcox (B&W) technicians were dispatched to TMI-2 to monitor and record the LPM outputs. They replaced the Rockwell readout system with a B&W system having a magnetic tape recorder and various filters and signal conditioning electronics. The channels were monitored quite closely during the first week following the accident and then at least daily for the remainder of April, 1979. The channels were then monitored periodically for several months. During the month-long vigil most of the channels were believed at the time to be functional; i.e., normal sounds were heard. At the time in situ testing on YM-AMP-7023 and YM-AMP-7025 was done, we were informed by GPU that 7 of 8 channels were inoperable. Indeed, the in situ data show both YM-AMP-7023 and YM-AMP-7025 to be severely degraded or inoperable (see Section III).

On reviewing the information we have, it appears that most of the channels had severe degradation within a day or days after the accident began. This is indicated by the need to adjust the bias levels to "100%". It appears that this was necessary the day after the accident began, although we know of no written records of this. Several weeks after the accident these bias levels were recorded and all were near 100%. Another indicator of degradation was the need by B&W to increase channel gains on April 1 and 2, 1979.

C. Charge Converter Mechanical Description

The Endevco Model 2652M4 charge converter is shown disassembled in Figure 2. This particular unit is YM-AMP-7025. The electronic circuitry is potted and housed inside a metal tubular case 4.6 cm long and 1.9 cm in diameter. The case is actually an outer housing over an inner shield housing with the two being electrically isolated from each other. The Microdot(R) connector and BNC connector are electrically grounded to the inner shield case. An outline drawing is given in Appendix B.



2. Disassembled Remote Charge Converter. The double shield is used to provide extra isolation from electromagnetic interference.

D. Charge Converter Functional Description

The function performed by the Model 2652 charge converter is the conversion of an electrical charge generated by a piezoelectric transducer into a voltage proportional to the input acceleration (shock or vibration). This voltage is then supplied to a remote readout calibrated in g's to indicate the vibration level. The Model 2652 is usually located in close proximity to the transducer and is designed to drive long coaxial cables which are used to interconnect the read-out. The M4 version of the Model 2652 has a conversion gain of 1 millivolt per picocoulomb. The remote readout has selectable peak acceleration ranges of 0.1g, 0.3g, 1.0g, 3.0g, 10g and 30g.

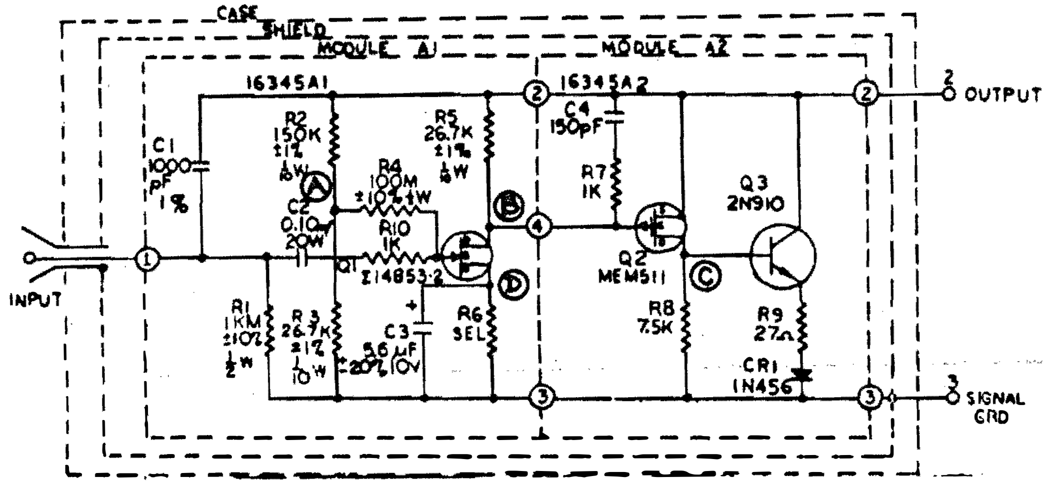
Figure 3 shows a schematic of the charge converter. The output line serves both to supply DC power to the device and to carry the AC output signal to the remote readout. The circuit consists of a very high input impedance input amplifier (Q1), a second amplifier (Q2), and a low output impedance line driver (Q3). In operation, the output AC voltage which occurs as a result of the charge input signal is fed back to the input via C1. The polarity is such as to maintain the voltage at the input near zero. This means that the input charge is stored on capacitor C1 and thus the output voltage $e_o(t)$ is given by

$$e_o(t) = -\frac{1}{C1} q(t)$$

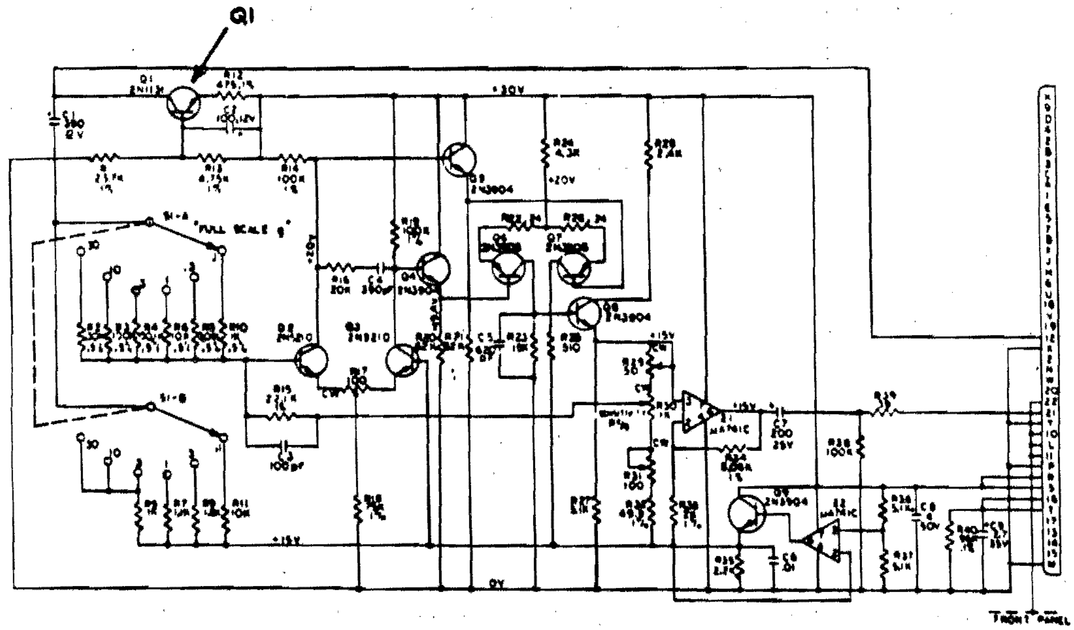
Where q(t) is the input charge. The advantage of this feedback arrangement is to effectively "swamp out" input cable capacitance variations with a large capacitor. The circuit gain of this particular circuit is

$$\frac{Eo}{Q} = \frac{1}{C1} = \frac{1}{1000pf} = \frac{1mv}{pc} .$$

The 2652M4 is biased with the constant current source Q1 shown in Figure 4. This circuit nominally drives the 2652M4 with 8 milliamperes DC. The DC compliance voltage is set by selection of R6 in Figure 3 and is nominally 13.5 volts. Resistor R6 is used to adjust the drain current of Q1 so that the voltage drop across R5 is sufficient to overcome the gate-to-source threshold voltage (VGS_{th}) of transistor Q2. The threshold voltage of the MEM 511 is nominally -4.5 volts. Since the circuit is being driven by a current source, the DC voltage (compliance voltage) appearing across the circuit from output to ground (Pin 2 to Pin 3) will rise until the circuit does in fact draw 8 milliamperes. This happens because an increase in the bias voltage tends to turn Q2 on harder and more base current is supplied to Q3 causing it to sink the required 8 milliamperes. This method of negative DC feedback is normally very good in stabilizing the operating points of the three transistors against variations in temperature and component parameters. As we will see later, the increase in VGS_{th} of Q2 caused by radiation results in the need for the compliance voltage to rise in order to keep Q2 on.



3. Charge Converter Schematic. The operating point measurements in Table 3 were made at the points indicated by letters A,B,C & D. Q2, an MEM 511 MOS transistor, was found to be degraded by radiation.



4. Model 4479.1 Line Driver Conditioner Schematic. Transistor Q1 is configured as a constant current generator providing the bias current to the Remote Charge Converter through pin 12 of the connector.

III. ELECTRICAL EVALUATION

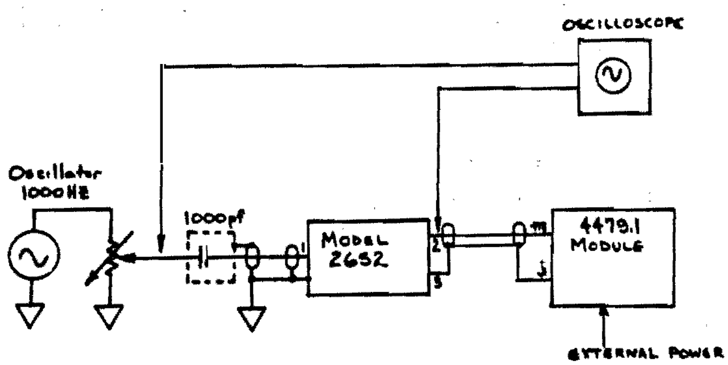
In this section we describe the electrical evaluations performed on YM-AMP-7025 and YM-AMP-7023 and discuss the cause of degradation or failure. We found that YM-AMP-7025 was completely non-operational, and YM-AMP-7023 had output distortion for acceleration levels in excess of 1g. The cause of failure was found to be radiation degradation of the MEM 511 MOS transistor used in the Q2 slot.

A. Test Sequence

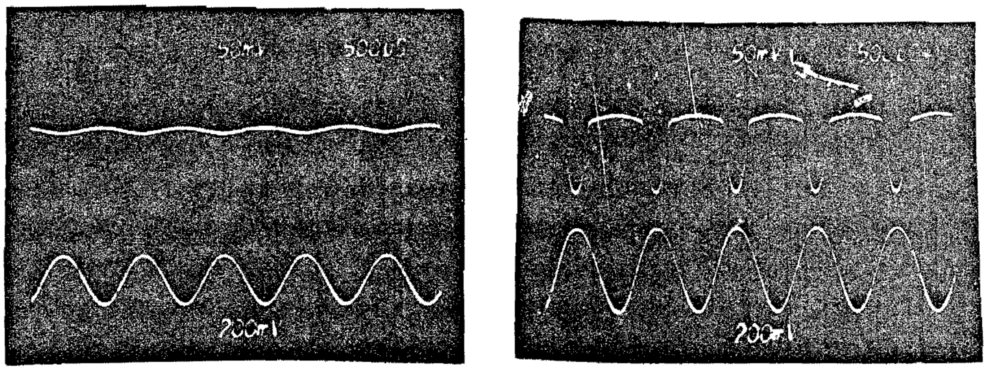
Both YM-AMP-7025 and YM-AMP-7023 charge converters (Endevco SN ZB47 and ZB50) were found to be slightly contaminated upon arrival from Three Mile Island. Each was carefully scrubbed using alcohol before any electrical tests were done, and care was taken to avoid getting alcohol inside the Microdot or BNC connectors. After decontamination the two devices were taken to the laboratory for the electrical examination. Each underwent passive and powered testing before disection and troubleshooting. The passive and powered in situ tests performed at TMI-2 indicated normal resistance and capacitance values but abnormal bias currents and voltages. There was no AC output from YM-AMP-7025. Our examination verified the in situ measurements and provided additional data because we could use a calibrated input stimulus.

B. Evaluation of YM-AMP-7025

Electrical evaluation of the Model 2652 requires a charge generator to provide an input signal and a DC source to provide power. The test set-up shown in Figure 5 was used for testing as it is recommended by the manufacturer for 2652 operational checkout. A schematic of the Endevco 4479.1 signal conditioner used is shown in Figure 4.



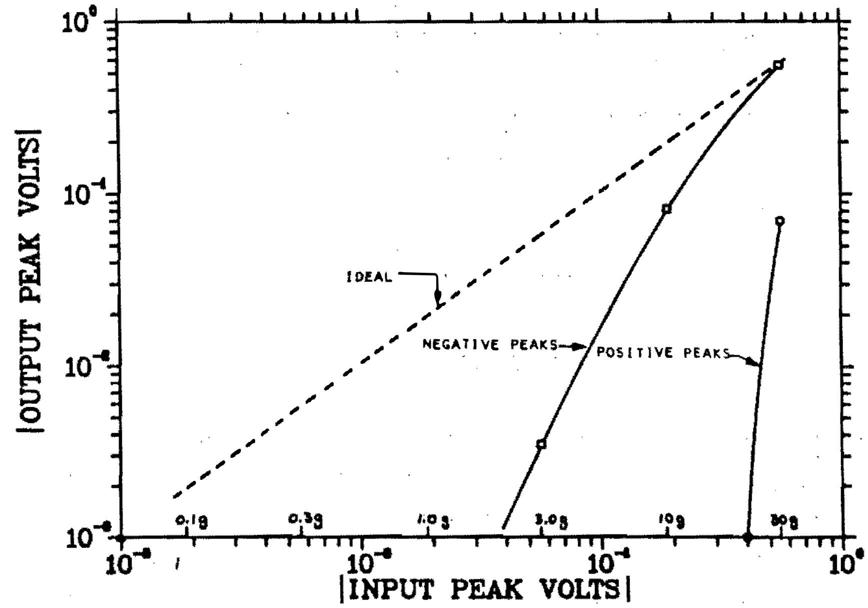
5. Model 2652 Set-up. This set-up is identical to that recommended by Endevco except that the Charge Converter output is monitored instead of the 4479.1 output.[6]



(a) (b)

6. YM-AMP-7025 Oscilloscope/Tracings. These actual photographs of the Charge Converter input and output signals illustrate the non-linear operating mode of YM-AMP-7025. The waveforms shown in (a) are for an input level (lower trace) equivalent to 13 g's peak. For this input signal the output (upper trace) would indicate about 0.1g peak. Tracing (b) shows an equivalent input level of 20g's peak and the distorted output indicating perhaps 2.5g peak.

Initial AC measurements were made using a 1 kilohertz variable amplitude source. We found that the charge converter output was essentially zero until quite large input signals were applied. Even then the output was severely attenuated and distorted. The output positive going portion of the sine wave was found to be more attenuated than the negative going portion. This is shown in the oscilloscope pictures in Figure 6. Figure 7 shows a plot of the AC voltage transfer characteristic, where the amplitudes of the positive peaks and negative peaks are plotted for various input peak voltages. The amplitude of the negative going portion of the output signal is only correct at high signal levels. The amplitude of the positive going portion is always attenuated. At this point the unit was disected, so that the DC operating points could be determined.



7. YM-AMP-7025 Transfer Characteristics. The charge amplifier output peak magnitude is plotted versus input peak amplitude. The ideal and post repair characteristic is shown dotted. With the degraded transistor both positive going peaks and negative going peaks are attenuated. Equivalent input g levels are also shown.

The Model 2652 is housed in a double shielded metal enclosure, and requires the use of a cutting disc to remove the case shield. The unit was potted in an amber epoxy compound which was easily spot-removed by applying heat and crumbling with a soldering iron. Points of interest were exposed in this manner. These points are shown on the circuit schematic as A,B,C, and D. DC voltages were measured at these points and at the output.[7] Also, the DC input current into pin 2 was measured. The recorded values are shown in Table 1 under the heading; "YM-AMP-7025, pre-repair."

	YM-AMP-7025		YM-AMP-7023	
	PRE-REPAIR	POST-REPAIR	PRE-REPAIR	POST-REPAIR
VOLTAGE at A	4.399 VOLTS	1.722 VOLTS	4.297 VOLTS	1.712 VOLTS
VOLTAGE at B	20.25 VOLTS	6.871 VOLTS	19.10 VOLTS	6.808 VOLTS
VOLTAGE at C	0.156 VOLTS	1.585 VOLTS	1.385 VOLTS	1.634 VOLTS
VOLTAGE at D	5.085 VOLTS	2.514 VOLTS	4.711 VOLTS	2.273 VOLTS
VOLTAGE at 2 (Output Bias)	29.28 VOLTS	11.42 VOLTS	28.72 VOLTS	11.43 VOLTS
CURRENT into 2 (Input Current)	0.484 mAmps	7.88 mAmps	2.80 mAmps	7.84 mAmps

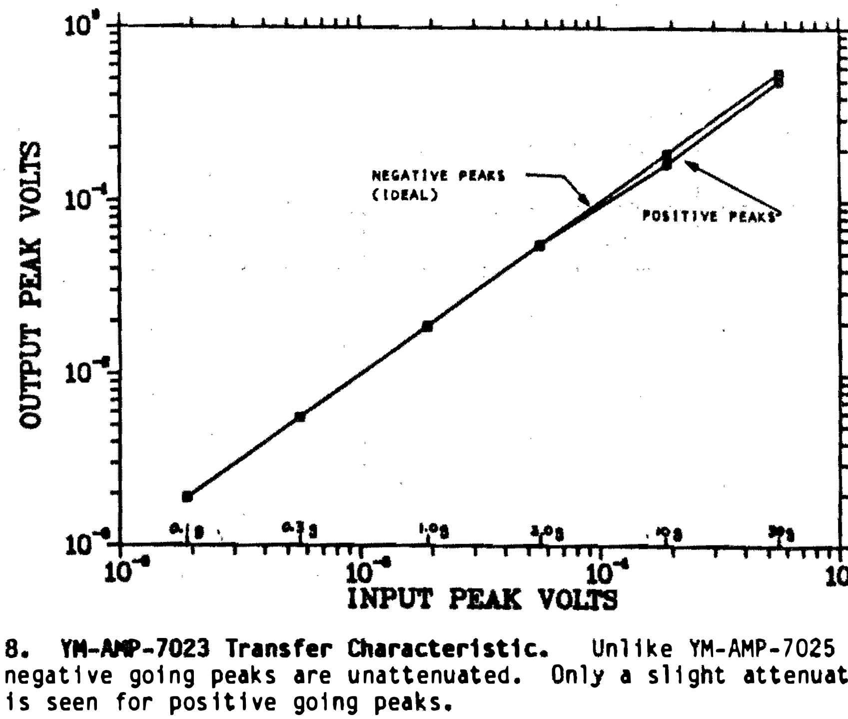
TABLE 1. DC OPERATING POINT MEASUREMENTS

Analysis of the DC measurements indicated that a shift in the DC operating point had occurred. The output bias (voltage at pin 2) had shifted upward to 29.28 volts from a nominal value of 13.5 volts and the input current had decreased to 0.484 milliamperes from a nominal 8.0 milliamperes. The voltage at point C was insufficient to bias Q3 "on" ("on" being operational), explaining the low input current and high output DC voltage. Also, the clipping of AC output signals was easily explained as Q3 would require a relatively large positive input to produce an output. Measurements at points A,B and D indicated that Q2 had failed. The voltage at point B was sufficient to overcome the normal threshold voltage of Q2 and bias it on. This should, in turn, bias Q3 at a suitable operating point. Q2, an MEM 511 MOS field effect transistor, was removed for failure analysis and was found to have an out-of-spec VGS_{th}. The specified range of VGS_{th} for a normal MEM 511 device is from -3 to -6 volts (Appendix C).

The performance of the converter was restored to within specification limits by the replacement of Q2. Post repair AC and DC measurements are shown in Figure 7 and Table 1, respectively, for comparison with the pre-repair data. The output bias voltage decreased to 11.42 volts and the input current increased to 7.886 milliamperes. These are both near nominal levels. The select resistor, R6, could probably be adjusted so that the output bias voltage and input current approached the nominal values of 13.5 volts and 8.0 milliamperes.

C. Evaluation of YM-AMP-7023

YM-AMP-7023 was evaluated using methods identical to those used on YM-AMP-7025. The AC voltage transfer characteristic obtained is shown in Figure 8. The output was free from distortion and attenuation for low signal levels but was slightly distorted at higher levels. The charge converter operated properly for input levels up to 1g on the Endevco system. Negative input signals above this level produced outputs which were slightly attenuated due to the same clipping action exhibited by YM-AMP-7025. Positive input signals produced unattenuated outputs beyond the maximum 30g equivalent input level. Voltages at points A,B,C,D, pin 2, and the input current into pin 2 were measured after all points were exposed. The recorded values are listed in Table 1 under the heading; "DC Measurements, YM-AMP-7023, pre-repair".



8. YM-AMP-7023 Transfer Characteristic. Unlike YM-AMP-7025 the negative going peaks are unattenuated. Only a slight attenuation is seen for positive going peaks.

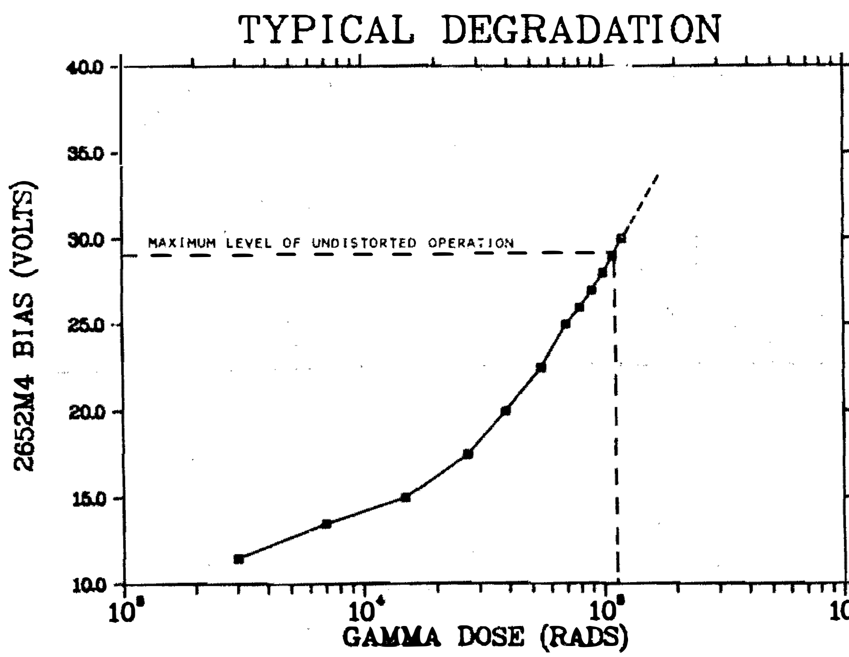
Analysis of the DC measurements indicate a DC operating point shift similar to the shift in YM-AMP-7025. The output bias voltage increased to 28.72 volts and the input current decreased to 2.8 milliamperes. The voltage at point C, however, was sufficient to keep Q3 biased slightly on for low signal levels, accounting for the difference in input currents between YM-AMP-7023 and YM-AMP-7025. The voltages at operating points A,B, and D indicate that Q2 was operating at an incorrect bias point. Specifically, the voltage measured at point B was more than adequate to insure strong bias of the Q2 and Q3 stages. Q2 was removed for failure analysis and found also to have an abnormally high VGS_{th}.

D. Effect of Degradation on Circuit Operation

The effect of a gradual increase in the VGS_{th} of Q2 as radiation dose is accumulated is to cause a proportional increase in the charge converter bias voltage. This happens because the transistor DC operating points are stabilized by the control loop described earlier. As the threshold voltage of Q2 increases, the available drive to Q3 is reduced, causing the bias voltage (pin 2) to increase. This, in turn, provides Q2 with a higher gate-to-source voltage, and the drive to Q3 increases. This give and take can continue until it is limited by the recommended 30 volt DC supply. As the bias voltage nears 30 volts, large output signals become distorted as shown in Figure 6. As the bias voltage continues to approach the 30 volt supply, proportionally lower levels will become distorted. This limit, nominally 29 volts, is the point where Q2 cuts off and can no longer provide bias to Q3.

Positive input levels of sufficient magnitude may overcome this limit by indirectly providing bias to Q3. These inputs, however, produce attenuated outputs. The input level required to overcome this threshold continues to increase with increasing Q2 threshold voltage for all practical inputs. The limit approached here is not meaningful as it would exceed the recommended operating range of the converter. The converter could also be made to operate simply by increasing the bias voltage were it not for the MEM 511 maximum rated drain to source breakdown voltage of -30 volts. To summarize, as dose is accumulated the first effect seen is that large output signals resulting from large amplitude vibrations become distorted. When enough dose is accumulated small vibrations will not be measured, and large ones will be severely attenuated.

We have quantified the effect of VGS_{th} increases in Figure 9. Here, we plot the expected upward shift in charge converter bias voltage as a function of radiation dose. (The variation of VGS_{th} with radiation dose for "typical" MEM 511 transistors is shown in Part IV in Figure 10.) Assuming a 30 volt supply and a half-volt drop across the current source transistor, we see that the distorted peak voltage amplitude would be 0.5 volts, for a radiation dose of 1×10^5 rads. Above approximately 29 volts bias, the output would be distorted (this corresponds to a 30 g input level). The maximum dose for undistorted outputs is therefore approximately 1×10^5 rads.



9. Linear Operating Region vs. Gamma Dose. For linear operation, the maximum bias voltage must be no greater than approximately 29 volts, assuming a 30 volt supply voltage. If the supply voltage were raised above 30 volts, the absolute maximum breakdown voltage specified for the MEM 511 would be exceeded. Thus, for a typical charge converter, the degradation of the output signal begins at 1×10^5 Rads.

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IV. FAILURE MODE AND RADIATION DOSE

The Siliconix MEM 511 is a p-channel enhancement mode MOS field effect transistor designed for small signal amplifier applications. As with all non-hardened MOS transistors, the MEM 511 is sensitive to total radiation dose; and, in fact, we have determined radiation dose to be the cause of degradation of YM-AMP-7025 and YM-AMP-7023. The effect of radiation (gamma radiation in this case) is to cause an increase in the gate-to-source threshold voltage, VGS_{th}, of the MOS transistor. The MEM 511 data sheet given in Appendix C specifies a VGS_{th} of nominally -4.5 volts. The VGS_{th} voltages measured for Q2 of YM-AMP-7025 and YM-AMP-7023 were -11.46 volts and -8.92 volts respectively (measured at ID = -10μA and VDS = -12 volts). Using these values, we estimate the total gamma doses received by YM-AMP-7025 and YM-AMP-7023 to be 5.4×10^5 Rads and 1.8×10^5 Rads respectively.

A. Failure Mechanism

In a p-channel enhancement mode transistor, a negative bias is normally applied between drain and source. Drain current will flow provided that a large enough negative voltage is applied to the gate. A negative voltage, exceeding a certain threshold (VGS_{th}), between the gate and substrate converts the normally n-type substrate material directly under the gate into p-type. This happens because the electric field produced between gate and substrate draws minority carrier holes to the surface interface with the gate oxide.

The gate electrode is separated from the substrate by a thin insulating layer of SiO_2 (gate oxide). Gamma irradiation creates hole-electron pairs in this gate oxide. Electrons, being more mobile, are rapidly swept out of the region by the application of a bias, leaving trapped positive charge in the lattice. In order for the substrate region under the gate to be converted, additional negative voltage must be applied to the gate. Thus, the gate-to-source threshold voltage, VGS_{th}, increases with radition dose.

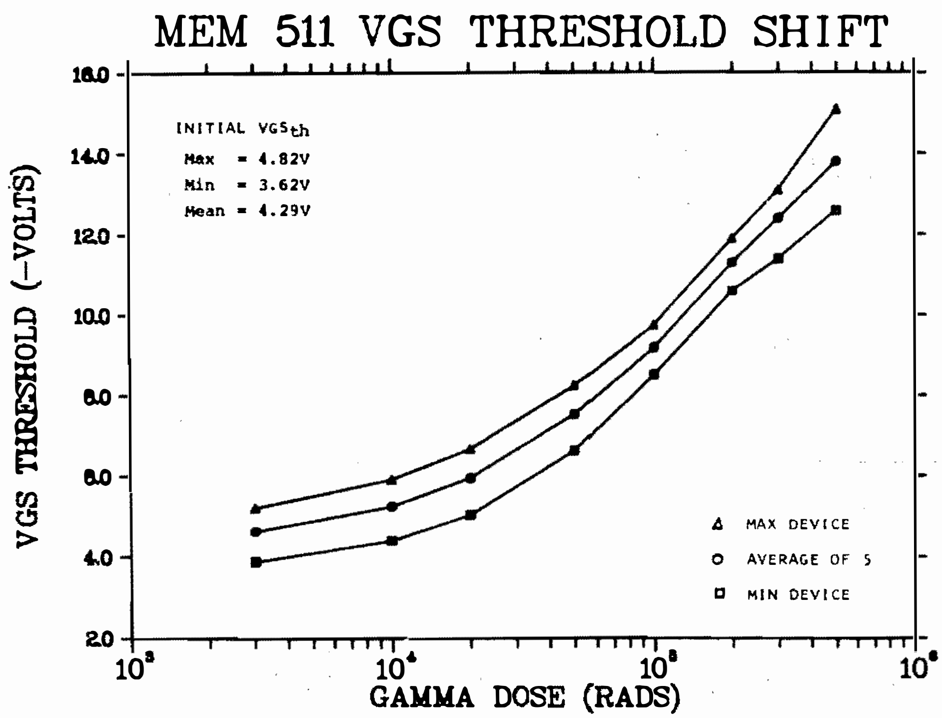
B. Total Dose

Reports would indicate that shifts in VGS_{th} cannot be used to determine radiation total dose accurately because of damage annealing - even at room temperature.[8] We have conducted experiments to characterize annealing and have concluded that, for the accuracies required here, we can account for annealing effects and still estimate the total gamma dose received by the device. In the laboratory we exposed 5 MEM 511 transistors to gamma radiation from a ^{60}Co source and measured the resulting VGS_{th} as a function of dose. These data are plotted in Figure 10. Each transistor was biased during gamma exposure since it is felt that the majority of radiation damage at TMI-2 occurred when the charge converters were biased. The bias circuit used is shown in Appendix D. This circuit is similar to that of the charge converter and its external constant current bias circuit even including the aspect that, as the threshold voltage of the MEM 511 increases after irradiation, the bias or compliance voltage increases.

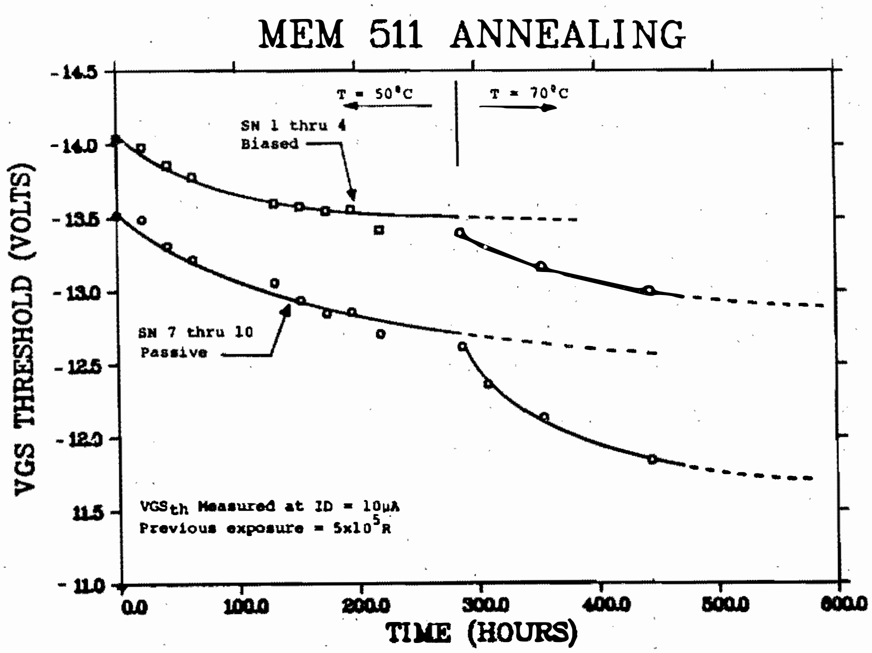
Unfortunately Figure 10 cannot be used directly to estimate the radiation total dose received because the annealing characteristics of the device must be taken into consideration. For an MOS transistor it is possible to anneal out practically all gamma induced damage by thermally baking the device.[8] A combination of temperature and time will supposedly, through excitation of the trapped holes in the gate oxide, eventually rid the gate oxide of that charge. The problem is to first determine the temperature and time dependence and then estimate the amount of annealing which occurred before we were able to finally measure the threshold voltages of the charge converter transistors. To do this, we conducted an experiment where we baked 4 devices biased, as in Figure 11, and 4 devices passively at temperatures of 50°C and 70°C. The transistors were baked at 50°C for 287 hours, and then at 70°C for an additional 157.3 hours. Measurements of VGS_{th} were made at various intervals. The result is shown in Figure 12. For each temperature case the threshold voltage decreases rapidly at first, and then flattens out to some reasonably constant steady-state value. It appears that a certain amount of damage is annealed in the first few hundred hours at a given temperature and then after that a very slow annealing process takes place. We have further evidence of this threshold stabilization. Table 2 shows long term data we collected on the transistors used to generate Figure 10.

MEM 511 TRANSISTORS	VGS_{th} INITIAL (-V)	VGS_{th} FINAL (-V)	TIME BETWEEN MEASUREMENTS (INITIAL TO FINAL) (days)
5 TRANSISTORS EXPOSED TO $5x10^5$ R (AVERAGE)	13.79	11.81	323
3 TRANSISTORS EXPOSED TO $2x10^5$ R (AVERAGE)	13.18	12.38	280
Q2 OF YM-AMP-7023	8.92	8.92	242
Q2 OF YM-AMP-7025	11.46	11.46	242

TABLE 2. ROOM TEMPERATURE ANNEALING



10. **VGS$_{th}$ Shift with Gamma Dose.** Five MEM 511 transistors (SN 21 through 25) were exposed in steps to a ^{60}Co source. VGS$_{th}$ was measured at a drain current of 10 microamperes. The upper curve is the maximum device tested, etc. These curves do not account for annealing.



11. **MEM 511 Annealing Characteristics.** Eight MEM 511 transistors which had previously been exposed to $5x10^5$ R were annealed at first 50°C and then at 70°C. Notice the early, rapid decrease in threshold voltage and then a leveling out thereafter at each temperature. No particular significance is attached to the fact that the passive devices annealed further than the active ones. (The step decreases at 219 and 287 hours are believed to be measurement errors incurred possibly during computer recalibration.)

These transistors were stored at room temperature for hundreds of days and only minor changes in VGS_{th} occurred. Interestingly, neither TMI transistor VGS_{th} changed during the 242 days between our first to last measurements. We can speculate that trapped charges from deeper and deeper in the oxide layer are released as the temperature is increased. Eventually, possibly all the damage will be annealed; however, for the times and temperatures of interest here long-term annealing is not a significant factor.

To make our total dose estimates we assume that at TMI-2 annealing took place in a state of bias during the first few hundred hours after the accident at a temperature of 50°C. For the next two years, until we measured them they annealed passively to their present states. Figure 10 is essentially the unannealed case since measurements were made almost directly after exposure to the ^{60}Co source. Using the appropriate curves of Figure 11 and the passive values from Table 2 along with Figure 10 we estimate that the gamma doses received were approximately as shown below.

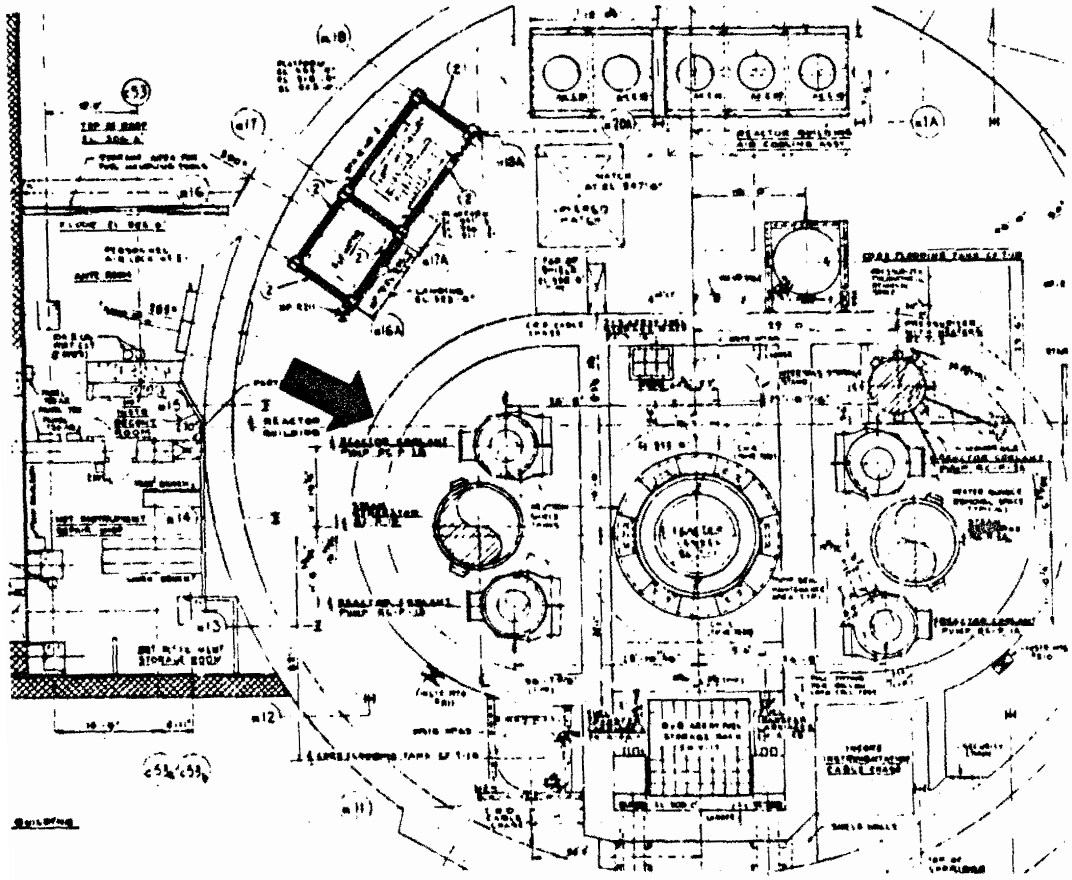
	TOTAL Dose Range ($\times 10^5$ R)		
Device	MIN	NOM	MAX
YM-AMP-7023	1.2	1.8	3.0
YM-AMP-7025	2.7	5.4	8.5

V. COMMENT

To summarize, the Model 2652 appears to be well designed for non-nuclear environments; however, the circuit sensitivity to radiation generally makes it unsuitable for use in nuclear applications. The charge converter is not designed to be radiation tolerant, nor does the manufacturer, Endevco, claim it to be. Unfortunately, the device was used in an application where it shouldn't have been. Perhaps the problem and its solution lie in the area of the LPM system design.

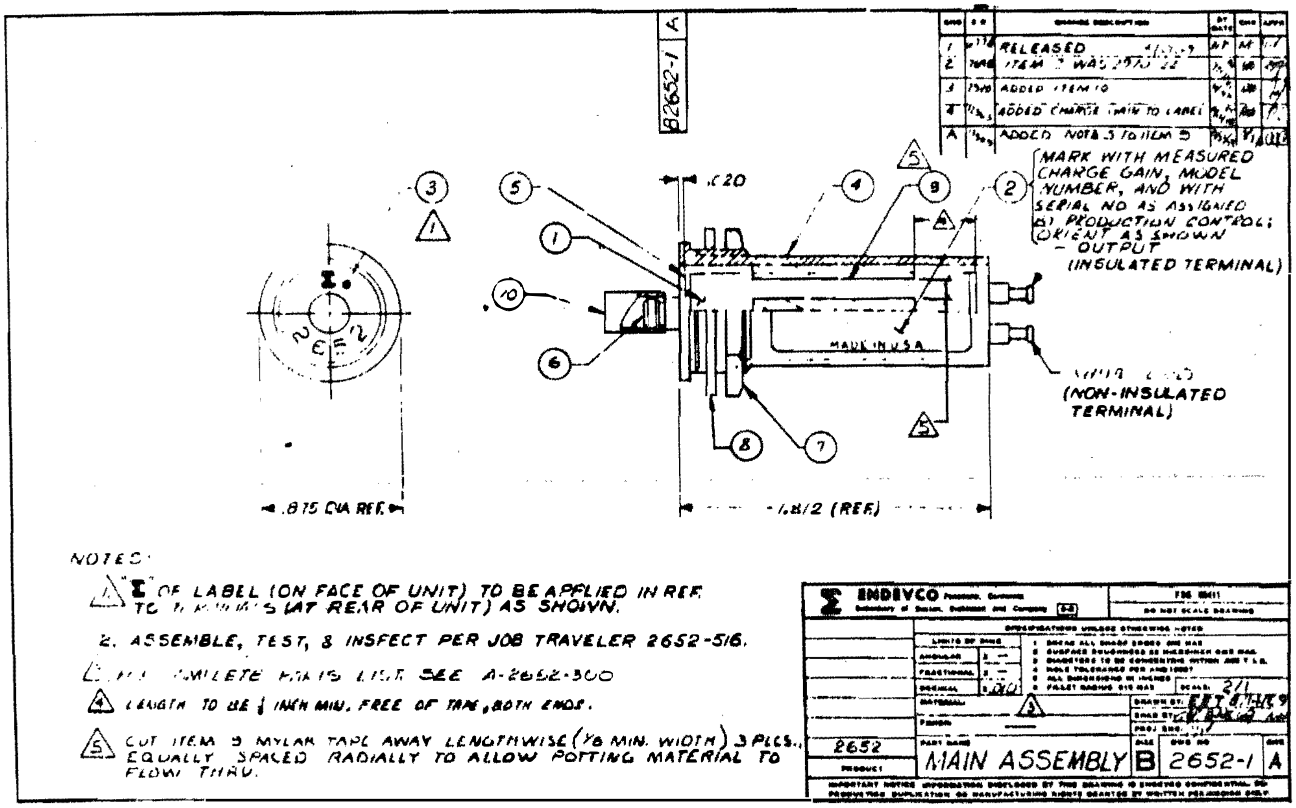
We feel that U.S. Nuclear Regulatory Guide 1.133 adequately states the usefulness of loose parts monitoring systems in that these systems allow plant operators to avoid or mitigate accidents. We believe that the Guide does not go far enough, however, in specifying radiation survival levels. As a minimum, the LPM system should survive a small LOCA such as that at TMI-2. This particular Endevco charge converter could probably be made to easily withstand a TMI-2 accident by replacing the MEM 511 transistor with a suitable bipolar transistor and adjusting component values to accommodate it. The use of an MOS transistor in this particular charge converter automatically limits its usefulness in a radiation environment. In this case, care must be taken to avoid failure simply because of the normal background radiation levels in an operating plant. In fact, operators of plants where this, or similar, charge converters are used should measure charge converter bias voltages to determine if degradation may have occurred. We recommend that Regulatory Guide 1.133 be changed to help prevent this in future designs, and that existing plants replace these (and similar) charge converters with more radiation tolerant ones.

Appendix A. Unit 2 305' Elevation Floor Plan



The approximate locations of the two remote charge converters used in the loose parts monitor system in Unit 2 are shown above in the 305' elevation plan view.

Appendix B. Outline Drawing of the Endevco Remote Charge Converter



The standard output terminals shown in the drawing may be replaced with an optional BNC type connector. Both YM AMP 7023 and YM AMP 7025 had the BNC type output connector.

Appendix C. Manufacturers Specification Listing for the MEM 511

M511
M511A
P-CHANNEL ENHANCEMENT-TYPE MOS SILICON FIELD-EFFECT TRANSISTOR

NORMALLY-OFF, TYPE C, INSULATED-GATE FET FOR ANALOG-GATE AND GENERAL-PURPOSE AMPLIFIER APPLICATIONS

- Integrated Zener Clamp Protects the Gate

TO-72
Body & Case connected internally

PRODUCT CONDITIONING

Units receive the following treatment before final electrical tests:

High Temp Storage: 24 Hours at 150°C
Thermal Shock: +100 to 0°C for 5 Cycles
25,000g Acceleration/Impact in the Y_1 Plane
Helium and/or Gross Leak Tests for Hermeticity

ABSOLUTE MAXIMUM RATINGS (25°C)

Drain-to-Source Voltage	-30 V
Gate-to-Source Voltage	-30 V
Gate-to-Drain Voltage	-30 V
Drain Current	-50 mA
Gate Current (Forward Direction for Zener Clamp)	+0.1 mA
Storage Temperature	-65 to 150°C
Operating Junction Temperature	-55 to 125°C
Total Dissipation at 25°C Ambient Temperature (Derate 2.25 mW/°C)	225 mW

ELECTRICAL CHARACTERISTICS

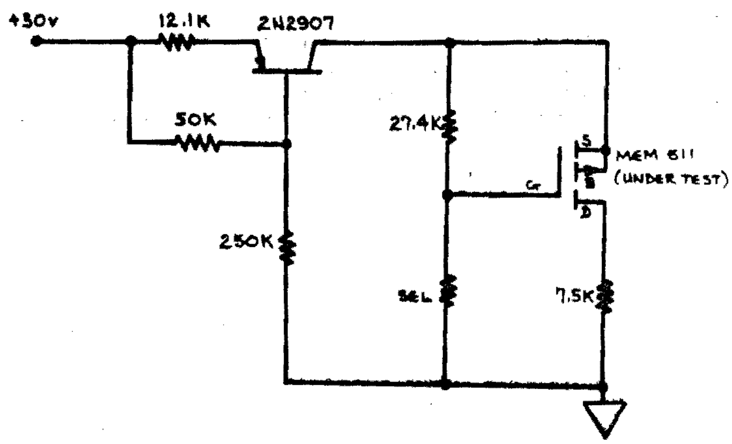
Characteristic		Test Conditions		M511 Min	M511 Max	M511A Min	M511A Max	Unit
$r_{DS(ON)}$	Drain-Source ON Resistance	$V_{GS} = -15$ V, $I_{DS} = -1$ mA, $V_{BS} = 0$			300		300	Ω
$V_{GS(th)}$	Gate Threshold Voltage	$V_{GS} = V_{DS}$, $I_D = -10$ µA, $V_{BS} = 0$		-2	-6	-2	-6	V
BV_{DSS}	Drain-Source Breakdown Voltage	$I_D = -10$ µA, $V_{GS} = 0$, $V_{BS} = 0$		-30		-30		V
BV_{SDS}	Source-Drain Breakdown Voltage	$I_S = -10$ µA, $V_{GD} = 0$, $V_{BD} = 0$		-30		-30		V
BV_{GBS}	Gate-Body Breakdown Voltage	$I_G = -10$ µA, $V_{SB} = 0$, $V_{DB} = 0$		-30	-90	-30	-90	V
I_{DSS}	Drain Current at Zero Gate Voltage	$V_{DS} = -20$ V, $V_{GS} = 0$, $V_{BS} = 0$			-10		-10	nA
I_{SDS}	Source Current at Zero Bias	$V_{SD} = -20$ V, $V_{GD} = 0$, $V_{BD} = 0$			-10		-10	nA
I_{GSS}	Gate-Body Leakage	$V_{GS} = -15$ V, $V_{DS} = 0$, $V_{BS} = 0$			-1.0		-1.0	nA
$I_{D(ON)}$	Drain Current*	$V_{DS} = -10$ V, $V_{GS} = -10$ V, $V_{BS} = 0$		-3		-2		mA
g_{fs}	Common-Source Forward Transconductance*	$V_{DS} = -10$ V, $V_{GS} = -10$ V, $V_{BS} = 0$	f = 1 kHz	1000		1000		µmho
			f = 10 MHz	1000		1000		µmho
C_{gs}	Gate-Source Capacitance	$V_{GB} = V_{DB} = V_{SB} = 0$, f = 1 MHz, Body Guarded			4		2	pF
C_{gd}	Gate-Drain Capacitance				4		1.5	pF
C_{sb}	Source-Body Capacitance	$V_{GB} = 0$, $V_{DB} = V_{SB} = -5$ V, f = 1 MHz			5		3.5	pF
C_{db}	Drain-Body Capacitance				4		2.5	pF
C_{ds}	Drain-Source Capacitance	$V_{GB} = 0$, $V_{DB} = V_{SB} = -5$ V, f = 1 MHz, Body Guarded			0.2		0.2	pF

These devices are manufactured to meet or exceed the requirements of MIL-S-19500.
Specifications subject to change without notice.
*Pulse test required pulsewidth 300 µs, duty cycle ≤3%.

MB MKA

APPENDIX D. MEM 511 BIAS CIRCUIT

The circuit shown below was used to bias MEM 511 transistors being irradiated in steps to estimate the gamma dose received by TMI-2 MEM 511 transistors. The circuit simulates the changing bias condition of the TMI-2 device. The select resistor (approximately 45KΩ) is initially adjusted to produce a 12 volt bias on the MEM 511. The constant current source initially supplies approximately 300μA to the MEM 511 being exposed to gamma radiation.



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