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DEVELOPMENT OF A HYBRID MICROELECTRONICS SOLID STATE RELAY FOR 2500 VOLTS ISOLATION AND -120^0 C TO 80^0 C THERMAL CYCLING RANGE

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ABSTRACT

A hybrid microelectronics solid state relay was developed in a TO-116 package for the MINX project. The relay provides 2500 V_{dc} input to output isolation and operated from a MHTL logic signal to switch a load of 400 V_{dc} at 2 mA. The relay is designed to operate in space and survive 1000 thermal cycles of -120° C to 80° C. The use of X-rays for failure analysis in small hybrid circuits proved valuable and the applications of vacuum deposited Parylene[1] as a dielectric coating proved extremely valuable.

INTRODUCTION

The solid state relay to be discussed in this paper was designed for a flight project called MINX (Miniature High Voltage Array Interaction Experiment). The objective of MINX is to measure the effects of space plasma in earth orbit on exposed high voltage systems (1) as well as flight evaluation of a new photovoltaic device, the edge illuminated, multijunction solar cell (MJ cell). The MINX array (fig. 1) is a series connected circuit of 36 MJ cells with a solid state relay across each 4 cell string. Total array voltage during constant exposure is 1100 V_{dc} (80° C) and will be double just after coming out of the earth's shadow (-120° C). Compared with a conventional solar cell (fig. 2) the MJ cell is a diffusion bonded stack of 96 P-N-N+ junctions. The incident solar energy impinges on the solar cell parallel to the junctions' plane, whereas illumination is perpendicular in the conventional cell. A typical MJ cell output is 40 V at 1 mA in a 2 cm x 2 cm device. To measure the effect of plasma at various voltages, the MINX experiment plan requires that each 4 cell subgroup by "in" or "out" of the total circuit. "Out" is accomplished by shorting the string of 4 MJ cells with the solid state relay. Switch capability must be isolated (input to output) to 2500 V_{dc}, since the input drive circuit is basically at spacecraft ground and the output switch is connected across one of the 4 solar cell strings, which under worse case could approach 2500 V relative to spacecraft ground.

Due to a rather tight time schedule it was decided to adapt a proven solid state relay being manufactured by Sterer Engineering and Manufacturing Co. to the MINX experiment requirements. For example the Sterer Engineering device SLS 2500 is rated for operating from the TTL logic gate input to switch a 28 V, 1 A output and provides 1000 V rms isolation.

It appeared that the basic circuit technical approach could be modified to perform the required switching function of 400 V at 2 mA but for 2500 V dc isolation a new layout would be necessary. In addition the SLS 2500 temperature range of -55° C to 125° C appeared to be close to the MINX requirement at the time of -60° C to 80° C. However, as the program developed the lower temperature limit was modified to -120° C which was one of the areas requiring technology development and will be discussed below.

DISCUSSION

For convenience, the technical discussion will be by switch models, i.e., (a) the Sterer SLS 2500 solid state relay, (b) MINX experimental switch, (c) MINX flight switch, and (d) the latest Sterer SLS 2500 relay design. The SLS 2500 is a commercial solid state relay developed by Sterer Engineering and Manufacturing Co. which provided the basic technology for development of the MINX experimental switch. The MINX experimental switch was the test bed for demonstrating the techniques for H.V. isolation and environmental testing required. The MINX flight switch was designed utilizing the technology demonstrated in the experimental switch and was qualified for the MINX flight requirements. The latest Sterer SLS 2500 relay is a new design that has evolved using concepts proven in the MINX program.

STERER SLS 2500 Solid State Relay

Technical approach. - The SLS 2500 is a SPST normally open, 1000 V rms input to output isolated, solid state relay. Its contacts are rated at 1 A and 28 V_{dc} and its input drive is TTL compatible at 2.4 to 32 V_{dc}. This device is manufactured in a ceramic TO-116 package as was used for the MINX switch.

The SLS 2500 solid state relay utilizes the basic circuit approach shown in Fig. 3(a). The input signal sees a constant current load through the current limiter. When the input signal exceeds 2.4 V an oscillator is triggered. The os-

[1]PARYLENE - registered trade name, Union Carbide.

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cillator signal is transformer coupled (for 1000 V rms isolation) to the rectifier-filter in order to drive the trigger circuit which triggers the driver circuit and provides the snap "on" and "off" action with a minimum of 250 mV hysteresis. The driver drives the output switch which couples the load to its source voltage.

An equivalent diagram of the SLS 2500 solid state relay is shown in Fig. 3(b), where the numbers indicate the TO-116 leads.

Layout. - The photo in Fig. 4 shows the physical layout of the SLS 2500. As one can see from this photo while adequate for 1000 V rms this layout is not conducive to higher voltages. The transformer shown in Fig. 4 was located at one end of the package. Also the transformer is wound for good coupling with primary, feedback, and secondary windings wound on top of each other. And although there are separate input and output substrates the rectifier and filter were located on the input substrate due to the location of the transformer. These features are shown in Fig. 4. It was reasoned that a more suitable arrangment for H.V. would be to have all input circuitry on the input substrate and all the output circuitry on the output substrate with the transformer between them. Also the transformer should be wound with the input and feedback coils on the opposite side of the toroid core as the output winding to give maximum potential input to output isolation.

Test results. - Several production SLS 2500 devices were tested for leakage and corona inception. Leakage currents could be 10 μA at 1000 V (typical) and corona inception was 1400-1800 V dc using a James G. Biddle Co. corona detection system. Corona is monitored by observing an oscilloscope display for partial discharges. Corona inception is that voltage stress that partial discharges as low as 1 picocoulomb (pC) are initially observed.

Experimental Minx Switch

Technical approach. - For the MINX requirement the SLS 2500 design could be simplified somewhat since it was interfacing with the logic output of a MHTL gate where the "one" would be greater than 10 V but limited to the 15 V supply from which the gate is operated. The use of the MHTL gate allowed the input threshold to be raised to 10 V for noise immunity and eliminated the need for a snap action trigger circuit therefore simplifying the output circuitry to a rectifier, filter and transistor switch as shown in Fig. 3(c). Also a reverse current diode was required across the output switch for protection and redundancy if a solar cell should open on the array as shown in the block diagram Fig. 3(e).

Layout. - The major changes were in the new layout for high voltage isolation as shown in Fig. Fig. 5 where all the input circuitry is located on the input substrate and all the output circuitry is located on the output substrate. The transformer windings are separated and the transformer is located between the input and the output substrates. The photo in Fig. 5 shows the physical layout for the experimental devices. In these devices the existing SLS 2500 substrates were utilized with parts relocated to test the new layout concept. However, as can be seen in Fig. 5 the transformer could not be optimally placed with the input and output windings adjacent to their respective substrates for lack of room. For the flight hardware new substrates would be designed to eliminate any unused leads on substrates in order to minimize leakage paths and allow room for proper positioning of the transformer. During evaluation of the experimental devices it was found that coil positioning and leakage could be correlated as predicted. Also higher voltage wire and welded leads rather than soldered leads were used to reduce leakage associated with substrate contamination by flux.

Test results and problem areas. - Tests were run to determine if coating of the transformer core would reduce leakage and it was found that a Urethane coating used on experimental switches helped to reduce leakage but was still marginal for use on flight switches. It was decided that a larger core would be used on the flight switches if space allowed to increase physical separation of windings and later findings proved that a Parylene coated core would give the best isolation through the transformer. Test results of this evaluation is shown in table I. The first experimental switches had an RTV type junction coating applied to the inside of the switch for electrical isolation, to hold leads in place and pin down loose particles. Later environmental tests and X-ray analysis proved that this type coating was not adequate for the environment in which the switch had to survive. Initially, the thermal cycling range for the MINX experiment was -60° C to +80° C but this was changed to -120° C to 80° C as the thermal analysis was refined. The spacecraft on which the MINX experiment is attached is made of fiber glass and other dielectric materials and the MINX array is fabricated using flexible Kapton film with a low thermal mass. Therefore, when the spacecraft falls in earth's shadow the MINX array rapidly cools down and will reach -120° C by the time it comes out of earth's shadow.

The presence of an encapsulation is desirable to hold leads in place during handling as well as pin down loose particles that could destroy the device internally during vibration. A third requirement for this device was high voltage isolation.

The industry accepted method for a final hybrid package encapsulant is the use of polymer materials. Where extreme cold temperature survival is necessary, that is no less than -55° C, a flexible material such as RTV (Room Temperature Vulcanize) is used. Most RTV's undergo a ductile to brittle transition below -55° C, in addition the new brittle phase has a higher thermal contraction coefficient (2). There are newer RTV's which are ductile to -110° C but not -120° C. In addition to ductile/brittle transition there exists the problem of dimensional mismatch. Over the temperature range of MINX, with a ΔT of 200° C, the relay case and internal circuit Al_2O_3 changes size by 1.3 mils/in. and the RTV, 60 mils/in. The results of this dramatic difference is shown in Fig. 7. Some of the leads completely within the RTV have been pulled away from and broken off of internal circuit components. The pin-circuit leads projecting out of the RTV have been fatigued back and forth, some being broken. In addition RTV's are not generally considered as high voltage materials, having only 500 V/mil bulk breakdown strength.

It was necessary therefore to coat the relay interior with a high dielectric strength, clean, relatively thin film, that would survive the MINX environment. A vacuum deposited polymer, whose generic name is Parylene was chosen. This material was developed and is manufactured by Union Carbide Corp. The substrate to be coated need not be above room temperature, thus it presents no serious processing problems. Coating thickness and rate of deposit can be controlled such that as little as 0.007 mils or as great as 1 mil may be built up per minute. Parylene has a dielectric breakdown voltage of 5600 V/mil and can be deposited thin enough that it would not cause destructive physical stresses but still be dielectrically strong enough to provide the necessary voltage isolation. Two experimental design switches were coated with 0.8 mils of Parylene, requiring about 2 hrs time. This was in lieu of RTV encapsulation. After coating, the switches were replaced into the manufacturing cycle and mounted onto the experimental array which requires nine switches. The other seven array shorting switches were coated with RTV junction coating.

After two hundred 45-minute long cycles from -120° to 80° C only the 2 Parylene coated devices worked unimpaired. An X-ray of a Parylene coated switch is shown in Fig. 8. One RTV device still operated but was partially failed, while the remaining six were completely failed. All subsequently manufactured MINX design solid state relays have been coated inside with at least 0.7 mil Parylene, and have passed all environmental tests, especially thermal cycling.

X-ray photographs were made using film contact radiography. Film to tube distance was 18 in., radiation source was tungsten. G.A.F. 100, ultra fine grain film radiographs were enlarged with standard photographic equipment and 8x10 black and white prints made from the X-ray positives. Wire breakages in the 1 mil diam gold wire used for flying leads were clearly shown in these X-rays.

The MINX experimental switches were also evaluated for leakage and corona inception. Leakage currents were approximately 1 μA at 1800 V (typical) and corona inception was in the neighborhood of 1800 to 2000 V dc. Leakage was improved by more than an order of magnitude when compared with the Sterer SLS 2500 relay.

An unexpected problem occurred with testing under 1 AMO (the sun's intensity in mean earth's orbit) sun conditions. The output transistors had leakage currents up to 20 μA with 200 V across it. This was traced to photon transmission through the ceramic package and tests showed that the addition of a 0.015 in. thick cover of black Lexan would effectively block the light transmission and eliminate this problem. Black Lexan covers were fabricated and bonded with RTV to the ceramic case. This effectively eliminated the problem but caused a thermal problem with an absorptivity (α) of 0.8 and emissivity (ϵ) of 0.8. A silver backed Teflon tape was applied that provided an α of 0.1 and ϵ of 0.7. This thermal control lowered the 105° C expected temperature with black Lexan to 48° C.

<u>Flight MINX Switch</u>

<u>Layout</u>. - A photograph of the physical layout of the flight switches is shown in Fig. 6. The circuit approach is the same as the MINX switch so no further discussion is necessary. The switch in the photograph has not been Parylene coated so its construction can be seen clearly. When the transformer core is Parylene coated prior to winding, it is held by a small wire in the vacuum chamber, this causes the defect will be covered up when the final Parylene coating is applied to the inside of the switch. The substrates and the transformer are attached using nonconductive epoxy and minimum contact between the windings and the epoxy are maintained to minimize the possibility of leakage. In constructing the transformer, the largest possible core was used to increase physical separation between windings and at the time reduce the number of turns required thereby maximizing possible isolation. Also the transformer was optimally positioned and the highest voltage high temperature wire practical was utilized as well as the use of welding to secure the transformer leads. The new substrate layouts for the flight switch eliminated any unused circuitry and allowed for proper attachment of all components by conductive epoxy attachment to the substrates. In the experimental switches the relocation of the filter capacitor from the input to the output substrate forced it to be attached with nonconductive epoxy and wirebonds made from the capacitor to the circuitry, these wirebonds were one of the prime failures during the experimental switch environmental testing. Triple redundancy of all substrate to pin wiring is used.

<u>Test results</u>. - The flight switches were constructed in full conformance with MIL-STD-883 and performance verification (100 percent testing) was performed as specified in the MINX switch specification. Performance verification included temperature cycling, 10 cycles - 100° C to 80° C at a rate of 45 minutes maximum per cycle, Burn In 96 hrs at 80° C at normal load of 2 mA contact current with 15 V drive and finally a high pot test to insure a minimum of 1000 MΩ input to output isolation at 1800 V dc differential at 25° C. Contact voltage drop and contact leakage were recorded before and after each test and a 10 percent deviation of either voltage drop or leakage was considered a failure.

X-rays were taken of each flight MINX switch. A typical X-ray picture is shown in Fig. 9. No thermal cycling stresses can be seen and the improved layout and transformer winding is apparent.

In the flight units the Parylene coated cores and new layout demonstrated dramatic improvements in leakage and corona inception. Leakage currents measured with Hewlitt Packard high resistance meter (Model HP4329A) were less than 0.001 μA at 1000 V dc. This represents an isolation resistance of greater than 10^{12} Ω at 1000 V. No corona was detected in any flight units tested to 3000 V dc minimum. Two units were tested to breakdown and corona inception was observed in the 5.5 to 6.0 kV range. Breakdown occurred in the 7 to 8 kV region.

Two flight MINX switches were exposed to 1 MeV electron radiation to 10^{15} electrons/cm^2 dose. The input trigger level increased slightly and the output saturated voltage drop decreased slightly. Both of these trends are to be expected with reduced gain of the transistors. However, leakage remained less than 0.001 μA at 1000 V and no corona was detected to 3000 V dc as typically observed in all flight units.

At the time of this writing, no problems have been experienced with the flight MINX switches.

SLS 2500 Redesign

The production SLS 2500 was redesigned and physically relayed out as best possible maintaining the same pin configuration and electrical specifications to incorporate the desirable features proven through extensive testing of the MINX switch.

The new SLS 2500 layout is shown in photograph in Fig. 10. The windings were separated in the transformer, high voltage high temperature wire is used to wind it, the core is epoxy coated, the coil wires are attached by welding, and the coil is properly positioned between the input and output circuitry on the substrate. The utilization of these techniques increased the yield of SLS 2500's in production by lowering the number of units failed for lack of required isolation.

CONCLUSION

A hybrid microelectronics solid state relay was successfully developed in a TO-116 ceramic case for the MINX project that provides 2500 V dc input to output isolation. The relay was designed to operate in space and survive 1000 thermal cycles of -120° C to 80° C.

The use of enlarged pictures from X-rays for analysis of failed hybrid experimental units proved extremely valuable in evaluating RTV and Parylene coatings' stress due to thermal cycling. These pictures clearly showed cyclic stress on flying leads where differences between thermal expansion of materials was a problem. In addition sheared leads in failed units can be clearly observed. Vacuum deposited Parylene with its 5600 V/mil dielectric strength and ability to be applied in thin applications proved indispensable. Parylene was used to insulate the transformer core prior to winding and to coat the internal assembly prior to enclosing. With Parylene, thermal cycling from -120° C to 80° C appeared to be stress free primarily because the Parylene can be applied in uniform thin applications.

In this small package (TO-116 size) devices appear to be clean in corona up to 5000 V dc and the isolation built into the transformer appears to be as good as that inherent in the package itself.

Radiation degradation was not apparent in this design and the microelectronics solid state relay developed appears fully space qualified for the MINX experiment.

REFERENCES

(1) Plasma Reports:
   (a) W. Knauer, et al., "High Voltage Solar Array Study," Hughes Research Labs., NASA CR-72675, 1970.
   (b) W. F. Springgate, and H. Oman, "High Voltage Solar Array Study," The Boeing Co., D2-121734-1, NASA CR-72674, 1969.

(2) A. M. Solama, et al., "Stress Analysis and Design of Silicon Cell Arrays and Related Material Problems," Jet Propulsion Lab., Tech. Rep. 32-1557, Mar. 1, 1972.

TABLE I. - TRANSFORMER ISOLATION TESTS

[Leakage current in μA vs voltage stress]

	Voltage stress, V dc					
	500	1000	1500	2000	2500	3000
Leakage currents for:						
Old XFM'R - Uncoated	0.2 μA	0.6 μA	1.2 μA	1.9 μA	3.0 μA	5.0 μA
Old XFM'R - Urethane	<0.001	<0.001	<0.001	1.4	2.3	5.6
New XFM'R - Uncoated	0.1	0.38	0.9	2.0	3.5	6.0
New XFM'R - Urethane	<0.001	<0.001	<0.001	2.2	4.5	6.0
New XFM'R - Parylene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Old XFM'R - small core, 25:25:50 windings
New XFM'R - large core, 9:9:18 windings

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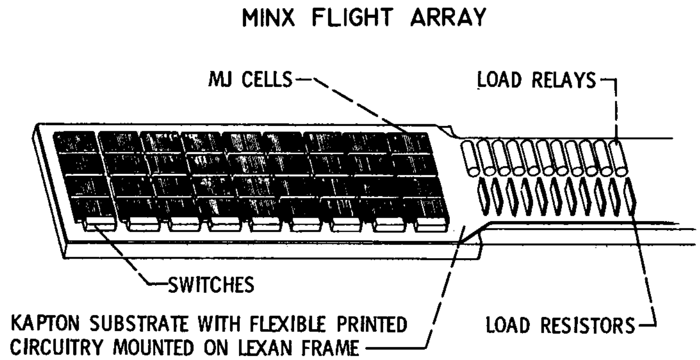

Figure 1. - MINX flight array. CS-66786

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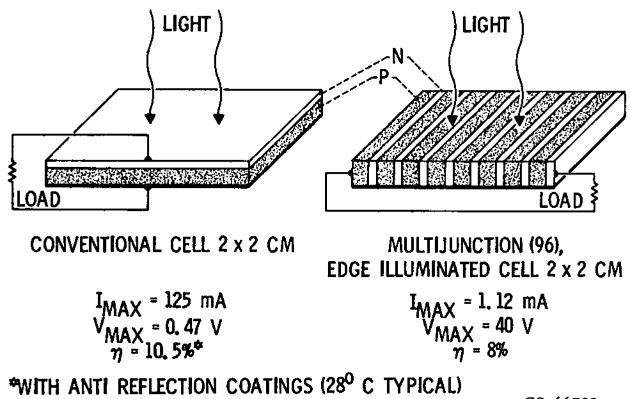

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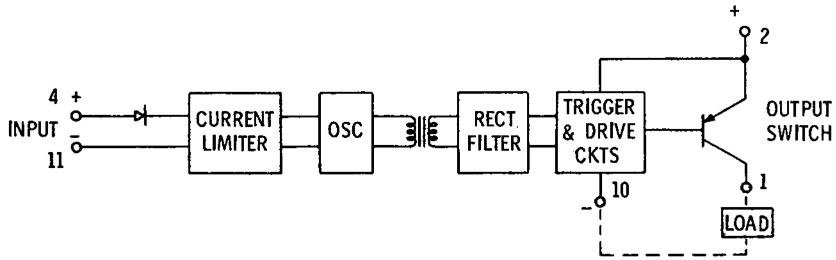
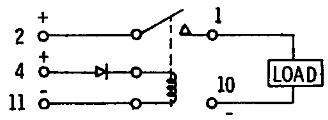
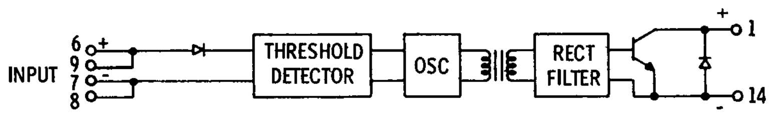
Figure 2. - Multiple junction edge illuminated solar cell.



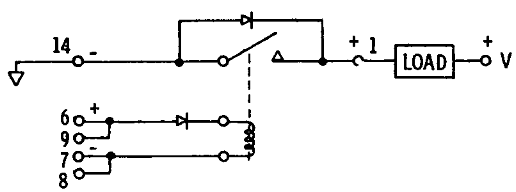
(a) SLS2500 BLOCK DIAGRAM



(b) SLS2500 EQUIVALENT DIAGRAM



(c) BLOCK DIAGRAM MINX SWITCH



(d) MINX SWITCH EQUIVALENT DIAGRAM

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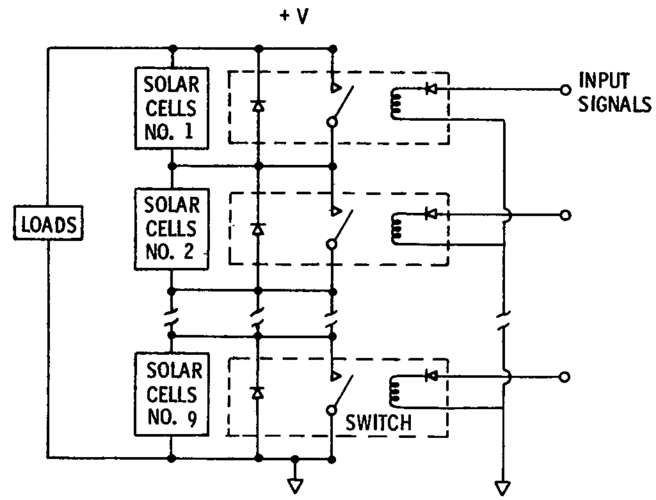
Figure 3.



(e) BLOCK DIAGRAM - SWITCH IN MINX APPLICATION

Figure 3. - Concluded.

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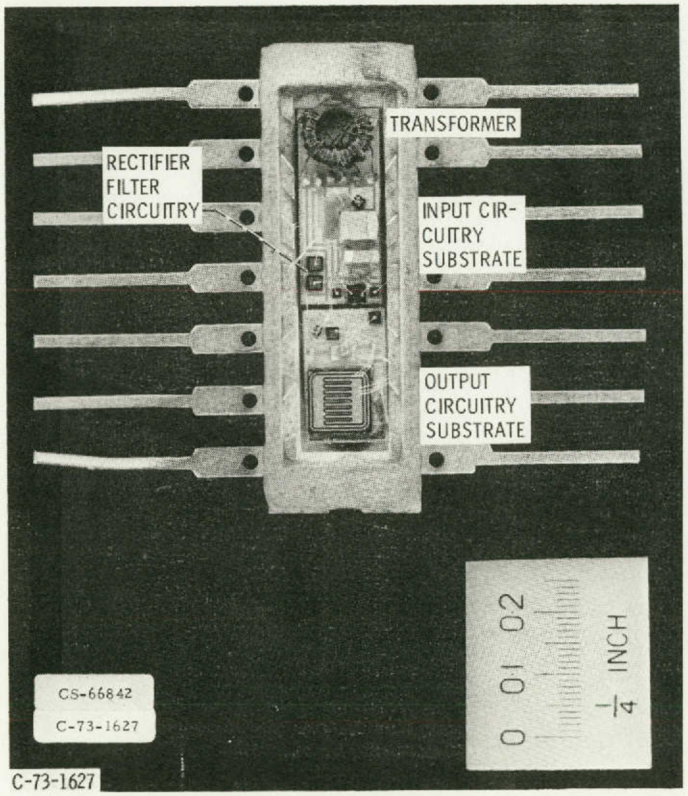

Figure 4. - SLS 2500 solid state relay.

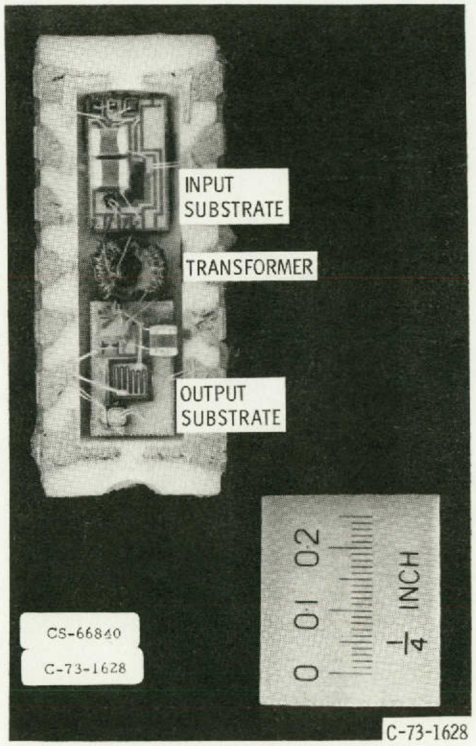

Figure 5. - MINX experimental switch.

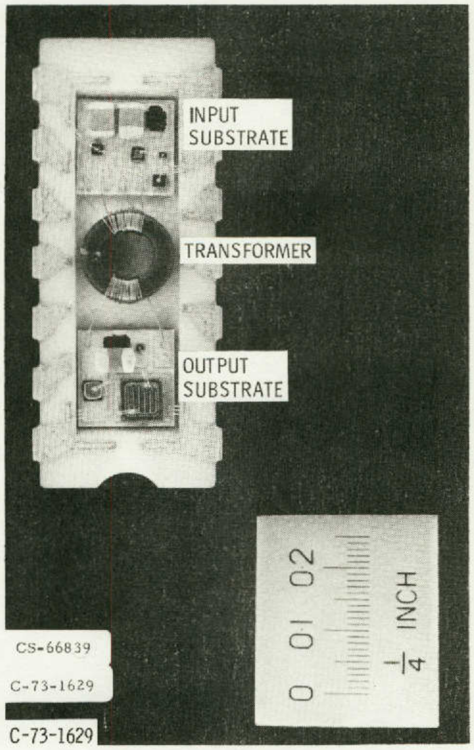

Figure 6. - MINX flight switch.

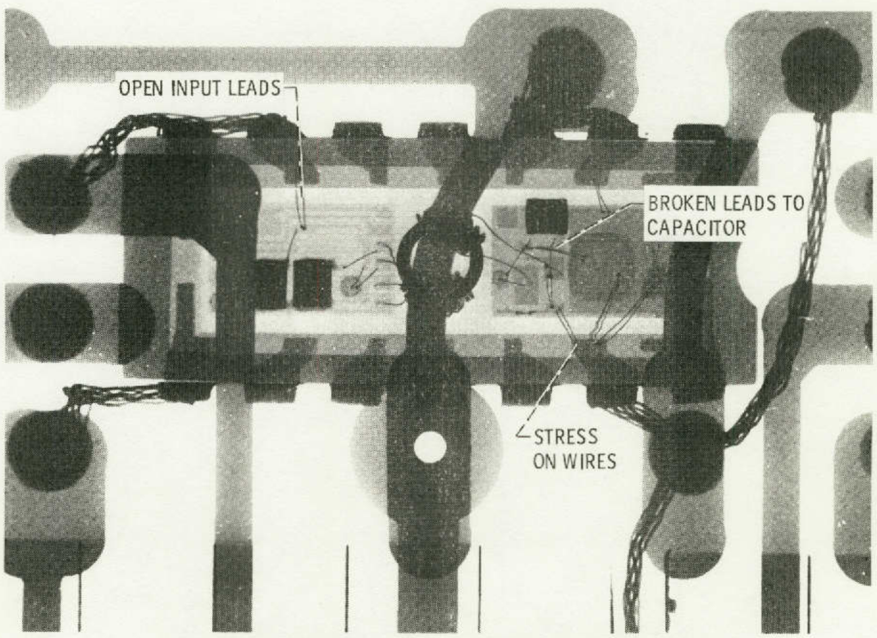

Figure 7. - X-ray of RTV experimental switch.

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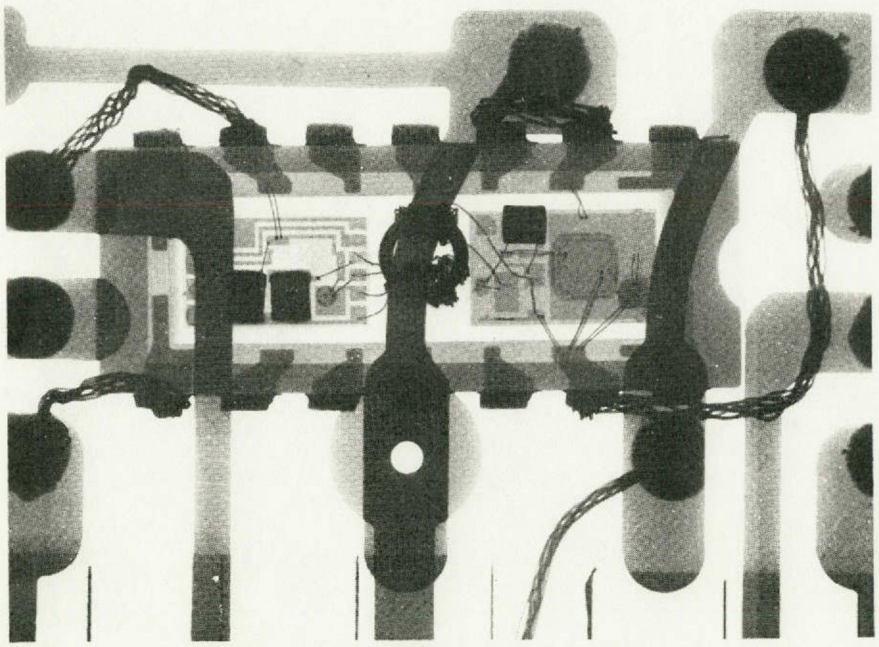

Figure 8. - X-ray of parylene experimental switch.

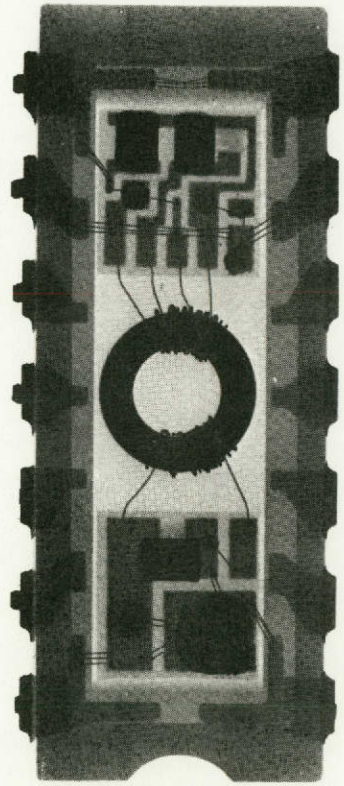

Figure 9. - X-ray flight switch.

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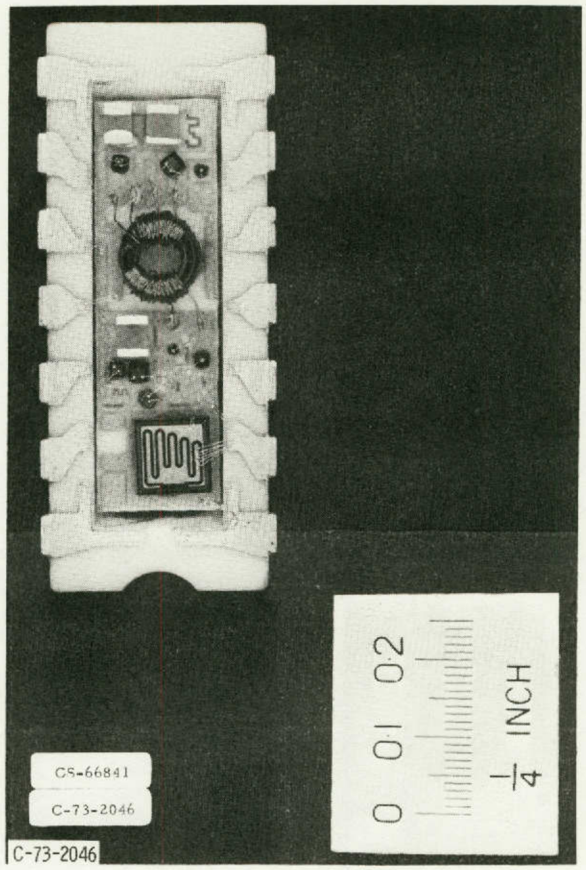

Figure 10. - New SLS 2500.