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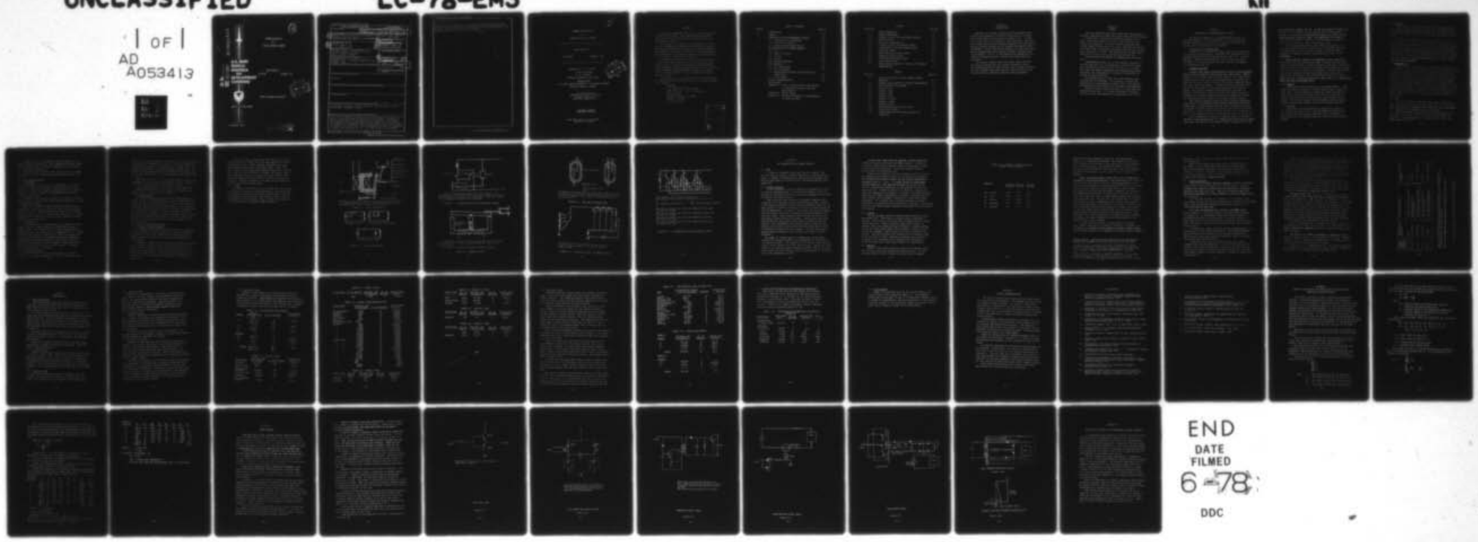

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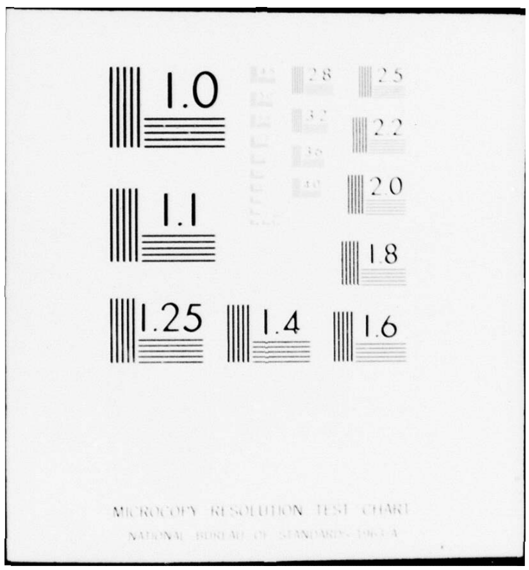
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STORAGE RELIABILITY

OF

MISSILE MATERIEL PROGRAM

U.S. ARMY
MISSILE
RESEARCH
AND
DEVELOPMENT
COMMAND

RELAY ANALYSIS

LC-78-EM3 FEBRUARY 1978

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This report documents findings on the non-operating reliability of relays. The study covers 2086 million part-hours. Elements of relay design and of the processes at the contacts are reviewed. The possibilities of solid state and saturable core alternatives are described. Recommendations include periodic test and inclusion of oxygen in the fill gas. This information is part of a research program being conducted by the U. S. Army Missile R&D Command,

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Redstone Arsenal, Alabama. The objective of this program is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. This report updates and replaces report LC-76-EM3 dated May 1976.

STORAGE RELIABILITY

OF

MISSILE MATERIEL PROGRAM

RELAY ANALYSIS

LC-78-EM3 FEBRUARY 1978

Prepared by: D. F. Malik

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U. S. ARMY MISSILE RESEARCH & DEVELOPMENT COMMAND

REDSTONE ARSENAL, ALABAMA

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ABSTRACT

This report documents findings on the non-operating reliability of relays. Long term non-operating data has been analyzed and reliability predictions have been developed for relays.

This report is a result of a program whose objective is the development of non-operating (storage) reliability prediction and assurance techniques for missile materiel. The analysis results will be used by U. S. Army personnel and contractors in evaluating current missile programs and in the design of future missile systems.

The storage reliability research program consists of a country wide data survey and collection effort, accelerated testing, special test programs and development of a non-operating reliability data bank at the U. S. Army R&D Missile Command, Redstone Arsenal, Alabama. The Army plans a continuing effort to maintain the data bank and analysis reports.

This report is one of several issued on electromechanical devices and other missile materiel. For more information, contact:

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SECTION 1
INTRODUCTION

Materiel in the Army inventory must be designed, manufactured and packaged to withstand long periods of storage and "launch ready" non-activated or dormant time. In addition to the stress of temperature soaks and aging, they must often endure the abuse of frequent transportation and handling and the climatic extremes of the forward area battle field environment. These requirements generate the need for special design, manufacturing and packaging product assurance data and procedures. The U. S. Army Missile R&D Command has initiated a research program to provide the needed data and procedures.

This report updates report LC-76-EM3, dated May 1976 and covers findings from the research program on relays. The program approach on these devices has included literature and user surveys, data bank analyses, data collection from various military systems and special testing programs.

SECTION 2
SUMMARY

Data was collected from four sources and three missile programs representing 2,086 million part hours with 45 failures.

Statistically significant differences appear in the data. These may indicate a trend in time resulting from changes in technology. The best consistent sources show a mean storage failure rate of 8.7 fits (failures per billion part hours) and a 90 percent confidence that the true failure rate lies below 17.0 fits. The data showing failures shows a range of 8.7 to 637 fits in the storage failure rate.

Failure modes attributable to storage were not identified.

Recommendations made are (1) for storage, periodic inspection and test, (2) in manufacture, inclusion of oxygen as a significant fraction of the fill gas, (3) in design, care that the contact ratings are not exceeded during make and break, and consideration of possible alternatives to perform the relay function.

The possibilities of solid state and saturable core alternatives are described. The elements of design and application of electromagnetic relays, and of the physical processes which take place at the contacts, are discussed.

Operating failure rates are from 1 to 7,298 times the storage failure rate. In a common environment (ground), the failure rate non-operating to operating ratio is 1:20.

SECTION 3

INTRODUCTION TO ELECTROMAGNETIC RELAYS

The design or selection of electromagnetic relays is a field too extensive to be covered here. An outline and some selected examples will be given to introduce the terminology and the type of consideration which enters.

3.1 Construction and Terminology

Figure 3-1 is a sketch of a common type of relay construction showing the terminology. The term relay implies that the voltage interrupted at the contacts is not high, i.e., not over 300 volts. Devices which interrupt high voltages are termed contactors or circuit breakers, and have special arrangements for extinguishing the arc.

3.1.1 Contact Functions

Contacts have three functions which should be distinguished, namely, making, breaking, and carrying the load current. Making current may be several times the load current, e.g., motors when starting have no back emf, the cold resistance of incandescent lamps may be only a tenth of the hot resistance, capacitor inputs will draw a charging current. Although the excess current flows only for a short time, it can cause welding of the contacts. Mercury and tungsten contacts are particularly resistant to welding. Two parallel contacts can more than double the inrush capability, the reason being that the contact bounce on closing will not draw an arc if there is a parallel contact closed.

The carrying capacity depends on the allowable temperature rise which in turn depends on the conductivities and cross sectional area. A soft contact material such as silver will deform to create a relatively large cross section area with a given contact force. Where current flows thru springs, it is customary to allow a large margin to avoid destroying the temper of the spring.

Ac is substantially easier to interrupt than dc, because the arc is extinguished when the voltage across the contacts passes thru zero. Ratings show the carrying current capacity for ac and an interrupting capacity for dc. If the dc voltage is halved, the contacts will be capable of interrupting three times as much current. The process of interrupting current will create voltage transients with inductive loads. The insulation will usually stand these transients. Circuitry is often added to reduce the voltage peak, Figure 3-2 shows two possibilities.

In a configuration such as that shown in Figure 3-1, an arc formed across one set of contacts on interruption may still be present when the other contact is made. Either a slower transfer or a magnetic blowout could be used if this is unacceptable.

Where possible, contacts are designed to have snap-action, which means that the contacts are under a positive pressure when closed, and separated by a definite distance when open. Where this cannot be done, the contacts will chatter, and the external circuit must be such that the chatter is acceptable. Usually, the chattering contact activates another relay which locks in (or out). Examples are thermostats (cf. Figure 3-3) and voltage or current level controls. Multiple contacts are often used, e.g., make-before-break and break-before-make pairs.

3.1.2 Pigtail

Where current must be brought to a movable contact, a soft copper stranded wire wound in a spring shape called a pigtail is often used. It is customary to design the pigtail so that its fatigue life exceeds the contact life, but it is necessary to insure that the pigtail is replaced when the contacts are replaced. The use of a pigtail can be avoided by using a double movable contact which bridges a pair of stationary contacts.

3.1.3 Armature

The inertia of the armature is a significant factor in the opening and closing rate. For resistance to shock and vibration the armature is made symmetrical about the hinge, so that torques are not produced about the hinge by linear accelerations.

3.1.4 Spring

The retract spring supplies all of the contact force for the normally closed contacts, and also tends to prevent shock and vibration from disturbing the contacts. The opening force is partly from the retract spring, but primarily from the contact spring.

A number of mechanical limits must be observed: the elastic limit is maximum stress which does not permanently alter the spring geometry, the proportional limit is the maximum stress for which the deflection is linear with the stress, the fatigue limit is the maximum stress which will not result in eventual failure, the drift limit is the maximum stress for which constant load does not produce a significant change in ultimate deflection. These are given in (usually) descending order. None of these limits should be exceeded.

3.1.5 Magnetic Core

If the coil is energized by ac, the magnetic core should not saturate and should be laminated to reduce eddy current losses. A shading coil can be used with ac to prevent the torque on the armature from going to zero, this will reduce hum and chatter in the relay. Since the air gap is substantially less when closed, the coil current required to hold the relay closed is substantially less than that required to close it. This may result in specifications for current for (1) pickup, (2) hold, (3) dropout, and (4) nonpickup. A non-magnetic standoff called an antifreeze pin may be used to prevent the air gap from becoming too small, which could result in failure of the relay to open or in slow opening.

3.1.6 Coil

The coil typically consists of many turns of fine wire. Very fine wire is difficult to work with, and is also more subject to corrosion. In some circuits corrosion can be minimized by connecting to the negative side of the supply.

Coils often have a shorter shelf life than service life. The reason is that the heat of operation tends to drive out moisture. In sealed relays, with a controlled fill gas, this effect should not occur.

Changing flux in the magnetic circuit, whether ac or dc, induces voltage in the coil. This induced voltage may represent a problem either in terms of insulation, or of reaction in the external circuitry.

Ac coils, and fine wound coils, have a greater tendency to develop hot spots, which limits the overall rating of the coil.

3.2 Other Relay Features

3.2.1 Latching

The commonest type of latch is electrical. One set of contacts is used to apply power to the relay coil, so that once it is activated it remains activated until the latching circuit is broken. Figure 3-3 illustrates the use of an electrical latch also.

A magnetic latch can be used when it is desired to maintain a relay in either state without power consumption. Figure 3-4 shows one geometry.

Where it is important that two sets of contacts not be closed at the same time, a mechanical latch can be provided, so that one set of contacts can be closed only if the other is open. (Both sets can be open at the same time.) A classic application is forward and reverse drives, which must not be activated at the same time.

3.2.2 Time Delay

Very long and very accurate delays are obtained by using a motor and cam. Long delays can be obtained by using a thermal timer. The heating cycle is rather dependent on the applied voltage, but the cooling is independent of it. Either (or both) can be used. Short delays, under one second typically, can be obtained by increasing the contact spacing or by using an additional shorted coil which acts to prevent build up of the magnetic field. Negative temperature coefficient resistors can be used to create a delay. A dashpot can create delays up to a minute.

3.2.3 Reed Construction

A construction offering many advantages is shown in Figure 3-5. A magnetic material is used for the reeds which matches the thermal expansion coefficient of the glass envelope. An external coil actuates the switch. It is not uncommon for as many as 20 switches to be actuated by a single coil. The switches can be built in normally closed, normally open, or double throw configurations. The envelope is typically filled with a non-reactive gas. For high voltage levels a vacuum may be used.

When operated dry, i.e., at very low voltage levels, life expectancy is on the order of 500 million cycles. Contacts are usually gold plated for this type of service.

The resonant frequency of the reed is about 800 hertz in standard designs and up to 5000 hertz in microminiature designs (0.5 in. long by 0.1 in. diameter).

3.2.4 Classification

No generally accepted classification scheme exists for relays, and it is usually possible to find a relay which cannot be fit into a proposed scheme. It is the usual practice to further identify a relay by some feature, e.g., latching, time delay, reed, rotary,crystal can, vacuum, but these terms are not mutually exclusive. Crystal can refers to a size (that of the can standard for quartz frequency control crystals) and implies an hermetically sealed can. Rotary implies that one pole may be connected with any one of a number of stationary contacts.

3.3 Circuits Using Relay Control

3.3.1 Multiple Control Circuits

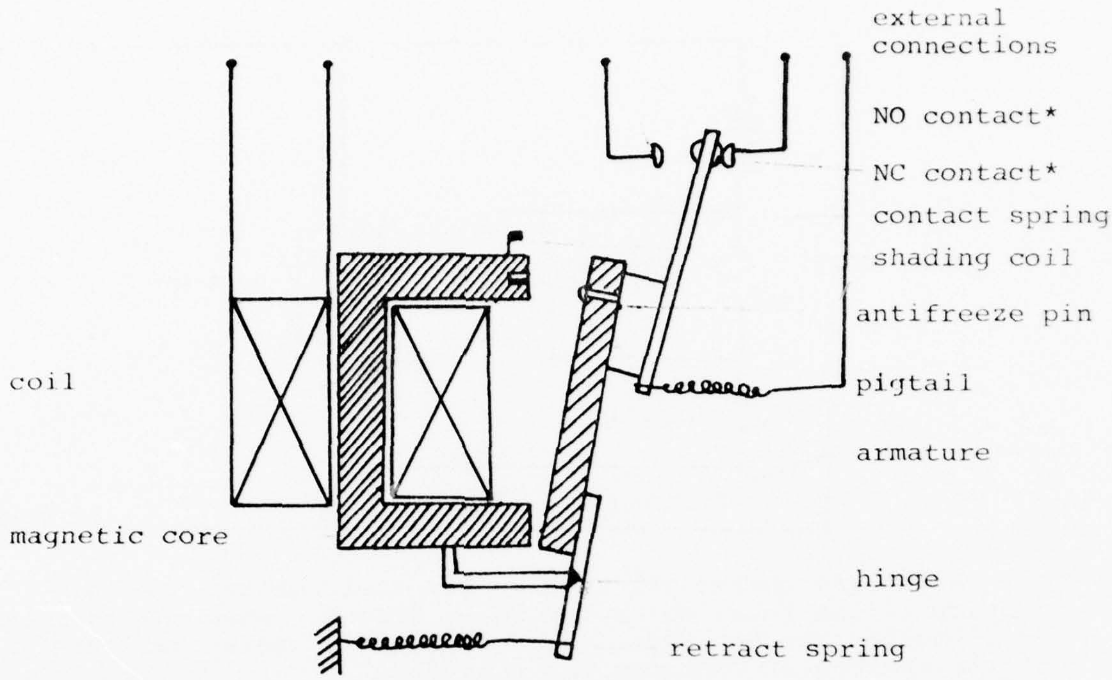
The question of obtaining multiple control at a distance using a minimum of control wiring has received a good deal of attention. Well known communication techniques such as phantom circuits and tones on a carrier can be adapted for relay control.

A number of simpler but less obvious techniques are available. Figure 3-6 shows a bridge circuit which can be used to drop out any single relay at a distance using only one control wire and ground. Connecting the control wire to one of the set points creates a bridge balance which puts zero voltage across the selected coil, while all of the others are energized.

Figure 3-7 shows a progressive lock and unlock circuit. Every time PB1 is closed, the first odd numbered relay that is open will close. Every time PB1 is opened, the first even numbered relay that is open will close. Every time PB2 is closed, the highest odd numbered relay that is closed will open, and everv time PB2 is opened, the highest remote even numbered relay that is closed will open. (PB1 and PB2 should be mechanically interlocked to prevent simultaneous closure.) Multiple contacts on the same relay provide many possibilities and are often used.

3.3.2 Logic

It should be noted that Boolean algebra does not provide a satisfactory analysis of relay operation. The differences in timing of the opening and closure of contacts on the same relay produces uncertainties which cannot be dealt with in the formalism of the algebra. Many circuits take advantage of these variations to produce desired effects.



*"Normally open" and "normally closed" define the position of the contacts when the relay is not energized, which is not necessarily the usual position of the contacts.

FIGURE 3-1. RELAY TERMINOLOGY

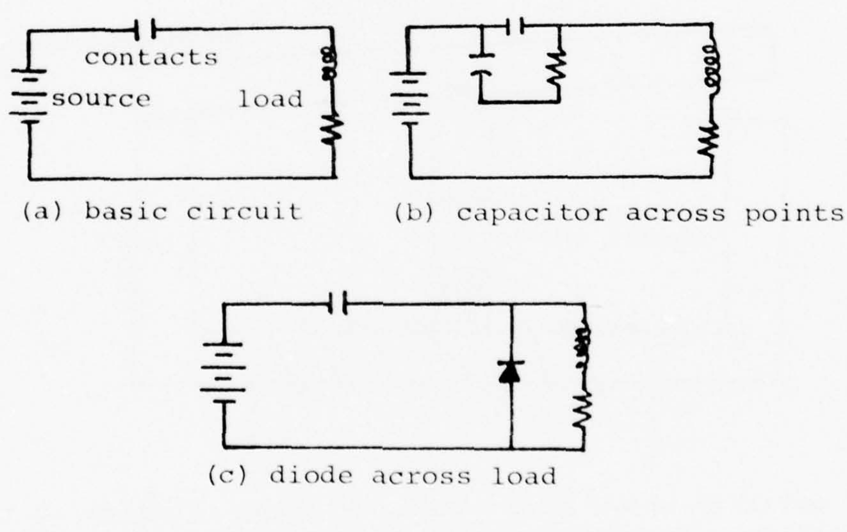
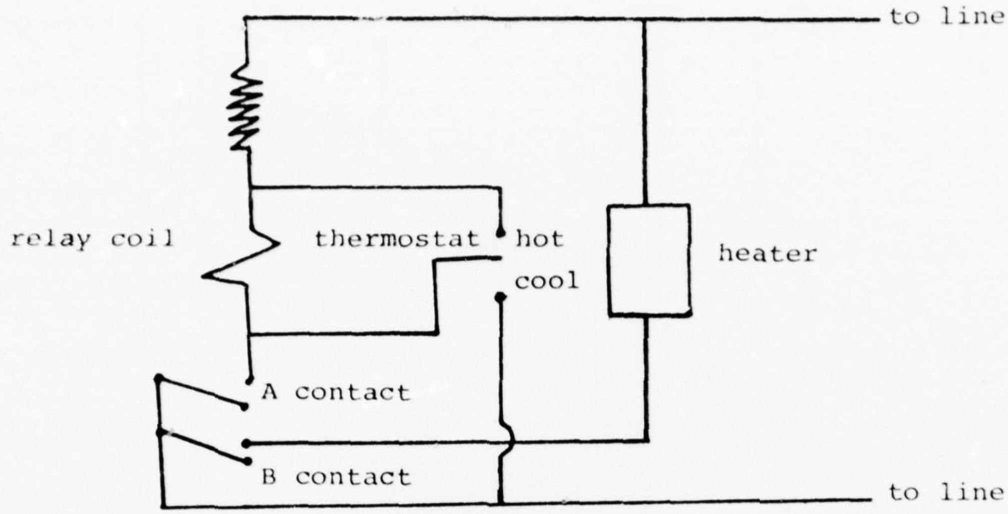
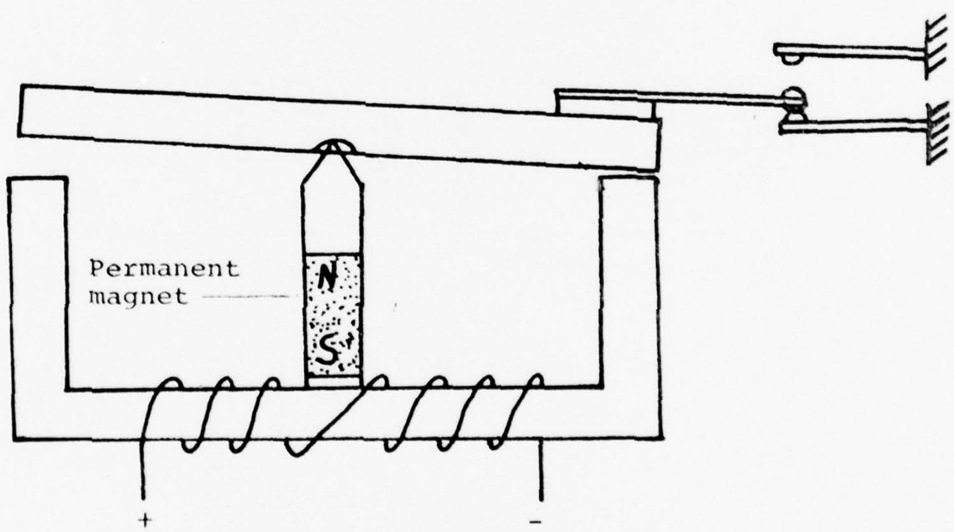


FIGURE 3-2. CONTACT PROTECTION



After the thermostat touches its cool contact, the A contact of the relay holds the relay closed. When the thermostat touches its hot side, the relay opens. Note that chatter at the thermostat contacts has no effect.

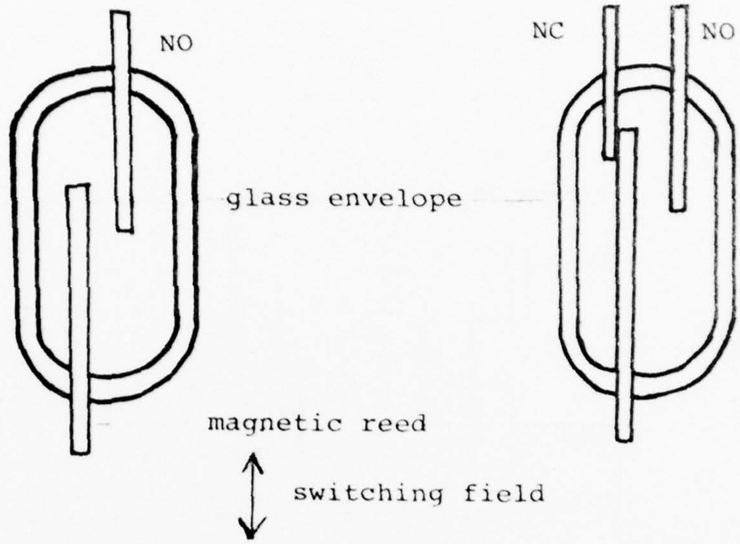
FIGURE 3-3. LATCHING CIRCUIT FOR CHATTERING CONTACT



The polarity shown will cause the relay transfer to the other position. Reverse polarity places the relay in the position shown.

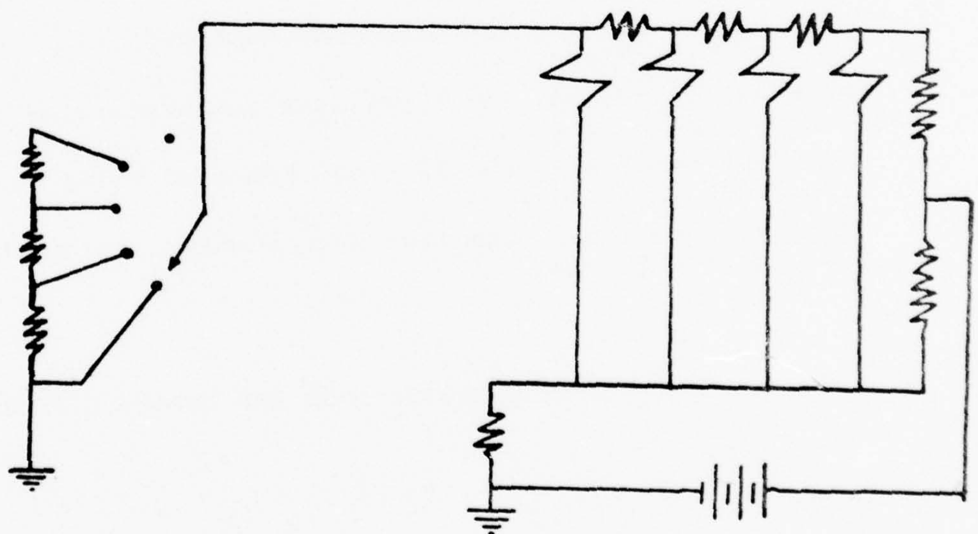
No power is required to maintain either position.

FIGURE 3-4. MAGNETIC LATCH



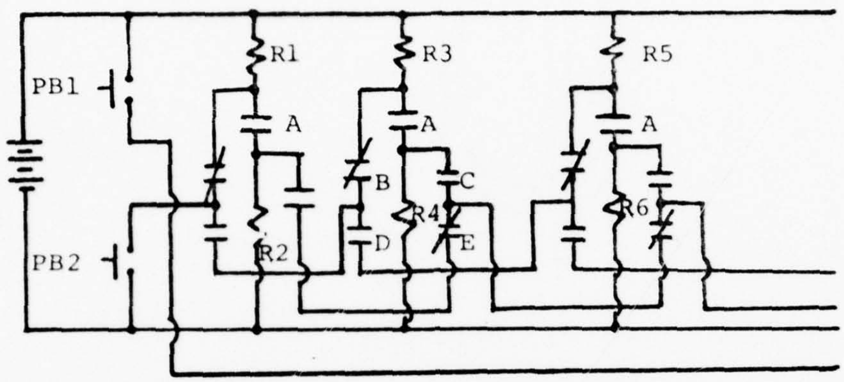
The magnetic reed bends to the right when a magnetic field is applied in the vertical direction on the page, thereby closing the normally open contacts and opening normally closed contacts.

FIGURE 3-5. REED RELAY CONSTRUCTION



Suitable setting of the switch on the left will cause any one (or none) of the relays on the right to open.

FIGURE 3-6. A BRIDGE CIRCUIT FOR REMOTE CONTROL



Odd numbered relays have one contact, A.
Even numbered relays have four contacts, B, C, D, & E.

 normally open contact  normally closed contact

When PB1 is closed, the first odd numbered relay that is open will close.

When PB1 is opened, the first even numbered relay that is open will close.

When PB2 is closed, the last odd numbered relay that is closed will open.

When PB2 is opened. the last even numbered relay that is closed will open.

FIGURE 3-7. A PROGRESSIVE LOCK AND UNLOCK CIRCUIT

SECTION 4

AN INTRODUCTION TO CONTACT PHYSICS

4.1 Life

A number of phenomena take place at the contacts, some of which tend to provide a wearout mechanism in the reliability sense. A common life expectancy is one million operations, but the dry reed types run to 500 million, and mercury wetted types above that.

4.2 Current Carrying

A metal exposed to air will quickly be covered with a film of oxide or adsorbed oxygen. If the film is thick, it will be practically insulating; if thin, it will be permeable to electrons by means of the tunnel effect.

When two such metal surfaces are pressed together, only a portion of the surfaces carries the mechanical load. Because of the surface roughness of even polished surfaces, there will be small regions of plastic deformation as well as larger regions of elastic deformation. In parts of the regions of plastic deformation the surface film will be separated and metal-to-metal contact will occur. These isolated spots account for most of the electrical conductivity of the contact. These spots are always cold-welded, but the elastic forces help to break the weld on opening. The influence of the surface films in limiting cold welding and friction is desirable, and lubrication may be added to electrical contacts for this purpose. For the same reason, oxygen should be present if the contacts are within a sealed enclosure.

The number of contact spots is proportional to the force pressing the contacts together, but independent of the area of the contact surfaces. The geometry of the contact spots does not change, on the average, with the contact force. Notice that this model of the contact surfaces predicts Coulomb's law of friction, which states that the friction force is proportional to the normal force, but independent of area.

If more than a few volts are applied, another mechanism, called fritting, creates metal-to-metal contact. Fritting is a result of metallic ion migration due to electrostatic fields at the metal-film interface. It can both expand existing contact spots and create new ones.

Because the equations for heat conduction and for electrical conduction are similar, there is a fixed relation between the voltage drop across a contact and the maximum temperature attained within it. Table 4-1 shows values for some common contact materials. The required voltages are quite low, so that the corresponding phenomena can be expected in most practical circuits. Softening refers to an annealing temperature. When this temperature is reached in a contact, the work hardening caused by the plastic deformation is relaxed, and the metal-to-metal contact area increases, resulting in a decreased contact resistance. In a similar way, a further decrease in contact resistance is noted when the melting point is reached. The boiling point is only reached during processes associated with the opening of contacts.

4.3 Closing

As the contacts close, the voltage stress rises until the gap breaks down. Thus there is usually a brief discharge on closing. For 10 volts across the gap, breakdown occurs at about 0.0001 mm in air. There is usually some contact bounce at closure, which can produce arcing and welding. Inrush currents can be far higher than steady state currents, factors of 10 to 20 are not uncommon. Many things can be done to minimize the effects: multiple contacts will prevent an arc forming as long as one of them is closed, cadmium and tungsten are resistant to welding, the mechanism can be designed with leverage to break the welds, and circuit modification is a possibility.

4.4 Opening

There are two major processes of material transfer across the contacts, both occur during the opening process. As the contacts begin to open, a bridge of molten metal is formed,

TABLE 4-1. CRITICAL VOLTAGES FOR SOME COMMON CONTACT MATERIALS

Material		Softening Voltage	Melting Voltage	Boiling Voltage
Ag	Silver	0.09	0.37	0.75
Au	Gold	0.08	0.43	0.9
Cu	Copper	0.12	0.48	0.8
Pt	Platinum	0.25	0.71	1.3
W	Wolfram	0.6	1.1	2.1

unless the contact voltage is very low. As this bridge is drawn out, it eventually separates. The separation is usually due to boiling of the metal at the hottest point, but sometimes due to surface tension. The heating is usually unsymmetrical (due to the Kohler effect* in short bridges, and to the Thompson effect** in long bridges), so that there is a net transfer of material.

After the bridge breaks, arcing will occur if sufficient voltage and current are available. The requirements are quite low: about 9 volts and under 0.5 ampere, depending somewhat on the material of the contacts and the atmosphere.*** Arcing is characterized by intense heating of very small spots on the contacts and conduction thru an ionized plasma. Material loss depends on the temperatures attained. In short arcs, the spots are virtually the same size, and the anode becomes hotter and therefore loses more material. In long arcs, the cathode spot is smaller and develops a higher temperature, and so loses more material, even though more heat is delivered at the anode. Curiously, arcs in air lose much less material than arcs in vacuum; the reason is that the cathode spot is much larger and cooler because the oxygen lowers the work function at the cathode surface. Some materials with a high melting point, notably wolfram (tungsten) and carbon, are able to support an arc without melting, and material loss is thus reduced.

In both bridges and arcs, the net material transfer is only a small fraction of the material involved in exchange. It is possible to balance out the material transfer to some extent, but the usual practice is to replace the contacts after a number of

*Kohler effect: Electrons tunneling thru a film will deliver energy which appears as heat when they arrive at the anode.

**Thomson effect: Heat is given off or absorbed by current carriers coming from warmer to cooler regions of the current path in a conductor. The Thomson effect may be of either sign, and is known to change sign with temperature in platinum.

***The voltage is required to produce ionization in the plasma between the contacts. The current is required to produce sufficient heating to produce thermionic emission at the cathode.

operations. Where arcing is intense, they may be replaced after every operation.

When the cold welds are pulled apart at contact opening, the break is apt to occur within one of the contacts rather than at the original interface. The material in and about the original interface is stronger than the parent material because of the work-hardening. This is considered to be a wear process rather than a material transfer process.

4.5 Contact Materials

The choice of contact material depends on the duty required. Usually both contacts are made of the same material. Material transfer would make this effectively the case even if different materials were used initially. The use of different materials introduces thermoelectric effects because of the high temperatures at the contact.

For very low voltages and currents, it is important that the contact material be free of corrosion and not form an insulating film. Gold is the most satisfactory material, metals in the platinum group are also used.

For light and moderate duty, silver is the most satisfactory material. The oxide tarnish, although readily visible, is conducting. (In atmospheres containing sulfur, however, a nonconducting sulfide is formed which is a serious problem.) High conductivity of the bulk material, softness, and low melting point, all help to insure a low resistance contact with moderate contact force.

For heavy duty, where arcing is the prime consideration, the melting point is the prime consideration. Wolfram, molybdenum, and carbon are able to sustain an arc without reaching their melting point (sufficient thermionic emission occurs at temperatures below their melting point).

Sliding contacts are not used in relays, but require somewhat different considerations. For high power applications carbon is used almost exclusively, because of its low wear and low friction, despite a rather high bulk resistivity. Although used against copper, the actual contact is carbon to carbon after a brief run in.

Mercury provides a contact material that is not damaged by arcing. Designs in which the liquid requires a fixed position are not suited for applications where shock and vibration are problems. By using thin films in which surface tension is the dominate force, devices which can be mounted in any position and will withstand moderate acceleration (5 G) in any direction have been constructed. Designs using liquid mercury cannot be used below the freezing point, -40°C.

The common conductors are unsatisfactory as contacts. Copper tends to weld, and is readily damaged by arcing. Aluminum forms a thick, tough insulating film of oxide, and is one of the few metals which creep indefinitely at room temperature, so that it is difficult to maintain contact force.

The pure metals (cf. Table 4-1) are fairly satisfactory as contact materials, but there has been a great deal of study of alloys and composites. Some examples: The addition of 30 to 50 percent palladium to silver will avoid the formation of sulphides. Wolfram with silver added will resist arcing nearly as well as wolfram alone, while the silver improves the conductivity. The addition of wolfram carbide to gold inhibits material transfer resulting from cold welding though the wolfram carbide takes the form of isolated particles rather than a solid solution. Perhaps the particles constitute weak spots, so that the break is always made at the same place in the cold weld.

Silver with gold plate is suitable for either very light or moderate duty, though not for both at the same contact. The gold is effectively removed by arcing or bridging in the higher power circuits.

The addition of a small percentage of cadmium to silver helps to suppress arcing. The cadmium near the surface becomes oxidized, and the dissociation temperature for cadmium oxide is slightly below the melting point of silver.

Table 4-2 is a classification of the duty requirements. The terminology is not standardized, despite several attempts, so this figure is illustrative rather than definitive.

Voltage across contacts (Note 1)	Classification (Note 2)	Dominant mechanism	Typical contact material
0 - 0.5	dry	Surface films are critical	Gold
0.5-2.0	light duty	Bridging takes place, but no arcing	Silver
2.0-10	medium duty	Vaporization takes place, but arcing cannot be sustained	Silver-Cadmium
10-300	heavy duty	Arc can be sustained, but will not reignite	Wolfram
300-up	breaker	Arc must be extinguished by lengthening and cooling	Copper under oil

Note 1: Voltage across contacts is voltage at break. It is influenced by inductance, and so is often larger than the source voltage. Voltage values vary somewhat with the materials used.

Note 2: The terms are widely used, but the definitions given vary.

TABLE 4-2. CONTACT CLASSIFICATION BY SERVICE REQUIREMENTS

SECTION 5
DATA ANALYSIS

5.1 Data Description

Data was received from four sources and three missile programs representing 2085.7 million part non-operating hours with 45 failures reported. Table 5-1 summarizes the relay data from each source.

The data in Source A contained data from Source C. A comparison was performed which identified common data between the two sources. Data was removed from Source A to avoid duplication. The hours and failures in parenthesis below Source A data represents total Source A data while the hours and failures listed on the same line represents unique data to Source A.

The data represents a wide variety of devices. Failure rates for individual devices range from 8.7 fits (failures per billion hours) to 637 fits. The overall failure rate is 20.2 fits.

Table 5-2 through 5-8 presents data from each source identifying the type of relay where available. Each data source is described below.

5.1.1 Source A Data

Source A represents a reliability study performed under contract to RADC in 1974. This source identified the type and quality grades for the devices, however, it provided no information regarding storage conditions or individual programs. Data for the device types which are in parenthesis in Table 5-2 is a duplication of data from Source C in Table 5-4.

5.1.2 Source B Data

The storage data under Source B actually represents standby data in an orbiting satellite environment. One failure was indicated in 7.46 million relay standby hours.

5.1.3 Source C Data

Source C data represents a reliability study performed under contract to RADC in 1968. No environments were provided. For approximately 642 million relay non-operating hours, 20 failures were reported. The data includes non-operating hours on a number of different types of relays. The failures, however, were recorded against relays for which the type was not identified.

5.1.4 Source P Data

Source P represents a special aging and surveillance program. Devices are stored in a controlled environment. The data included 42 holding relays stored for an average age of 66 months (the oldest unit was 71 months) and 39 latching relays stored for an average age of 55 months (the oldest unit was 60 months).

One latching relay failed at test age 20 months. No failure analysis was available, however, a retest by the manufacturer could not duplicate the failure.

5.1.5 Missile E-1 Data

Missile E-1 data consists of 874 missiles stored for 20 months. The missiles were stored in containers exposed to external environmental conditions in the northeast U. S. They were also transported once from coast to coast. The data included three types of relays: DPDT, rotary motor and thermal. Two failures were recorded on the rotary motor relays.

5.1.6 Missile G Data

Missile G data consists of 39 missiles stored for periods from 28 months to 56 months for an average storage period of 39 months. The missiles in storage containers experienced the following environments: 12 missiles stored outside in the southeast desert; 12 missiles stored outside in the northeast U. S.; 12 missiles stored on the Gulf Coast; and 23 missiles stored in bunkers in the southeast U. S. No failures were recorded for the armature relays.

5.1.7 Missile I Data

Missile I data consists of 2,070 missiles stored for periods from 1 month to 40 months for an average storage period of 14 months. Approximately 80 percent of the missiles were stored in U. S. depots while the remainder were stored at various bases around the country. Two failures were recorded in armature relays at test age 8 months and age 12 months.

TABLE 5-1. NON-OPERATING DATA SUMMARY

SOURCE	MILLION PART NON-OPER. HRS.	NO. OF FAILURES	FAILURE RATE IN FITS
A	165.793	0	(<6.0)
	(797.111)	(19)	
B	7.46	1	134.0
C	642.109	20	31.1
P	3.59	1	278.6
MISSILE			
E-1	382.812	2	5.2
G	4.5	0	(<222.2)
I	82.36	2	24.3
TOTALS	1288.624	26	20.2
	(2085.734)	(45)	

TABLE 5-2. SOURCE A DATA

DEVICE TYPE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
(General)	(587.4)	(19)	(32.3)
General, Sub	144.1	0	(<6.9)
(Crystal Can, Latching)	(43.46)	(0)	(<23.0)
Latching, Gen.	12.33	0	(<81.1)
(Thermal)	(0.458)	(0)	(<2183.)
Non-Latching, General	9.363	0	(<107.)

TABLE 5-3. SOURCE B DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
-	1912	7.46	1	134.0

TABLE 5-4. SOURCE C NON-OPERATING DATA

DEVICE TYPE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
Microminiature	.1168	0	(<8562)
Miniature	.7244	0	(<1380)
Rotary	.164	0	(<6098)
Solenoid	.370	0	(<2703)
Sw.- 2 pole	.318	0	(<3145)
Thermal	.458	0	(<2183)
Goldplated-4 pole	79.0	0	(<12.7)
Armature	.322	0	(<3106)
"	.0658	0	(<15198)
"	.8510	0	(<1175)
"	1.2604	0	(<793)
"	.3699	0	(<2703)
"	9.6177	0	(<104)
"	5.1564	0	(<194)
"	2.6460	0	(<378)
"	1.8096	0	(<535)
Crystal Can	1.0562	0	(<947)
" "	9.9152	0	(<101)
" "	1.0168	0	(<983)
" "	2.6577	0	(<376)
" "	27.872	0	(<36)
" "	.0728	0	(<13736)
" "	.8792	0	(<1137)
-	1.85	0	(<541)
-	12.576	0	(<80)
-	3.050	0	(<328)
-	37.688	0	(<27)
-	12.207	0	(<82)
-	128.	3	23.4
-	281.	15	53.4
-	9.982	1	100.2
-	8.976	1	111.4

TABLE 5-5. SOURCE P DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
Holding	42	2.02	0	(<495)
Latching	39	1.57	1	637.

TABLE 5-6. MISSILE E-1 DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
DPDT	6118	89.323	0	(<11.)
Rotary Motor	15732	229.687	2	8.7
Thermal	4370	63.802	0	(<16.)

TABLE 5-7. MISSILE G DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
Armature	156	4.5	0	(<222)

TABLE 5-8. MISSILE I DATA

DEVICE TYPE	NO. OF DEVICES	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
-	2070	20.59	0	(<49.)
Armature	6210	61.77	2	32.

5.2 Data Evaluation

The data from the various sources was combined by device type. Only three relay types plus the general category reported failures. The resulting failure rates range from 8.7 fits for rotary relays with two failures reported to 71.9 fits for latching relays with one failure reported.

Since the failure rates by device type represent a very small number of failures except for the general category a test of significance (described in Appendix A) was performed to test whether a single failure rate could describe all the relay types that showed failures. The test indicated that there was no significant difference. The combined data for all relay types showing failures including the "general" type represents 833.4 non-operating hours with 26 failures giving a pooled failure rate of 31.2 fits.

Next a test was performed to pool all relay data (including 0 failure data) into a single general relay category. This test indicated there was a significant difference when the 0 failure cases were included.

Since the failure data by device type was insufficient to determine differences. The data was broken out again by source and regrouped. All relay data from missile programs were placed in one group and the other sources into a second group. These pooled data groups were tested and no significant differences were measured within the groups. The pooled data is shown in Table 5-10.

In Table 5-10 the data under group 1 gives a failure rate of 26.9 fits with a 90% confidence that the true failure rate is below 35.7 fits. Group 2 gives a failure rate of 8.5 fits with a 90% confidence that the true failure rate is below 17.0 fits.

The missile sources represent newer devices than the other sources. Until sufficient data becomes available to distinguish between relay types, it is recommended that the non-operating failure rate of 8.5 fits be used to represent the best case for a "general" relay category within the current state-of-the-art.

TABLE 5-9. NON-OPERATING DATA BY RELAY TYPE

TYPE	NON-OPERATING STORAGE HRS. IN MILLIONS	FAILURES	FAILURE RATE IN FITS
General	523.379	21	40.1
General, Sub	144.1	0	(<6.9)
Latching, Gen.	13.9	1	71.9
Non-Latching, Gen	9.363	0	(<106.8)
Microminiature	.1168	0	(<8561.6)
Miniature	.7244	0	(<1380.5)
Rotary	229.851	2	8.7
Solenoid	.370	0	(<2702.7)
Sw. - 2 pole	.318	0	(<3444.7)
Thermal	64.260	0	(<15.6)
Goldplated 4 pole	79.0	0	(<12.7)
Armature	22.1588	0	(<45.1)
Crystal Can	43.4699	0	(<23.0)
Holding	2.02	0	(<495.0)
DPDT	89.323	0	(<11.2)
Armature	66.27	2	30.2

TABLE 5-10. POOLED DATA GROUPS

GROUP 1

SOURCE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
A	165.763	0	(<6.0)
B	7.46	1	134.0
C	642.109	20	31.1
P	3.59	1	278.6
TOTALS	818.952	22	26.9

GROUP 2

MISSILE	NON-OPER. HRS. IN MILLIONS	NO. OF FAILURES	FAILURE RATE IN FITS
E-1	382.812	2	5.2
G	4.5	0	(<222.2)
I	82.36	2	24.3
TOTALS	469.672	4	8.5

5.3 Operational/Non-Operational Reliability Comparisons

Operational failure rate data for relays was extracted from report RADC-TR-74-268, Revision of RADC Nonelectronic Reliability Notebook, D. F. Cottrell, et al, Martin Marietta Aerospace, dated October 1974. This data is shown in Table 5-11 and compared with the non-operating failure rate prediction. Comparing the common environment (ground) indicates a non-operating to operating ratio of 1:20.

TABLE 5-11. OPERATIONAL/NON-OPERATIONAL RELIABILITY COMPARISON

ENVIRONMENT	PART HOURS (10^6)	NO. OF FAILURES	FAILURE RATE IN FITS	$\lambda_{op}/\lambda_{no}$
Non-Operating				
Ground, Fixed	469.672	4	8.5	-
Operating				
Satellite	118.835	1	8.4	1.
Ground	78.261	13	166.	20.
Airborne	8.602	58	6743.	793.
Helicopter	2.531	157	62031.	7298.
Shipboard	22.552	17	754.	89.
Submarine	43.031	55	1278.	150.

5.4 Failure Modes

There is no available data on the failure modes of the failed relays in the studies of Table 5-1. The commonest operational failure mode is open or intermittent contacts, which is caused by contamination, usually particulate, of the contacts. Sticking contacts is the second most common operational failure mode, and is caused by either hot or cold welding.

SECTION 6

STORAGE RECOMMENDATIONS

The field of protective relaying has some close parallels with missile requirements. The purpose there is to prevent damage to power systems. The system is continually monitored by a complex set of relays which are able to distinguish faults both as to time and location, and which disconnects any part of the system containing a fault. Practice in this field has been to inspect and test the protective relays annually.

No applicable storage experience is at hand, but it is suggested on general principles that electromagnetic relays be inspected and operated periodically. The inspection should particularly look for evidence of corrosion, and the operation should test for shorts and opens. Operation under load would not seem to be a requirement.

Where the contacts are in a sealed enclosure, the fill gas should include oxygen. Appendix C is a copy of a report giving detailed references to the literature on the role of oxygen.

Of possible importance for storage are failure modes due to corrosion. Historically, this has been a problem where fine wire is used for the coil, but sealed construction has overcome it. The coil must have insulation, and there has been some problem due to vapors of organic material from the insulation or potting compound on the contact surface, when the coil and the contacts were sealed into a common enclosure.

Relay design and practice have matured to the point where hardly any failures remain to be examined.

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APPENDIX A

TEST OF SIGNIFICANCE OF DIFFERENCES IN FAILURE RATES (MORE THAN TWO POPULATIONS)

The storage reliability data is obtained from numerous sources. A detailed qualitative analysis is performed on the data to classify devices, environments, uses, quality levels, failures modes & mechanisms, and so on. Once the data sets are grouped according to these analyses, it is still not certain whether grouped sets of failure data are in truth from the same statistical population. It is possible that the failure rate characteristics of identical devices from the same manufacturers, with the same application, use environment, and so on, are not from the same population in terms of reliability -- possibly due to some problem on a production line for a certain lot or other factor.

Therefore a statistical test is performed to determine if the different data sets could be from the same statistical population.

The technique used is for more than two data sets and is taken from "Statistical Methods for Research Workers," R. A. Fisher, 13th edition, Hufner, 1963, pages 99-101.

The techniques assumes that the underlying failure distributions each have the same constant failure rate (λ). Therefore, the probability of a number of failures for each population can be represented by the Poisson distribution.

A single failure rate is calculated based on the pooled data sets being tested.

$$\lambda = \frac{\sum_{i=1}^{N} f_i}{\sum_{i=1}^{N} T_i}$$

where λ = Mean failure rate for all data sets

f_i = the number of failures in data set i

T_i = the total storage hours in data set i

n = the number of data sets being tested

The expected number of failures and the difference between the expected number of failures and actual failures is calculated for each data set based on the pooled data:

$$M_i = \lambda T_i$$

$$d_i = |f_i - m_i|$$

where

M_i = expected number of failures for data set: (based on the pooled data sets)

d_i = absolute value of the differences between the expected number of failures and the actual failures for data set i.

Next, lower and upper limits are calculated for the Poisson distribution:

$$U_i = [M_i + d_i] \text{ (if } U_i = f_i\text{, set } U_i = f_i - 1)$$

$$L_i = \langle M_i - d_i \rangle \text{ (if } L_i = f_i\text{, set } L_i = f_i + 1)$$

$$\text{(if } L_i < 0\text{, set } L_i = 0)$$

U_i = upper limit for data set i

L_i = lower limit for data set i

[ ] = rounded down to integer value

< > = rounded up to integer value

The probability that f_i failures would occur in data set i given the population failure rate is λ, is expressed by the Poisson distribution:

$$P_i = 1 - \sum_{j=L_i}^{U_i} P_{ij}$$

$$= 1 - \sum_{j=L_i}^{U_i} e^{-M_i} \frac{M_i^{\,j}}{j!}$$

The individual probabilities, P_i, are the significance probabilities for the individual distributions. It is required to test whether the ensemble of P_i taken together represents an improbable configuration under the null hypothesis which is that the underlying distributions have the same constant failure rate (λ).

The test is done as follows:

$$C_i = -2 \ln P_i$$

$$C = \sum_{i=1}^{n} C_i$$

Find Cr for $\alpha = .05$ (5% level of significance) and 2n degrees of freedom from the tables of chi square.

If C>Cr reject the null hypothesis (that all of the populations have the same failure rate.)

If the null hypothesis is not rejected, the data sets can be pooled and the common failure rate λ used.

If the null hypothesis is rejected, engineering and statistical analysis is required to remove data sets from the pooled data until the null hypothesis is not rejected.

EXAMPLE 1:

DATA SET	T_i	F_i	M_i	d_i	U_i	L_i	P_i	C_i
1	587.4	19	12.9	6.1	18	7	.0936	4.74
2	144.1	0	3.2	3.2	3	1	.0849	4.93
3	65.6	1	1.4	.4	2	2	1.000	0
4	95.8	1	2.1	1.1	3	2	.5406	1.23
5	128.	3	2.8	.2	3	3	1.000	0
6	281.	15	6.2	8.8	14	0	.0018	12.60
7	78.6	2	1.7	.3	1	1	1.000	0
8	484.8	0	10.7	10.7	21	1	.0016	12.93
	1865.6	41					ΣC_i =	36.43

pooled - λ = 21.98 fits

C = 36.43

2n degrees of freedom = 16

(from chi-square dist. at α = .05) Cr = 26.30

Since C>Cr ---- the null hypothesis, that all of the populations have the same failure rate, is rejected.

EXAMPLE 2:

DATA SET	T_i	f_i	M_i	d_i	U_i	L_i	P_i	C_i
1	587.4	19	19.5	.5	20	20	1.0	0
2	65.6	1	2.2	1.2	3	2	.536	1.2
3	95.8	1	3.2	2.2	5	2	.277	2.57
4	128.	3	4.2	1.2	5	4	.641	.89
5	281.	15	9.3	5.7	14	4	.070	5.33
6	78.6	2	2.6	.6	3	3	1.02	.0
	1236.4	41						9.99

Pooled λ = 33.16 fits

C = 9.99

2n degrees of freedom = 12

Cr = 21.03

C<Cr - accept null hypothesis --

All data sets have the same failure rate (λ = 33.16 fits).

APPENDIX B

STATIC RELAYS

The term static relay includes several types of device, such as photoconductors, silicon controlled rectifiers, vacuum tubes, magnetic amplifiers, transistors; which are able to control the power to a load without the separating (moving) contacts of the electromagnetic relay. An equivalent exists based on each of these devices, and only a sampling will be described here.

Fluidic devices are able to perform logic and switching, and the input sensors and output drives can often be designed to use the same fluid power supply. Response times on the order of one millisecond are typical, and radiation hardening is not a problem. Reference 13 discusses the advantages and disadvantages as well as the operating principles of fluidics.

Snap action requires either regenerative elements, such as the controlled rectifier, the unijunction, the four layer diode, and the tunnel diode; or regenerative circuitry, such as the blocking oscillator, the Schmitt trigger, and the bistable multivibrator.

In general, to attain specific features such as isolation or suppression of voltage spikes in a static circuit requires additional complexity. Most of the static devices are very fast compared to electromagnetic relays, which usually require a few milliseconds to transfer. Saturable core devices are comparatively slow, however, the fastest response being a half cycle of the drive frequency, typically 1000 hertz or less. Multipole switching with static devices generally requires duplication of the output circuitry. There is usually some consumption of power in both states of a static switch.

Figure B-1 shows a simple SPDT switch. Such a circuit has been used to create a digital-to-analog convertor. One circuit is used for each bit, the output currents being summed. Accuracy better than 0.1% can be attained without matching.

Figure B-2 shows a high power SPDT switch. In this circuit only a pulse is required for the switching. Diodes may be added to limit voltage spikes, and additional SCRs can be used to achieve multipole operation.

Figure B-3 shows a transistor static relay with transformer coupling to provide isolation between input and output. At low input voltages, the output transistor is virtually an open circuit. When the input voltage exceeds the Zener voltage the gain of T1 increases and oscillations are produced. These oscillations are rectified in the secondary to create a bias for T2 which drives it into saturation, thus creating a virtual short at the output. Two versions of this device are in production.

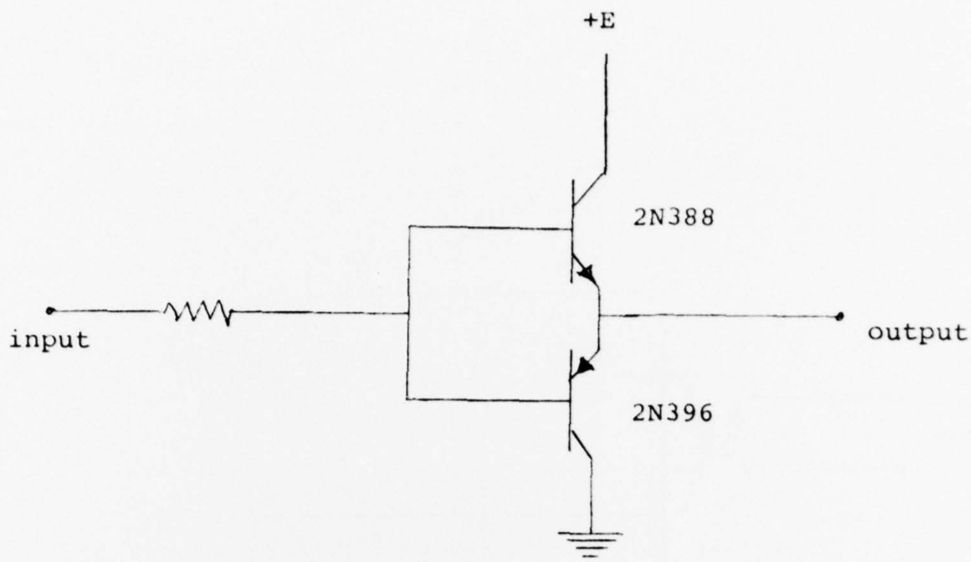
Figure B-4 shows a signal relay which uses a phototransistor rather than a transformer to achieve isolation. The Zener diode and the SCR implement a requirement that the control voltage be of the right polarity and a proper voltage before the relay is activated. A latch can be created by using a second lamp across the load.

Figure B-5 shows how diodes can be used as contacts. The principle is, that when a diode is conducting a forward current, it can pass a reverse current up to the value of the forward current at the same time. An oscillator similar to that of Figure B-3 is used. Its output is rectified and filtered to create the control voltage. When this voltage is present, forward current is passed thru the four diodes in the bridge, and the drive voltage is effectively applied to the load.

Figure B-6 shows the basic full wave self-saturating magnetic amplifier circuit. The transfer characteristic is also shown, from which it can be seen that the voltage across the load, for a certain range of control current, is in one of two states, depending on what the control current was before it entered that range, i.e., the load is either powered up or not.

The reliability of a magnetic amplifier is essentially that of the diodes used, the transformer-like cores and windings are being comparatively failure free.

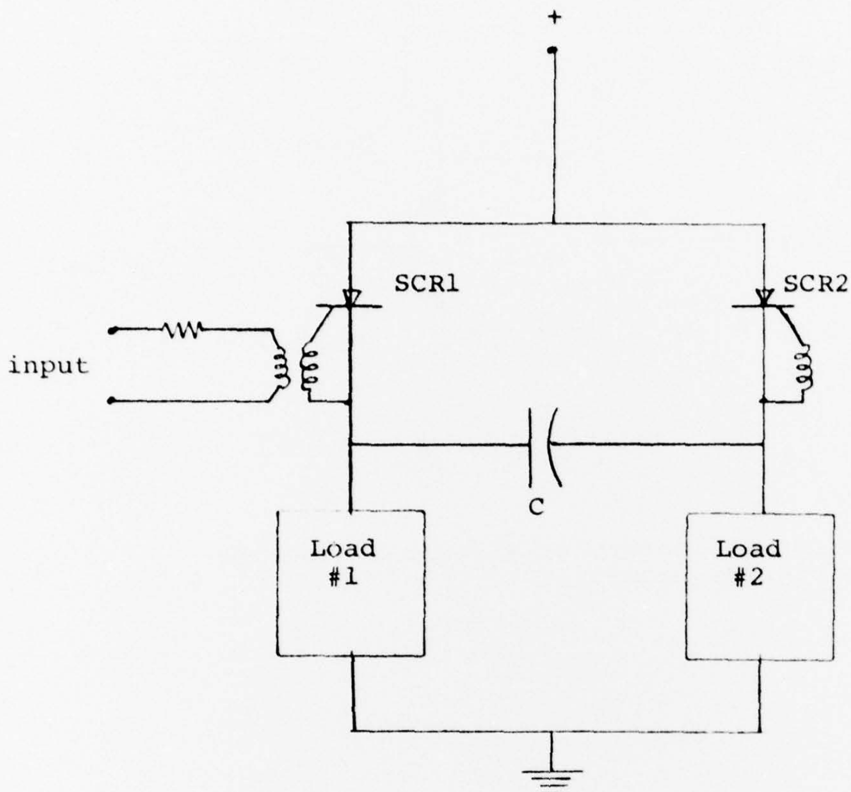
The reliability of the electronic circuits is determined in the usual way.



The output is zero or +E as the input is positive or negative.

PRECISION CLAMP

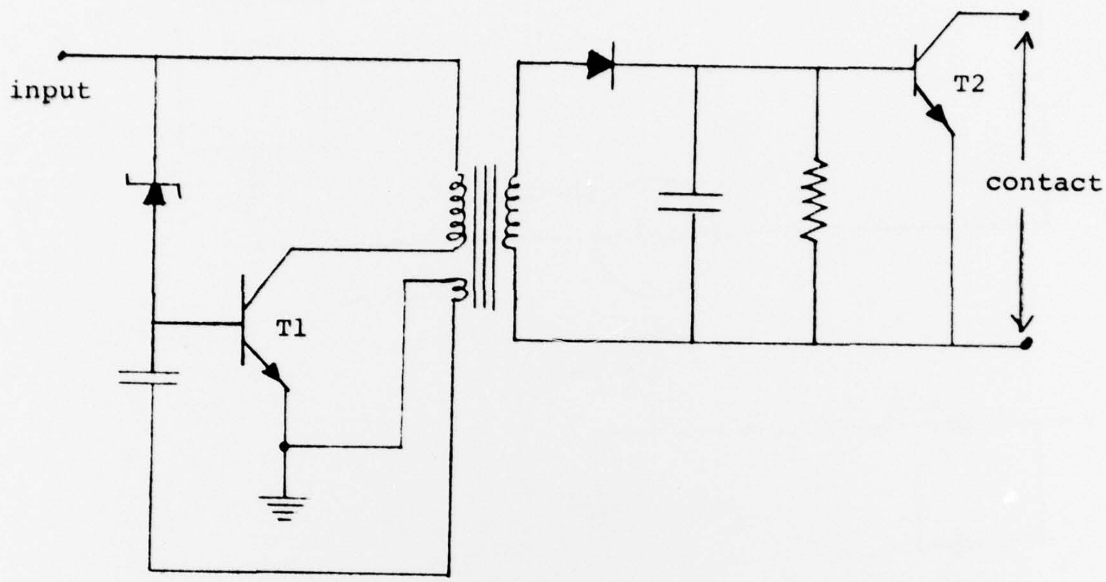
Figure B-1.



A positive pulse turns on load #1, a negative pulse turns on load #2.There is a short make-before-break period, typically 100 microseconds.

HIGH POWER SPDT STATIC SWITCH

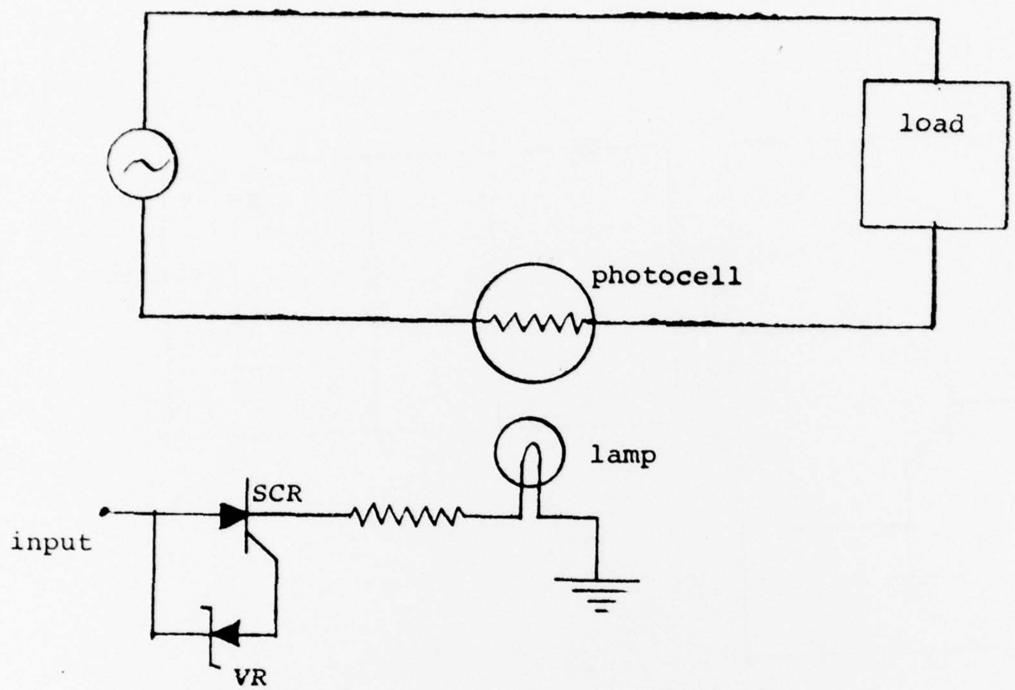
Figure B-2.



When input is sufficiently positive,
T2 is saturated and the contact is closed.
Otherwise, T2 has zero bias and contact
is open.
This relay can be cycled up to 20 kHz.

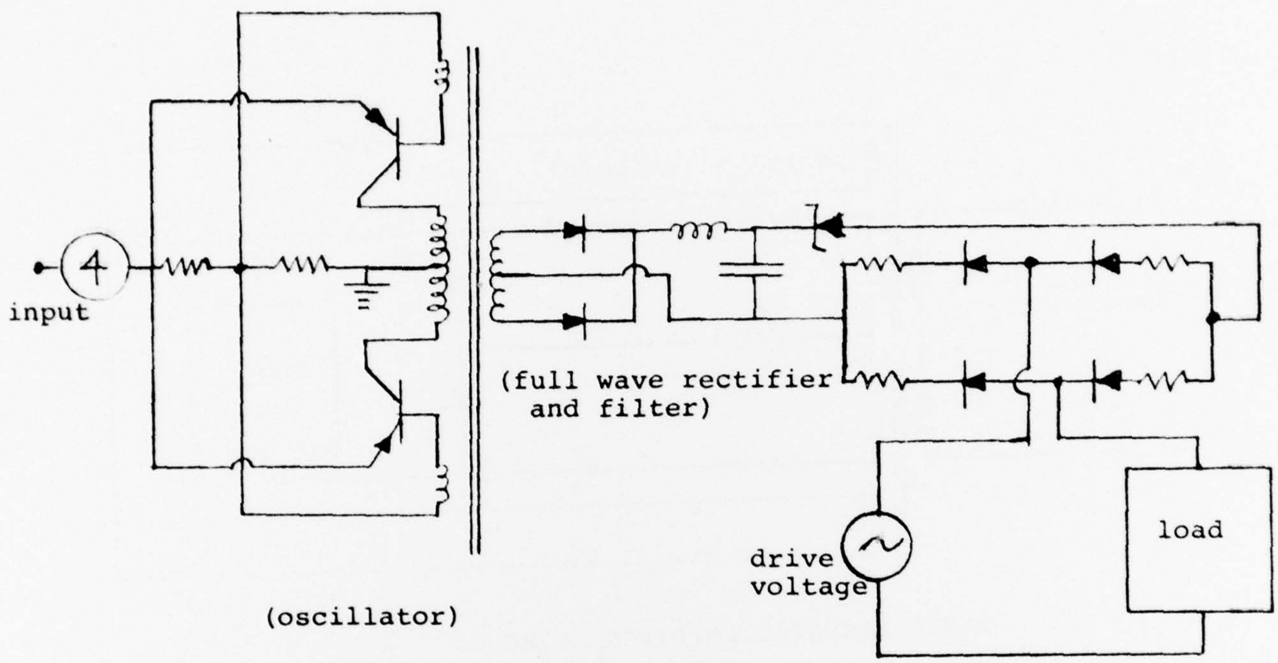
TRANSISTOR STATIC RELAY

Figure B-3.



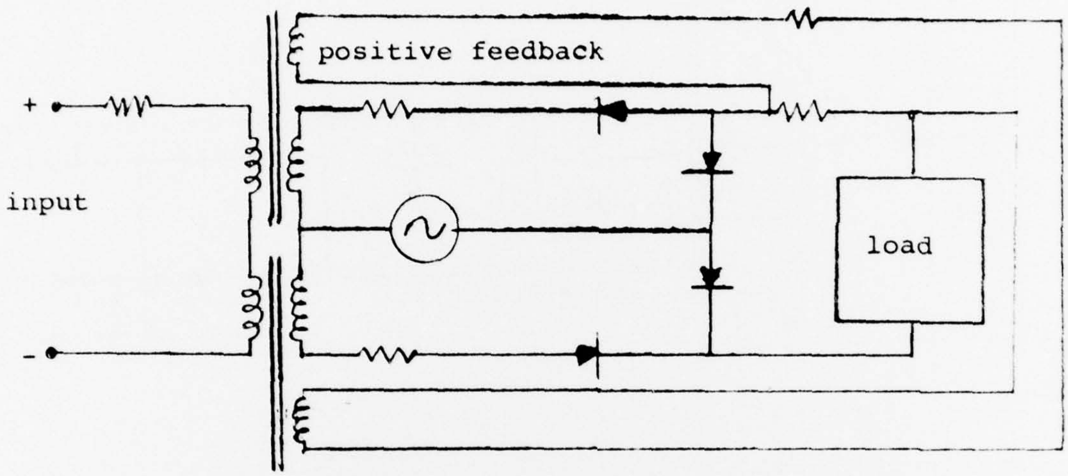
PHOTOCONDUCTOR SIGNAL RELAY

Figure B-4.



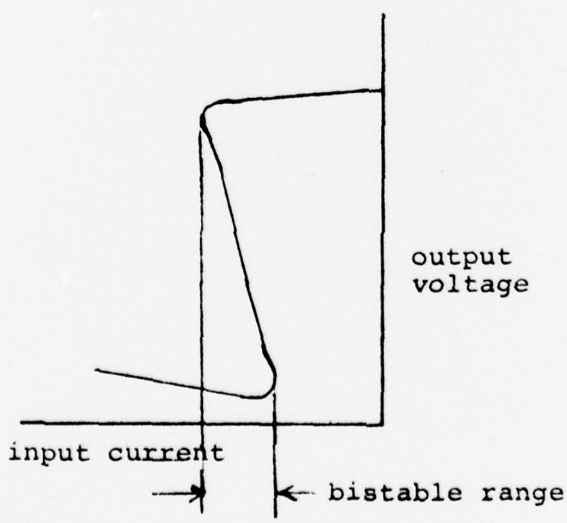
DIODE BRIDGE RELAY

Figure B-5.



BASIC MAGNETIC AMPLIFIER CIRCUIT

Figure B-6a.



MAGNETIC AMPLIFIER TRANSFER CHARACTERISTIC

Figure B-6b.

APPENDIX C

THE ROLE OF OXYGEN IN THE ATMOSPHERE OF RELAY CONTACTS

It has become common practice to enclose switch and relay contacts within an hermetically sealed case. The use of a chemically inert atmosphere turns out to be disadvantageous. Oxygen in substantial proportion is desirable for two reasons, both related to the formation of a film at the contact surface. One is that the film acts as a lubricant, preventing sticking of the contacts; the other is that the film substantially reduces damage to the cathode from arcing.

Holm (1) describes several experiments on adhesion at pages 155-157. (The terms adhesion, sticking, and cold welding refer to the same process.) He describes experiments on arc damage at pages 308-311, see especially figures 56.09 and 56.10. The reduction in loss of contact material is large, a factor of ten or so, but the theoretical explanation for it is not entirely satisfactory. The cathode spot is larger and cooler, and this suggests that the oxygen somehow reduces the work function.

Bates (2) describes the industry experience with sticking contacts in general terms and gives several case histories. He remarks that dry oxygen is added to the fill gas by several manufacturers in amounts up to 30 percent by volume.

Some current specifications do not permit the use of oxygen in the fill gas. Reference (3) calls for a "suitable inert gas" at section 3.4.5.2 Reference (4) calls for the "desired inert pressurizing gas" at section 6.4 (e). Referces (5) thru (8) make no mention of the fill gas.