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Sandia Corporation

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SOME CAUSES AND REMEDIES FOR UNDESIRABLE VARIABILITY OF RELAY PERFORMANCE CHARACTERISTICS

by
Jay W. Grear, Jr.

June 1958

WORK PERFORMED UNDER AEC CONTRACT AT-(29-1)-789

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Presented at

THE SIXTH NATIONAL CONFERENCE ON
ELECTROMAGNETIC RELAYS

School of Electrical Engineering

Oklahoma State University, Stillwater, Oklahoma,
April 1958

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ABSTRACT

This talk on electromagnetic relays includes a discussion of some causes and remedies for undesirable variability of relay performance characteristics within individual relays, and between relays within a lot, and from lot to lot. Discussed are test results, methods of determining the causes for instability (including the replica technique for studying contact contamination), and examples of corrective action taken to decrease the instability. Recommendations are made concerning steps to improve the designs, to stabilize the performance characteristics during preproduction and production fabrication, and to obtain useful information during final testing.

ACKNOWLEDGEMENT

The major portion of the studies on contamination and cleaning methods reported in this paper was planned and performed by L. M. Berry of the Metallurgy and Analytical Division within Sandia Corporation. Liaison with manufacturers has been implemented by personnel of the Manufacturing Engineering Components Department. The over-all coordination of these above activities plus relay design, specification, and evaluation has been the responsibility of the personnel of the Power and Switching Components Division. The author is indebted to his associates within these groups for their work, and for their comments and constructive criticism throughout the preparation of this paper.

SOME CAUSES AND REMEDIES FOR UNDESIRABLE VARIABILITY OF RELAY PERFORMANCE CHARACTERISTICS

In matching the characteristics of a specific relay to the requirements of a system application at Sandia Corporation, we have experienced the usual problems of locating a relay having the proper contact arrangement and rating, a small coil power requirement, a suitably miniature size, and a satisfactory immunity to various military-service environments. However, it has been our experience that the most severe problem we have encountered is the extreme variability of relay performance characteristics. By this I mean not only the unstable, nonrepeatable performance characteristics within a single relay from one operation to the next, but also the wide variation of performance characteristics between individual relays within a lot, and from lot to lot.

In this talk I would like to relate a few of our experiences in relay evaluation, a summary of our findings in determining the prime causes for relay variability, and some of the action we have taken in conjunction with several relay manufacturers to reduce the variability of relay performance characteristics.

Instability of Performance Characteristics Within a Single Relay

Test Results

In our evaluation of individual relays, we have experienced a number of cases of instability in such characteristics as pull-in and drop-out currents, insulation resistance, and contact bounce transients from one operation to the next. However, we have found that contact resistance is the characteristic which shows by far the greatest instability. The following examples illustrate this contact resistance problem.

Some of our relay contact circuits operate at relatively low currents and voltages. Among these are "dry" circuits, handling currents of a few microamperes at several millivolts. To simulate these circuit conditions, we utilize a "dry" circuit tester in the laboratory which automatically life tests the relay contacts at 10 microamperes and 10 millivolts, and records the total number of contact operations and the total number of times the contact resistance exceeds a preselected value. We have found that in many instances contact resistances at these low energy levels will increase from several ohms to tens of thousands of ohms after only a few thousand operations.

Another type of application requires stable contact resistance in the current range of 0.1 to 3 amperes. We have found that during life tests of certain relays for 10,000 operations in these current ranges, there is a sporadic and increasingly severe rise in contact resistance into the range of thousands of ohms.

Many of our relay applications require the relay to withstand long-term passive storage of months, or even years, followed by a single critical operation in which the relay must function properly. We have received field reports

concerning failures of sealed relay contacts in which the contacts exhibited many megohms of resistance after being stored for a year. A twelve-month accelerated storage test of this same type of relay in our laboratory showed that the contact resistance increased by a factor of at least 10 in one-third of the relays and by a factor of over 100 in more than 10% of the relays.

A final example of test results that exemplify the instability of performance characteristics within a single relay again involves contact resistance. Relays that had passed a contact resistance acceptance test at the manufacturer's plant failed an identical test during one of the subsequent inspections of larger and still larger electronic assemblies which contained the relay. Furthermore, a significant quantity of these relays that failed one of the inspections did not repeat the failure upon further testing but showed a low, stable resistance.

Determination of the Causes for Instability

Since most of the critical problems we have faced with individual relays have concerned variable contact resistance, we have concentrated on determining the major causes for this phenomenon.

When a specific relay shows erratic contact resistance we normally examine the contact surfaces by use of the "replica" technique, originally developed by the Bell Telephone Laboratories. In this process a thin disc of transparent plastic, often vinylite, is pressed against the surface of a contact and is heated to about 240°F. The contact is then allowed to cool. A major portion of the particles that are on the contact surface adheres to the plastic, enabling a microscopic examination of the particles after the disc is removed from the contact. Ultra-violet light, solubility tests, and other microchemical techniques are used on these particles in an attempt to identify them. In many cases we have thus found such things as human hair, carbonaceous material, orlon fibres, lint, mineral fibres, epidermal scales (skin), fingernail polish, cellulose fibres and mineral particles. By other techniques, we have identified copper contamination on palladium contacts, machine cutting oil on silver-cadmium oxide contacts, abietic acid which is a derivative of rosin flux, and a host of other foreign materials on contacts that had demonstrated erratic contact resistance.

Once we have identified the contaminating materials that most probably caused the variable contact resistance, we attempt to locate their source or sources. In general there are two sources: (1) Contaminants can emanate from the materials purposely designed into the relay; (2) The contaminants can be inadvertently introduced into the relay during the manufacturing and processing.

The materials designed into the relay can cause erratic contact resistance in a number of ways. Usually insulators are the chief sources of trouble. For instance experiments at both Sandia Corporation and BTL have shown that certain organic vapors near contacts that are being rubbed together in a sliding motion under zero current circuit conditions can be "polymerized." Although the exact process is not completely understood, this condition usually causes a deposit of powder on the contacts, which in turn causes an increase in contact resistance. Although these powders are often referred to as "brown" powders, their color may range into the yellows and even white. This phenomenon occurs more readily when the contact materials are palladium or platinum, although gold will also produce the same effect to a smaller extent. Silver apparently does not produce these "polymers."

A second type of contaminant originating from the materials designed into the relay consists of small fibres or particles of the insulators which are dislodged during vibration and mechanical shock. These move about and can become lodged between the contact surfaces, again creating erratic resistance.

As a final example, organic vapors can be condensed in layers on all surfaces within the relay during thermal cycling. The contacts are especially susceptible to this type of filming because of the thin wedge of air or nitrogen between the contact masses. These adsorbed layers can also cause unstable contact resistance brought about by a partial decomposition during arcing at the contacts.

During the manufacture of a relay there are many opportunities for contaminants to become attached to surfaces of the relay parts. The fact that skin, hair, dirt, lint, etc., have been found in opened relays indicates that the assemblers themselves contributed to the contaminant problem.

A severe contact resistance problem we experienced recently was traced to the use of ordinary solder rosin flux used during the hermetic sealing operation. Flux entered the relay and was heated to a high temperature during the sealing operation. As stated previously, the heated flux decomposed into several materials including abietic acid which then deposited on the contacts. Although the exact decomposition process is not fully understood, the abietic acid is a white crystalline material sometimes referred to as "popcorn" because of its appearance under a microscope. Since this contaminant sublimates at about 190°F, techniques other than the replica method were employed to identify it.

Copper and iron found on contact surfaces have been traced to welding and coining operations at the manufacturer's plant in which copper welding electrodes and steel coining dies caused a transfer of material to the contact surfaces. In another instance, we traced a contaminant on silver-cadmium-oxide contacts to a sulfurized cutting oil used in fabricating the contacts. Even after thorough cleaning of the contacts, high resistance was encountered later due to a continual exuding of the oil trapped in the pores of the contact material. The last examples represent only a few of the many ways in which erratic contact resistance in sealed relays have been attributed to the manufacturing process.

Examples of Corrective Action at the Manufacturer's Plant

Since contact resistance has been the predominant unstable characteristic in sealed relays, we have concentrated on improving the design and manufacturing processes of the relays to reduce this problem. We have usually taken two approaches to the problem of contact contaminants. These include: (1) reducing the total quantity of contaminants within the contact chamber of the sealed relay, and (2) improving the mechanical action of the contacts to reduce the effects of the contaminants that do exist. The extent of design and process changes in relays already in production has often been controlled by such additional factors as non-interruption of production, structural strength of new parts, lack of space within the relays for new parts, lack of space within the manufacturer's plant for new processing equipment, and so forth.

To reduce the amount of contaminants originating from insulators within the relay, we have replaced fibrous materials such as dacron thread, phenolic spacers, and paper discs with nonfibrous materials including teflon tape, ceramic spacers and molded nylon discs. Since the outgassing of organic materials has caused "brown powder" formations and carbonization due to decomposition during arcing, wherever possible we have substituted inorganic materials such as glass and ceramic for organic insulators. Where it has not been feasible to eliminate organic materials from the contact region, we have selected those materials that exhibit relatively low vapor pressures such as teflon. Wherever the formation of "brown powder" has been a problem with palladium contacts, we have substituted silver, silver-cadmium-oxide, gold, or other less active materials, whenever their other characteristics, such as erosion rates, were satisfactory.

To reduce the amount of contaminants introduced into relays by soldering and welding processes, in one case the shape of a copper electrode used in welding palladium contacts to springs was changed. The change made it possible to avoid

touching the electrode to the critical contact surface during the welding operation, and thus to avoid copper transfer. In another instance, the mechanical crimp between the steel case and base was improved to eliminate the flow of rosin flux into the relay during the solder-sealing of the case-to-base joint. In a third instance, the selection of a particular stainless steel alloy for the case and base material was influenced by a surface flaking problem experienced in heliarc welding certain ferrous materials.

The observation of foreign particles such as hair, lint, and airborne dust on relay contacts that exhibited erratic contact resistance led us to the construction of special atmosphere-controlled relay assembly areas. In some cases, the assembly area consists of glass-hooded benches into which filtered air is forced. The relay assembler inserts his gloved hands into the hooded bench through a slot, performs final cleaning operations, and assembles the final subassemblies of the relay. In other cases, special "white" or "sterile" rooms have been constructed into which dust-, temperature-, and moisture-controlled air is pumped. The assembly personnel wear lint-free clothing and perform the final assembly and inspection in this room. In one case glass-hooded benches within the "white" room are used to further decrease the possibility of contaminants being inadvertently sealed into the relays. These rooms are quite similar in design to some of the finer gyro assembly rooms now in existence.

To further decrease the amount of foreign contaminants being enclosed in sealed relays, controlled cleaning processes have become a part of the manufacturing process. The particular cleaning method depends on such factors as contact configuration, insulating materials, process-induced contaminants, and production rates. We have, for example, introduced the cleaning of relay parts in ultrasonically agitated liquids, including isopropyl alcohol, distilled water, and detergent solutions. In another case, a stream of isopropyl alcohol is directed at the exposed surfaces. Although hot trichloroethylene has been used as a cleaning solvent for some parts, we have found that parts which are cleaned in this particular solvent to remove rosin flux subsequently exhibit a gummy residue which cannot be easily removed.

In all cases the attempt is made to (1) dissolve or dislodge the contaminants from all exposed surfaces of the relay parts, (2) carry the contaminants away, and (3) avoid recontaminating clean surfaces with contaminated cleaning solution. These steps require very strict control of the racking of parts to be cleaned, and the continual replacement of contaminated cleaning solutions with pure solutions. We have found that we obtain the best results when the relay parts and subassemblies are cleaned a number of times during the manufacturing procedure instead of only once at the final assembly stage. For instance, some of the parts of one type of relay are subjected to a total of twelve cleaning operations during various stages of assembly by immersion in ultrasonic baths of various solvents and distilled water. The purpose of the repeated cleaning is two-fold: (1) To remove the major portion of the contaminants, and (2) To minimize the amount of contaminants that have to be removed by the final cleaning operation, and thus minimize the recontamination of parts due to "dirty" cleaning solution. This multiple cleaning requires strict control of the parts between cleaning operations to avoid recontamination. Usually the parts are vacuum-baked between certain cleaning steps to help drive off residual volatiles.

Obviously not all contaminants can be excluded from the contact vicinity. Therefore we have taken steps to minimize their effects. Wherever possible we have increased the contact approach velocities and the static contact forces to help dislodge particulate contaminants and cause fissures or ruptures of film contaminants on the contact surfaces. Although a sliding action of contacts certainly helps reduce the deleterious effects of certain contaminants, we have found that contaminants such as some inorganic films often remain on the mating contact surfaces in spite of this action. In addition, there is some possibility of a "polymerization" of certain organic vapors with the associated deposition of

"brown powder" on sliding contacts operated under no-load conditions. Thus, sliding action is advocated only after a careful analysis of side effects. The use of a different contact material or shape has also decreased the effects of contaminants in some cases.

Variability of Performance Characteristics Between Individual Relays Within a Lot, and from Lot to Lot

Thus far I have discussed briefly the problem of instability of characteristics of individual relays from one operation to the next. We have found that a second major problem is the gross variability of performance characteristics between individual relays within a lot and between relays manufactured in different lots.

Test Results

In observing troublesome characteristics from one relay to the next, once again the variability of contact resistance predominates. A review of contact resistance measurements of all the relays in a single lot has revealed in some cases contact resistance 10 to 100 times higher than that of other relays in the same lot. We have also experienced a wide variation in the mean values, standard deviations and ranges of contact resistances of separate lots of relays. In still other cases the contact resistances of two "identical" groups or lots of relays were essentially the same immediately after manufacture; however, after a year of storage there was a significant difference in contact resistance between the two groups, one having remained relatively constant, the other increasing by a factor of two to ten.

Possibly the second most variable characteristic we have experienced between individual relays is the ability to withstand vibratory environment without contact chatter or internal catastrophic damage. Within a single lot of relays we have observed contact chatter at as low as 5 g's in the 400 to 500 cycle range in some relays while contacts of other relays in the same lot did not chatter until they were vibrated at 25 g's acceleration. Breakage of internal connecting wires also has appeared to be dependent more on the idiosyncrasies of individual relays within a lot than upon the amplitude, frequency or duration of vibration.

Contact life, drop-out current, pull-in current, and coil resistance are additional relay characteristics that have shown wide variation from one relay to the next in certain instances. In some cases, relays operate thousands of times without malfunctioning while other relays of the same lot fail after only a few operations. Although the variability in drop-out current, pull-in current, and coil resistance can be measured before the relays leave the manufacturer's plant, there is far too often an unaccountable change in these characteristics from one lot of relays to the next, indicating a possible trouble area. Variations in other characteristics including transient operate times, dielectric strength, and insulation resistances have thus far not caused a great deal of trouble in our particular applications.

Determination of the Causes for Variability

The immediate causes for the variation in characteristics from one relay to the next can sometimes be determined by an actual physical comparison of the relays that behaved differently. The amount or kind of contaminants can cause differences in contact resistance characteristics. In an instance previously cited, we found that a small change in a crimp dimension between the case and base allowed a significant increase in solder flux and abiatic acid to enter the relay, causing a severe contact resistance problem that had not previously existed. As another

example, contact resistance variations between two groups of "identical" relays were traced to a dimensional change in which one group, showing consistently low contact resistance, had a contact sliding action of about 0.010 inch while the second group, exhibiting high variable contact resistance, had essentially no sliding action. Another variation in contact resistance was traced to the use of a cutting oil during machining of contacts, whereas earlier contacts had been machined with no lubricant.

Variations in vibration performance of different relays from a single production run have been traced to a number of causes. These include wide variations in contact forces, bad alignment of contacts, and variations in dimensions of structural parts which cause differences in transmissibility functions of internal subassemblies. Breakage of internal wires during vibration in several instances has been attributed to nicks in the wires suffered during insulation stripping or wire bending operations during assembly.

When tested to destruction during life tests, some relays within a group outlast others by a factor of ten or higher. Contact bounce transients during contact making affect electrical erosion of contacts. In fact, the wide differences in contact bounce transients can cause severe problems in attempting to define the contact "making" ability without the occurrence of undesirable welding of the contacts. Poor adjustment of contacts and actuating mechanisms have caused variations in approach velocities, bounce transients, and release velocities, all contributing to an unpredictable life expectancy.

Coil drop-out and pull-in currents are usually affected more by variations in physical dimensions, clearances of the magnetic structure and spring adjustments, than by variations in the properties of the magnetic materials.

Examples of Corrective Action at the Manufacturer's Plant

To reduce the variability of characteristics between individual relays, we have introduced a number of controls at the manufacturing plants. Efforts to stabilize the characteristics within a single relay, for example eliminating fibrous materials and introducing cleaning operations, as mentioned earlier, have also helped minimize the variation in characteristics between relays.

A second control area is that of processing. We have found that some manufacturers have difficulty in controlling processes within their plant. We have asked the manufacturer in several cases to prepare process control sheets that precisely describe critical operations, such as welding, so that different operators will perform the job in the same manner. The same type of control has been required for cleaning, adjusting and assembly.

Quality control of adjustments has also been a big factor. Requiring a 100% measurement of all contact forces and critical adjustment gaps has helped. In a motor-starting relay we found that much less variation was experienced by adjusting the contacts using a distance measurement rather than a force measurement. This naturally required good control of relay spring materials and piece-part dimensions.

Closer control of dimensions of piece-parts and subassemblies has significantly lessened the variation between individual relays in their ability to withstand vibration. In one instance, where it was impractical to hold close enough dimensions to avoid either loose or interference fits due to tolerance buildup, a dimpling, or indenting, operation was incorporated into the case after final assembly to tighten up the fit between the outer case and the internal structure. This type of "fix" is condoned only where dimensional control cannot be tight enough to prevent undesirable tolerance buildups.

Control of certain critical raw materials has to be maintained. Certificates of conformance from the raw material suppliers have been useful, but for more complete control actual chemical and physical analyses of the raw stock of certain critical materials such as contacts and springs has proven to be very valuable.

Conclusions

Summarizing our experience, the most important cause for unstable performance of a relay from one operation to the next has been the presence of contaminants on the contacts. In addition, the more important causes for variations in performance characteristics between individual relays have been, in descending order of influence, (1) the presence of contaminants, (2) variations in manufacturing processing, (3) variations in contact adjustments, (4) variations in piece-part materials, and (5) variations in piece-part and subassembly dimensions.

We have concluded that steps which should be taken to reduce the variations in relay characteristics include the following:

Design

It is desirable that all organic materials be excluded from the contact chamber. As consistent with other requirements, the contacts should have high impact velocity, short bounce transient, small radius of curvature, large static force, some wiping action, and a positive "lift-off" type of break. Consideration should be given to twin, or bifurcated, contacts. Adjustments by the use of screw threads rather than by bending of parts appear to be desirable. Nonadjustable metal joints should be welded wherever possible to avoid solder-flux contaminants. Finally, sufficient tests must be performed to establish that development models have reasonably large safety factors in regard to characteristics such as contact current rating, dielectric strength, pull-in and drop-out currents, and immunity to high ambient temperatures and vibration.

Preproduction Fabrication

Prior to release of the design for full production, a statistically significant quantity of relays should be built on production tools, jigs, and fixtures to establish the capability of the production line in terms of stability and flow rate. By means of performance and environmental tests, the capabilities and limitations of the preproduction relays must be established. These tests should be increased in severity to the degradation or destruction limits of the relay, or to the limits of the test equipment. During the fabrication of the preproduction relays all critical materials, processes and dimensions must be determined, and quality control procedures including control limits on critical parameters, established. Analysis of contact "replicas" of completed relays helps determine that the cleaning procedures are satisfactory for the particular type of relay.

Production

Critical raw materials such as contacts and springs should be subjected to analyses by a chemical laboratory on a sampling basis to verify the composition and condition. Certificates of conformance obtained from subcontractors for less-critical materials will help control material quality. All critical piece-part dimensions should be subjected to statistical quality control methods such as frequency distribution, probability, $\bar{X}$ and R charts. Noncritical dimensions can be sampled in accordance with a stated plan. All processing such as welding, heat treating, adjusting, and cleaning must be controlled by use of process control sheets with a complete description of the process, the equipment used, and the setting or limits for the equipment. Wherever possible these processes should be

automatic to avoid variations due to the inevitable subjective influence of the factory personnel. Tools and gages must be subjected to regularly scheduled inspections. The flow of piece parts and subassemblies should be controlled to avoid recontamination of cleaned parts. All assembly work of contacts should be performed under "sterile" or "white room" conditions in which extraneous contaminants are reduced to a minimum.

Final Testing

We recommend that three major groupings of tests be performed on completed relays:

1. Nondestructive Tests on All Units -- All relays should be subjected to pull-in and drop-out current tests, coil and contact resistance, and dielectric strength tests under both high and low temperature conditions. A test in which the transient coil current rise and contact bounce characteristics are repeatedly displayed on an oscilloscope can be used to indicate the dynamic characteristics of the relay.
2. Destructive Tests on Sample Units -- Sample quantities of relays extracted periodically from each production lot in accordance with a stated procedure, should be subjected to life and environmental tests to determine their failure points under such conditions as vibration and high temperature.
3. Storage Tests on Sample Units -- Small quantities of relays should be periodically extracted from production and stored for an indefinite time for invigilation purposes. Periodic tests will indicate the effects of the storage environment.

In all of these tests the results are much more meaningful if they are of the variables rather than attributes, or "go no-go", type. If the data are recorded for each serialized relay and translated into quality control charts for each parameter, it facilitates comparison of two or more lots.

Unless the relays are of sound design and are manufactured under controlled conditions it is extremely risky to state that a particular lot of relays is "acceptable" if the sample relays from that lot meet the sampling test requirements. Likewise it can be erroneous to conclude that a particular relay from that lot is "acceptable" even though it meets all the non-destructive test requirements. This is especially true in regard to contact performance. Good design and rigid quality control rather than acceptance testing must be utilized.

Nevertheless, the data derived from these tests can be used to serve as a warning that the manufacturing process may be out of control. This is usually indicated by a shift or abnormality of one or more of the relay performance characteristics as shown by control chart curves plotted from the test data. If an undesirable trend is observed, the cause should be determined and the necessary design or manufacturing action taken to eliminate the source of the trouble.

Issued by
Technical Information Division
Sandia Corporation
Albuquerque, New Mexico