# SOLID STATE BISTABLE POWER SWITCH

# STUDY

By Herman Shulman and John Bartko

August, 1968

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NUCLEAR SYSTEMS DIVISION
ISOTOPES
Baltimore, Maryland

Electronics Research Center

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FINAL REPORT

SOLID STATE BISTABLE POWER SWITCH STUDY



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## SUMMARY

The purpose of this program was to determine the feasibility of transforming an in-house developed device, the Diristor, into a resettable fuse for high current applications. The device is a metal-impregnated organic insulator into which two electrodes are introduced. A high electrical current switches the device from "on" to "off," while "reset" is accomplished by momentary application of a large voltage.

To meet the objectives of this program, many individual tests were run. In each test, a compositional parameter was varied and its effect on device operational parameters such as trip current, reset voltage, spread in trip currents and longevity were noted. The following compositional parameters have been varied: the metal particles, particle size, matrix material, metal/matrix ratio by volume, electrode size, electrode separation, electrode material, device design. It has been found that the device is capable of carrying and tripping at high currents, i.e., $\sim$3 amp, if large metal particles ($\sim$ 20 mesh) are used; the metal used must possess a coefficient of thermal expansion equal to or greater than that of copper, and the average trip current is a function of the size of the particles. The matrix material plays an important role in the device operation, and only materials possessing fairly well defined parameters will be successful. For each matrix material there exists a range of mixture ratios which will provide optimum performance, while device parameters, such as average trip current and reset voltages, can be adjusted by choice of suitable mixture ratio. The electrode material has little or no bearing on the device operation or its parameters, while an increase in the width of the electrodes will result in a narrower distribution of trip currents. The average trip current is inversely related to the electrode separation while the reset voltage is directly related to the separation. A suitable design for the device must allow for the expansion of the ingredients. The transformation of the diristor to a high-current device appears feasible. Much information has been obtained for the further development of this device, including possible directions for this effort.

## INTRODUCTION

Diristor is the name given to a device whose essential components is a metal-impregnated organic insulator, into which there are inserted two metal electrodes with lead wires. The d.c. resistance of the diristor, as measured between electrodes, can be switched between two stable states, designated as "on" (low resistance) and "off" by the following means. When a current that is in excess of the rated "trip" current is passed through a device that is in the on state, it rapidly switches ("trips") into the high-resistance state. In order to "re-set" into the low resistance state, a voltage, in excess of the minimum reset-voltage, is momentarily applied between the electrodes. Of course, during reset, a resistor must be inserted between the power supply and the Diristor to limit the on current to a value less than that for trip. The device indefinitely remains in the state into which it was last switched, and, thus, has the characteristics of a bi-stable relay.

During early investigations, it was found that the on state is perfectly ohmic in every sense; the relationship between applied voltage and current is linear and bipolar for currents between $10^{-10}$ Amp (the lower limit of the ammeter on which the measurements were made) and the trip current (typically 100 mAmp for some early devices). Moreover, both trip current and reset voltage are bi-directional, so that there is no preference for polarity, at any time, for either electrode.

It was also observed during the earliest investigations that the on resistance after reset for any single device may differ substantially from its values after other resets. A systematic study of this phenomeonon revealed that the reciprocal of the resistance, conductance, was always almost exactly an integer multiple of a base value. This strongly suggests that conduction does not take place throughout the bulk of the device, but is constrained along a set of fairly identical parallel paths; and that, moreover, the resetting of the paths usually does not proceed with maximal efficiency. Some hypotheses on the fundamental mechanisms(s) responsible for the actions of the Diristor are reported in the appendix to this document.

Potential applications for the Diristor include, among others, logic elements, computer, memory elements, oscillators, and resettable fuses. Initial applications work centered on uses in computer circuitry and was concerned with design parameters for a device that would switch faster than a microsecond and trip with low currents (milliamperes). The purpose of this three-month program was to study the feasibility of developing a high-current (amperes) tripping device that could be used as a resettable fuse. Included was a study of the effects of variations in compositional parameters of the device which can be of use in further developmental work.

This document is the final report for the program. It includes, with significant elaboration, the material documented in earlier monthly reports, as well as additional material not reported previously.

# EXPERIMENTAL PROCEDURE

Two circuits were used for all the device testing; one will be designated "the slow-trip test circuit" and the second "the fast-trip test circuit." These circuits, and their use, will be described below, following which the motivations for the device - parameter variations will be delineated.

## Circuits

A simple test circuit was devised to test devices conveniently and rapidly. This is shown in Fig. 1. The circuit essentially consists of two separate circuits, which are designated A and B. The Diristor can be switched into either one by means of the mercury switch Sl. Circuit A is the reset circuit characterized by a high voltage (0-120V) low current (1/2 amp) power supply with a limiting resistor to keep the reset current low. The power supply consists of three 40V supplies linked in series, and the ammeter is a multirange D.C. milliameter. Circuit B consists of a low voltage (40V) high current (0-25 amp) power supply and an ammeter which is part of the supply.

The procedure used during the tests was as follows. A tripped device was switched to reset through Circuit A by means of switch Sl. A voltage, which was preset on the power supply A, was pulsed across the device by the closing of mercury switch S2. A current reading on ammeter A indicated that the device had reset. The device was then retransferred to circuit B by switch Sl. The B voltage was increased slowly until the current level was reached at which the device tripped to the off state. The voltage was increased to 10V, beyond the 1 to 3V necessary for tripping, to check that the device remained off. During this procedure, records were made of trip currents and reset voltages.

For the fast-trip testing, the circuit shown in Fig. 2 was devised. This simple circuit contains the reset function as well as the facility to provide a high current pulse with a short rise time. Tests with other devices had indicated that the speed of switching is a function of the amplitude of current pulse and the pulse rise time, thus it was imperative that the rise time be short. A typical device resistance is about 0.2 ohms, hence the rise time for a pulse is about 30 microseconds.

The operation is similar to that for the Slow Trip Test Circuit. A tripped device is reset by opening the mercury switch, Sl, and closing briefly the reset contact, S2. This results in the appearance of 50V across the device which is in series with a 1K$\Omega$ limiting resistor. An ammeter on the power supply indicates the reset of the device.

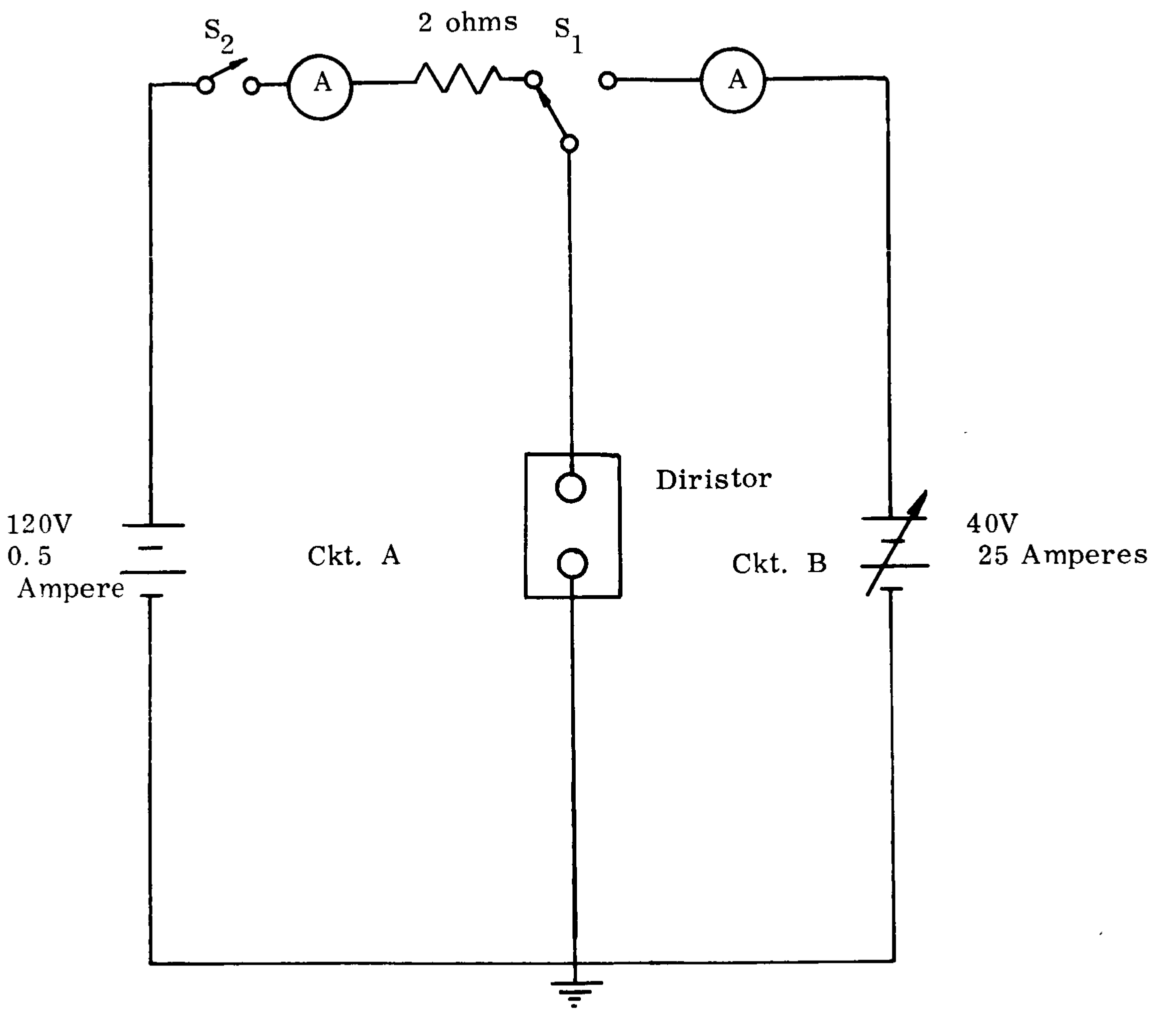



Figure 1. Slow-Trip Test Circuit

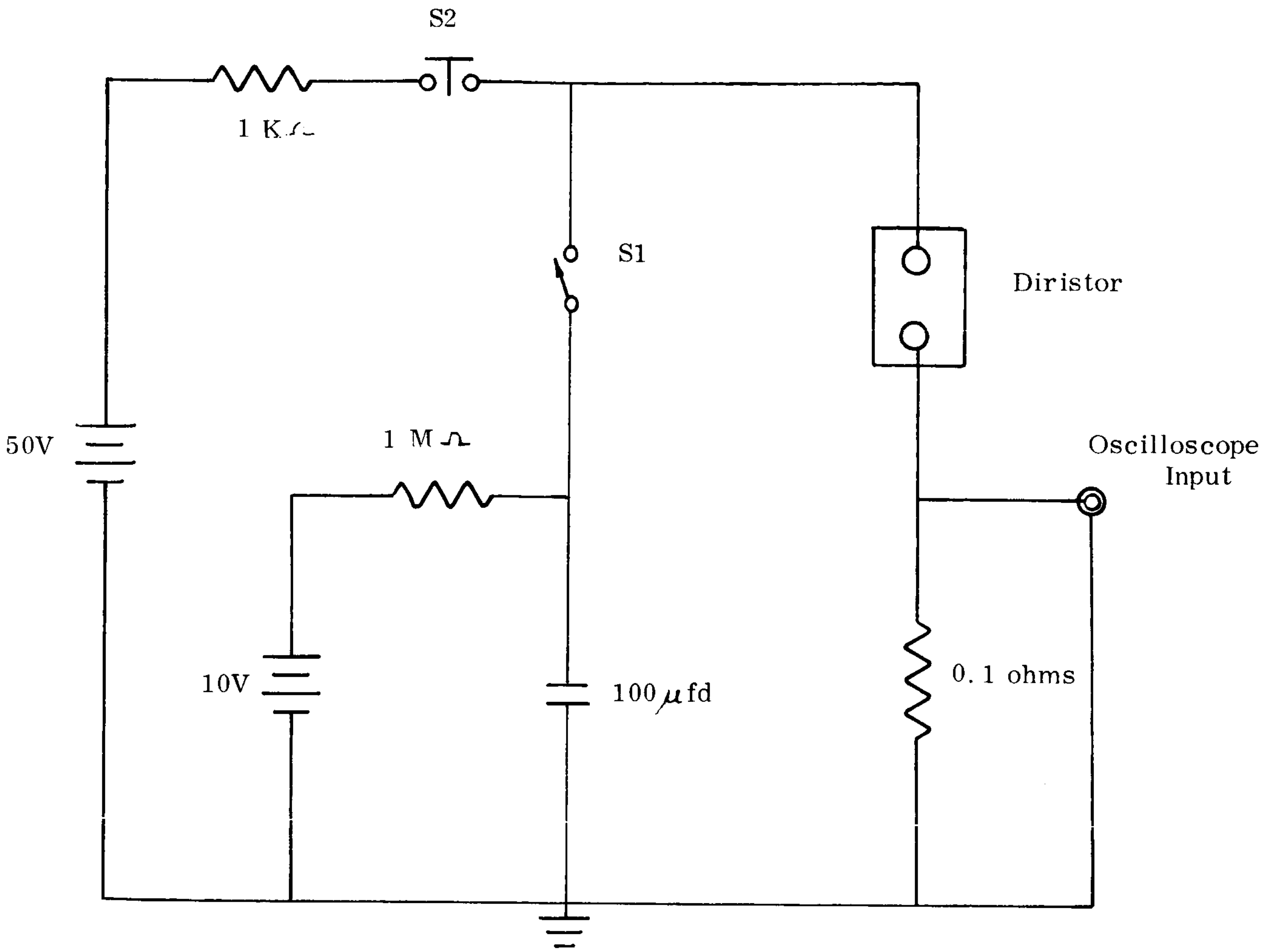


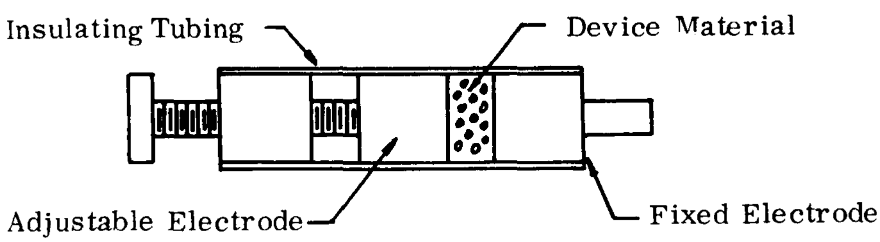

Figure 2. Fast-Trip Test Circuit

The device is then tripped by closing the mercury switch. This provides a current pulse from the capacitor which had been charged by the 0-40V power supply. The amount of charge can be changed by varying the charging voltage. Polaroid photographs of the voltage across the 0.1 ohm resistor during trip are obtained from an oscilloscope which is fed through the BNC connector.

## Device Test Procedures

The transformation of a low current device to high current resettable fuse necessitated many tests. The basic idea in this development was to begin with a device which showed some high current capability. A parameter to be tested was chosen and several devices were fabricated which were identical except for variations in this parameter. These devices were then evaluated on the basis of stability, repeatability, trip current values and reset voltages. For these studies, the slow-trip test circuit and procedure previously described was used.

Those devices which appeared to show the most promise were then used as the starting points for another cycle of testing involving a different parameter. The parameters tested were choice of metal, particle size, matrix material, metal/matrix ratio by volume, electrode size, electrode separation, and electrode material. The results of these tests are presented below in the section entitled "Results." The device arrangement used in all the above studies is shown below. The tubing used was a plastic,




either nylon or Teflon. The advantages of this arrangement was that the effects of variations in any of the parameters, with the exception of electrode area, could be studied with the same device arrangement. Effects of variation of electrode area could be studied by changing to a different size tubing and making electrodes which fit.

During the program, problems arose with the method of encapsulation. The procedure used for the solution of this problem was similar to that for the other tests except that the variable under study was device-package design.

## RESULTS

### Metal Particle Study

The objective of this study was to determine which metal powders would be suitable for use in the high-current resettable fuse. Previous work with a low-current device had indicated that any metal possessing a linear coefficient of thermal expansion greater than that of copper, ($\sim 16 \times 10^{-6} {}^{o}C^{-1}$) would prove satisfactory in performance. Since emphasis of the low-current device program was placed on switching-speed, that work was primarily concerned with the use of metals such as tin, aluminum, zinc and lead; this resulted in devices possessing switching speeds which are less than 10$\mu$ sec.

The early work in this program was concentrated on these metals. During the last stage, some work was done using copper, brass and stainless steel for devices having switching speeds up to 100 $\mu$sec. As mentioned in the preceding section, the devices were identical, as far as possible, in all parameters except the metal used. The electrodes were circular with a diameter of 3/8" in and were separated by 150 mils. The particle size for all metals was between 40 and 20 mesh, with the degree of sphericity varying from metal to metal. The matrix ingredient used for all devices was the silicone-rubber compound 501 RTV, obtained from Dow Corning. Metal/matrix ratios, by volume, were 70/30 and 80/20.

Table I summarizes the results of this study. It is evident that of the last four metals listed, tin and copper are best for use in a high current fuse, as determined by trip current and degree of reliability. They also possess the lowest coefficients of thermal expansion within the group. Tin was chosen for use in the other tests since it combined excellent switching speeds, stability and high trip currents.

### Particle Size Study

This study was one of the most significant, since the transformation of the Diristor to high current applications was largely accomplished by a discovery in the area. Early experiments with particle size indicated that high currents would cause small particles ($\sim$ 325 mesh) to melt and fuze together. In order to decrease the on-resistance, and thereby increase the trip current, the total fraction of metal had been greatly increased over that normally used in low current devices.

The other method of obtaining a low resistance was to increase the area of the particles, thereby decreasing the resistance per path. Tin particles with a size of 20 mesh were found to be successful. No evidence of failure due to fusing has been noted for devices made with tin in that size in a 70/30 mixture ratio. This will be discussed further in the following paragraphs.

Tests with 20 and 30 mesh particles of the same metal indicated little or no difference in device behavior.

## Matrix Material Study

The material used in initial devices was a polyester, designated as "Ward's Bio-Plastic Polyester," which had functioned very well for low-current applications. A Diristor was made with large tin particles ($\sim$ 20 mesh) in the ratio of 30 parts of metal to 50 parts polyester, by volume, which is the standard mixture ratio for low-current devices. After several successful high current (1 to 3 amperes) trips, the device exploded. The reason for this occurrence was surmised to be the high pressures created within the device due to heating in conjunction with a high viscosity matrix. A search was undertaken for materials with a lower viscosity, under the restriction that the material produce a conducting residue during manufacture. This requirement is deduced from observations made during studies conducted with low-current devices where the conducting residue was shown to be an intrinsic requirement of the device. It was found that silicone compounds possessed low viscosity, produced residues, and also possess approximately the same coefficient of thermal expansion and dielectric strength as the polyester. Several silicones were studies using a standard 70/30 mixture with 20 mesh tin particles, with other parameters held constant. The results are shown in Table II. The RTV compound was used without a catalyst; hence, its consistency was similar to that of a paste rather than rubber like. When the catalyst was added the device failed after the first trip.

The results are summarized in table II from which it can be seen that all of the materials were successful with little or no appreciable difference in the results, except for the Scotchcast material. The results presented represent the information obtained before degradation (degradation is defined as a steady decrease in trip current values to about 1 ampere, while the magnitude of the voltage necessary to reset the devices increases) appeared to begin. Degradation has been attributed to the influence of the tubing on the device operation and will be discussed in a subsequent section.

On the basis of the material study and previous in-house experiments, many properties for a successful matrix material can be defined. First, the material must produce a conducting residue when arcing occurs. The polyesters and silicone rubbers both produce carbon-based residues. Secondly, the melting point must be at least as high as 200°C. This figure represents the lower range of melting points of some of the metals used. With the high temperature generated, it would be disasterous for a material to melt and allow the particles to form connecting chains. Both successful substances have similar coefficients of expansion and equivalent dielectric strengths. Although the functions of these parameters are not completely understood, the

Table I

DEVICE PARAMETER DEPENDENCE ON METAL-PARTICLE TYPE

| Metal | Size | Avg. Trip Current | Reset Voltage | Stability |
|---|---|---|---|---|
| Pb | 20 mesh | 12 amperes | <50V | Erratic |
| Zn | 20 mesh | Occasional tripped, mostly remained on | | Very Erratic |
| Al | 40 mesh | 3.5 amperes | <50 V | Erratic |
| Sn | 20 mesh | 7 amperes | <50 V | Fairly Stable |
| Stainless Steel | 20 mesh | 2.5 amperes | <120V | Fairly Stable |
| Brass | 40 mesh | 6.5 amperes | <120V | Fairly Stable |
| Cu | 20 mesh | 5 amperes | <120V | Fairly Stable |

Table II

DEVICE PARAMETER DEPENDENCE ON MATRIX DIELECTRIC

| Material | Avg. Trip Current | Reset Voltage |
|---|---|---|
| Scotchcast, resin #234 | Burst into flame at 15 amps. | |
| Dow Corning 501 RTV | 7 amperes | <50V |
| Dow Corning Silicone Grease #3 | 7.5 amperes | < 50V |
| Dow Corning Silicone Grease #4 | 6 amperes | < 50V |
| Insulgrease G-640 | 8 amperes | <50V |

"embryonic" theory of the Diristor indicates that the first is important in tripping and the latter for resetting. The values of these parameters are 100 x $10^{-6}$ °$C^{-1}$ and 500 V/mil. They must, of course, also be excellent insulators; thus the resistivity should be at least of the order of $10^{15}$ ohm-cm.

## Metal/Matrix Ratio Study

The first trials of the silicone compounds were not successful since very high voltages ($\sim$ 500V) were necessary for reset and trip currents were quite low. During early trials, the 30/50 ratio (metal/dielectric), that had been successful in low-current devices which were fabricated with a polyester, was used. By increasing the metal content in the devices, a vast improvement was effectuated.

The mixture ratio was varied as shown in table III. The significant item to be abstracted from this table is that the trip current and reset voltage can be changed by suitable variations in mixture ratio. The trip current increases and the reset voltage decreases as the mixture ratio increases. With a 90/10 mixture ratio, some devices would occasionally carry 25 amperes, the limit of the supply, for several seconds before tripping.

As previously mentioned, the original successful devices used a polyester as a matrix. For this material, the metal/matrix ratio was 30/50 for all metals and for all sizes of metal particles. Successful low-current devices using fine powders (325 mesh) could only be made with RTV if the metal/matrix ratio was 70/30. Thus it appears that for each workable matrix there exists a ratio which will provide the best performance.

## Electrode Size Study

For this study, two devices were utilized: one with circular copper electrodes having a diameter of 5/16 in. and the other with circular copper electrodes that were 0.5 in. in diameter. The results of this study are illustrated by figures 3 and 4. The only effect noted was a reduction in width-at-half-maximum of the distribution of trip currents. This information is quite significant for future development and will be amplified under "Discussion" below.

## Electrode Separation Study

Three separation distances were tried in the same device for this study, 100 mils, 150 mils and 200 mils. The average trip currents were 9, 7 and 5 amperes, respectively, and the reset voltages were $<$ 50 for the first two and less than 100 V for the last. As expected from the parallel path idea, the device on-resistance should vary according to distance. From previous experience, on-resistance varies

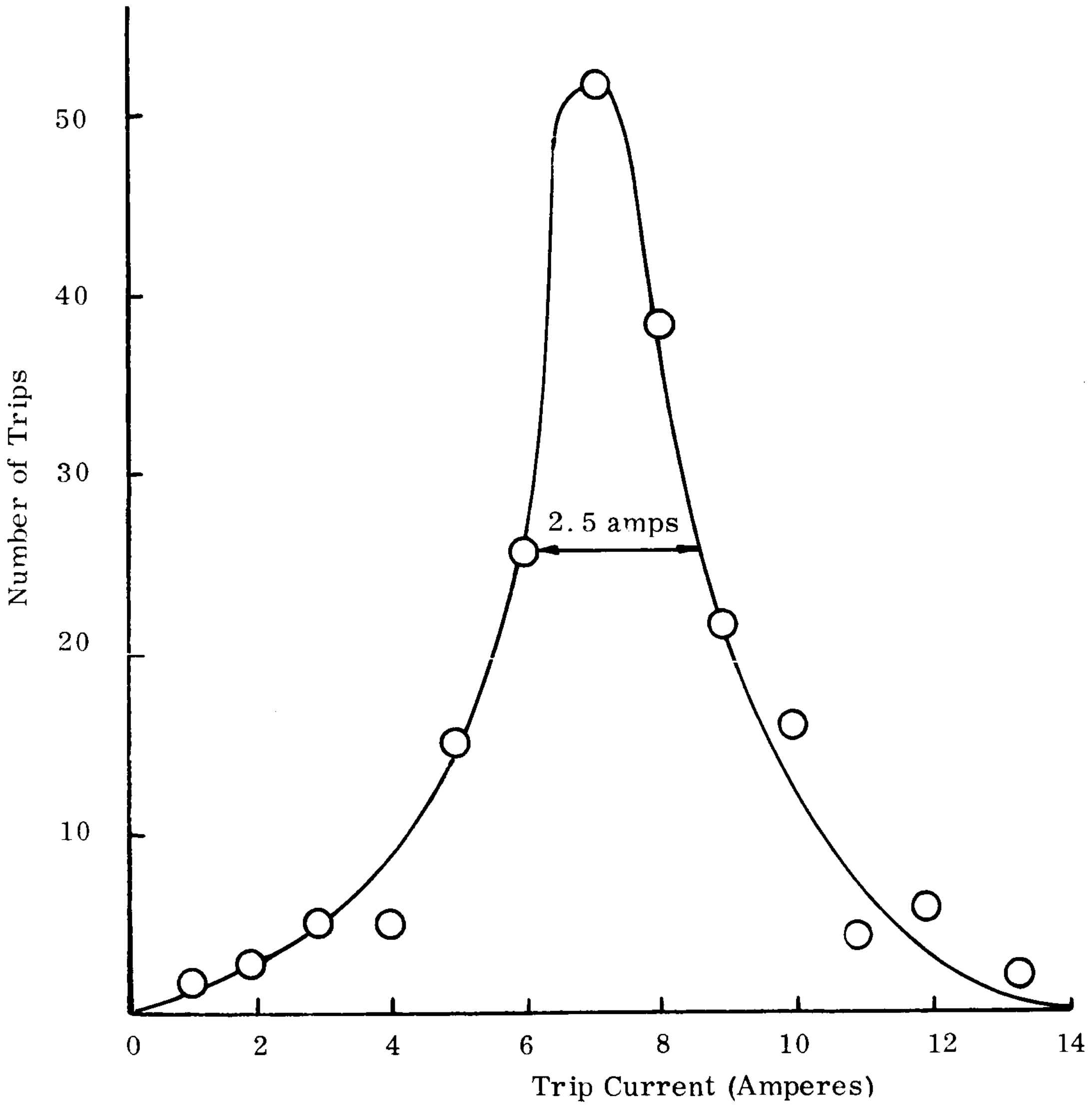



Fig. 3. Distribution of Frequency of Trips vs. Trip Current for Device with 0.5 in. Diameter Electrodes

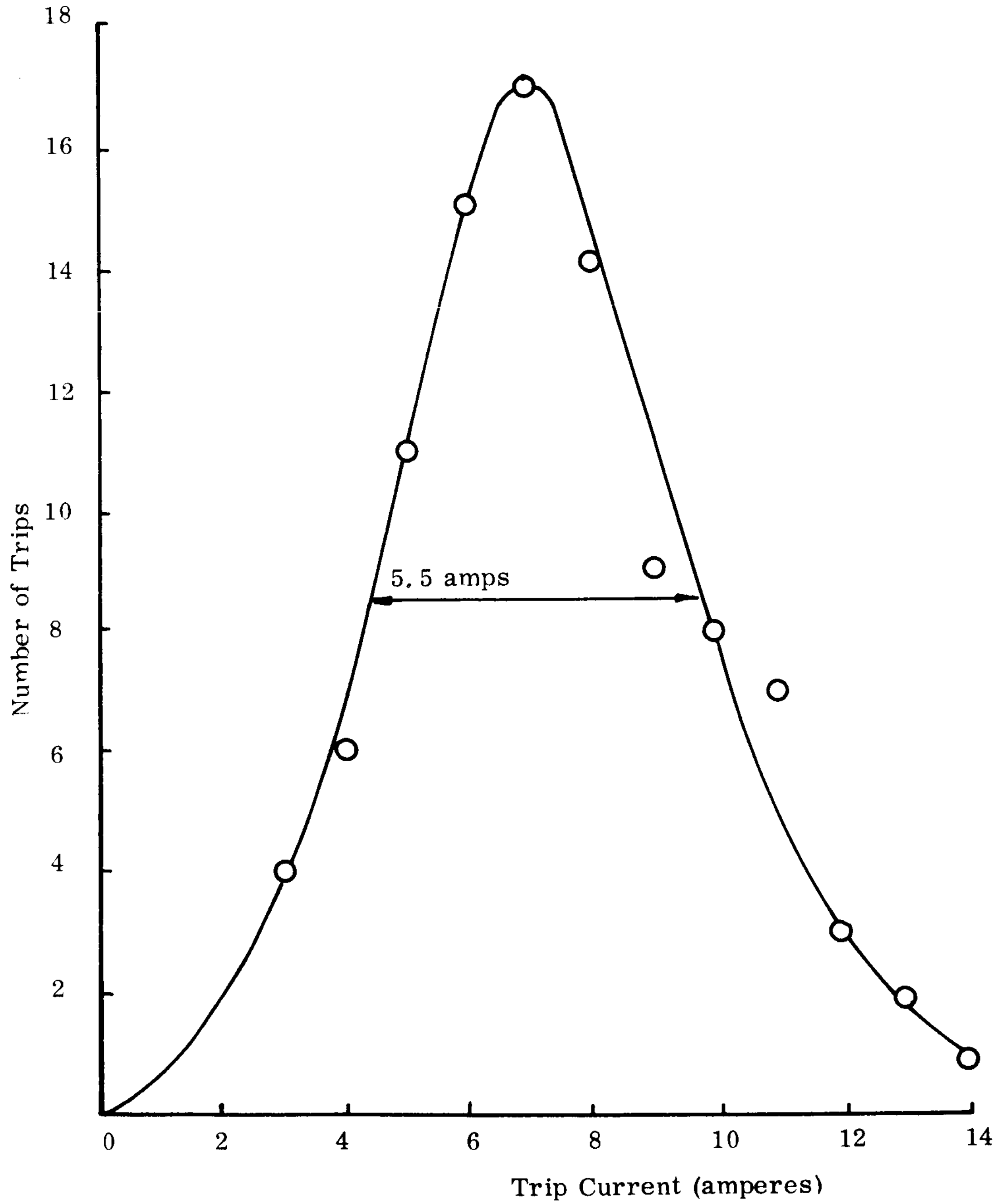



Fig. 4. Distribution of Frequency of Trips Vs. Trip Current for Device with 5/16 in. Diameter Electrodes

Table III

DEPENDENCE OF DEVICE PROPERTIES ON METAL/MATRIX RATIO

| Metal | Matrix | Metal/Matrix Ratio (by volume) | Avg. Trip Current | Reset Voltage | Comments |
|---|---|---|---|---|---|
| Sn | RTV | 90/10 | 12 amperes | < 40V | Occasional difficulty in trips at high currents |
| Sn | RTV | 80/20 | 10 amperes | < 50V | |
| Sn | RTV | 70/30 | 7 amperes | < 50V | |
| Sn | RTV | 60/40 | 8 amperes | < 50V | |
| Sn | RTV | 50/50 | 4 amperes | 50-100V | Difficulty in resetting |

inversely as trip current. The inverse dependence of trip current on electrode separation is consistent with this general rule. Devices with larger separations also require higher reset voltages.

## Electrode Material Study

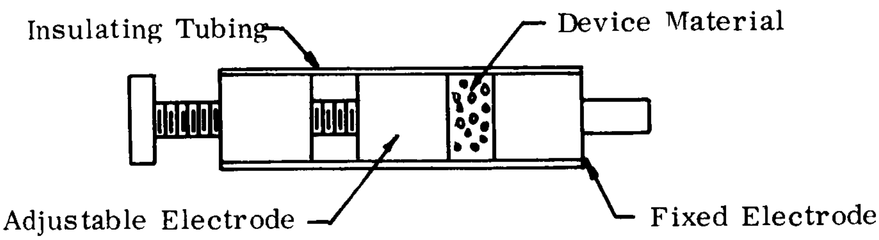
Two materials, copper and brass, were used in this study. No appreciable differences in performance was noted in device performance. The nominal trip current, reset voltages and spread in trip currents were approximately the same.

## Device Degradation Study

During the course of this program, a problem arose with device performance during extended cycling (tripping and resetting) of the devices. After 50 or more successful cycles, the trip currents would gradually decrease to about 1 ampere, while the reset voltages increased.

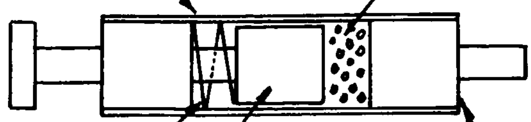
A recent in-house study has demonstrated that low-current RTV devices can be cycled 30,000 times without failure, and no evidence of degradation has ever been observed in any other devices. Since all of the devices tested to 30,000 cycles had RTV as a matrix, the effect could not be attributed to that compound. The only difference between the devices, besides the particle sizes, was the encapsulation of the high current devices.

To determine what effect the tubing might play in device deterioration, a power switch was made using the experimental arrangement shown below. When positioned horizontally, the device conducted very heavily (~ 25 amperes, the limit of the power supply) with no indication of tripping. In a vertical position, the device




also conducted heavily initially. After a few seconds, it was noted that the current gradually decreased in steps to about 15 amperes then suddenly dropped to zero. A careful examination of the device revealed the presence of a very narrow gap between the particles and the upper electrode. After a few seconds, the device reset; and it could be cycled in this fashion many times. The trip currents gradually decreased and it became more difficult to reset the switch. Since this action is remarkably similar to the deteriorating devices, it appeared to confirm that much of the difficulties can be attributed to the expansion and contraction of tubing.

For a more definitive determination of the effect of the tubing on device operation, the arrangement was modified as shown below in cross section. The adjustable electrode was milled down so that it moved freely in the tubing. A small spring, positioned between the adjustable electrode and the fixed electrode, held the adjustable electrode in contact with the device material (consisting of Sn-RTV mixture in 4/1 ratio by volume). This device was tested 500 times with no evidence of failure or degradation. The width at half maximum of the trip current distribution was about 5 amperes with the peak at about 9 amperes. It appears, on the basis of this study, that the degradation




of the previous devices may have been due to the teflon tubing. This is consistent with the previous work on low current Diristors where the device material was always free to expand.

## Switching Speed Study

Using the circuitry and procedure outlined earlier, i.e., Fig. 2 and discussion pertaining thereto, a study of the switching speeds of the devices was undertaken. The results show that the device will trip reliably in less than 100 $\mu$sec. Actually, out of 59 fast-trip tests, 23 occurred in less than 10 $\mu$sec.

## DISCUSSION OF RESULTS AND CONCLUSIONS

In outline, the important experimental results described in the last section are:

1. The device is capable of carrying and tripping at high currents if large-sized metal particles ($\sim$ 20 mesh) are used.

2. The metal must possess a coefficient of thermal expansion equal to, or greater than, that of copper.

3. The average trip current is a function of the size of the particles.

4. The matrix material plays an important role in the device operation, i.e., only materials possessing fairly well defined parameters will be successful.

5. For each matrix material, there exists a distinctive range of mixture ratios which will provide optimum performance.

6. Device parameters such as average trip current and reset voltage can be adjusted by choice of a suitable mixture ratio.

7. An increase in the width of the electrodes will result in a narrower distribution of trip currents.

8. The average trip current is inversely related to the electrode separation while the reset voltage is directly related to the separation.

9. The electrode material has little or no bearing on the device operation or its parameters.

10. A workable design for this device must allow for the expansion of the ingredients.

The major objective of this program was to determine if a high current resettable fuse could be developed and this objective has been clearly met. There are, however, several items to be resolved, for which a short study program is inadequate.

One of the problems is with the interdependence of the many variables at our disposal. This can best be illustrated by means of a simple example. Suppose that the device contained only two inter-dependent variables. One would hold one fixed and vary the other for best performance. The next step would be to fix the second variable at this point and vary the first. Because of their inter-dependency, one or more iterations may be necessary to "fine tune" the device. Obviously, this is a time-consuming, but necessary, procedure for the proper development of a device with a large number of variables.

A second problem concerns that of the spread in trip currents and reset voltages. The average values for these parameters can be changed at will by suitable adjustments in the physical makeup of the device. The problem is to reduce the spread to a very small range. A suggestion of how this could be accomplished is provided by the result of the electrode size study. By enlarging the area of the electrodes, the probability for forming paths is also increased. Suppose that the resistance per path is about 10 ohms, a value obtained experimentally for a single chain. It has been observed that the device resistances range from .1 to .5 ohms, suggesting that the range in the number of paths formed is 20 to 100. This means that the number of paths that fail to reset during any one pulse may be large. It appears that the magnitude and extent of the spread can be diminished either by devising a way of resetting all or most of the paths every time, or by increasing the number of paths, e.g., by an increase in the size of the electrodes.

A third problem is concerned with a method of encapsulation. The composite material must be free to expand and contract while maintaining contact with the electrodes. By coincidence, the two most successful types of matrices, polyesters and silicone compounds, possess approximately the same coefficient of thermal expansion. The role that this property plays in device performance, especially in conjunction with the expansion of the metal, is not known at this time and should be the object of future study. It appears that the ideal solution to the problem of packaging consists of the utilization of a material of sufficiently high viscosity so as to obviate encapsulation. All other parameters of importance such as coefficient of thermal expansion melting point, etc., would have to approximate the same values as the RTV to result in similar performance.

On the basis of the foregoing, the problems outlined appear to be soluble, but will require further in-depth work. All of the results, with the possible exception of the necessity for matrix expansion, coincide with the empirical theory of the device operation as presented in the introductory section of this report. Thus there exists sufficient knowledge of the effect of compositional variations on device performance to enable the development of a perfected high current resettable fuse.

## APPENDIX

## STATE OF THE THEORY OF THE DIRISTOR

In the present stage of investigations into the parameters that affect Diristor operation, there are two broad theories that can account for its properties. Each is consistent with the salient features: the properties of reset and trip. On the other hand, it cannot be stated that any single existing theory adequately predicts the many nuances that have been reported to date during the exploratory and developmental studies.

Mechanical action is the essential hypothesis of the first theory. In this model, the dielectric matrix plays an entirely passive role in the electronic conduction processes, serving merely to securely insulate non-contacting metallic particles. The on-state of the device is realized when a continuous path of metallic conduction is established between the electrodes. Alignment of particles into such arrays can be readily accomplished by an electric field, provided the matrix is sufficiently fluid to permit some translational motion of the metal. This effect can be, and has been, witnessed under a microscope by observing the motion of large lead particles immersed in a transparent, slightly viscuous, dielectric fluid when a large voltage is supplied to two copper wires that are immersed in the fluid. The speed of the reset process, according to this model, is determined by the size and shape of the particles, the maximum separation distance between any two members of a chain, and the magnitude of the voltage applied.

Trip action clearly requires particle separation, which may result in one of several ways as a result of the passage of a large current. First, expansion of the dielectric under $I^2R$ heating local to the metal contacts is always larger than that of the metal, so that, for any small temperature gradient across the metal-to-metal contact, a net pressure gradient could easily develop in such a manner as to separate the particles. A more interesting model relates to the surface energies of the metal when in contact compared to those for the metal-to-dielectric surfaces. It is reasonable to suppose that the latter energy decreases appreciably as the temperature is raised, while the former is only slightly modified by temperature below the melting point of the metal. Hence, local heating might result in a "wetting" of the metal surface by the dielectric fluid so as to disrupt the contact. At the present time, there is little information on which to base a choice between these two mechanisms. The dependence of the dynamics of the tripping action on parameters such as viscosity and coefficient of thermal expansion of the dielectric have not been investigated. No information is available, at present, on the numerical values of the surface free energy at metal-dielectric interfaces.

An alternate theory, more properly: class of theories, for Diristor action is based on electronic mechanisms within the dielectric. It is postulated that the oncondition represents a meta-stable state of the dielectric, in which a dense set of excited electronic states are populated by the action of an applied electric field. These states either spatially overlap sufficiently to form a band or are in thermal equilibrium with an energetically neighboring band of normally unoccupied states. (The choice between these alternatives might be resolved by a study of the Diristor at the temperature of liquid helium.) The instability of the conducting state may be related to alignment of the polymeric molecules that make up the dielectric in the following manner. The side links, which have unsaturated bonds in the monomer, are able to bond to each other when the polymer is "curled up" on itself. However, under the stress of a polarizing electric field, the chain is forced to "straighten itself out," leaving the side links with many unused bonding electronic states. It is these states that provide for the conducting property of the re-set device.

Trip action, in the electronic model, is simply the transition from the meta-stable conducting state to the more permanent insulating state. The key provision for tripping is, again, the local dissipation of a large quantity of thermal energy, through $I^2R$ heating, within the dielectric. If the re-set action is initiated through polarization of the polymer molecules, as postualted above, then trip is brought about by sufficient thermal disordering to allow "curl-up" to recur.

Other purely electronic mechanisms have been suggested to account for the tripping mechanism. However, in the present conjecture-like state of the theory, the polymer-chain-polarization model seems to be the most appealing. An experiment that could rule this mechanism out (but which cannot positively indicate that it is correct) would consist of the demonstrated operation of a Diristor in which the dielectric is an inorganic viscuous fluid. It is somewhat difficult to imagine what such a matrix material could be; perhaps a paste-like suspension of an insoluble substance in a non-polar fluid might do.

There are some rather obvious mechanisms that, equally obviously, must be discounted at the outset. These include tunneling and double injection. Neither of these mechanisms can be expected to provide a linear dependence of current on applied voltage throughout the eight orders of magnitude over which the ohmicity of the Diristor has been checked in the conducting state. Moreover, the effect of high current in generating trip is entirely obscure in both the injection and tunneling models.

The most serious objection to the electronic-mechanisms models is the clear evidence, in the cured polyester devices, that the thermo-mechanical properties of the metal are important parameters for successful device design. At this time, the coefficient of thermal expansion, for example, would appear to play a negligible role in a purely electronic theory. On the other hand, little is known about the effects of pressure on the polarizability of polymeric substances; on the basis of the findings of these studies alone, this question certainly bears further investigation.

The mechanical action theory is in accord with virtually all findings to date, except in one very significant respect. It has been observed that small particle devices (Al in RTV) are switched on by the action of very strong R. F. pulses from an antenna that is in close proximity. Moreover, the turn-on time has been observed to be consistently less than 50 nanoseconds after initiation of the R. F. spike. It is difficult to see how mechanical switching, which certainly would require the dissipation of a rather large amount of energy, could take place without a more direct coupling. Furthermore, the speed of this action mitigates very strongly against purely mechanical notion.

The above discussion suggests that much more diagnostic work can and should be done before a firm theory of the Diristor action can be formulated. While most of the suggestions are really no more than plausibility arguments, they can certainly serve as a groundwork for further experimentation. One thing is clear. Analysis that is merely incidental to an engineering development for specific applications will not provide unambiguous answers to the outstanding conceptual questions that have been formulated to date. In order to make substantial progress towards comprehending the basic mechanisms within this device, a full research effort (experimental and theoretical) is indicated.

## NEW TECHNOLOGY APPENDIX

An Attachment to the Final Report, "Solid State Bistable Power Switch Study" (August, 1968), under Contract NAS-12-647.

Improvements and innovations in the design and operational characteristics of this device are described in pages 7-15 of the referenced report. These include characterization of effects on trip current and reset voltage of: metal particle types in a silicone rubber compound, variations in metal particle size, selected matrix dielectric materials, variations in metal/matrix ratio, and electrode separations. Reliability of the device was found to depend on electrode size and on device configuration.