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Summary

This paper describes the design and fabrication of a 5000 volt isolated hybrid switch developed by Hughes Aircraft Company under contract to NASA/Lewis. Hughes did the packaging design and NASA did the circuit design. This unique microcircuit is intended for use as a shorting switch for large extraterrestrial solar cell arrays. The packaging design for the 5 kV isolated hybrid switch is different from most hybrid microcircuits in that it utilizes a compartmentalized plastic case (a portion of which is encapsulated), is not hermetic, and is designed for high voltage operation.

Introduction

The switching of isolated voltages is desirable in many circuit applications. As the voltage between the switching point and the control point increases, similar increases in the problems associated with the design of the switch device also occur. One application where such switching would be required is in the direct utilization of solar array power. Here, regulated power is delivered directly from the solar cell array to the loads. This approach eliminates the power processor with its attendant losses and offers the potential for a lighter weight, more efficient and more reliable power system. Since the output voltage of a solar array varies with temperature, cell degradation and load current, some means of regulating the array output voltage must be employed. One method of providing this regulation is to short out blocks of solar cells with a switch.

Several isolation and switching schemes were considered for the array. Isolation schemes considered included: magnetic coupling through an isolation transformer, mechanical arrays, and optical coupling through a light pipe isolator. It was determined that the optical technique offered the most advantages for the array application in terms of requirements such as size, weight, reliability and power consumption.

The resulting development was a 5 kV solid state switch employing optical couplers contained in a unique plastic package. Following are details of this device, including the description of the switching circuit, a summary of the package design, its construction, and a review of the evaluation results.

Switching Circuit

The switching circuit is unique in several aspects. These include:

- Self-latching such that a continuous signal is not required to hold it in either the "on" or "off" state.
- Positive switch control, having separate signal lines for "on" and "off" control rather than a single line with the first pulse during the switch "on" and the second identical pulse turning the switch "off".
- Self-protecting such that current surges which may occur during load transients will not cause switch failure.
- Electrical isolation from input signals so that supplies which float at high potentials can be regulated.

The circuit is shown in Figure 1.

The switch is turned on by providing a current pulse to LED D1. The light output from D1 activates transistor Q1 allowing Q3 to turn "on", thereby providing base drive to Q4. Once Q4 reaches saturation, the path through D3 provides a latch to hold the switch "on". The voltage at which the power supply will operate is the sum of the emitter-base drop of Q3, the drop across D3 and the collector-emitter drop of Q4.

To turn the switch "off", a current pulse is provided to LED D2. The light output from D2 activates Q2 allowing Q5 to turn "on". Q5 then shorts out the base drive to Q4 turning the switch "off".

The optical paths between the LEDs D1 and D2 and their respective transistors Q1 and Q2 provide the electrical isolation between the control signals and the rest of the circuit. Other than for diodes D1 and D2, the entire circuit including its power source floats at the supply potential.

When solar cells are used as the power supply, their characteristics are used to provide protection for Q4 during transient conditions. As the current through Q4 increases, its V_{ce} will also increase driving the operating voltage of the switch power supply up toward the knee of the curve. As the operating point moves around the knee, the base drive current to Q4 starts to decrease, further increasing V_{ce} of Q4. Eventually the power supply is no longer capable of providing enough voltage to maintain current through the latch leg and Q3 is turned "off" which in turn shuts off Q4. If the voltage of the switch power supply is sized properly, this turn-off will start to occur before Q4 has pulled out of saturation. This prevents the situation from occurring where Q4 could operate for long time periods in a non-saturated condition.

The diodes D4 and D5 are used to prevent false turn-on in the switch due to transients, while R and C across the emitter-to-base junction of Q3 are used to put a slight delay in the turn on.

This circuit, while not universally applicable to all switching requirements, is aptly suited for solar array switching.

Package Design and Construction

The design of the package was determined by both the switch design and the functional requirements of the assembly. The switch design provided for an all solid state construction, while the functional and environmental requirements included:

- Switch activation by a single pulse of 10 mA of 50 micro-second duration.
- Switching capability for 200 vdc at 400 mA.
- Forward voltage drop at Q4 of 0.2V or less at 400 mA.

- High voltage isolation between LEDs and switch of 5 kVdc.
- Illuminating at one-half (1/2) and one (1) sun (equivalent to 70 and 140 mW/cm^2) without changes in output leakage current at maximum bias or in LED activation characteristics.
- Isolation resistance, input to output, of 10^{11} ohms or greater at 3 kVdc.
- Operating temperature range of 0° to 80°C (273°K to 353°K), at maximum rated voltage with storage to -55°C (218°K).
- Operating pressures of one (1) atmosphere (1.01 bars) and 1 x 10^{-6} torr (1.3 x 10^{-4} Nm^{-2}) at maximum rated voltage.

The resulting design was an all plastic package incorporating the requirements for both a high voltage assembly as well as those for a hybrid solid state device. The package is shown in Figure 2.

The design employed an encapsulated optical coupler section and a hollow configuration for the hybrid switching circuit. The encapsulated couplers provide the maximum voltage stand-off capability, while the unencapsulated hybrid section provides a design compatible with hybrid construction. The absence of an encapsulant in this section eliminates undue thermo-mechanical stressing of the hybrid, permits repair of the hybrid, and reduces the overall weight of the assembly.

The package resulting from the design has dimensions of 1.565 x 0.656 x 0.300 inches or 1.55 cm x 1.18 cm x 0.06 cm (length-input to output, width and height), and weighs 6.2 grams for a package density of 1.21 grams per cubic centimeter (0.04 pound per cubic inch). The size of the package was determined in part by the commercial optical couplers used in the assembly.

Following is a summary of the materials, components and general fabrication format used to produce the switch.

Materials

Two basic materials were used in the construction of the package. Both were epoxy resins, one a rigid compound for the case and cover, the other a flexibilized material as the coupler encapsulant.

The case material was composed of a diglycidyl ether of bisphenol A coreacted with an aromatic — heterocyclic amine mixture. Carbon black was added to the formulation to achieve optical opacity. Using this formulation, the cases and covers were vacuum cast. The products were void-free optically-opaque structures having moderate impact properties and capable of service at temperatures in excess of 120°C (393°K). Dielectrically, the properties of the case exceeded both the resistance and critical field strength requirements for the assembly.

The coupler encapsulant was a modification of the case-cover material employing in addition a flexibilizing agent, a diglycidyl ether of an aliphatic diacid ester. This modification was made to:

- Improve adhesion to the polyacetal case of the coupler.
- Improve the coefficient of thermal expansion match with the acetal material.
- Reduce the surface tension and viscosity in the liquid phase.

Improved adhesion and thermal expansion matching are important to the high voltage integrity of the assembly to eliminate interfacial separations which can become sites of electrical discharge.

The reduced surface tension and viscosity were necessary to produce a liquid phase system which yielded a void-free product when injected into the package at atmospheric pressure without benefit of vacuum cycling. Vacuum processing was eliminated because of problems associated with the coupler package.

The product resulting was a semi-rigid, void-free, optically opaque material whose dielectric properties exceeded the requirement for this application. The encapsulant resin and a primary aliphatic amine was used as the adhesive for bonding the cover to the case.

Components

The components used in the switching circuit were all discrete chip devices of commercial quality. Of the ten components used, three posed some prob[illegible] — the two optical couplers and the output transistor, Q4.

The optical couplers consisted of an LED and a photo transistor optically-coupled through a polycarbonate light pipe which also functioned as the primary high voltage isolator. This assembly was then contained in a polyacetal package formed by bonding two preformed segments. The problem encountered centered on the package construction. The problems resulted from a physical leakage path for the encapsulant into the optical path of some devices. When such leakage occurred the transfer ratio of the device (ratio of output to input current) would be lowered and the device would fail to meet the specified 10 percent requirement. Alternately, if the lead exit areas were not encapsulated the partial discharge voltage would be lowered due to the air inclusions. The solution to the problem was to accept the attrition resulting from either effect and to use those commercial parts which passed both preliminary screening for the high voltage and transfer ratio characteristics as well as similar testing after encapsulation. For the manufacturing run, the losses were due almost entirely to low transfer ratio since the encapsulant and the encapsulating process had been specially designed to achieve maximum penetration and fill which would result in the presence of the encapsulant in the optical region if leakage paths were present.

Problems encountered with the output transistor, Q4, centered on the combined requirements for a low saturation voltage and a high reverse bias breakdown voltage. Increasing the saturation voltage alters the switching response and increases the power dissipation within the switching circuit, while a reduction in the reverse breakdown voltage reduces the safety margin for the switching voltage. To meet both requirements for this component required individual selection of devices to be used in this assembly. The use of commercial components including the optical couplers contributed significantly to the final package size. The development of custom components, particularly the couplers, could reduce the package size

30-50 percent while maintaining the 5 kV isolation capability.

The components including the case and cover as well as a partially completed assembly are shown in Figure 3.

Fabrication

The fabrication techniques employed for the switches were those generally used in hybrid and high voltage construction. The primary exception was in the coupler high voltage encapsulation which was done at atmospheric pressure, as previously noted. Figure 4 is a flow diagram summarizing the fabrication and test sequence used in the switch construction while Figure 5 presents a pictorial review of the switch at various stages of assembly.

Evaluation

The evaluation centered on establishing the high voltage characteristics of the package containing the encapsulated couplers. In addition, preliminary tests were performed on the unencapsulated couplers to establish their suitability for this application. The parameters used to assess the performance were the electrical discharge potential and the leakage current. The conditions used in the evaluation included thermal and vacuum cycling in addition to room ambient determinations.

The initial evaluation was made on the unencapsulated couplers to determine the suitability of these commercial devices as the primary high voltage isolating element. Tests were conducted at room ambient conditions. The evaluation involved the determination of the partial discharge (corona) inception voltage both in air and in Freon TF. The current-voltage properties were also determined as a further indicator of the high-voltage behavior. These tests were made in air. The discharge determinations were made using a detector capable of sensing a charge of one (1) picocoulomb and low ripple, low noise dc high voltage power supply. The test apparatus is shown in Figure 6.

Leakage currents were measured with the power supply used in the discharge determinations substituting a picoammeter (HP 425A or equivalent) for the 100 K resistors and oscilloscope.

The results of the partial discharge and leakage current determinations are summarized in Tables 1 and 2. These results demonstrate the range displayed by four test samples, conditioned 100 hours at 22°C (295°K) and 50 percent RH prior to testing.

The test results in air and Freon show the devices to have discharge inception voltages equal to or greater than the maximum operating voltage of the switch. It should be noted here that it was the objective in developing the switch, but not a requirement, to build a device which was free from any high voltage related electrical discharge phenomena. This achievement will maximize the life of the assembly.

The Freon results show that with a liquid dielectric displacing air the inception voltage is increased. This result suggests that the discharge sites are within the coupler package. If the leads were the cause then all of the packages would show nominally the same inception voltage in air, barring some major internal defect. The increased discharge inception voltage noted in Freon should also be present with a solid encapsulant assuming the encapsulant penetrated the device and adhered to the materials. However, since the encapsulant has a higher surface tension, the penetration would be less. But even with reduced penetration the inception voltage should not be less than that of the unencapsulated coupler, in air, and probably will be higher. If the encapsulated voltages were lower it would indicate an interface separation or similar defect in the encapsulant. The postulated improvement for encapsulated couplers was verified in the encapsulant evaluation and in the manufacturing run. The resistance measurements show the unencapsulated couplers to exceed the design requirement of 1×10^{11} ohms over the operating voltage range with the devices showing a nominal resistance of 1×10^{14} ohms at 5 kV. This result indicated that the couplers could be used as-packaged without concern for shunting resistance effects due to the coupler and its package.

Table 1. Partial Discharge Inception Voltages for Unencapsulated Optical Couplers

Device	Partial Discharge Inception Voltage (k Vdc)	
	Air at 1 Atmosphere	Freon TF
No. 1	5	6
No. 2	7	>10
No. 3	8	>10
No. 4	5	8

Table 2. Typical Voltage Resistance for Unencapsulated Optical Couplers

Applied Voltage, k Vdc	Leakage Current $\times 10^{-12}$ amps	Resistance $\times 10^{14}$ ohms
1.0	2	5
3.0	10	3
5.0	40	1

Having established the usability of the commercially package coupler as a component, the next investigation involved determinations of the high voltage characteristics of the encapsulated couplers within the case. The case materials and the encapsulant were the carbon-filled epoxies previously mentioned.

Two encapsulated couplers were used in this series of evaluations. Each was separately encapsulated in an individual case. It should also be noted that the assemblies (case and encapsulated coupler) were tested without covers.

The results of coupler encapsulation are summarized in Tables 3 and 4. The increased values for the partial discharge voltages in air indicates some penetration of the encapsulant into discharge sites within the coupler package. That these increases are due to lead discharges and the increases are due simply to increased lead separation is not indicated based on the previous measurements of the couplers separately. See Table 1. While there appears to have been some encapsulant penetration into the coupler package, the penetration was not complete as evidenced by the

Table 3. Partial Discharge Properties Resulting from Encapsulation

Assembly	Partial Discharge Inception Voltage (kVdc)	
	Air at 1 Atmosphere	Freon TF
Before Encapsulation:		
Coupler No. 1	5	6
Coupler No. 4	5	8
After Encapsulation:		
Coupler No. 1	6	6
Coupler No. 4	7	8

Table 4. Voltage-Resistance Characteristics for Encapsulated Optical Couplers

Applied Voltage (kVdc)	Leakage Current x 10^{-12} amperes	Resistance x 10^{12} ohms
1	50	20
3	500	6
5	1000	5

discharge values when immersed in Freon. It was not expected that these values would be greater for the encapsulated couplers since the encapsulant with its higher surface tension was not predicted to penetrate cracks and separations as well as the Freon. The resistances of the encapsulated couplers as shown in Table 4 are less than the unencapsulated devices but approximately 50 times greater than the design objective. It should be noted that on the initial manufactured units significant variations in resistance were encountered ranging from 10^9 to 10^{14} ohms. The problem was in the encapsulant and associated with the carbon filler. When this problem was solved the unit resistance values were greater than 10^{14} ohms. The results at this point indicated that the commercially packaged coupler could be encapsulated without the benefits of vacuum processing to produce an assembly which had equivalent or superior high voltage characteristics. Further, the results demonstrated that the objective of a discharge free device could be achieved using the materials, processing techniques and package design and that this combination would exceed the isolation resistance requirements.

Two encapsulated couplers were used in this series of evaluations. Each was separately encapsulated in individual cases. It should also be noted that the assemblies (case and encapsulated coupler) were tested without covers.

Next, the two devices were subjected to thermal cycling. These tests were conducted to determine whether defects could be generated due to thermo-mechanical stressing which would impair the high voltage performance or optical coupling capabilities of the assembly. Defects capable of affecting the function include crack generation, interfacial separations, and lead breakage. Initially, the two assemblies were cycled from room temperature to -60°C (213°K). After 8 cycles the partial discharge voltages were remeasured. The devices were then cycled from +85°C (358°K) to -60°C (213°K) with rates and soak periods as previously noted. After 15 such cycles, the partial discharges were redetermined. The results are given in Table 5. The absence of any significant change in the discharge inception voltage after either cycle indicates the absence of thermo-mechanical activity which would alter the performance of the assembly. It can be noted that the optical transfer ratios remained unchanged through these cycles further substantiating the absence of mechanical degradation.

Next, the two assemblies were subjected to vacuum conditions. The purpose of this test was to determine whether gas diffusion from the inclusions within the coupler resulted in a lowering of the partial discharge voltage (i.e., would a Paschen-type phenomenon occur within the assembly, and if occurring what time constants would be associated with the development and disappearance of the reduced voltage). It should be noted that the two couplers used in these encapsulant studies were specifically selected because of the presence of gaseous inclusions as evidenced by the initial discharge tests in Freon. Thus, if Paschen phenomena were possible it should be noted for these devices. In these tests, devices were measured initially in air at one atmosphere (1.01 bars), and then 30 minutes after the start of the vacuum cycle. After 30 minutes there was an external discharge between the high voltage leads of the assembly and the vacuum chamber. Reference is made to Table 6. When the chamber pressure reached 1×10^{-5} torr, the external discharge had extinguished and the discharge characteristics noted for the devices were similar to the one atmosphere (1.01 bars) air value both in terms of inception voltage and change transfer. These characteristics were maintained throughout the 160 hours of the test. When repressurized to one atmosphere on completion of the vacuum cycle, no significant difference in the discharge behavior was observable.

These results indicate that the gas diffusion both through the bulk materials and along the interface regions is occurring at a very slow rate. That the gas inclusions were not evacuated is evidenced by the same discharge characteristics at the reduced pressure as was evidenced at one atmosphere. If the inclusions had been evacuated to the nominal system pressure, the discharge inception voltage should have been detectably higher under the vacuum than at one (1) atmosphere.

Discussion

In developing the switch design, the objectives were minimum size and a construction which would achieve the required high voltage performance, but would not compromise the behavior of the hybrid switching circuit. Several designs were considered including an all-solid, completely encapsulated construction and a hermetically sealed, unencapsulated pressurized gas package.

The plastic package was selected in preference to a ceramic-metal or all-ceramic package primarily because of the high voltage requirements. The metal-ceramic would not, for an equivalent size, provide the necessary high voltage isolation lacking the effective surface separation.

While an all-ceramic package would provide the necessary surface separation for the required

Table 5. Effects of Thermal Cycling on the Partial Discharge Voltage of Encapsulated Optical Couplers

Assembly	Number of Cycles	Cycle Range	Partial Discharge Voltage, kVdc*	
			Air at 1 Atmosphere	Freon
No. 1	0	-	6	6
No. 4	0	-	7	8
No. 1	8	-60° to +30°C	6	6
No. 4	8	-60° to +30°C	7	8
No. 1	15	-60° to +85°C	6	6
No. 4	15	-60° to +85°C	7	8

*Measured at room temperature

Table 6. Effects of Vacuum Exposure on the Partial Discharge Characteristics of Encapsulated Optical Coupler

Assembly	Time, Hours	Pressure, Torr	Partial Discharge Voltage, kVdc
No. 1	0	760	6
No. 4	0	760	7
No. 1	0.5	1×10^{-5}	6*
No. 4	0.5	1×10^{-5}	6*
No. 1	100	1×10^{-5}	6
No. 4	100	1×10^{-5}	8
No. 1	160	1×10^{-5}	6
No. 4	160	1×10^{-5}	8
No. 1	0.5	760	6
No. 4	0.5	760	7

*External glow discharge emanating from HV leads

voltage isolation, problems do exist for an encapsulated ceramic assembly. The problem centers on the thermo-mechanical stresses which could exist between the ceramic, the encapsulant and the optical coupler assemblies. The presence of such stresses could cause mechanical defects which would lead to electrical failure. The plastic package provides both the required dielectric surface separation to prevent both flashover and tracking and the minimal thermo-mechanical stress to eliminate internal defects which become electrical discharge sites leading ultimately to failure. The plastic assembly also weighs less than the other two constructions.

General limitations for the plastic package are reduced power dissipation capability and the absence of a hermetically sealed hybrid section. The low total power dissipation of the switching circuit did not pose a limitation for the plastic in this application. Hermeticity in a high voltage hybrid assembly is important in two aspects. First, the gas permeability of the plastic structure can lead to deterioration of the hybrid circuit under certain environments. Secondly, under vacuum the reduction in pressure due to gas effusion could result in a critical pressure condition and the initiation of a discharge within the hybrid cavity which is "floating" at the high voltage. Such discharges would at least impair the operation of the circuit and could produce catastrophic effects for the device. For the intended application neither aspect of hermeticity has been shown to be a problem. However, before the devices were subjected to continuous vacuum exposure additional tests would be required to determine precisely the gas diffusion rates and the possible occurrence of the Paschen phenomenon.

In this design, the basic high voltage isolation is achieved by the optical coupler dielectric and the coupler encapsulant. For this package the maximum electrical stresses occur along the major axis of the package in the coupler-encapsulant section.

The electrical stresses in both the region below the couplers and beneath the hybrid substrate are maintained at sufficiently low levels such as to preclude discharge initiation if a ground plane were placed along the base of the switch. Stresses in the hybrid section must be maintained below the critical field stress of the cavity gas to prevent electrical discharge or arcing which would alter the switch function. The present design does not require operating with a ground plane adjacent to the base. If this were required, it would necessitate relocation and/or redesign of the output leads to provide adequate surface separation to prevent flashover or tracking. In the present design, the surface isolation between the low voltage (input) and high voltage (output) terminals is achieved by the plastic package. Because of the package size and the maximum operating voltage these surface stresses are well below the critical field stresses at normal atmospheric conditions and for the high vacuum environments.

It should be noted that the relatively large package size is due primarily to the use of commercial components and not to the dielectric surface separation requirements. For the 5 kV operating voltage required of the switch, the package length (distance between the high and low voltage terminals) could be reduced by 40 to 50 percent. To achieve this reduction would require development of custom components including the optical coupler assembly. Similarly, with an improved optical coupler assembly, and minor changes, the present package would be usable at 12 to 15 kV.

Conclusions

Based on the development and evaluations the following conclusions are made for the 5 kV switch:

- The all-plastic design which employed concepts of both high voltage construction and hybrid technology achieved all design objectives for both high voltage isolation and switching performance.

- The construction materials for the package, namely the case material and the coupler encapsulant, both epoxy compounds, combined with the design and the optical couplers, were integral elements in meeting the discharge and isolating resistance design goals. The suitability of these materials was demonstrated by the unchanged high voltage performance of the assembly when subjected to temperature and vacuum cycling.

It should be noted that while the current design performance exceeded the design requirements under vacuum, the long behavior (i.e., months or years of continued exposure) has not been established. Relevant to the success of the construction materials was the use of a carbon filler which, while initially presenting problems in variable resistances, was satisfactorily incorporated using special processing to yield a product having a high discharge inception voltage, isolating resistances and optical opacity.

A significant aspect of the switch is the high voltage characteristics with the maximum operating voltage and operating life dependent on the discharge inception voltage. Although the switch design requirement stated only that the switch have a voltage stand-off capability of 5 kV, the design objective was a partial discharge inception voltage equal to or greater than 5 kV. This objective, which was achieved, will result in a device having maximum life at the maximum operating voltage and increases the survivability to transient voltage surges. The study demonstrated the adequacy of the commercial optical couplers. While the overall package size could have been somewhat reduced by a custom designed coupler, the commercial parts performed satisfactorily when properly encapsulated. Circuit tests of the switch showed all of the requirements were met or exceeded including the photo sensitivity response, switching voltage and optical coupling characteristics. The circuit resulted in low power dissipation which is compatible with the package construction and the performance parameters are compatible with the switching requirements of a high voltage solar cell array.

Acknowledgement

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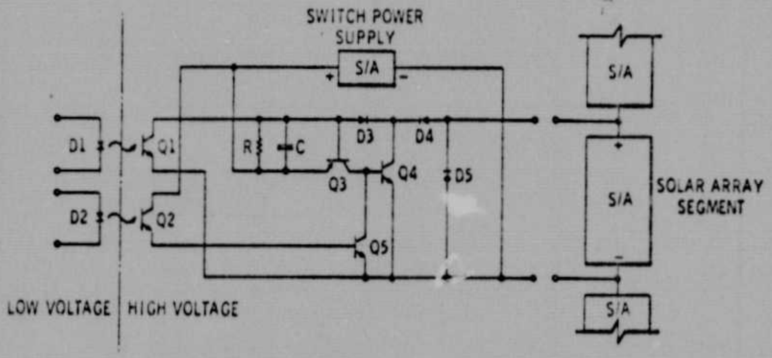

Figure 1. Schematic diagram of the switch circuit.

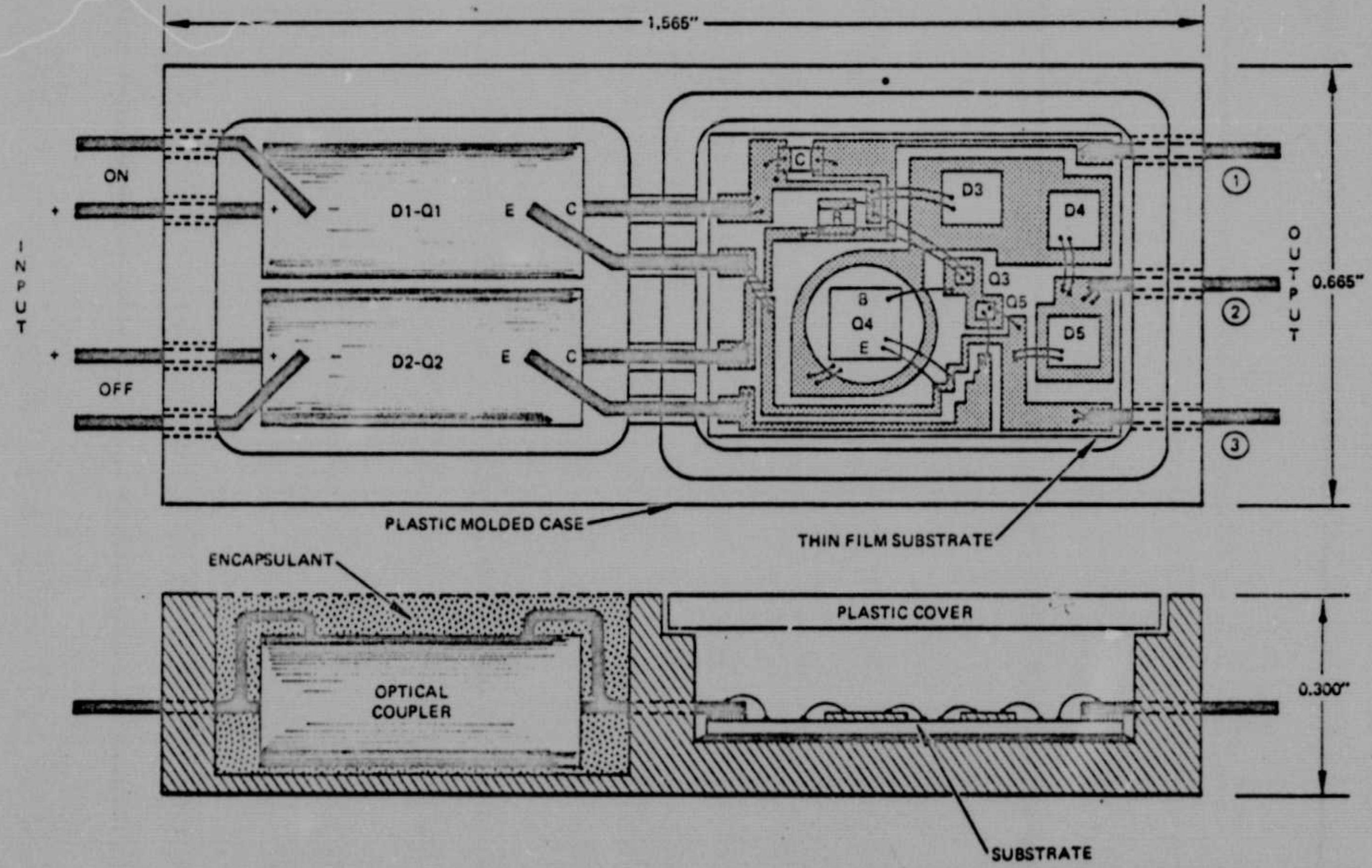

Figure 2. Sketch of packaging design for the 5 kV isolated hybrid switch.

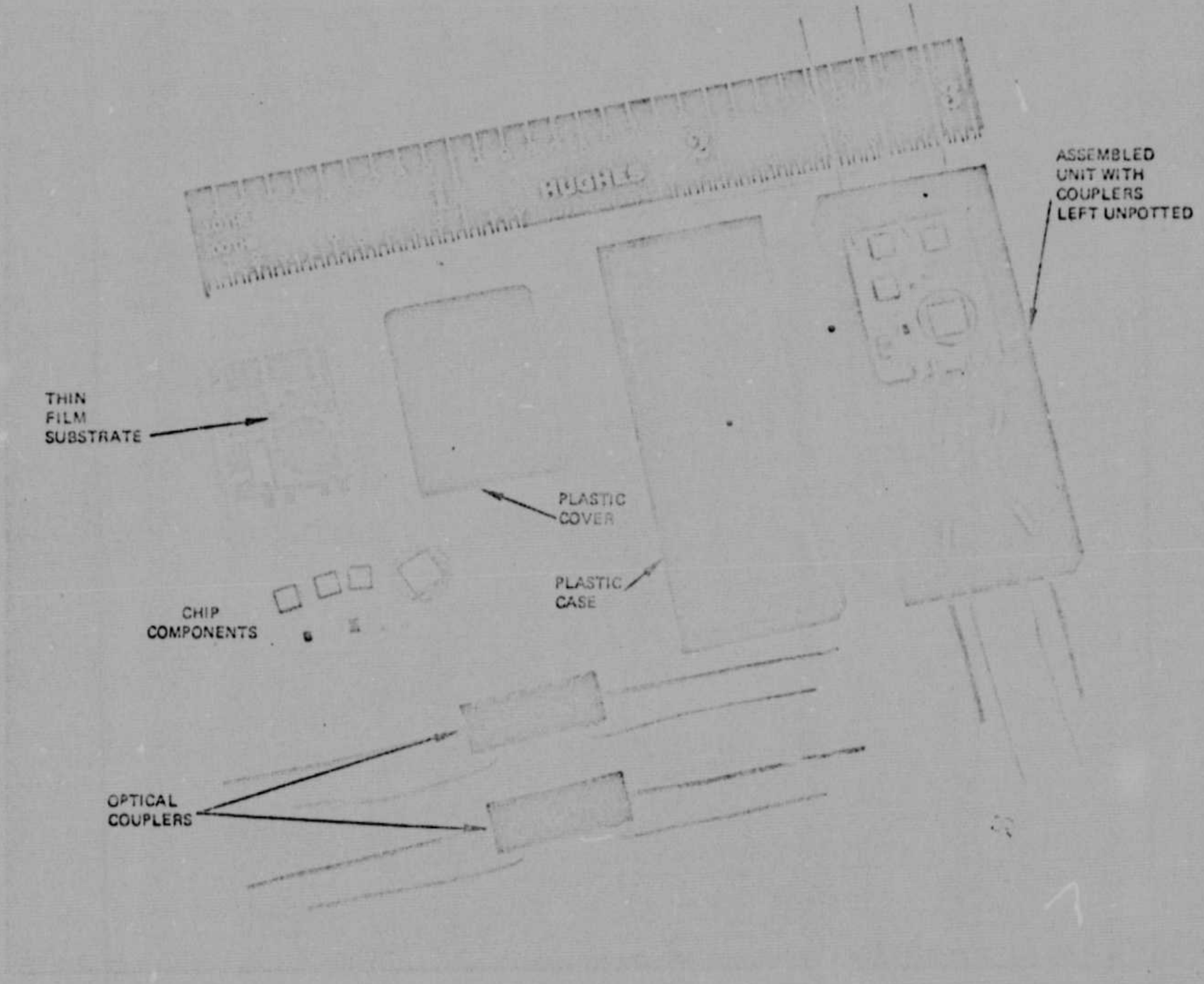

Figure 3. Various parts making up a 5 kV isolated hybrid switch.

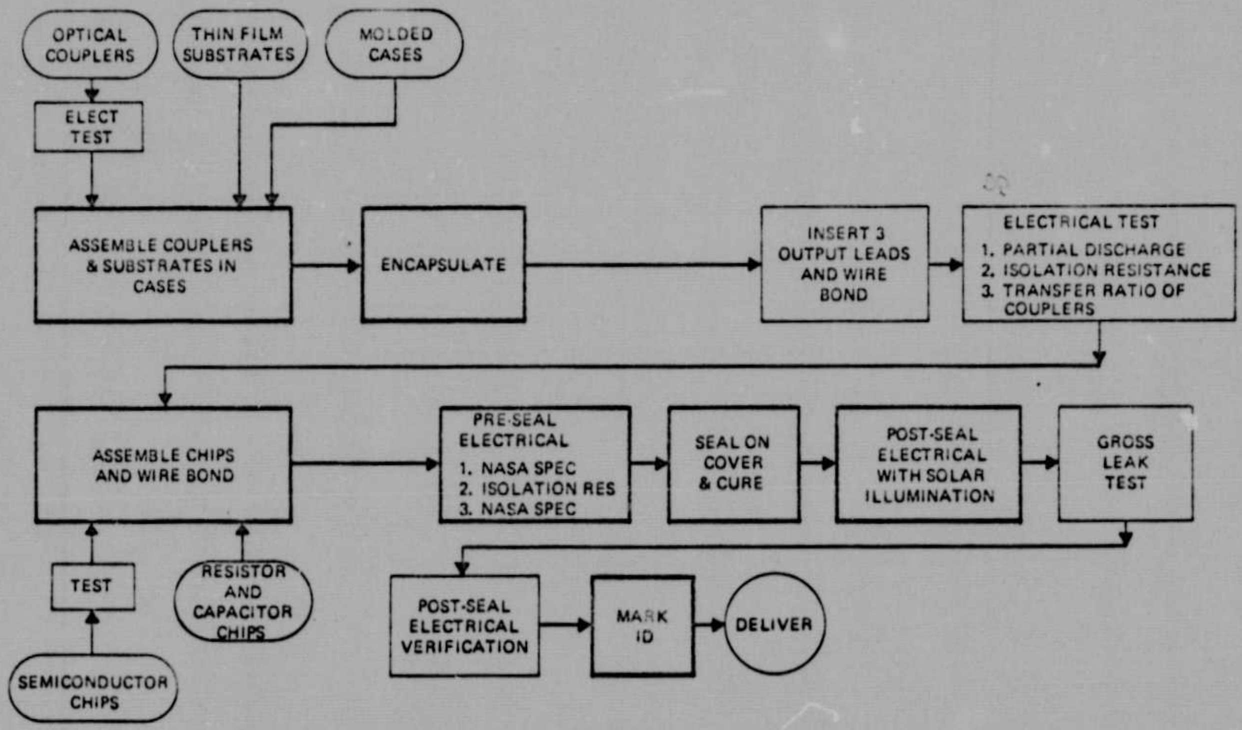

Figure 4. Flow chart showing fabrication of the hybrid switch.

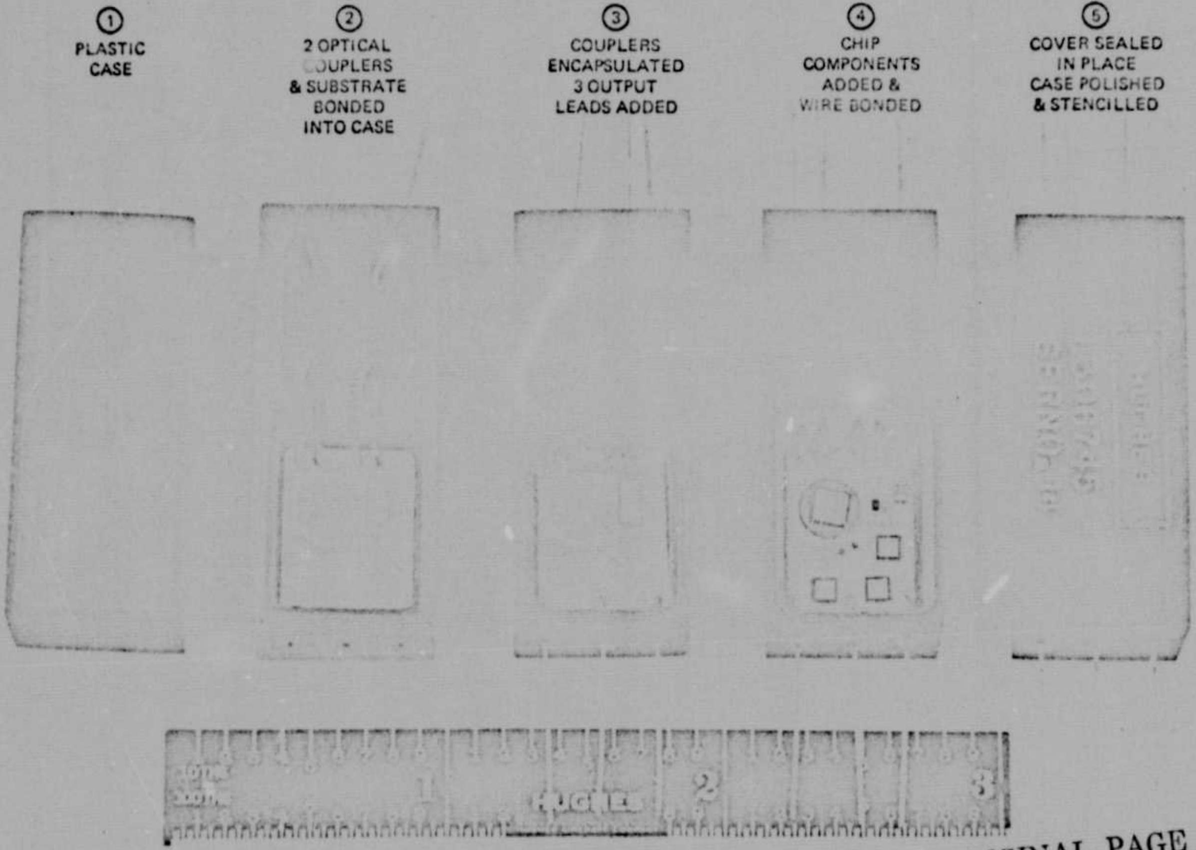

Figure 5. Hybrid switch at various stages in the fabrication process.

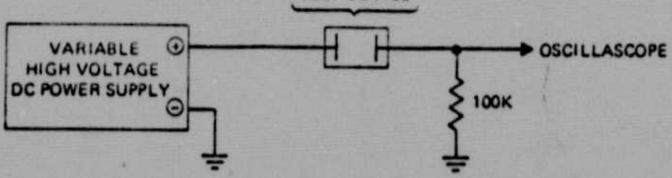

Figure 6. Test arrangement for partial discharge determinations.