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INVESTIGATION OF CONTACTLESS SWITCHING CONCEPTS
FOR
APPLICATION TO AIRCRAFT ELECTRICAL SYSTEMS
VOLUME I - AIRCRAFT SYSTEMS REQUIREMENTS

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March 11, 1963

Prepared under Navy, Bureau of Weapons

Contract NOw 62-0944-c

Phase I - Final Engineering Report 2-53727/3R449-1

11 June 1962 to 11 March 1963

CHANCE VOUGHT CORP.
Aeronautics and Missiles Division
A Division of Ling-Temco-Vought, Inc.
Dallas, Texas

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ENCLOSURE (1) TO
CV 62-0944-c
1-100

ABSTRACT

A study program was conducted to determine the factors that must be considered in the development of contactless switching devices and assemblies for performing the functions presently accomplished by conventional electromechanical switching devices. Problem areas and semiconductor characteristics are discussed in light of aircraft electrical system requirements so that design criteria can be established.

A chart comparing characteristics of typical electromechanical switching components to the contactless switching concept is presented.

Conclusions are offered concerning the factors to be considered in the development of contactless switching devices and assemblies to be compatible with present and anticipated aircraft electrical system requirements. These factors are discussed for devices and assemblies which will perform the functions of relays, circuit breakers and switches; including switching and control of the primary bus.

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PART I

1. Purpose

The basic purpose of the Contactless Switching Investigation Program is to determine the feasibility of developing a highly reliable and easily maintained aircraft electrical system, utilizing contactless switching techniques. The program consists of three phases: Phase I - Investigation of Contactless Switching Concepts with Reference to Aircraft Systems Requirements; Phase II - Investigation of Available Contactless Switching Concepts Within the Ranges Required for Switching and Control of Electric Power; and Phase III - Investigation of the Feasibility of Developing New or Improved Contactless Switching Concepts Meeting Aircraft Requirements. This report covers only the Phase I effort. Other Phase reports will cover the work performed during respective phases of the program.

The prime objective during Phase I of the Contactless Switching Program was to conduct an investigative engineering study of contactless switching concepts with reference to aircraft electrical systems requirements. The object of this investigation was to define, insofar as practicable, all the factors to be considered in the development of contactless switching devices and assemblies for performing the functions presently accomplished by such conventional electromechanical switching and control devices as relays, switches, and circuit breakers; including switching and protection of the primary bus. The basic aims were to determine the compatibility of contactless switching and protective concepts with existing and anticipated aircraft electrical systems requirements by considering application techniques which would enable the basic functions to be integrated into a switching control matrix capable of being operated from low level signals transmitted over small wires.

The investigations and studies included the following:

- a. Review of the F8U-2 (F-8C) schematic, applicable military specifications and characteristics of utilization components to determine and establish electrical system requirements.
- b. Review of the characteristics of existing semiconductor devices and assemblies to determine applications and compatibility of contactless switching and protective concepts.
- c. Analysis and evaluation of accumulated information to establish all the factors that must be considered in the development of contactless switching and protective devices and assemblies to meet aircraft electrical system requirements.

2. Detail Factual Data

a. Aircraft Electrical Systems Requirements

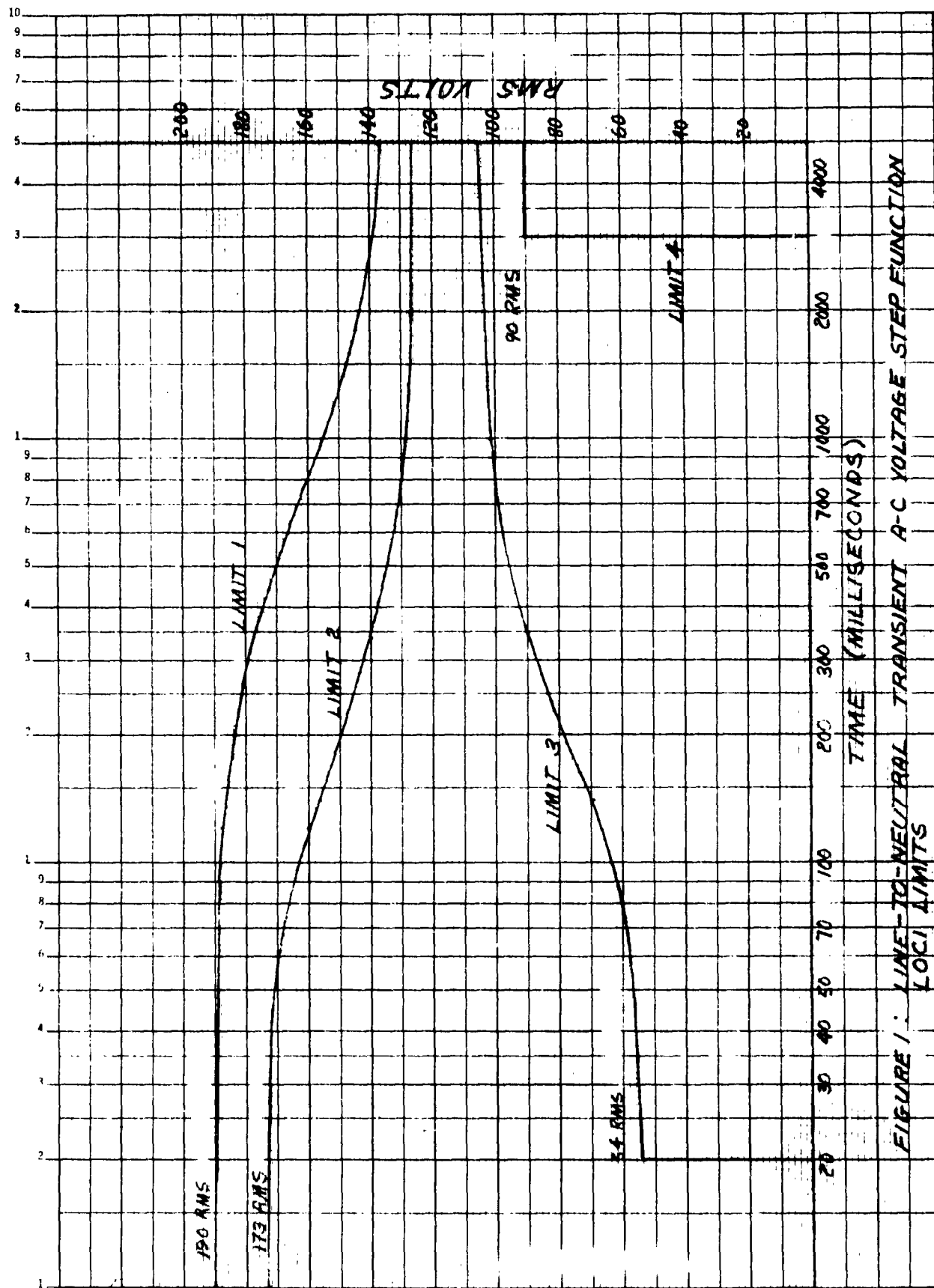
Investigations were conducted to establish the basic requirements of aircraft electrical systems, considering the present and future requirements of applicable military specifications and aircraft design practices. The aircraft electrical system was divided into four areas for the investigations: generation, distribution, utilization, and control.

(1) Generation

In order to establish compatibility between aircraft electric power generating systems and the contactless switching system, it is necessary that the characteristics of the generating system and associated regulating equipment designed to military specifications be investigated to establish the extreme limits to which the contactless switching system will be subjected. This investigation considered all sources of electric power supplied to the system.

(a) AC Power

The AC power generating system designed to MIL-STD-704 specification is a 3-phase 4-wire "Y" system with a nominal voltage of 115/200 volts. The neutral is connected to the primary aircraft structure and is considered as the fourth wire. The line-to-neutral voltage transients that can be imposed on the system are shown in Figure 1. The voltage transients, when converted to their step function loci are within the limits bound by curves 2 and 3 for normal operation and curves 1 and 4 for abnormal operation. Normal operation, as defined by MIL-STD-704, occurs at any given instant and any number of times during flight preparation, takeoff, airborne conditions, landing and anchoring. Examples of such operations are switching of loads, engine speed changes, bus switching and synchronization, and paralleling of electric power sources. Abnormal operation is an unexpected momentary loss of control of the system. This operation occurs possibly once during a flight or it may never occur during the life of the vehicle. An example of abnormal operation is the occurrence of a fault on the system and its subsequent clearing by a fault protective device. The line-to-line AC voltage transients that can be imposed on a system by the generation and regulation equipment are shown in Figure 2. The voltage transients, when converted to their step function loci are within the limits bound by curves 2 and 3 for normal operation and curves 1 and 4 for abnormal operation. The phase displacement between adjacent phases is $120^\circ \pm 1.5^\circ$. Maximum phase unbalance is 3 volts between phases of the highest and lowest voltage. The wave form of line-to-neutral and line-to-line sources has a crest factor of 1.41 ± 0.1 and a total harmonic content of 4 per cent of the fundamental (rms) with linear loads and 5 per cent with non-linear loads. The steady-state voltage limits for the AC system shall be within the limits shown in Table I. Emergency system operation is defined as that condition of the electric system during flight when the primary electric source becomes unable to supply sufficient or proper power, thus, requiring the use of a limited independent alternate source of power. Utilization equipment



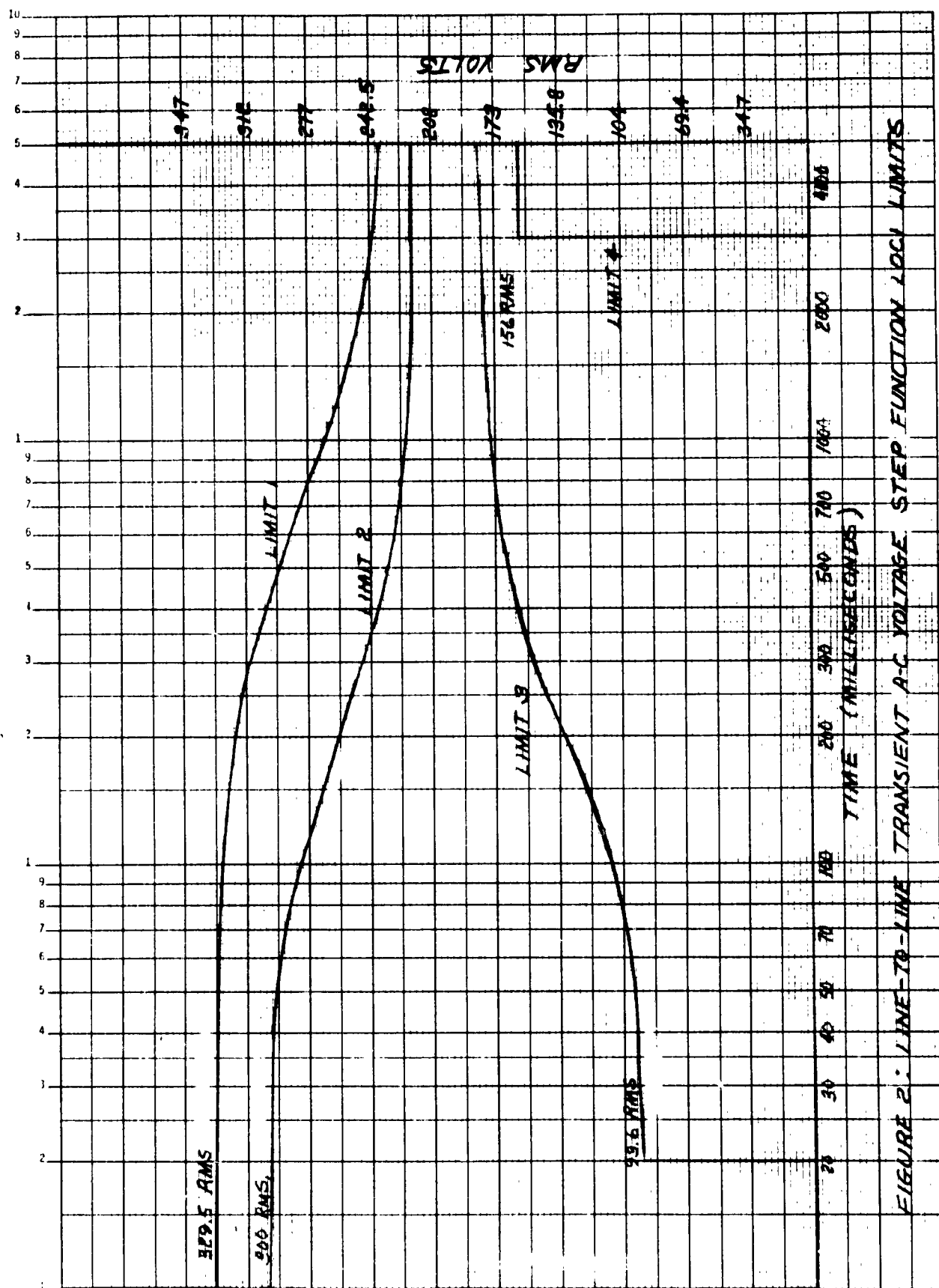


FIGURE 2: LINE-TO-LINE TRANSIENT A-C VOLTAGE STEP FUNCTION LOCAL LIMITS

TABLE I STEADY-STATE AC VOLTAGE LIMITS

Mode of Operation	Single-phase limits		Average of 3 phases limits	
	Normal	Emergency	Normal	Emergency
CATEGORY "A"	109.5-119.5	107-122	110.5-117.5	108-120
CATEGORY "B"	107.5-119.5	105-122	108.5-117.5	106-120
CATEGORY "C"	103.5-119.5	101-122	104.5-117.5	102-120

TABLE II STEADY-STATE DC VOLTAGE LIMITS

Category	Start Warmup	Takeoff Climb Cruise-combat	Landing	Emergency
"A"	21.5-29	25.5-28.5	21.5-28.5	17.5-29
"B"	21-29	25-28.5	21-28.5	17-29
"C"	20-29	24-28.5	20-28.5	16-29

TABLE III SYSTEM VOLTAGES AND ALLOWABLE VOLTAGE DROPS

NOMINAL SYSTEM VOLTAGE	MAXIMUM ALLOWABLE VOLTAGE DROP OPERATING CONDITIONS	
	CONTINUOUS	INTERMITTENT
28	1	2
115	4	8
200	7	14

categories are explained under the utilization section. The AC power generation and regulation system has a steady-state frequency of 400 ± 20 cps. Frequency transients are contained within limits 2 and 3 for normal operations and within limits 1 and 4 for abnormal operations as shown in Figure 3.

(b) DC Power

The DC power system is a 2-wire grounded system having a nominal voltage of 28 volts. The negative terminal of the power generation source is connected to the primary aircraft structure which is considered as the second wire. The DC voltage transients are contained within the limits shown in Figure 4. The voltage transients, when converted to their step function loci are within the limits bound by curves 2 and 3 for normal operation and curves 1 and 4 for abnormal operation. The steady-state limits shall be within the limits shown in Table II.

(2) Distribution

The aircraft electrical power distribution system consists of control devices, protective devices and wiring for the interconnection of electric power and utilization equipment. The wiring and associated control and protective devices shall be such that a safe and reliable distribution system will be provided. The total impedance of the wiring and ground paths, including control and circuit protection accessories, shall be such that the voltage drop between the point of regulated voltage and the utilization equipment does not exceed the limits shown in Table III. The power distribution system will be subjected to varying voltages depending on the operating conditions of the generating and regulating system. When the distribution system is supplying power to single phase AC loads, the wiring and control accessories will be subjected to 115 volts rms, during steady-state normal operating conditions and 190 volts rms during transient abnormal operating conditions. The three-phase distribution system is subjected to 200 volts rms line-to-line during steady-state normal conditions and to 330 volts rms during transient abnormal operating conditions. Wiring and control devices used for bus switching in the power distribution system are subjected to higher voltages. When switching AC power to a common bus from two generating sources, the wire and control devices can be subjected to voltages of 380 volts rms during a transient abnormal operating condition if the voltage from the two sources are 180° out of phase. The DC power distribution system is subjected to voltages of 28 volts during normal steady-state operating conditions and to 80 volts during transient abnormal operating conditions. When switching power to a common DC bus, the system will be subjected to a maximum of 80 volts; however, the control devices must be able to withstand the voltage in both the forward and reverse direction.

As previously stated, the distribution system must be safe as well as reliable. During a fault condition, power must be interrupted in any feeder exhibiting a fault condition. This interruption of power shall not cause an unsafe condition although the performance of the equipment connected to the feeder may be lost.

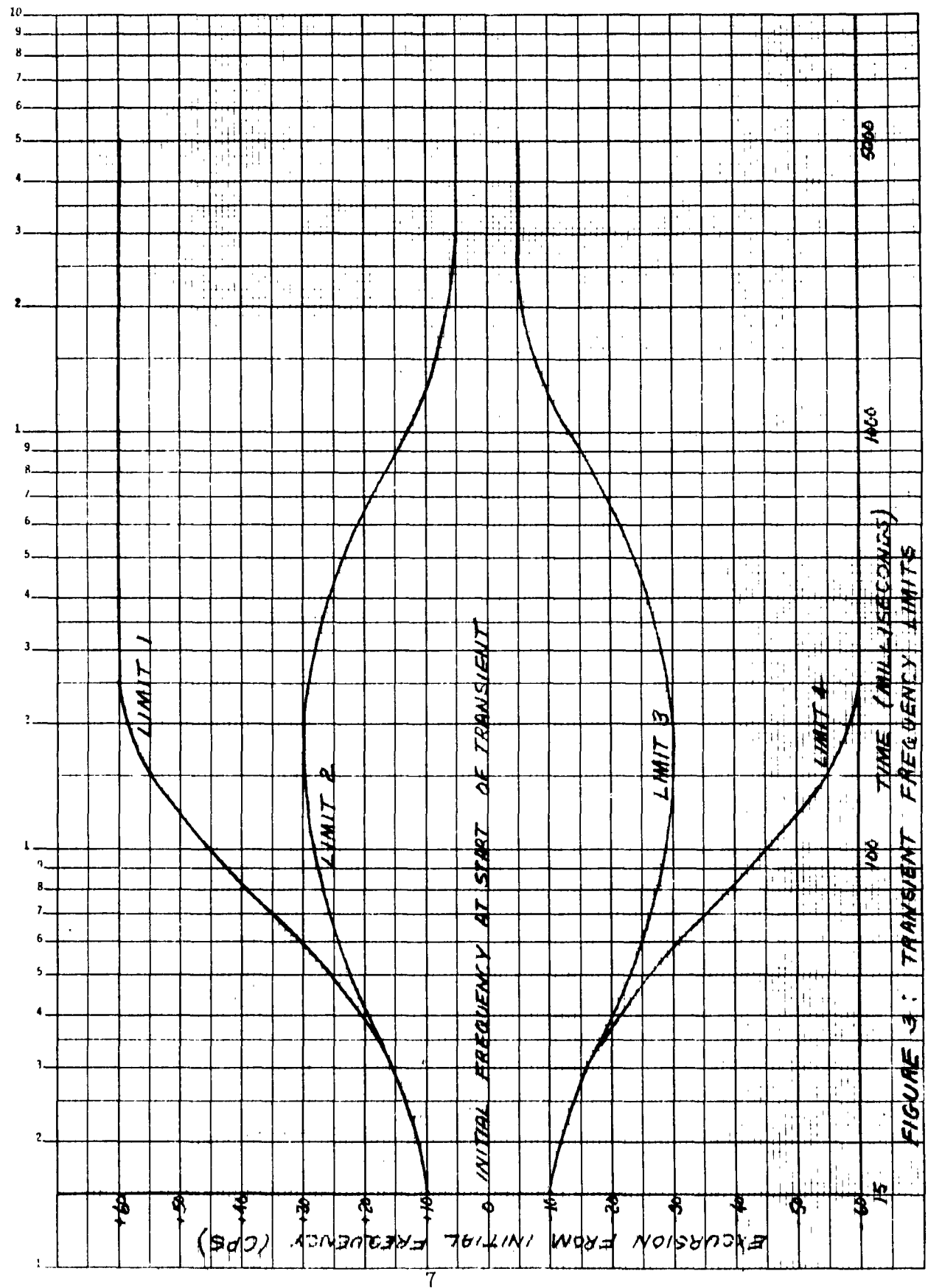


FIGURE 3: TRANSIENT FREQUENCY LIMITS

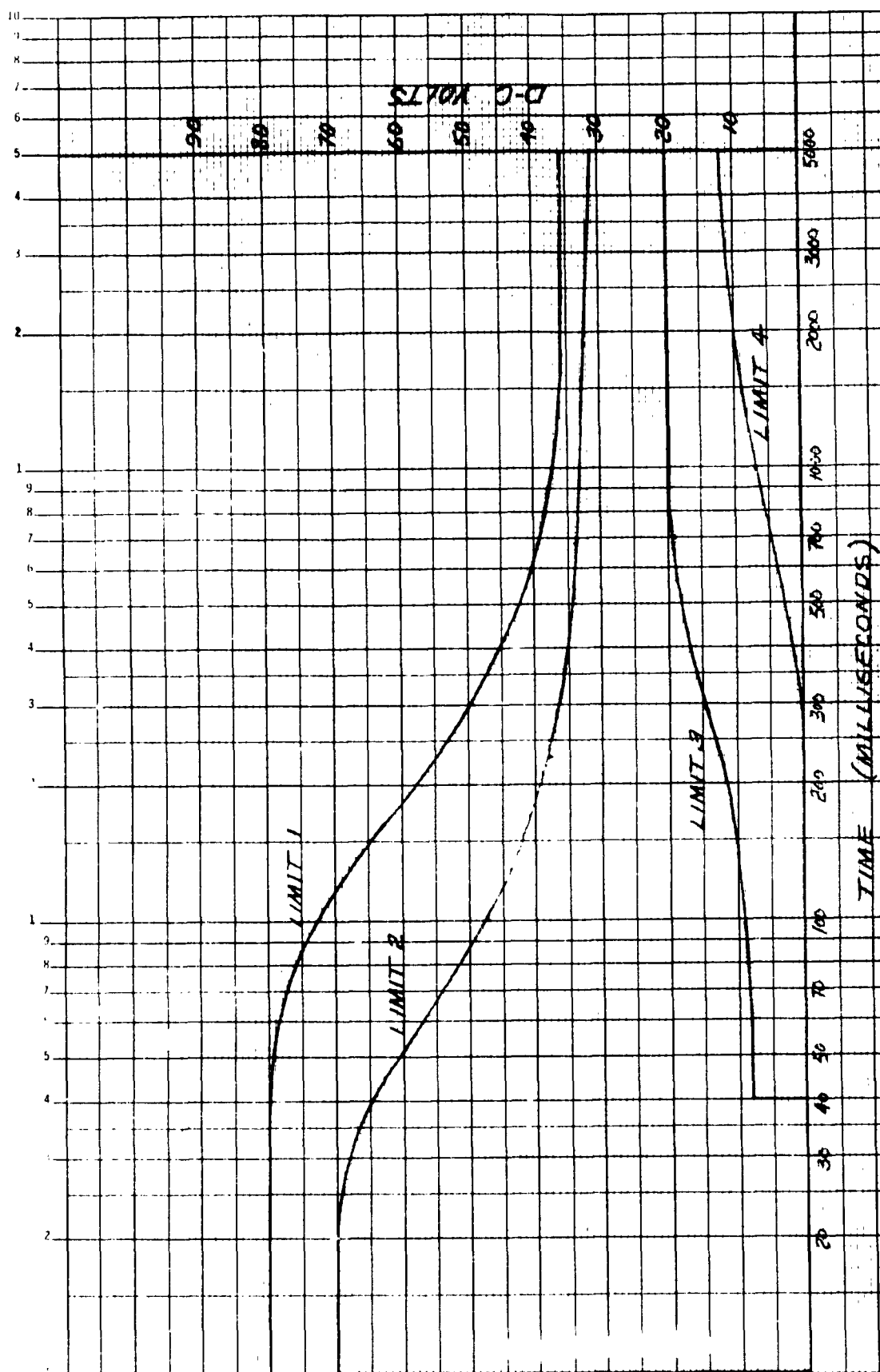


FIGURE 4: TRANSIENT D-C VOLTAGE STEP FUNCTION LOCI LIMITS

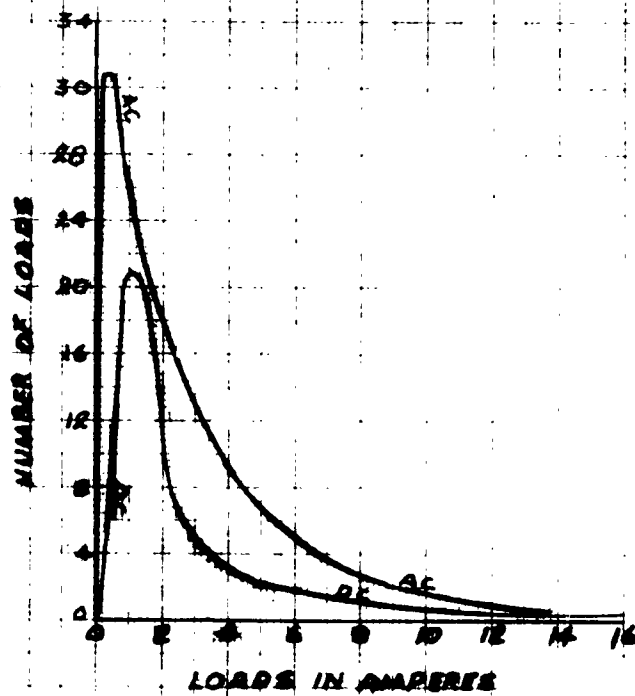
Power interruption devices presently consist of two general types; fusible links and electromechanical circuit breakers both of which are widely used. Circuit breakers have the requirement of being manually reset with trip free characteristics.

The electrical current requirements that must be supplied to loads in a typical aircraft electrical system, as determined from the model F8U-2 schematic are shown in Figure 5. The loads receive power from buses having various priorities such as emergency, primary and secondary. Each of these buses is supplied power from one or more sources. The bus switching control devices must remove one source from the bus before any other source is applied to prevent damage to the generating sources.

In order to insure satisfactory operation in aircraft, the components used in the distribution and control systems shall be subjected to environmental testing as specified in MIL-E-5272. These tests include:

- (a) High temperature per procedure I at the specified temperature up to 125 °C.
- (b) Low temperature per procedure I. (-54°C)
- (c) Vibration per procedure XII which requires cycling between 5 and 500 cps at an acceleration of $\pm 10g$.
- (d) Acceleration per procedure III. The acceleration force shall be 14g in each direction along each of its three axes.
- (e) Humidity tests per procedure I which requires a relative humidity of 95 per cent at the specified temperature.
- (f) Salt spray test per procedure I which is in accordance with Federal Test Method Standard No. 151, Method 811.
- (g) Altitude per procedure VI which specifies normal operations to altitudes of 100,000 feet at -54°C.
- (h) Fungus tests per procedure I.

Relays used for controlling power in the distribution system must have snap action operation "ON" and "OFF" in accordance with the level of the actuating signal. Circuit breakers and switching devices must have snap action operation "ON" and "OFF" in accordance with the manual force required for actuation. Electrical isolation must exist between the actuating circuit and contact circuits in relay type controls. The open circuit resistance shall exceed 100 megohms of resistance. The contact drop shall not exceed 200 millivolts at rated current. Contact bounce shall not exceed limits as required for specified devices which generally should be less than one millisecond. Typical values are in the neighborhood of 25 μ sec. Relay type devices shall



LOADS REQUIRED FOR TYPICAL AIRCRAFT
(BASED ON F8U-2 REQ'TS)
FIGURE 5

be capable of withstanding 1,000 % rated load for 200 milliseconds. Circuit breakers shall trip at overloads of 600% after one second at 25°C.

(3) Utilization

The utilization equipment power requirements were investigated to determine the power characteristics required for the equipments to function properly. The types of utilization equipment used in aircraft are of three categories, all giving specified performance when supplied with power having characteristics previously described. Category "A" equipment requires the power to be supplied through a distribution system with a maximum drop of 2 volts AC and 1/2 volt DC. The use of this equipment is limited. Category "B" equipment requires the power to be supplied through a distribution system with a maximum drop of 4 volts AC and 1 volt DC. This is the standard equipment used. Category "C" equipment is intermittently operated and requires a distribution system with a maximum drop of 8 volts AC and 2 volts DC. During normal operating conditions of the generating system, the utilization equipment must provide 100% performance, remain safe, and automatically recover to 100% performance and be unaffected in reliability when degraded performance is permitted during specific applications. During an abnormal electric system operation, the equipment need not meet performance requirements, must remain safe, may have momentary loss of function, and recover automatically to specified performance with negligible effect on reliability with the return of the electric system to normal operation. For all AC loads requiring more than 500 VA, 3-phase power will be used. Although it is desirable to have equipment utilizing AC power to present near unity power factor, the power factor on the worst phase can fall to the limits shown in Figure 6. The type of loads used in aircraft systems will include resistive, capacitive, inductive, lamp, and motor loads. Some of these loads have high inrush currents (up to 15 times normal rated current). While it would be desirable to limit the inrush current on such loads as heaters and lamps to achieve longer life, it is also a requirement to allow higher inrush currents on loads such as motors and solenoids to provide high starting torques. Some of the loads require power switching while others require ground switching.

(4) Control

Conventional electrical system specifications have no system requirements established for control per se, although specification requirements do exist for the individual components which together make up the control system. Toggle switches of one description or another provide the source of initiating signal from the pilot to actuate relays or to power loads, and relays perform the control logic function. The requirements for these conventional components are determined by the characteristics of the generated power and utilization loads. In the contactless system, the control components are only required to provide the necessary "ON" or "OFF" signal level to the power contact and remain totally isolated from the characteristics of the generated power and the utilization load power requirements. Since the nature of contactless switching is different from electromechanical switching, it is necessary to establish new design criteria to take advantage of the desirable

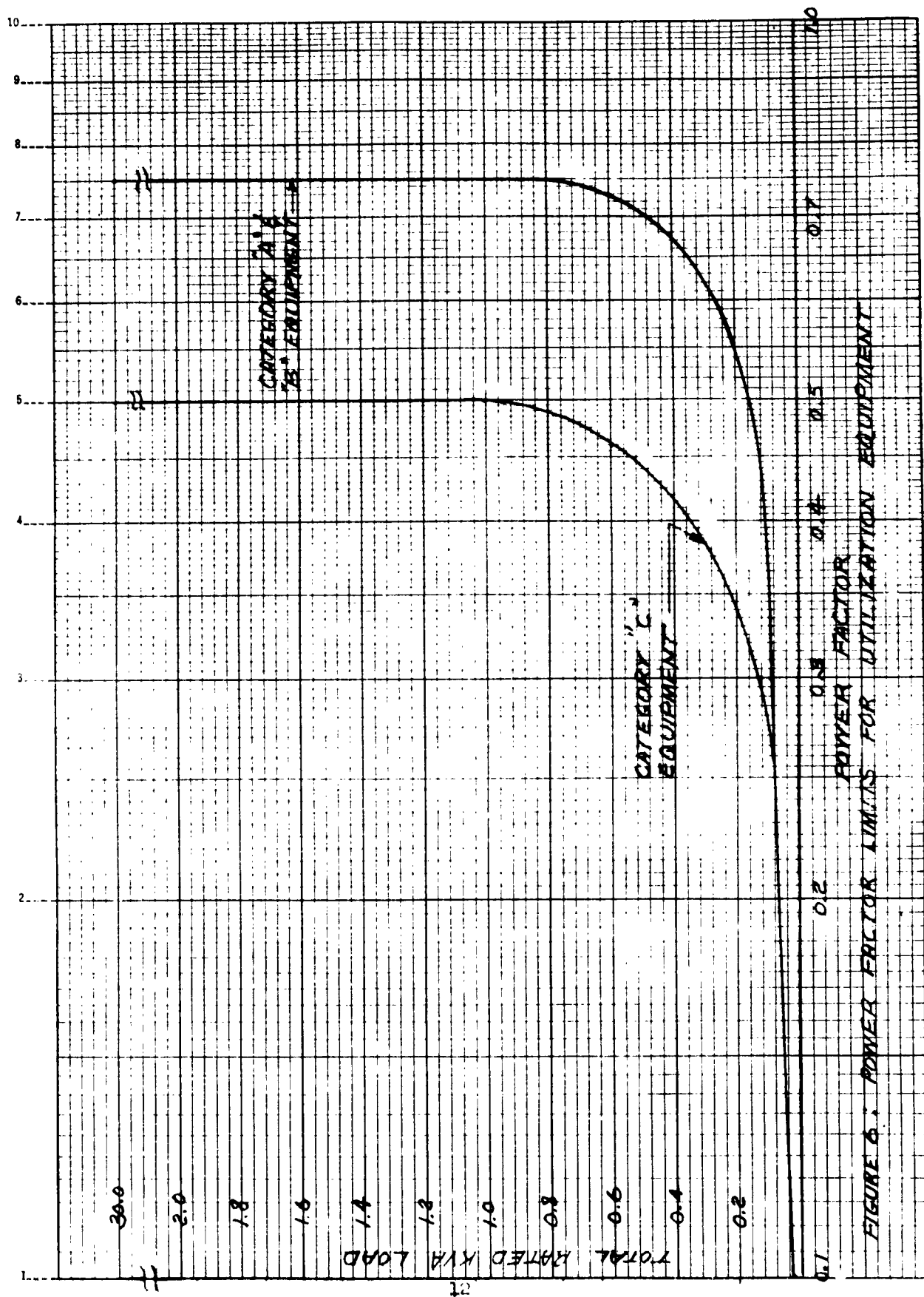


FIGURE 6: POWER FACTOR LIMITS FOR UTILIZATION EQUIPMENT

characteristics of semiconductors while retaining the desirable characteristics of electromechanical devices. Therefore, the investigation of electro-mechanical devices is undertaken to establish basic system requirements and thus provide a "yard stick" by which the requirements for contactless switching may be determined.

b. Contactless Switching Concept Requirements

Investigations were conducted to establish the basic requirements that should be imposed on future contactless switching concepts for application to aircraft electrical systems. These requirements are based on the present and anticipated requirements of aircraft electrical systems utilizing conventional techniques along with considerations for the additional capabilities and limitations of contactless switching techniques.

A basic system philosophy was assumed for the purpose of determining contactless switching concept requirements in light of aircraft electrical systems requirements. This basic philosophy has considerable possibility for simplification and functional integration of aircraft electrical systems. The philosophy assumed provides an electrical system which consists of three functional areas as shown in Figure 7. The signal source (analogous to a switch) transforms mechanical motion into an electrical signal. The control logic accepts the command signals from the signal sources and delivers a control signal to the desired power contact. The power contact controls the power to the utilization equipment. The area in which most of the existing electrical systems requirements are applicable is the power contact. Due to the variation in requirements between bus switching and protection, and load switching and protection, these areas will be discussed separately. Conversely due to the dependence of signal sources and control logic upon each other, these areas will be discussed together under the heading of control. Since the signal sources and control logic in the contactless switching system are not subjected to the same electric power characteristics as the power contacts, the existing established requirements imposed on the signal sources and logic are only those of an environmental nature.

(1) Bus Switching and Protection

The requirements established for the bus switching and protection system as characterized by the established basic philosophy shown in Figure 7 are discussed within the general areas of environment, performance and electrical characteristics. These requirements were established to determine compatibility of the contactless switching system with the aircraft electric system designed to specification MIL-STD-704 and airborne utilization equipment. Since circuit protection will be incorporated into the load switching power contacts, additional bus protection will not be required. The degree of bus protection obtained with the contactless switching concept will exceed present protection obtained with conventional power contactors and circuit breakers.

(a) Environment

The environmental requirements established for bus switching and protection are as follows:

1. High temperature - power contacts used in the bus switching system shall operate normally when subjected to the high temperature test per procedure II of specification MIL-E-5272 except the temperature shall be +85°C.

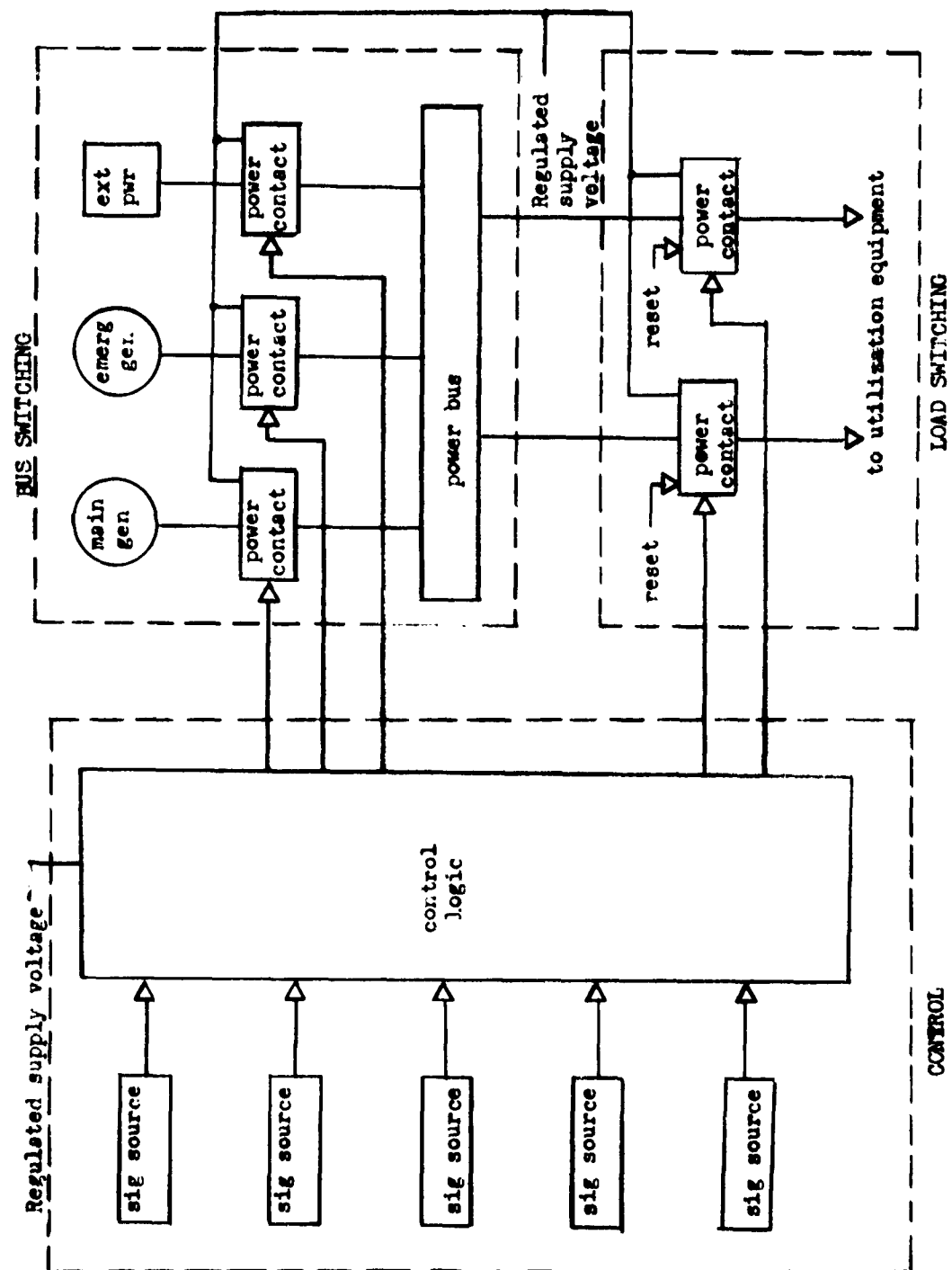


Figure 7. Block Diagram-Contactless Switching Concept

2. Low temperature - power contacts shall operate normally when subject to a low temperature test per procedure I of specification MIL-E-5272 (-54°C)
3. Shock - The power contacts shall operate normally when subjected to a shock test per procedure IV of specification MIL-E-5272. The power contact shall show no evidence of physical damage or contact ringing when subjected to a shock of 150 g's with a shock impulse of 11 milliseconds in each of its three axes.
4. Vibration - the power contacts shall be subjected to a vibration test per Standard MIL-STD-202 test condition D. The contact shall be subjected to 30 g's between the frequency range of 10 and 2000 cps in 20 minutes. The power contact shall have no intermittent operation or contact ringing during this test.
5. Acceleration - The power contacts shall be subjected to an acceleration test per procedure III of specification MIL-E-5272 except the acceleration shall be 100 g's. There shall be no evidence of intermittent operation or ringing of contacts.
6. Salt spray - The power contact shall be subjected to a salt spray test in accordance with Standard MIL-STD-202 test condition A with no evidence of corrosion on the device.
7. Moisture resistance - the power contact shall be subjected to a moisture resistance test in accordance with Method 106 of Standard MIL-STD-202 with no resulting deterioration of electrical characteristics.
8. Humidity (steady state) - the power contact shall be subjected to a humidity test in accordance with Method 103 of Standard MIL-STD-202 test condition A with no resulting deterioration of electrical characteristics.
9. Immersion - the power contact shall be subjected to an immersion test per Method 104 test condition A of Standard MIL-STD-202 to determine the effectiveness of the sealing. No deterioration in electrical characteristics shall be evident during or after the tests.
10. Altitude - the power contact shall operate normally when subjected to a barometric pressure test in accordance with Method 105 test condition D (100,000 ft) of Standard MIL-STD-202.

(b) Performance

The following performance requirements are established for bus switching power contacts:

1. Actuate with snap action "ON" and "OFF" in accordance with the level of the actuating signal.
2. Perform the desired functions at rated current and voltage for a minimum of 1,000,000 operating cycles during 10,000 hours life test with no degradation in performance.

(c) Electrical

The electrical characteristics requirements for power contacts in the bus switching and protection system are as follows:

1. Voltage rating - power contacts shall withstand a voltage of 600 volts in the forward and reverse directions for AC bus switching and a voltage of 100 volts in the forward and reverse directions for DC bus switching.
2. Contact drop - with the power contact carrying currents between one and 100 percent rated current, the voltage drop across the contact shall not exceed 1.0 volt.
3. Leakage current - the leakage current shall not exceed 3.0 milliamps at rated voltage and temperature.
4. Overload - the power contact shall withstand an overload of 600 percent rated current at rated voltage for 200 milliseconds with no detrimental effects to the device. The contact shall withstand the overload at a switching rate up to 20 cycles per minute for a 50 percent duty cycle provided the "ON" time does not exceed 200 milliseconds.
5. Surge - the power contact shall withstand a surge current of 15 times rated current for 50 milliseconds.
6. Pick-up voltage - the power contact shall assume a conducting state when a DC potential equal to or greater than two volts is applied to the device.

7. Dropout voltage - the power contact shall assume a non-conducting state when a DC potential equal to or less than 1.0 volt is applied to the device.
8. Control current - the control current shall not exceed 50 microamperes at rated voltage.
9. Contact bounce - there shall be no contact ringing when switching from conducting to non-conducting state or vice-versa.
10. Radio noise - the power contact shall not create electrical interference beyond the limits specified in specification MIL-I-6181.
11. Efficiency - the operating efficiency of the bus switching system shall be 95 percent minimum during normal operations.

(2) Load Switching and Protection

The requirements established for the load switching and protection system as characterized by the established basic design philosophy shown in Figure 7 will be similar to the requirements established for the bus switching and protection system. Only where the requirements differ will new requirements be established.

(a) Environment - same as bus switching and protection power contracts.

(b) Performance

The bus switching and protection requirements are applicable plus the following requirements are established:

1. The power contact shall perform the function of circuit protection as well as power control.
2. The power contact shall assume its non-conducting state when operating into a fault condition.
3. The power contact shall be capable of being reset remotely.
4. The power contact shall assume an "open" condition upon failure of the device.

(c) Electrical

The following electrical characteristics are established for load switching and protection:

1. Voltage rating - the power contacts shall withstand a forward and reverse voltage rating of 300 volts for single phase AC loads and 500 volts for three phase AC loads. The device shall have a forward voltage rating of 100 volts for DC loads.
2. Contact drop - same as bus switching.
3. Leakage Current - same as bus switching.
4. Overload - the power contact shall withstand an overload condition of 600 percent for 50 milliseconds and 200 percent for 200 milliseconds.
5. Surge - the power contact shall withstand a surge current ~~rating~~ of 10 times rated current for 10 milliseconds.
6. Pick-up voltage - same as bus switching.
7. Drop-out voltage - same as bus switching.
8. Control current - same as bus switching.
9. Radio noise - same as bus switching.
10. Efficiency - same as bus switching.
11. Trip current - The load switching power contact shall interrupt a 300 percent overload between 40 and 100 milliseconds. An overload in excess of 1,000 percent shall be interrupted within 10 milliseconds.
12. Reset-voltage - the power contact shall assume its conducting state when a reset voltage of equal to or greater than 2.0 volt is applied to the device.
13. Reset current - the reset current shall not exceed 50 microamperes at rated voltage.

(3) Control

Power is delivered from the power source to the utilization loads through power contacts in the contactless switching approach. The contacts are controlled "ON" or "OFF" by a control system consisting of signal sources and control logic. Since the contactless control system is not required to provide or transmit power with the same characteristics as the load power, the concept requirements for the control system may be considered separately from the concept requirements for the power contacts. This separation permits complete freedom in selecting performance and electrical characteristics of the control

system, except for the output signal to the power contact. The two elements of the control system are however somewhat interdependent, and therefore their concept requirements will be similar.

(a) Signal Sources

Signal source components are synonymous in purpose to mechanical toggle or micro-switches. The requirements for these are noted as follows:

1. Environment

Same as paragraph 2.b.(1)(a) except as noted.

Shock - 50 g's

Acceleration - 50 g's

2. Performance

- a. Transduce mechanical motion into an electrical output signal.
- b. Provide, in the case of pilot actuated signal sources, a visual indication of the signal source condition of "ON" or "OFF" and also, adequate human engineering to facilitate pilot manipulation.
- c. Produce a continuous signal output or continuous signal absence for steady-state signal requirements.
- d. Produce a short duration single output (pulse) or short duration single absence (pulse) for momentary signal requirements.
- e. Produce a clean snap action step change in output signal level.
- f. Provide a memory such that subsequent applications of power to a de-energized system will produce the same electrical response that existed before the system was de-energized.

3. Electrical

- a. Provide a suitable signal characteristic to succeeding stages of the electrical system, i.e. the control logic or power contact.

- b. Maintain the selected state of "ON" or "OFF" signal level independent of outside influences such as signal noise, temperature, shock, vibration, etc., incident within the flight vehicle.

The signal source elements have no precedent characteristics defining the manner in which the foregoing concept requirements will be met. It is therefore necessary that their detail characteristics such as supply voltages, signal levels, frequency responses and circuit configurations be evolved and tailored during the Phase II design study to meet the compatibility requirements of the associated contactless electrical system components.

(b) Control Logic

Control logic devices are synonymous in purpose with the majority of electromechanical relays used in typical aircraft in that they will receive the control impulses from the signal sources and determine by the ~~combinational~~ presence or absence of received signals what power contact is to be actuated. The concept requirements for the control logic are noted as follows:

1. Environment

See paragraph 2 b. (1) (a)

2. Performance

- a. Interpret the individual or combinational signals received from the signal sources and provide a steady output "ON" or "OFF" signal level to the power contacts.
- b. Transmit faithfully the momentary or pulse inputs from the signal sources to the power contacts.
- c. Provide a latching or lockup capability with or without a timed operation where required by the dictates of the functional utilization load.

3. Electrical

- a. Provide a suitable signal characteristic to the succeeding stages of the electrical system, i.e., the power contacts.
- b. Maintain the selected state of "ON" or "OFF" signal level independently of outside influences such as signal noise, temperature, shock, vibration, etc., incident within the flight vehicle.

In addition to the foregoing system concept requirements, the individual logic elements are presently constructed to existing manufacturer or military specification requirements which are primarily intended for computer and electronic system applications. These requirements principally concern the supply voltages, signal levels, frequency responses and circuit configurations; and although every effort will be made to utilize these existing performance characteristics, the suitability of these requirements will be determined during the Phase II and Phase III studies.

c. Device Characteristics and Compatibility with Established Requirements

Investigations were conducted to determine contactless switching device characteristics and to establish their compatibility with the contactless switching concepts. Numerous devices were investigated, but only devices exhibiting characteristics compatible with the established requirements are presented. In agreement with the basic system philosophy, all devices were considered in one of the following applications: signal sources, control logic, and power contacts. The following discussions compare the various device characteristics with the established concept requirements. Information supplementing these discussions is presented in the report appendices as follows:

Appendix A - Semiconductor Voltage Ratings for Contactless Switching Applications - Power Contact

Appendix B - Semiconductor Thermal Ratings for Contactless Switching Applications - Power Contact

Appendix C - Compatibility Chart for Electromechanical Components vs. Contactless Switching Concepts

Appendix D - Device Characteristics Charts for Signal Sources, Control Logic, and Power Contacts

(1) Signal Sources

The development of a contactless signal source to replace mechanical toggle or micro-switches can be affected through the application of any of the following devices: strain sensitive, piezoelectric, photo sensitive, and variable coupling. These devices all have the common capability of converting mechanical displacement into an electrical signal. Appendix D presents the applicable devices and their characteristics in tabular form. Rigorous treatises concerning the principles involved with each device are available in other writings and generally well known; therefore, a detail discussion will not be included. The mechanical design problem involving a human factors engineering effort is not within the scope of this study; but it is pertinent to note that although this task should not be taken lightly, the problems involved are not considered to be of serious concern. The very principles of operation will necessitate a rather strict control of the mechanical actuator due to the severe constraint imposed by the mechanical environment. What is important to this effort is how the signal characteristics of these devices may be made compatible with the input requirements of the adjacent electrical system contactless devices and how the aircraft environment would affect these characteristics.

(a) Strain Sensitive Devices

Strain sensitive devices provide an output signal level which is proportional to applied mechanical deformation; thus by causing these devices to be stretched or compressed, a signal level change is obtained. The desired snap-action operation can be provided by a mechanical design similar to that used in a micro-switch, i.e. mount the strain device on a ribbon of metal which would snap from one extreme position to the opposite when actuated. Another approach would be to use a tunnel diode to sense the output signal. Thus, as the signal voltage level changes as a result of strain and approaches the knee of the diode characteristic curve, the diode would snap from a low conduction state to the high conduction state and vice versa.

Strain devices, being resistive elements, change with temperature variation, which tends to blanket the desired signal level change. The problem is overcome by utilizing the device in a wheatstone bridge circuit. This requires a minimum of two devices for each signal source, but since the bridge operates on a ratio principle, a change in temperature causes a proportional change in both devices with no change in ratio; yet, a strain applied to a single device would alter the bridge ratio, thus providing the desired signal change.

This device has a low signal power capability and therefore requires amplification. An attempt to draw a sufficient quantity of power directly would heat the device to such an extent that temperature would again become a problem. Other than the possibility that some electrical filtering circuitry may be required to reject spurious signals caused by mechanical vibration, depending upon the adequacy of mechanical design, no other factors would prevent the use of this device for a signal source. The adjustment of the output level can be accomplished with little difficulty by simply controlling signal amplification, and no problem is therefore apparent in making the output compatible with the input requirements of the other system components.

(b) Piezoelectric Devices

Piezoelectric crystal devices provide a short duration, high voltage pulse signal, proportional to applied mechanical impact energy. The signal wave shape is related to the force magnitude and rate of application. These devices would lend themselves most readily to a momentary signal requirement application. Conversely, the operation of this device in other than a momentary requirement application requires supplementary circuitry in the form of a flip-flop such that successive pulses from the crystal would cause the flip-flop to change states. The flip-flop could then provide the steady signal level required for steady state applications. These devices do have one disadvantage associated with the steady-state application in that there is no convenient means of providing memory.

Piezoelectric crystals, unlike other devices, convert electrical energy directly from mechanical energy, thus not requiring the additional circuitry necessary for biasing. The high voltage level generated will require transformation; but adjustment of this output level appears to have no reservations attached; and it is felt that its use would be compatible with over-all system requirements.

(c) Photo Sensitive Devices

Photo sensitive devices provide an output voltage level change proportional to incident light intensity falling on the photo sensitive surface. Two types are currently available; photo-diodes and photo-transistors. Photo-diode output power capabilities are limited and will require amplification. The photo-transistor device has adequate power capabilities without amplification. Both devices respond to temperature changes, but proper circuit design will eliminate any problems in this area.

The only remaining area for concern is the steady source of light required with these devices. Incandescent light sources are of course presently available. But, whereas photo devices can stand considerable mechanical abuse, light sources are particularly susceptible. The degree to which this is true is generally well known throughout the aircraft industry. Recent developments in incandescent light bulbs have shown a marked improvement in their mechanical characteristics resulting in an order of magnitude improvement in life and reliability. In general, the photo sensitive devices can be used quite satisfactorily as a signal source; and the interruption of a light beam can be facilitated with very little difficulty in mechanical design.

(d) Variable Coupling Devices

Variable coupling devices produce a change in signal output as a result of a change in the magnetic circuit permeability for transformers or a change in electric field permittivity for capacitors. Both devices require an alternating bias signal for operation and therefore must be used in conjunction with a rectifying circuit to provide the proper output DC level. The power levels available from either of these devices will be adequate without amplification. The very small physical size variable capacitors used would require a rather high biasing power source frequency, thus inherently incorporating a source of generated interference. Some shielding techniques may therefore be required. Both devices have a minor problem with the electrical snap-action requirement, but the application of adequate mechanical design or the tunnel diode technique suggested for strain sensitive devices will eliminate the problem entirely. Temperature stability for these devices, neither are thought to be very much affected, can be provided in the biasing circuit if required. In summary, there are no insurmountable problems associated with the application of any of these devices for the contactless switching electrical system.

(2) Control Logic

The development of a contactless control system to replace electro-mechanical relays has principally taken a single course of endeavor--that of evaluating the broad technology currently existing for computer applications. The main effort therefore has been applied to the evaluation of characteristics of the existing logic devices of which there are nearly as many varieties as there are manufacturers.

These devices involve several classic logic circuit forms noted as follows: Resistor Transistor, Resistor Capacitor Transistor, Direct Coupled Transistor, Diode, Low Level, Current Mode, and Diode Transistor. In addition to the number of different classical logic circuits, manufacturers producing logic elements based on the same classical circuit description will often differ in the implementation of their design characteristics. These differences however generally lie in the power supply and signal voltage level requirements. There are also two manufacturing techniques available; namely, a modular construction versus micro-electronic. The distinction between these two is principally that modular construction involves standard semiconductor and other circuit elements with a state-of-the-art advance in packaging technique, whereas the micro-electronic technique generally implies the implementation of the circuit on a single semiconductor substrate. Some manufacturers combine these two techniques, thus conforming to neither one of the techniques singly. In general however, the term micrologic will always imply the smaller of the two in physical size.

The technique of micro-electronic construction is quite new whereas the modular form has been available for sometime, and as may be expected, considerably more experience is available on the older construction. However, since the micrologic element technique has already shown good service characteristics, there is little or no concern associated with their application in contactless switching, and their use will afford the advantages of reduced space and power requirements.

Very little effort has been applied in determining the type of classical circuit most suitable for application to contactless switching during this phase, although some initial impressions, to which the following comments apply, have been formulated. Some of these circuits would require amplification between succeeding logic stages to compensate for the signal power loss inherent with their application. Other circuits would require extracurricular circuitry to afford sufficient isolation between separate signal sources. Neither of these features would be particularly attractive in considering these circuits for contactless switching applications. As to the signal levels available from existing logic modules, little difficulty is expected in obtaining satisfactory levels for operation of the succeeding electrical system power contacts, i.e. the input circuits of the power contacts can be made as sensitive as required to accept the available levels. This approach is in keeping with the approach of using as nearly as possible the established logic design. As previously mentioned, the final determination

of this will be made during the evaluation of the design effort of Phase II. One point of some concern on this subject is the susceptibility of these devices to signal noise levels present in the aircraft. It may be desirable to provide logic design requiring higher operating levels as a more practical approach over extensive noise shielding. This, however, was not concluded during this phase of the study.

(3) Power Contacts

An investigation was made of semiconductor device characteristics to determine what devices are compatible with the contactless switching requirements as established in section (b). Following is a general discussion to show the compatibility of semiconductor devices used in power contacts with the established requirements for both the bus and load switching power contacts.

(a) Environment

The requirements imposed on power contacts by section (b) with regard to environmental conditions can be readily attained with silicon devices and good design practices. Silicon power transistors in general have a high junction temperature rating of 160°C and a low junction temperature rating of -65°C. Silicon controlled rectifiers in general have a high temperature rating of 150°C and a low temperature rating of -65°C.

(b) Performance

The actual life of semiconductor devices used in the power contacts is estimated above 70,000 hours of actual operating time with no deterioration in performance. The power contacts, when properly designed, have a capability of switching at rates up to and exceeding 10,000 times per second for literally billions of times without deterioration in performance.

(c) Electrical

Semiconductor devices that can be used in the power contact for switching either AC or DC power consists of rectifiers, silicon controlled rectifiers (SCR's) and transistors. When using SCR's or rectifiers as the power contact, it is only necessary that the peak reverse voltage (PRV or PIV) and the peak forward blocking voltage (PFV) ratings not be exceeded. In the case of SCR's, this rating is given with the gate open. Additional precautions must be taken so that positive voltages are not applied to the gate when the anode is negative or when the gate becomes more negative with respect to the cathode than the allowable limit. The PRV and PFV are the maximum allowable ratings and a safety factor of 10 per cent minimum should be added for improved reliability. SCR's with PRV and PFV ratings in excess of 600 volts are available and, therefore, are compatible with the established requirements for AC and DC bus switching as well as for AC and DC load switching.

Power transistors to be used for power contacts have a more complex voltage characteristic. The breakdown voltage between collector and emitter is dependent upon the associated external circuit as well as the device characteristics. A detailed description of voltage ratings for power transistors as well as SCR's is given in Appendix A. For ultimate reliability the BV_{CEO} rating shall govern the transistor power contact rating. Unlike SCR's, power transistors have high voltage ratings in one direction only. It is, therefore, necessary that two transistors be used in a single AC power contact to provide the required forward and reverse voltage ratings. Transistors are not presently available with sufficient voltage ratings for AC bus switching or three-phase load switching although a device is available (Delco 2N2580) for single-phase load contacts. As previously mentioned, two transistors are required to provide the forward and reverse voltage rating which is also required in DC bus switching. Although devices with sufficient voltage ratings are available, transistors with sufficient current rating for DC bus switching are not available. Power transistors for DC load switching are readily available and completely compatible with the established requirements for the DC load switching power contacts. Although transistors as well as SCR's can be made compatible with established requirements for both the AC and DC bus switching systems and the AC and DC load switching system, SCR's are more adaptable to AC power contacts and transistors to DC power contacts.

Electromechanical devices, of course, can more nearly approach the ideal switch than can semiconductor devices with regard to contact drop. The basic design philosophy shown in Figure 7 is being followed to minimize the over-all drop in the power distribution system. When using power transistors in the power contact module, the voltage drop across the device is a function of load current and base current. When the base current is great enough so that both the base-to-emitter junction and the base-to-collector junction are forward biased, the device is saturated and exhibits minimum resistance called saturation resistance. The voltage drop across the saturated transistor depends on the value of base current for a given load current. The greater the base current is made, the lower the contact drop becomes until a point is reached where the voltage drop developed across the ohmic emitter resistance tends to increase the drop. The amount of base current required is also dependent on the current gain (h_{FE}) of the device. The Westinghouse 2N2100 series of power transistors have a typical saturation resistance of 0.037 ohms at a collector current of 25 amperes and a base current of 5 amperes at 25°C. The same transistor has a typical saturation resistance of 0.05 ohms at a collector current of 10 amperes and a base current of 380 milliamperes. When using transistors in the low current power contacts, it is therefore possible to stay well under the established requirement of 1.0 volt maximum. When SCR's are utilized in the power contact, the voltage drop is essentially constant for any load current and is not dependent on any driving current. The voltage drop, however, is in the neighborhood of 1.0 volt for all devices. To compare the characteristics of power transistors and SCR's, Figure 8 presents a plot of forward voltage drops and Figure 9 presents a plot of saturation resistances versus load currents for typical devices at 25°C.

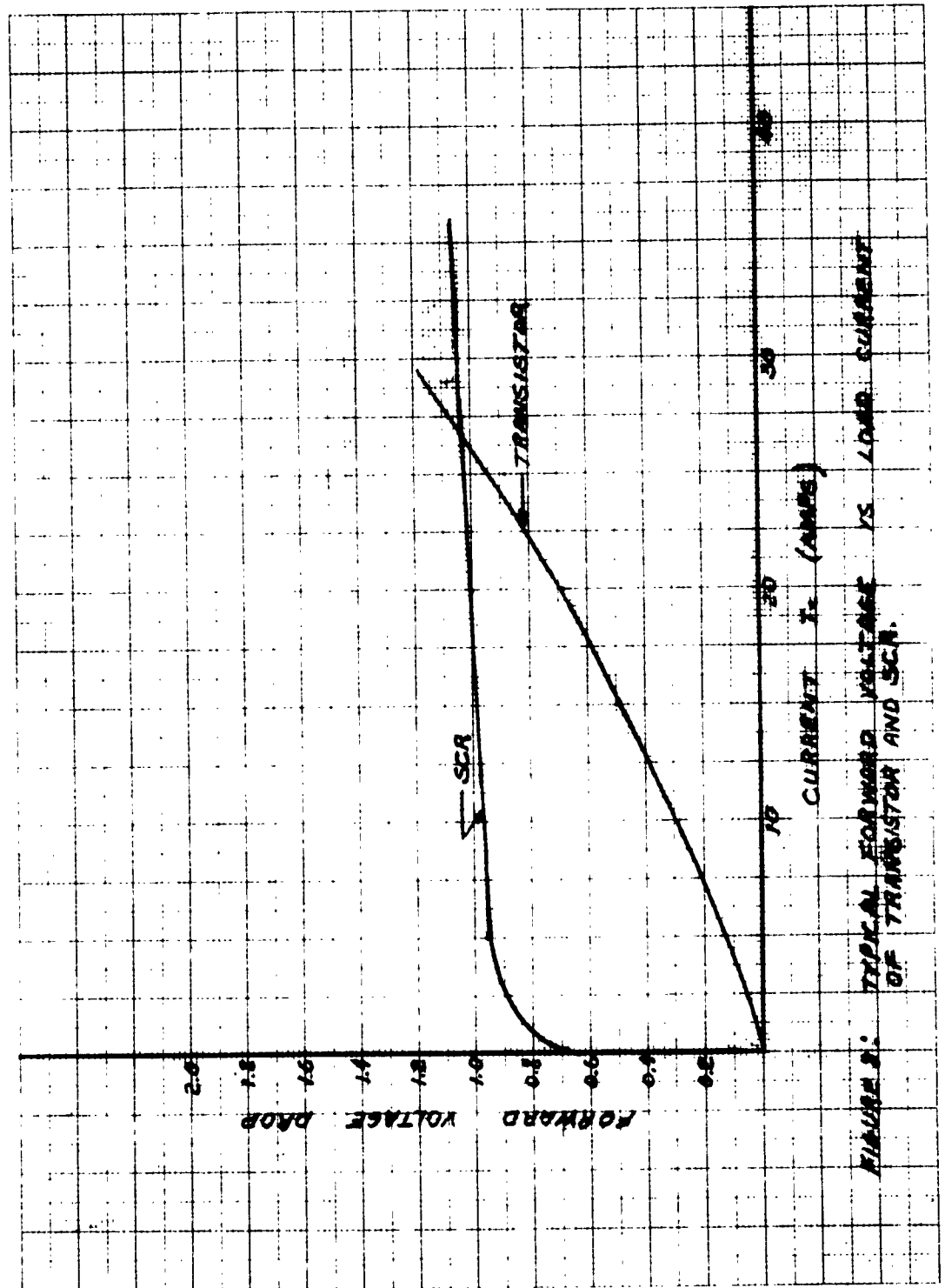
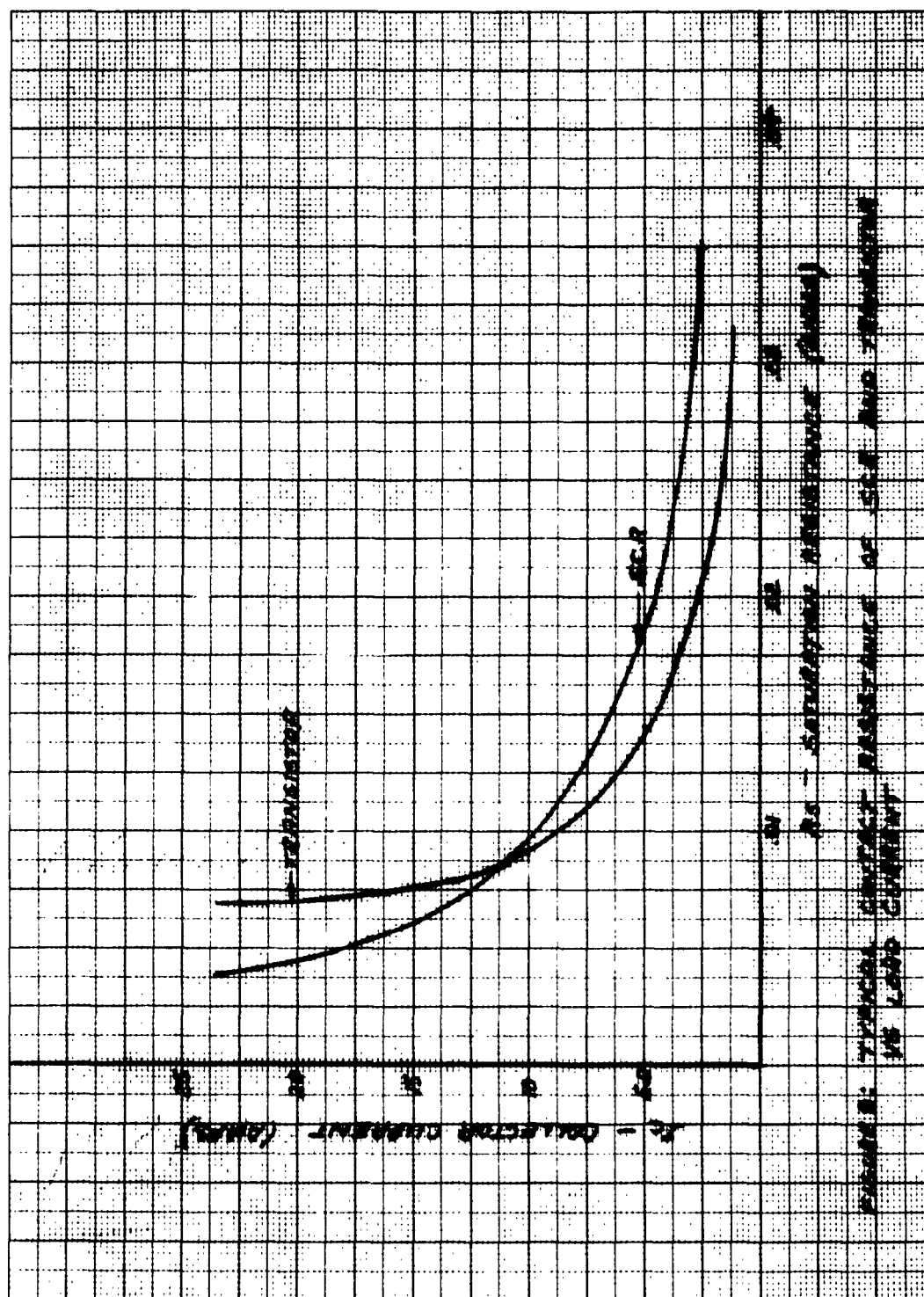


FIGURE 2: TYPICAL FORWARD VOLTAGE VS. LOAD CURRENT OF TRANSISTOR AND SCR.



Leakage currents (I_{CER}) to the load in power contacts utilizing power transistors in the emitter follower configuration are dependent on external circuit design. Leakage current measurements made on a Westinghouse 2N2131 transistor revealed zero leakage to the load with an 8.2k resistor connected from base to ground. This measurement was made at 25°C and at a collector voltage of 28 volts. It was determined that power contacts designed with transistors are compatible with the established maximum leakage requirements of 3.0 milliamperes. SCR leakage currents are independent of circuit parameters and they are available with leakage currents below the established limit.

SCR's with current ratings up to 235 amperes are available and therefore are compatible with the current rating requirements for both bus and load applications. Power transistors with current ratings up to 30 amperes are available, but this is not sufficient for DC bus switching since the devices must be derated; however, 100-ampere devices are in development.

The overload and surge ratings of semiconductors is complex and a brief discussion is required to show the compatibility of the devices with the established requirements. A more detailed discussion is given in Appendix B. The characteristic that determines current carrying capabilities of semiconductor devices are maximum allowable junction temperature (T_{Jmax}) and maximum collector current rating (I_{Cmax}). In silicon devices, the maximum allowable junction temperature is between 125°C and 200°C. The maximum collector current should never be exceeded because a phenomenon known as "Secondary Breakdown" could occur and destroy the device. During overload and surge conditions, power dissipation and I_{Cmax} ratings will be the governing factors in power transistors. In SCR's, surge current and the I^2t rating will be the governing factors.

The requirements established for overloads and surges can, of course, be met with power transistors as well as with SCR's. It would however require considerable current derating of the power contact and hence would be an inefficient design. A more efficient design incorporates current limiting which will be discussed in detail in the Phase II Final Report. To make power contacts compatible with the overload and surge rating requirements, the power contacts will have an "overload factor" rating. This rating is given to power contacts exhibiting current limiting and is defined as the overload or surge current that would flow through a device with no current limiting and is given in per cent of rated current. For example, a power contact rated at ten amperes supplying current to a thirty-ampere load would have an "overload factor" rating of 300 per cent even though the device limits the current to ten amperes. Current limiting, of course, requires that the power transistor operate out of saturation during the overload or surge condition to prevent exceeding I_{Cmax} . Hence, the power dissipated during the overload or surge condition is absorbed by the transistor. It is important to note, due to the relatively low thermal capacity of semiconductor devices as compared to electromechanical devices, the junction temperature rises quickly. How quickly the heat can be removed from the junction will determine the overload and surge capabilities of the device. It is therefore necessary that the power transistor have a low thermal

resistance junction-to-case (θ_{JC}) and a high thermal capacitance junction-to-case (C_{JC}). Manufacturers of power devices generally provide charts from which the designer can readily determine the maximum power dissipation which the device can withstand for various pulse durations. SCR's, unlike transistors, have surge and I^2t ratings for short nonrecurrent periods of time. The surge current rating (I_{surge}) is given for 8.3 milliseconds. The I^2t rating is given for durations shorter than 8.3 milliseconds. Since the established requirements are for longer time periods, phase control mode of operation will be used to give an effective current limiting characteristic. This too will be discussed in the Phase II Final Report. This same concept will apply to circuit protection in the load switching power contacts in order to make them compatible with the established requirements. Circuits can be designed, as will be discussed in the Phase II Final Report, that will sense current, voltage and time to provide the desired "trip" signal. AC load switching power contacts using SCR's must be phase controlled during turn-on since the device will not turn "off" faster than within one-half cycle which would be long enough to destroy the device during fault conditions.

Design techniques which will permit switching the AC power contact "on" at the zero degree point will permit the power contact to operate within the limitations of specification MIL-I-6181.

The power dissipated in the power contact consists of "on" losses and "off" losses. In the "on" condition the losses can be divided into three groups: (1) the main contact losses, (2) the driving power losses, and (3) the control circuit losses. In the "off" condition, the power losses in the power contact are due to leakage only which is small in silicon devices. Power losses in the "on" condition will depend on the device being used as the main contact. In a power contact using a power transistor as the main contact, the device passes through the active or high dissipation region when it is first turned "on". In contactless switching applications, this area is traversed so rapidly and at such low duty cycles that this power loss can be considered negligible. It is while the device is operating in the "on" condition that major power losses are developed. These losses can be given as:

$$P_{\text{loss}} = V_{CE} I_{CER} (1-t) + I_C^2 R_{CS}(t) + I_B V_{BE}(t) + \text{Control Losses} \quad (1)$$

Where: t is the time "on"

V_{CE} is the supply voltage in volts

I_{CER} is the leakage current in amperes

I_C is the collector or load current in amperes

R_{CS} is the saturation resistance in ohms

I_B is the driving current in amperes and

V_{BE} is the base-to-emitter drop in volts.

Assuming the first term is negligible and $t = 1$ (Continuous operation) then:

$$P_{\text{loss}} = I_C^2 R_{CS} + I_B V_{BE} + \text{Control Losses} \quad (2)$$

The efficiency of the power contact in the "on" condition is then given by:

$$Eff = \left[1 - \frac{(I_C^2 R_{CS}) + I_B V_{BE} + \text{Control Losses}}{V_{CE} I_C} \right] 100 \quad (3)$$

The contact losses ($I_C^2 R_{CS}$) will predominate. It is, therefore, necessary that the power transistor have a low saturation resistance characteristic. To minimize the driving power losses ($I_B V_{BE}$), the device should exhibit a low V_{BE} characteristic. Also the device should have a high current gain while operating in saturation so the driving current I_B is minimized. The control losses which consist of circuit protection, turn-on and turn-off should not exceed 10 per cent of the total losses. An example of the present state-of-the-art in transistor design, is the family of 30-ampere NPN silicon transistors developed by Westinghouse and designated as the 2N1830 and 2N2130 series. At 25°C these devices have a typical saturation resistance of 0.035 ohms, V_{BE} of 1.9 volts and a current gain of 5 at a collector current of 25 amperes. The devices also have a typical saturation resistance of 0.05 ohms at a collector current of 10 amperes when driven with a base current of 380 milliamperes. The efficiency of a 10-ampere power contact using the transistor in a 28-volt DC system from equation (3) is:

$$Eff = \left[1 - \frac{(10)^2 (.05) + (.38)(1.9) + .63}{(28)(10)} \right] 100$$

= 97%

Using the same transistor in an AC power contact would yield higher efficiencies since the losses are independent of supply voltages. The control function of an SCR, of course, is completely different from a power transistor. In the "on" condition, both the emitter and collector are biased completely "on"; and, as long as the external supply is sufficient to maintain the emitter and collector biases, the device remains "on" without the requirement of any driving power. The turn-on power loss is therefore negligible in a continuous operating circuit since only a pulse signal is required. The total power loss of a power contact in a DC circuit using an SCR can be given as:

$$P_{loss} = I_L V_F + \text{Control Losses} \quad (4)$$

Where: V_F = the forward voltage drop of the SCR at load current and
 I_L = the load current.

The efficiency can be given as:

$$Eff = \left[1 - \frac{I_L V_F + \text{Control Losses}}{V_{CC} I_L} \right] 100 \quad (5)$$

Where: V_{CC} is the supply voltage.

As an example, a power contact using the 2N687A SCR has a voltage drop of 0.86 volts at 20 amperes at 25°C. In a 28-volt DC circuit, the efficiency from equation (5) is:

$$Eff = \left[1 - \frac{(20)(.86) + 2.0}{(28)(20)} \right] 100$$

= 96%

Using the SCR in an AC contact, efficiencies of 99 per cent can be obtained since the drop across the SCR is independent of supply voltage and essentially constant with load current.

d. Development Factors

The development factors outlined herein are those device characteristics which must be considered in the development of new and improved devices and assemblies to meet the requirements established for contactless switching concepts for application to aircraft electrical systems. These desired characteristics are discussed for the applicable areas of signal sources, control logic and power contacts.

(1) Signal Sources

In considering the development requirements for signal sources, it must be understood that efficient use of electrical power is not of major importance, since the power requirements are in the milliwatt range. What is important, however, is efficient conversion of mechanical motion into an electrical signal and high reliability. Some developmental considerations to achieve these requirements are noted as follows:

(a) Strain Sensitive Devices

Gage factor is defined as the percentage change in output signal for a given change in stress. An increase in gage factor for strain sensitive devices would afford greater signal differential between the "ON" and "OFF" states of the signal sources. With the development of semiconductor strain sensitive elements, the state-of-the-art now provides an approximate maximum 30 per cent change in signal level. Further development in this area would make the design of signal sources with complete isolation of signal change resulting from temperature changes or mechanical shock and vibration much easier to accomplish.

(b) Piezoelectric Crystal Devices

Several manufacturers are now producing piezoelectric ceramics that will meet signal source design requirements under all conditions. However, some suitable type of actuating mechanism development should be undertaken. A mechanism meeting this requirement should insure that the crystal is not actuated as a result of mechanical shock and vibration and yet is uniformly actuated each time operation is desired.

(c) Photo Sensitive Devices

As it was pointed out earlier in this report, reliable light sources are the major shortcoming in the design of photo sensitive devices. Manufacturers are now engaged in the research and development of light sources composed of semiconductor materials such as Gallium Arsenide and Gallium Phosphide; and it is expected that these sources will be immune to shock and vibration and have essentially infinite life. Photo sensitive devices are presently being used in switching applications; and only the source of suitable illumination limits their life.

(d) Variable Coupling Devices

The development of a differential transformer with a higher output in the "on" condition and lower leakage in the "off" or "null" condition would be highly desirable. This would provide a greater differential between the two states and reduce the circuitry now required to construct a suitable signal source.

Several manufacturers are now engaged in research and development in these problem areas, and it is expected that most of the present deficiencies will be eliminated in the near future.

(2) Control Logic

Considerable care should be exercised before contemplating any alteration of the characteristics of devices which have evolved through the amount of experience presently available on logic elements. It is therefore pertinent to note that the following comments should be received with some reservation pending the results of the Phase II Design Study.

Future developments in devices for a control logic adapted for general aircraft application should consider the retention of such available characteristics as low power dissipation, small physical size, flexibility and reliability; and, in addition, achieving compatibility with the aircraft environment without extensive shielding or other suppressive requirements. The development of this type of control logic depends strongly upon the techniques required to produce logic elements compatible with the typical aircraft electrical system environment. This may require some adjustment of circuit design and power requirements to create a greater interference immunity. This obviously would affect the size of elements and the densities that can be obtained. Since flexibility also requires that the element density not exceed the point where economical replacement of a single failed device can be fostered, the natural result of increasing package size may turn out to be a compensating feature.

It will require further study to determine which of the design factors should assume major importance and how the design compromise can best be made between these factors to achieve the most feasible control logic.

(3) Power Contacts

Development factors that must be considered for new and improved devices in the area of power contacts are as follows:

- (a) Power transistors with current ratings above 100 amperes.
- (b) Power transistors with a maximum saturation resistance of 0.01 ohms at a collector current of 50 amperes.

- (c) Power transistors with a high junction-to-case thermal capacitance (typically $1.0 \frac{\text{watt-sec}}{^{\circ}\text{C}}$).
- (d) Power transistors with a low junction-to-case thermal resistance (typically $0.1 \frac{^{\circ}\text{C}}{\text{watt}}$).
- (e) Power transistors with high base-to-emitter threshold voltages (typically 0.5 volt).
- (f) Power transistors with voltage ratings (BV_{CEO}) above 600 volts.
- (g) Power transistors with high pulse power capabilities (typically 10,000 watts for 40 milliseconds).
- (h) SCR's with voltage drops of 0.5 volt maximum at rated currents up to fifty amperes.

3. Conclusions

a. Conclusions

The conclusions that are drawn from the investigations and analyses conducted during this phase of the program are listed below. Some of these conclusions are based on preliminary information and will be subject to change as additional information is made available by studies, investigations, and evaluations being conducted during Phases II and III of this program.

(1) The system philosophy assumed has considerable merit in the fact that only the power contact section will be exposed to the stringent requirements of MIL-STD-704 and MIL-W-5088.

(2) The electrical characteristics and requirements of the signal sources can be reasonably obtained with several devices such as piezoelectric crystals, differential transformers, pressure transducers, etc., within the present state-of-the-art of variable parameter device development. The mechanical design requirements which depend on human factors criteria will require considerable development.

(3) The control logic section can be made compatible with the aircraft environment and other sections of the contactless switching system by utilizing devices within the present state-of-the-art of microelectronic development.

(4) The requirements for AC power contacts and DC power contacts are so divergent that separate families of standards should be established rather than trying to establish a universal power contact to handle both AC and DC power switching.

(5) The electrical characteristics and requirements of the power contacts can be reasonably obtained with selected devices and compensating circuitry within the present state-of-the-art of semiconductor development.

(6) Voltage drop between the generation point and the utilization equipment within the limits specified by Military Specifications can be reasonably obtained with AC switching concepts but will be marginal with DC concepts.

(7) The present and future essential requirements for aircraft electrical systems can be reasonably obtained with judicious selection and proper derating of devices fabricated within the present state-of-the-art of semiconductor development.

PART II

1. Appendices

a. Appendix A - Semiconductor Voltage Ratings for Contactless Switching Applications - Power Contact

(1) Power Transistors

Power transistors, because of their solid-state characteristics, are inherently long-life, reliable devices. However, the lifetime of the device is largely determined by the circuit designer. There are certain basic limitations which must be well understood in achieving the utmost in reliability. Certain maximum ratings which are assigned by manufacturers to power transistors may be misleading if one is not fully aware of the meaning of these ratings. Power transistor voltage ratings are probably the parameters most frequently violated and this violation is the chief cause of power transistor failures. This discussion will present the basic power transistor voltage breakdown mechanisms and their relationship to the external circuit so that reliable circuits will be designed for aircraft electrical system applications.

Voltage ratings of power transistors in general are limited by: punch-through and breakdown voltage ratings. A discussion of each follows.

(a) Punch-Through

"Punch-through" phenomenon is a result of the depletion layer spreading more in the base region than the collector region and eventually reaching into the emitter region. When "punch-through" occurs, the emitter will be electrically shorted to the collector; and transistor action will cease. However, no permanent damage occurs to the transistor if the external circuit sufficiently limits the current; except for aluminum doped alloy power transistors. Punch-through voltage is a function of base width and base resistivity and is given as:

$$V_{PT} = \frac{630W^2}{\mu P} \quad (A1)$$

for germanium PNP transistors. Silicon devices which are grown diffused, double diffused, planar, mesa, and planar epitaxial do not normally exhibit this phenomenon. However, it is prevalent in silicon alloy devices and is given as:

$$V_{PT} = \frac{4.7 \times 10^{11} W^2}{\mu P} \quad (A2)$$

for silicon NPN power transistors. With large base widths and sufficient base region and collector region doping, punch-through ratings exceeding 500 volts can be obtained in silicon NPN power transistors. Hole mobility in silicon NPN devices is less than half the electron mobility of PNP devices; therefore, the maximum attainable punch-through voltage is doubled in NPN power transistors.

This is one of the reasons for the scarcity of silicon PNP power transistors. In low frequency applications, as will be the case in contactless switching applications, the base can be relatively thick so that punch-through will not be a limitation. Manufacturers normally do not specify punch-through voltages for power transistors since this voltage will usually be equal to or higher than the collector diode breakdown (BV_{CBO}) rating.

(b) Breakdown Voltage Ratings

The breakdown voltage rating between collector and emitter is more complex since it is a function of individual device characteristics and associated external circuit. These voltage ratings are generally listed on the device data sheets and are identified as: BV_{CBO} , BV_{CEO} , BV_{CES} , BV_{CER} , BV_{CEX} , and BV_{EBO} .

These ratings will be discussed individually for alloy devices since power transistors of the alloy-type generally will be applicable to contactless switching.

1. Collector-To-Base Breakdown - Emitter Open (BV_{CBO})

Collector-to-base breakdown is the result of avalanche multiplication. The curve of the collector cutoff current (I_{CBO}) showing the point where the current begins to avalanche, called breakdown (BV_{CBO}), is shown in Figure A1. Since leakage currents (I_{CBO}) are appreciable in alloy power transistors, they play an important part in breakdown ratings. The multiplication factor M for a given collector-to-base voltage is given as:

$$M = \frac{1}{1 - \left(\frac{V_{CB}}{BV_{CBO}} \right)^n} \quad (A3)$$

Both BV_{CBO} and n are constant for a power transistor of a given type and are dependent on the semiconductor material (silicon or germanium), the resistivity of the base, and the predominant type of charge carrier. Typically n is 3 for germanium PNP, 5 for germanium NPN, and 3 for all silicon transistors. As can be seen from equation (A3) and Figure A1, M approaches infinity at high collector-to-base voltages (V_{CB}), where collector current (I_C) begins to avalanche and breakdown occurs. This voltage is given by equations (A4), (A5), and (A6):

$$BV_{CBO} = 40 \mu^{(.75)} \text{ (NPN Silicon)} \quad (A4)$$

$$BV_{CBO} = 85 \mu^{(.63)} \text{ (PNP Silicon)} \quad (A5)$$

$$BV_{CBO} = 83.4 \mu^{(.6)} \text{ (PNP Germanium)} \quad (A6)$$

Note that breakdown voltage increases with an increase in base resistivity, whereas punch-through voltage decreases with an increase in base resistivity (equations A1, A2). The optimum voltage of a power transistor is obtained

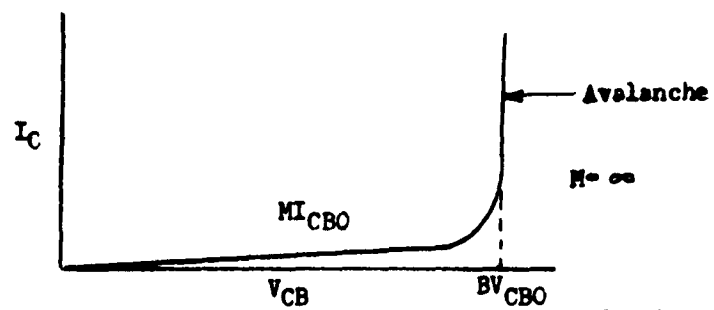


Figure A1. Typical Power Transistor Avalanche Characteristic

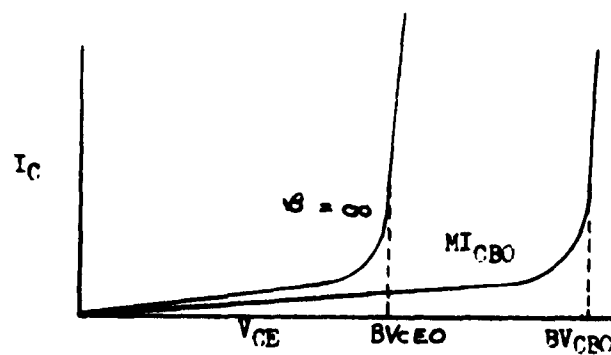


Figure A2. Typical BV_{CEO} and BV_{CBO} Characteristics

when breakdown and punch-through will occur approximately simultaneously for a given base material. Breakdown rating of power transistors exceeding 500 volts has been obtained. This voltage is very seldom encountered since leakage current and surface breakdown will usually occur first.

2. Collector-To-Emitter Breakdown - Base Open (BV_{CEO})

The collector-to-emitter breakdown is usually the lowest breakdown voltage of a power transistor. This breakdown occurs at the collector-to-emitter voltage where the common-emitter current transfer ratio β becomes infinite as shown in Figure A2. This voltage is given as:

$$BV_{CEO} = \frac{BV_{CBO}}{\sqrt[n]{1 + \beta}} \quad (A7)$$

It is interesting to note that BV_{CEO} is independent of I_{CBO} although the current-voltage path to breakdown is dependent on I_{CBO} . Also note that high current gains at low collector currents are undesirable.

3. Collector-To-Emitter Breakdown as a Function of External Circuit (BV_{CER})

A general equation can be derived for the I_C vs. V_{CE} curve for all conditions of the external circuit parameters shown in Figure A3. An expression for the general collector-emitter breakdown voltage is:

$$BV_{CE} = BV_{CBO} \sqrt[n]{1 - \frac{\alpha}{1 + \frac{R_L + r_e}{R_B + r_b}}} \quad (A8)$$

Assuming the internal emitter and base resistances are negligible, it can be seen from equation (A8) that if the load resistance (R_L) is allowed to approach infinity or R_B becomes zero, BV_{CE} will approach BV_{CBO} . Also, if R_B becomes infinite or R_L becomes zero, BV_{CE} will approach BV_{CEO} . If both R_L and R_B are zero (which would be base shorted to emitter), then the breakdown voltage designated as BV_{CES} is obtained and is given as:

$$BV_{CES} = BV_{CBO} \sqrt[n]{1 - \frac{\alpha}{1 + \frac{r_e}{r_b}}} \quad (A9)$$

The BV_{CES} voltage is usually specified as the maximum V_{CE} rating on the device data sheet. As can be seen in Figure A4, the BV_{CES} voltage curve approaches BV_{CBO} , then reverses and approaches BV_{CEO} as the collector current increases. Therefore, at low collector currents $BV_{CES} \approx BV_{CBO}$ and at high collector currents $BV_{CES} \approx BV_{CEO}$. The equation for BV_{CE} as a function of the external circuit is also valid where R_L and R_B are not zero so that resistance ratios can be fixed

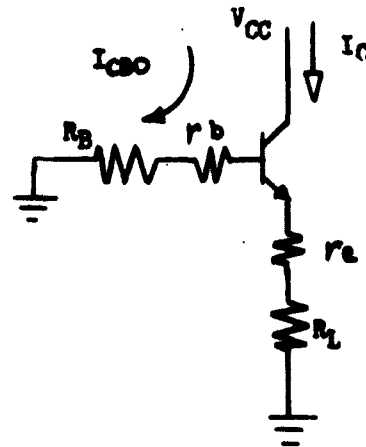


Figure A3. Transistor Schematic Showing External Circuit Parameters Without Reverse Base Bias

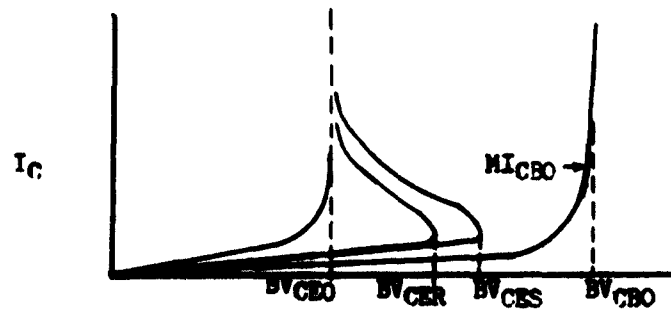


Figure A4. Typical V_{CE0} , V_{CES} , V_{CER} and V_{CBO} Characteristics

as desired. These voltage curves will fall between the BV_{CBO} and BV_{CES} curves and are designated as BV_{CER} . The breakdown is generally shown on data sheets and is given by:

$$BV_{CER} = BV_{CBO} \sqrt[n]{1 - \frac{\alpha}{1 + \frac{r_e}{R_B + r_b}}} \quad (A10)$$

This equation is the same as equation (A8), except R_L is zero. Note that at high values of R_B , the breakdown voltage decreases toward BV_{CBO} . An equation for BV_{CER} can also be given in terms of the leakage current (I_{CBO}) as:

$$BV_{CER} = BV_{CBO} \sqrt[n]{1 - \frac{I_{CBO} (R_B + r_b)}{V_D}} \quad (A11)$$

It is important to note that the breakdown voltage decreases with an increase in temperature since I_{CBO} increases with temperature, assuming R_B and r_b are constant.

4. Collector-To-Emitter Breakdown - Reverse Bias (BV_{CEX})

When a reverse bias is applied between the emitter and base, as shown in Figure A5, the breakdown voltage can be increased above the BV_{CES} value. As was previously mentioned, emitter injection takes place only when the base to emitter junction is forward biased above the threshold voltage V_D . That is, injection will occur when:

$$I_{CBO} (R_B + r_b) > V_D + V_{EB} \quad (A12)$$

The breakdown point is designated as BV_{CEX} and is given by:

$$BV_{CEX} = BV_{CBO} \sqrt[n]{1 - \frac{I_{CBO} (R_B + r_b)}{V_D + V_{EB}}} \quad (A13)$$

Figure A6 shows a series of breakdown curves for different values of V_{EB} . Note that BV_{CEX} increases with an increase of reverse bias. However, there is a limit of reverse bias that should be applied. When BV_{EB} is approached or when the IR drop across the junction renders reverse drive ineffective in removing leakage carriers, no further increase of reverse drive is desirable.

(c) Power Transistor Operating Regions

Definite areas of operation with regard to voltage and current exist in power transistors. In general, these areas can be divided into regions of operation as shown in Figure A7. The limits of region A, which is the forward

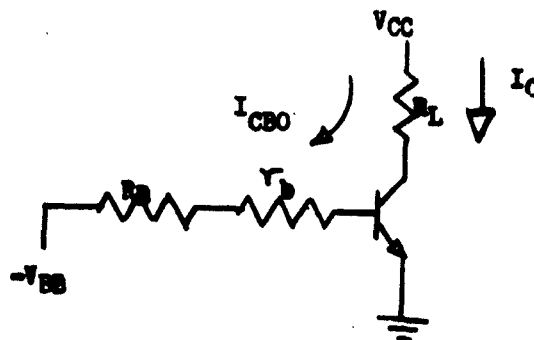


Figure A5. Transistor Schematic Showing External Parameters With Reverse Base Bias

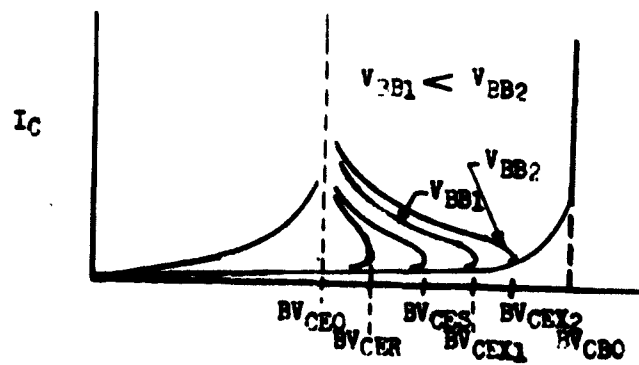


Figure A6. Typical Breakdown Characteristics

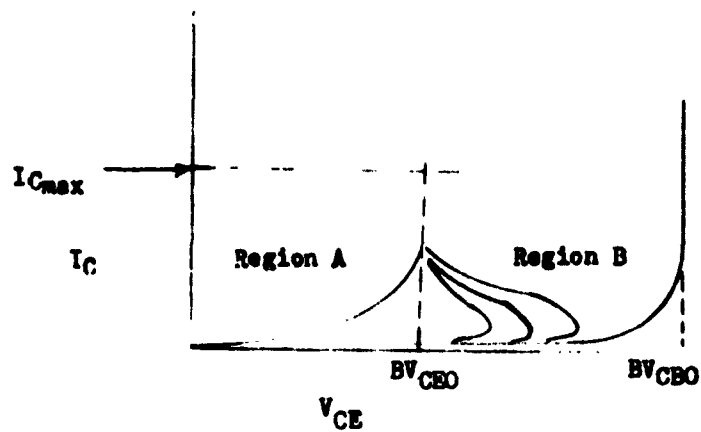


Figure A7. Typical Safe and Unsafe Operating Regions

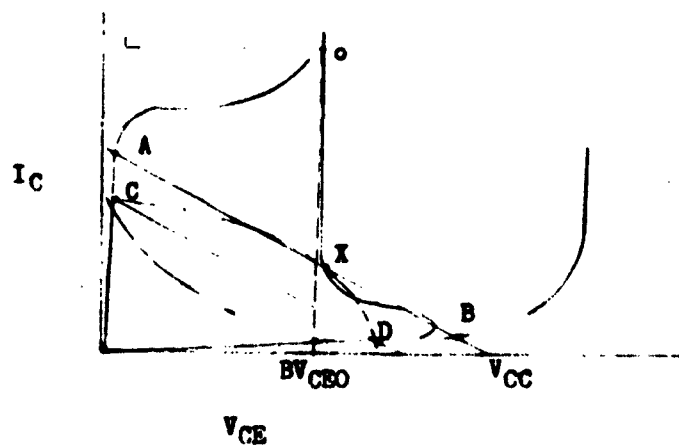


Figure A8. Typical Operating Load Lines

bias region, are determined by the avalanche breakdown BV_{CEO} and the maximum collector current rating for the transistor. This is the maximum reliability area. As long as the load line is in this area and dissipation is within allowable limits, the power transistor will not short out. Operation in this area will provide the designer with a safeguard insofar as unknowns or occasional power surges are concerned.

The limits of region B, which is the reverse bias region or negative-resistance region, are determined by the avalanche breakdown BV_{CEO} and the upper limits of the respective breakdown voltage for a particular external circuit condition. Passing a load line through this region can be a dangerous practice. A load line AXB intersecting the negative resistance area as shown in Figure A8 will cause the transistor to "hang-up" at point X. If the current is allowed to continue until point O is reached, a second negative resistance occurs and the curve will follow the dotted line. This is known as "second breakdown", and the transistor will be destroyed. A load line CD, as shown in Figure A8, would provide safe operation if the load is pure resistive. In practice, however, there are several factors that can cause deviation from this ideal case. Temperature, power supply transients, switching spikes, and reactive loads can cause the instantaneous operating point to be forced into the negative resistance region as shown by curve CXD. Operation in the dangerous negative resistance region can be avoided by making certain that voltages in excess of BV_{CEO} are never applied to the transistor.

(2) Silicon Controlled Rectifiers (SCR)

Although the basic theory of operation of SCR's is generally explained in the two transistor analogy, the voltage ratings of SCR's is different from that of transistors. A discussion of these ratings is given to provide the designer a general understanding of their meaning so that devices will be selected to provide reliable circuits. Voltage ratings of SCR's generally listed on device data sheets are identified as PRV , $PRV_{trans.}$, $VRDC$, V_{BO} , PFV and V_G . A discussion of each follows:

(a) Repetitive Peak Reverse Voltage (PRV)

This is the maximum allowable instantaneous repetitive reverse voltage that should be applied to the anode with the gate open. Although this is not a "breakdown" voltage as is shown on Figure A9, it should never be exceeded except by very short duration transients. If this rating is exceeded for relatively long durations (over 5 milliseconds), the device is likely to go into avalanche breakdown; and if the current is not sufficiently limited, the device will be destroyed.

(b) Transient Peak Reverse Voltage ($PRV_{trans.}$)

This is the maximum voltage that should be applied to the anode on a continuous basis which, of course, will be the rating used for applicable DC power contact applications such as bus switching.

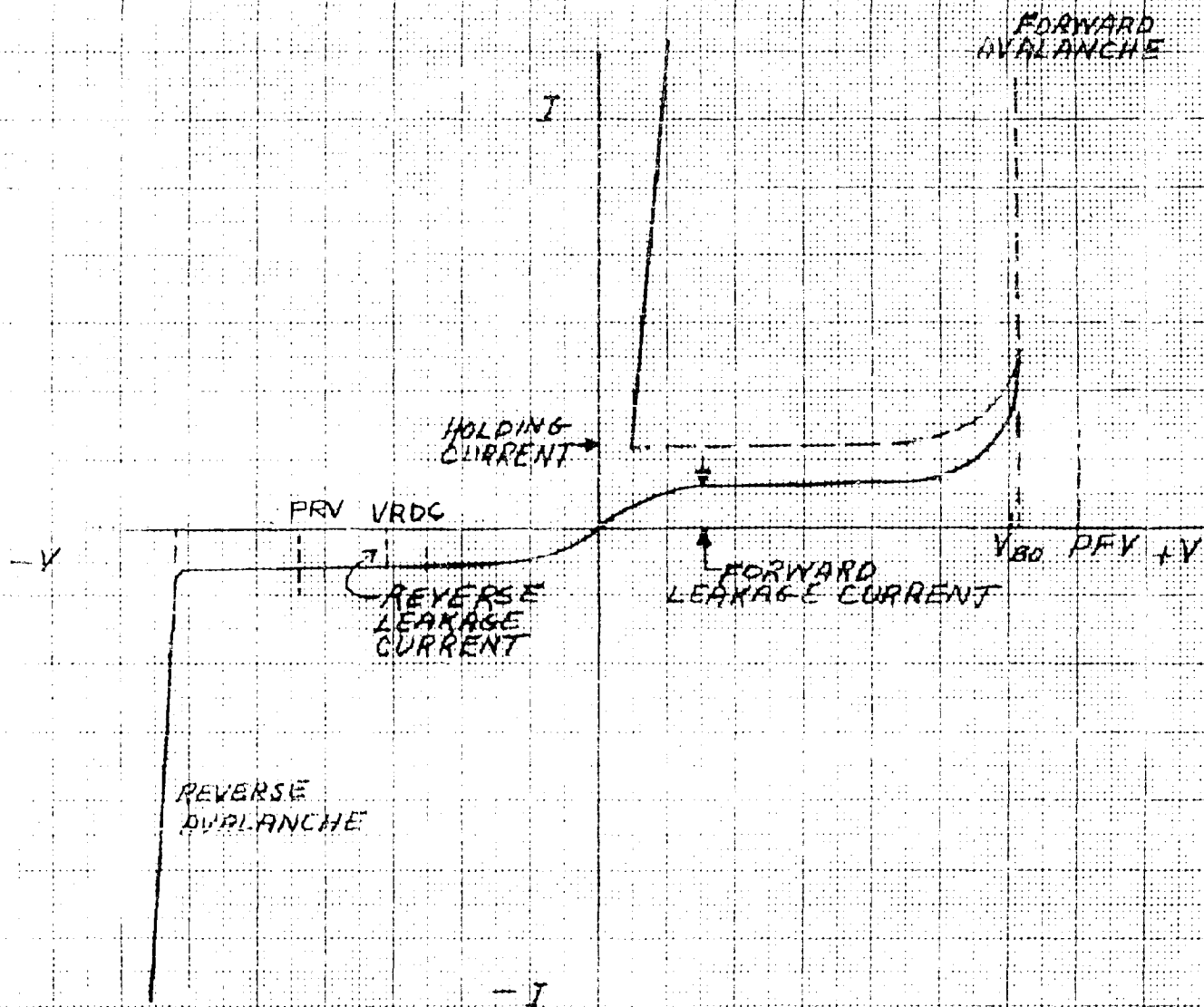


FIGURE A9: TYPICAL SCR VOLTAGE CHARACTERISTICS

(c) Forward Breakdown Voltage (V_{BO})

This is the value of positive anode voltage at which the SCR will switch into the "on" state with the gate circuit open. Device specification sheets give the breakover voltage for the worst case conditions which is with the gate open and at maximum allowable junction temperature since this rating is sensitive to temperature, gate drive and also to the rate of rise of forward voltage ($\frac{dv}{dt}$). V_{BO} decreases with an increase in temperature as well as with an increase in gate drive. Since a fast rate of rise ($\frac{dv}{dt}$) effectively reduces V_{BO} , an SCR can fire independent of any gate signal. This, of course, is an important characteristic in circuits with high frequency transients. Data is usually given on data sheets which will permit a designer to select devices whose V_{BO} ratings will not be exceeded under the possible maximum rates of rise to which the device may be subjected. Curves showing the maximum rate of rise of forward blocking voltage for the 2N680 series of SCR's is shown in Figure A10. Note that a higher voltage rated device will allow a higher rate of rise of forward voltage for a given peak circuit voltage. The $\frac{dv}{dt}$ characteristic is also dependent on the external circuit configuration. For example, reverse biasing the gate with respect to the cathode will increase the device $\frac{dv}{dt}$ capability.

(d) Peak Forward Blocking Voltage (PFV)

This is the instantaneous value of forward voltage that may be applied to the anode. As shown in Figure A9, this voltage rating is higher than the V_{BO} rating. However, since it is of an instantaneous nature, the SCR may or may not breakover when V_{BO} is exceeded. It is important to note, however, that if anode breakover should occur above the PFV limit, the SCR can be damaged. On the other hand, no damage to the SCR would be experienced should breakover occur below this limit. Since SCR's are not designed to be brought into conduction by exceeding the V_{BO} rating, an external circuit should be designed to trigger the SCR through the gate prior to exceeding the PFV limit.

(e) Gate Firing Voltage (V_G)

This is the gate-to-cathode voltage required to fire the SCR. Several limitations are imposed on the gate signal for reliable operations. One limitation is that the gate to cathode voltage rating (normally 10 volts) not be exceeded and the negative voltage rating between gate and cathode (normally 5 volts) not be exceeded. It is also important that a continuous dc gate bias not be used for triggering when an alternating voltage is being applied to the anode. During the reverse part of the AC cycle, the anode reverse current would be greatly increased by an appreciable flow of positive gate current, and the excess power could destroy the device. This dissipation can be limited with external circuit design techniques. In AC circuits using two SCR's shunted in reverse directions, for example, one of the two SCR's always "short out" the other, so that the device which is reversed biased can allow a considerable gate dissipation.

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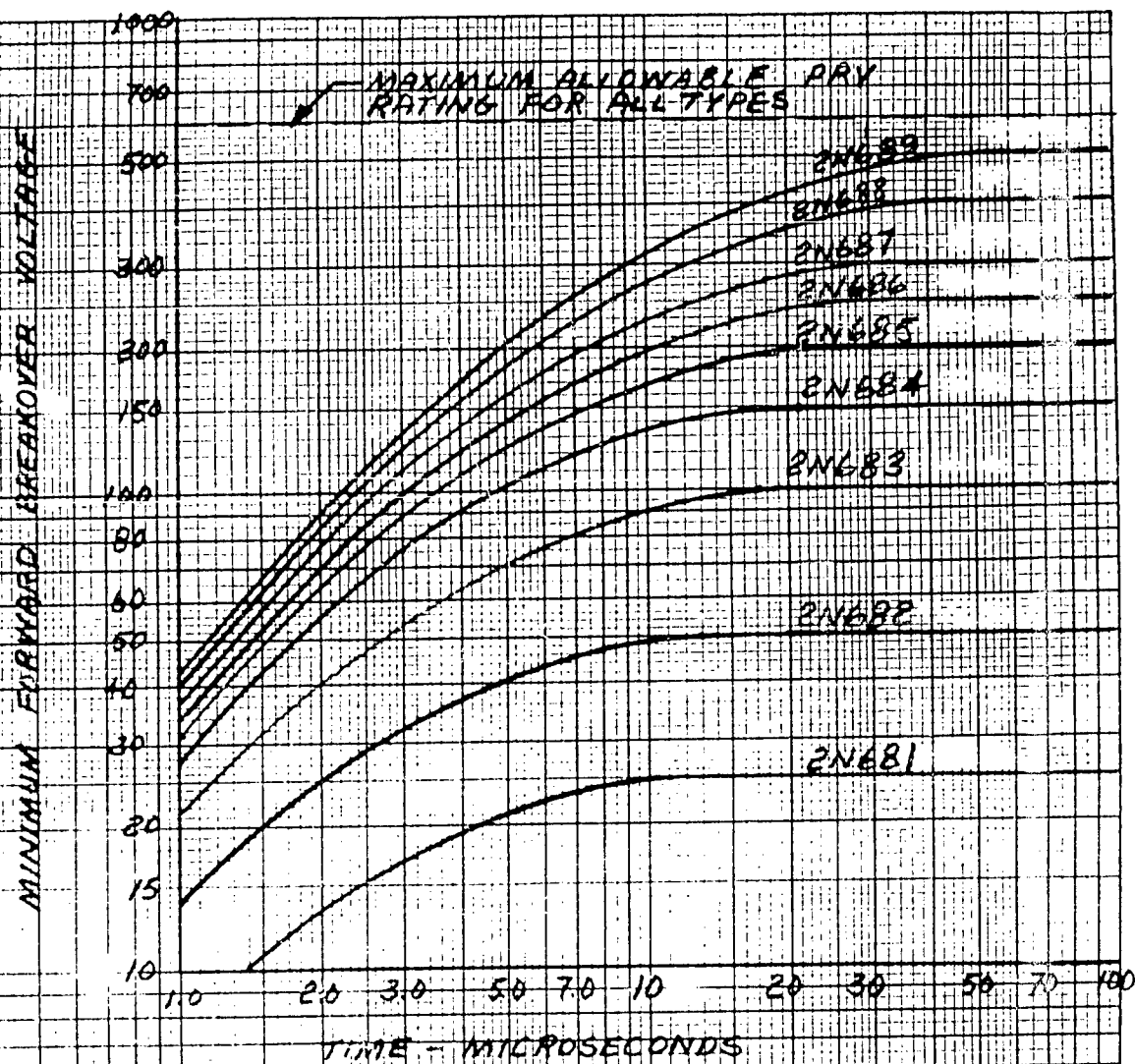


FIGURE A10: MAXIMUM RATE OF APPLICATION OF FORWARD BLOCKING VOLTAGE FOR THE 2N680 SERIES OF SGR'S

In conclusion it can be said that when SCR's are applied well within their ratings and not subjected to over-voltages, the device is one of the most reliable of all semiconductor devices.

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LIST OF SYMBOLS

BV_{CBO}	- Breakdown Voltage, Collector to Base, Emitter Open Circuited
BV_{CEO}	- Breakdown Voltage, Collector to Emitter, Base Open Circuited
BV_{CER}	- Breakdown Voltage, Collector to Emitter, Base Connected to Emitter through a Resistor
BV_{CES}	- Breakdown Voltage, Collector to Emitter, Base Shorted to Emitter
BV_{CEX}	- Breakdown Voltage, Collector to Emitter, Base to Emitter Diode Reverse Biased
BV_{EBO}	- Breakdown Voltage, Emitter to Base, Collector Open
I_C	- Collector Current
M	- Multiplication Factor in Collector to Base Breakdown
n	- Rate of Multiplication
R_B	- External Base Resistance
r_b	- Internal Base Resistance
r_e	- Internal Emitter Resistance
R_L	- Emitter Load Resistance
V_{BB}	- Supply Voltage for Reverse Bias
V_{BO}	- Blocking Voltage of an SCR
V_{CB}	- Voltage, Collector to Base
V_{CC}	- Collector Supply Voltage
V_D	- Base to Emitter Threshold Voltage Below Which No Emitter Multiplication Occurs.
V_{PT}	- Punch-through Voltage in Volts
W	- Base Width in Centimeters
α	- Common Base Current Gain

- β - Common Emitter Current Gain
- ρ - Base Resistivity in ohm - Centimeters
- μ - Base Majority Carrier Mobility in cm/volt-sec.

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b. Appendix B

Semiconductor Thermal Ratings for Contactless Switching Applications-
Power Contacts.

This discussion is intended to serve as a guide in thermal considerations. In order to be as general and yet as pertinent as possible, only those theories and practical factors which influence the thermal ratings and use of transistors and SCR's as power contacts will be discussed.

Transistors represent a radically different thermal problem from SCR's. At a given load current and contact drop, they will have a higher dissipation than SCR's due to losses in the base which are caused by base drive current across the base to emitter junction. This tends to make transistors dissipate substantially less power than SCR's at low currents but more at high currents. SCR's are limited to high thermal impedances and low thermal capacities compared to transistors due to the radically different device geometries. For both devices, however, the absolute limit of dissipation is that which will cause the junction temperature to rise to the maximum permissible junction temperature $T_J \text{ max}$.

(1) Transistor Power Contacts

Transistors exhibit a saturation characteristic so close to a true resistance that it is referred to by the semiconductor industry as saturation resistance (R_{CS}). Thus, the dissipation in a transistor while in saturation is roughly proportional to the square of the load current. This is given as:

$$P = I_C V_{CE} + I_B V_{BE} \quad (B1)$$

We can, by studying the transconductance curves on typical transistors, find that to a very close approximation:

$$P = I_C(I_C R_{CS}) + I_C/\beta_s (I_C R_{BS} + .75)$$

$$\text{because } V_{CE} = I_C R_{CS}, I_B = I_C/\beta_s, V_{BE} = I_C R_{CS} + .75$$

where .75 is the threshold voltage of the base to emitter diode. But R_{BS} is almost exactly equal to R_{CS} on nearly all transistors, so:

$$\begin{aligned} P &= I_C^2 R_{CS} I_C^2 R_{CS}/\beta_s + .75 I_C/\beta_s \\ &= I_C^2 R_{CS} (1 + 1/\beta_s) + .75 I_C/\beta_s \end{aligned} \quad (B2)$$

If we hold R_{CS} constant and investigate the effect of changing values of β_s , we find that at high currents ($.75 I_C/\beta_s \ll I_C^2 R_{CS}$) changing β_s from infinitely great to 10 results in approximately 10 per cent dissipation,

which does not seem an unreasonable increase for most applications. Dropping from β_s equal 10 to β_s equal 5, we find an additional 10 per cent increase in dissipation, which might be acceptable in some cases. At low currents ($I_C R_{CS} \ll .75 I_C / \beta_s$), the β_s becomes increasingly important in gaining efficiency and thus lowering steady-state dissipation. We can see that high values of β_s are not essential in high current contacts, but may be very important in low current contacts.

If we assume $\beta_s = 10$, which is a practical value for β_s for the current state-of-the-art in high efficiency power transistors, we can rearrange equation B2 as follows:

$$\begin{aligned} P &= I_C^2 R_{CS} + I_C^2 R_{CS} / 10 + .75 I_C / 10 \\ &= 1.1 I_C^2 R_{CS} + .075 I_C \end{aligned} \quad (B3)$$

We therefore see that at high currents ($I_C^2 R_{CS} \gg .075 I_C$) the power consumed is nearly equal to the square of the current multiplied by 1.1 R_{CS} . It is immediately apparent that in high current contacts, R_{CS} is by far the most critical parameter.

(a) Current Limiting Power Contacts

Power contacts with current limiting represent a trade-off between steady-state performance and transient dissipation capabilities. For this reason, one of these factors must be balanced against or considered along with the other to determine contact suitability for a given application.

1. Integral Heat Sink

In this application, the contact is considered as depending solely on its attached heat sink for heat removal. In any thermally conductive structure such as an aircraft, avoiding small enclosures will prevent the contact from being exposed to temperatures greater than 85°C (185°F) during operation, and by making the enclosure large enough to allow at least 5 cubic feet per minute air flow, the following discussion applies.

a. Continuous Ratings

At the low levels of power dissipation which will be encountered in a saturated contact, no damage to the contact will ever occur. However, this dissipation should cause the minimum possible temperature rise at the junction.

Examining commercially available heat sinks, we find that the model NC-441 Cooler made by Delta-T Co. offers a natural convection θ of .54 °C/W at 100 watts (see Figure B1). This sink is 4.5" X 4.75" X 5.5", and is mounted 3/32" off the horizontal with the long axis vertical. Although other heat sinks approach this performance, no less θ

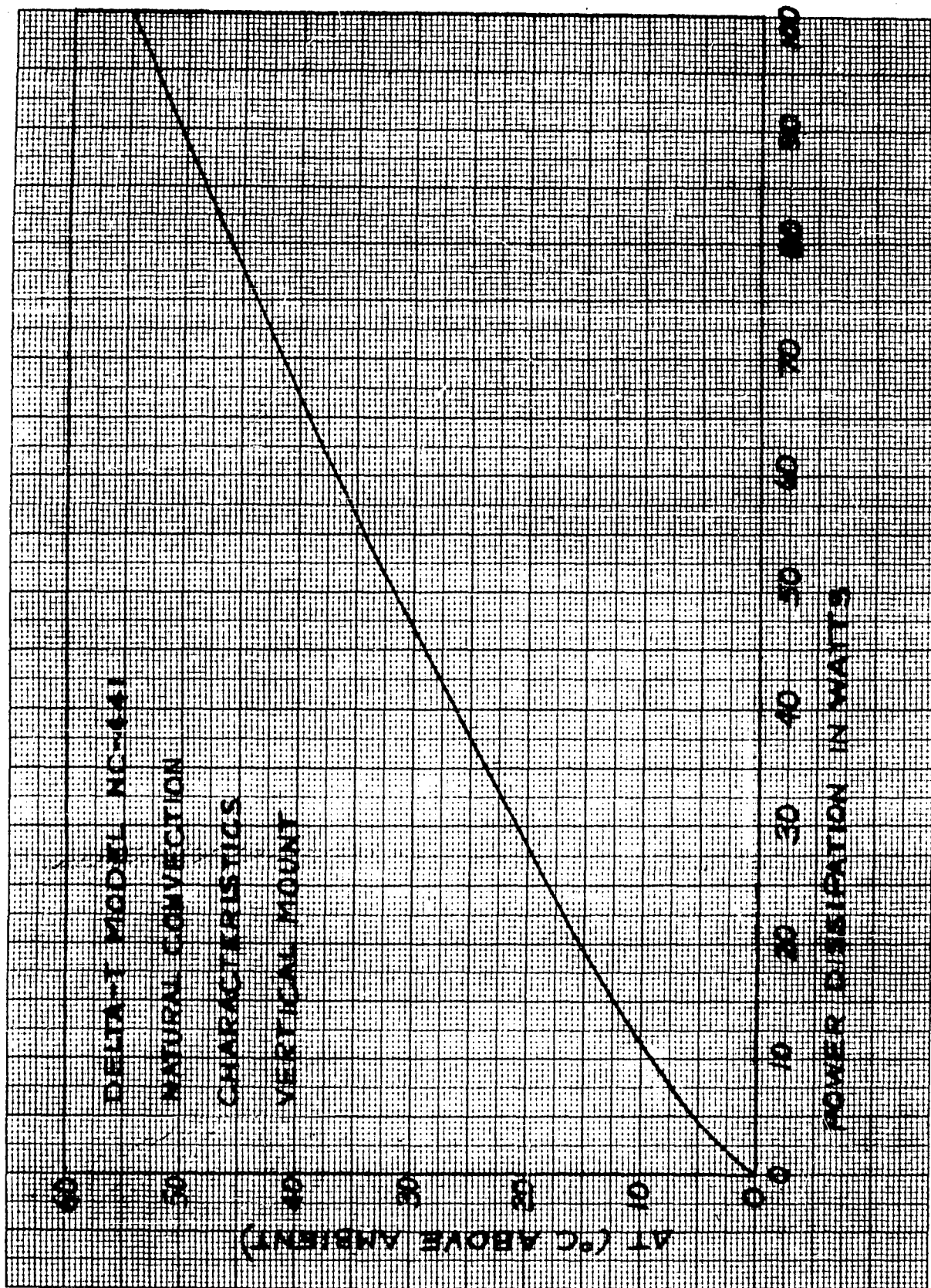


FIGURE B1: TYPICAL HEAT SINK CHARACTERISTICS

should be considered for the ten-ampere transistor contacts presently available unless forced air is used or enough contacts are grouped or stacked to provide "chimney action." Improvement offered by such variations are determined by the individual configurations and are seldom discussed in literature in any other way; nevertheless, considering that the largest θ in such a case is from the sink to the ambient because of the very low conductivity of air, and consulting the forced convection characteristics of Figure B2, it can be assumed that nearly any configuration which offers additional driving power to the convective process will greatly improve heat transfer to the ambient.

b. Pulse Ratings

Figure B3 shows the equivalent thermal circuit of a typical high power transistor for pulse power analysis. Since these pulses are considered as being very short term, the case of the transistor will be assumed to remain at a constant temperature during the pulse. This will introduce a negligible error in light of derating factors used elsewhere and is in agreement with the manufacturer's literature.

Upon application of a pulse of power, the temperature of the junction begins to rise exponentially per the equation:

$$\Delta T = P \theta_{JC} (1 - e^{-\frac{t}{\tau}}) \quad (B4)$$

Using typical values per MIL-STD-704, we obtain:

$$\begin{aligned} \Delta T &= (500) (.35) (1 - e^{-\frac{.040}{.180}}) \\ &= 175 (1 - e^{-.222}) = 35^{\circ}\text{C} \end{aligned}$$

for an 80 volt, 40 millisecond pulse
and

$$\begin{aligned} T &= 300 (.35) (1 - e^{-\frac{.180}{.180}}) \\ &= 105 (.63) = 66^{\circ}\text{C} \end{aligned}$$

for a 60 volt, 180 millisecond pulse. Figure B4 gives a more complete plot of dissipation allowable versus MIL-STD-704 requirements. Sufficient time must be allowed between pulses for the transistor to recover, of course, but this is easily accomplished in the design of the reset circuitry.

c. Combined Steady-State and Pulse Ratings

To better illustrate the interdependence of steady-state and pulse power ratings, let us cover a typical design example:

Required: Design a 10 ampere contact which will current limit at 11 amperes and which will comply to MIL-STD-704 at 85°C

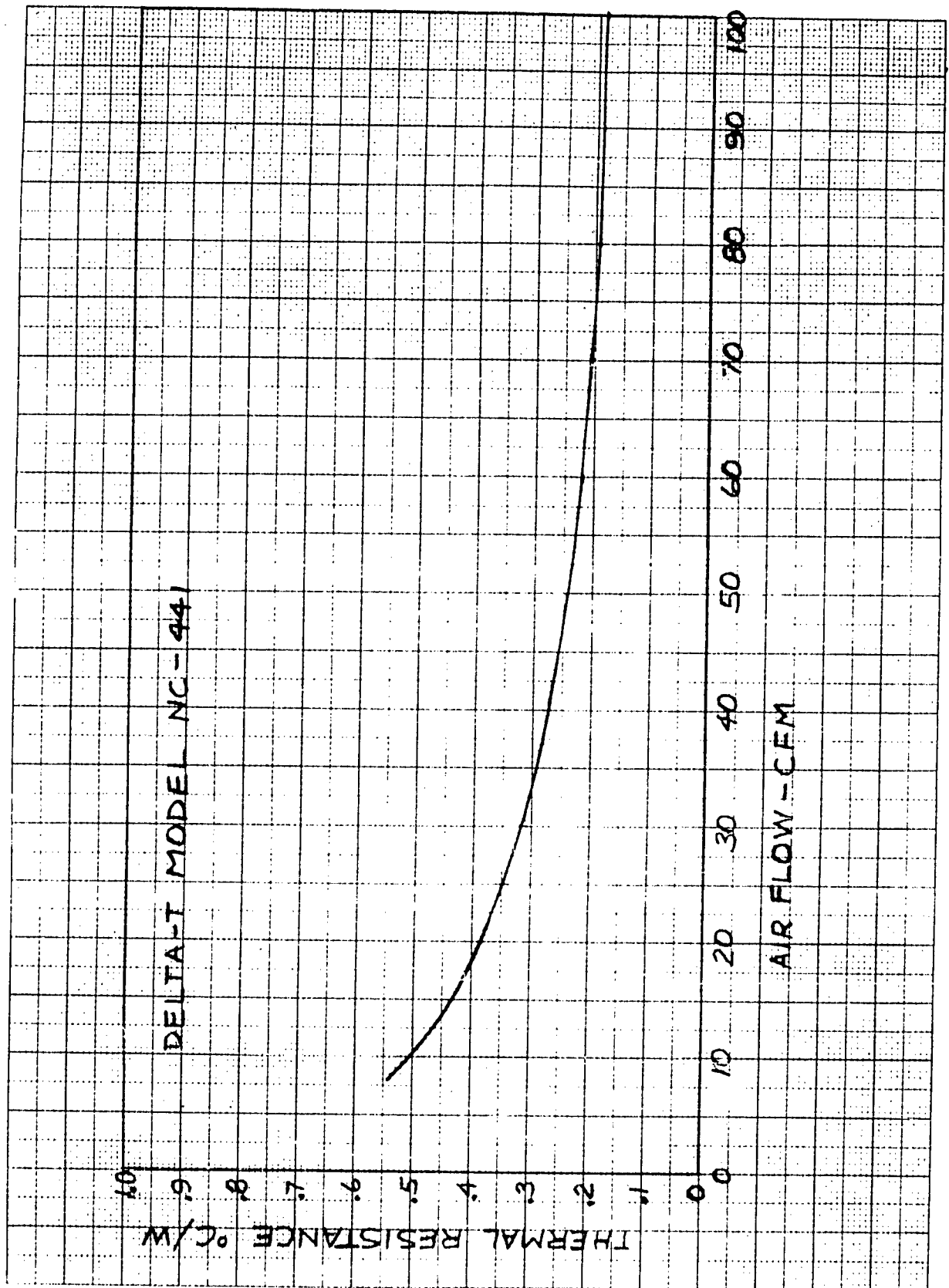


FIGURE B2: HEAT SINK FORCED CONVECTION CHARACTERISTICS

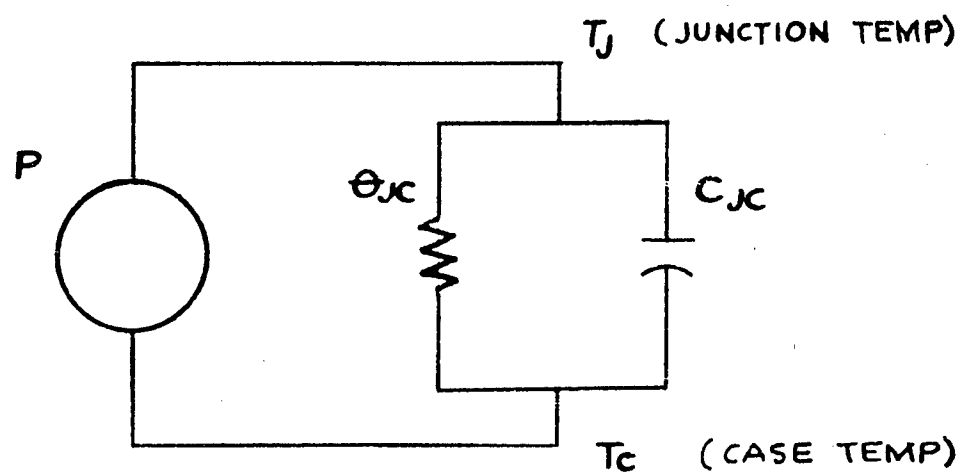
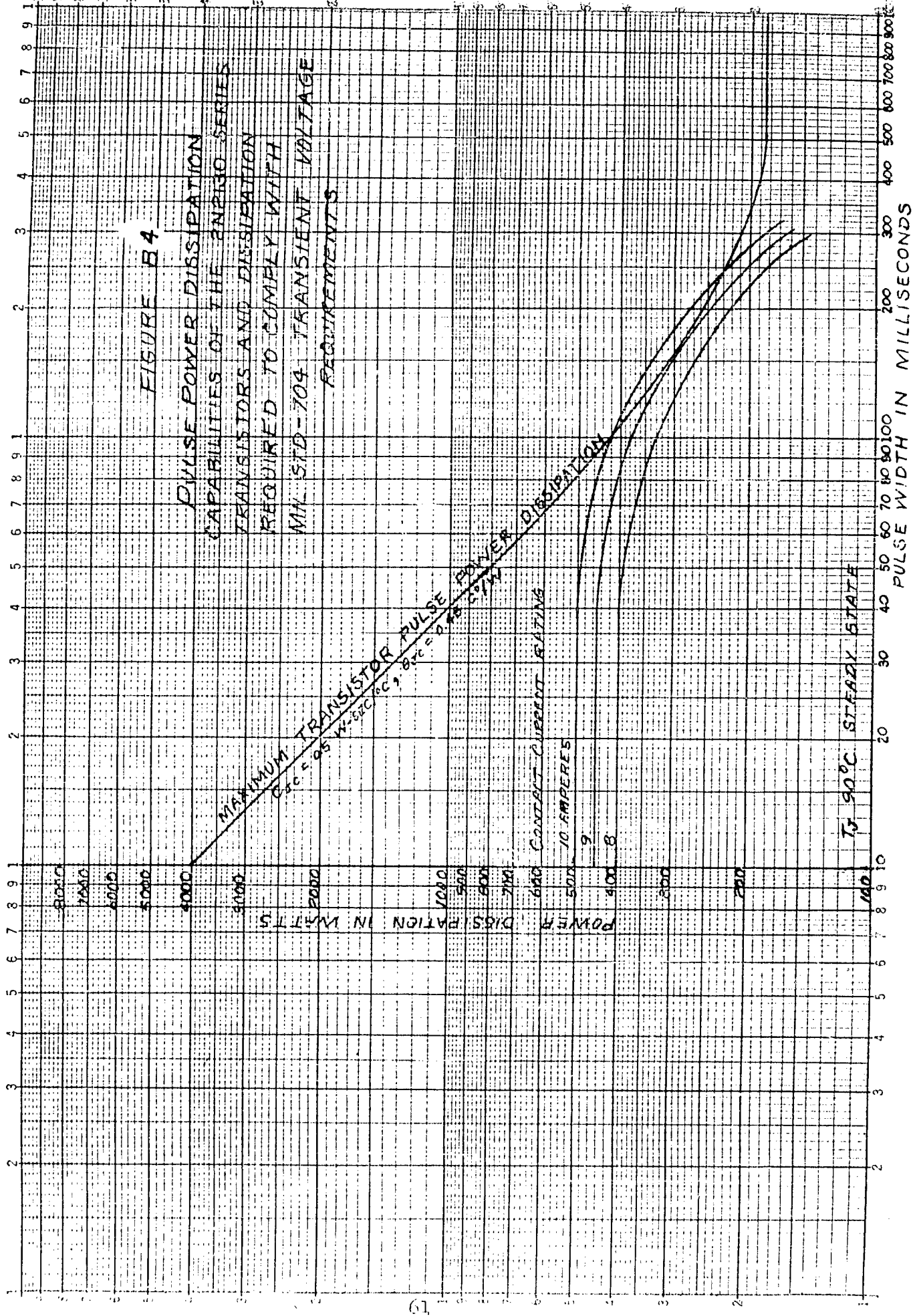


FIGURE B3 TRANSISTOR THERMAL NETWORK
FOR PULSE POWER ANALYSIS.



ambient. Use typical values, as tolerances will be determined by the requirements established in the initial design.

Referring to equation B4: $\Delta T = P \theta_{JC} (1 - e^{-\frac{t}{\tau}})$.
 Select MIL-STD-704 requirement of a 60 volt transient for 180 milliseconds as the worst transient indicated by Figure B4. By equation B4, we obtain:

$$\Delta T = 300 (.35)(1 - e^{-1}) = 105 (.63) = 66^\circ\text{C}$$

Assume, for the moment, that the junction temperature will be able to rise to an absolute maximum allowable junction temperature of 175°C . The initial temperature of the junction must be no greater than:

$$T_J = T_{J \text{ max}} - \Delta T \quad (\text{B5})$$

or, in our case:

$$T_J = 175^\circ - 66^\circ = 109^\circ\text{C}$$

Since the sink, ignoring the very small θ from case to sink, may rise to no more than 109°C in an ambient of 85°C under steady-state conditions, we can find the maximum allowable sink θ with a variation of Ohm's Law:

$$T = P \theta_{SA} \quad (\text{B6})$$

where P is equivalent to current and T is equivalent to voltage. Therefore:

$$T = 109 - 85^\circ\text{C} = P \theta_{SA} = 24^\circ\text{C}$$

The trip out point on a typical device would be at a minimum of $R_{CS} = .06$ ohms to allow for the rise in R_{CS} with temperature, so from equation B2:
 $T = 1.1 (10)^2 (.06) + .075 (10) = 7.35$ watts. So $7.35 \theta_{SA} = 24^\circ\text{C}$, or θ_{SA} = approximately 3.2°C/W . Allowing $.1^\circ\text{C/W}$ for the thermal impedance of the transistor case to heat sink joint, we have $\theta_{SA} = 3.1^\circ\text{C/W}$.

It would seem reasonable to keep the actual thermal impedance of the sink as low as possible, consistent with space and weight. Commercial sinks of very reasonable size and weight are obtainable in this range of θ_{SA} .

2. External Heat Sink

External sinks will be considered to be in the form of thin metal plates on which multiple contacts are mounted, and the maximum heat dissipation from all these contacts is small compared to the dissipating capabilities of the plate, or in the form of installations where adequate heat paths to structure exist to keep ΔT very small.

a. Continuous Ratings

With the above assumptions, continuous ratings are limited to a maximum value determined by the thermal resistance of the transistor, or $\Delta T = 7.35 (.35) = 2.6^{\circ}\text{C}$ per equation B5 for a typical 10 ampere contact. Commercial convective sinks will allow about 8°C rise under the above conditions, and it seems reasonable to assume that an external sink would allow some improvement over integral sinking, so a 3 to 6°C maximum rise in temperature at the connection to a transistor seems to be practically attainable for a 10 ampere contact.

b. Pulse Ratings

No change in pulse ratings can be achieved with sinks external to the case of the transistor with existing transistors other than in the repetition rate. Attainable repetition rates being quite adequate, no further consideration will be given to them.

(b) Non-current Limiting Power Contacts

The maximum continuous rating necessary is the only one which need be considered, since any other rating will be lower and less stringent. Therefore, considering the maximum allowable current at the (by MIL-STD-704) maximum voltage across the contact, we have by equation B2 for the 2N2130 series:

$$P = 1.1 (900)(.067) + .075 (30) = 68.25 \text{ watts}$$

Consulting the manufacturer's data sheets, we find that the maximum permissible sink temperature at this dissipation is approximately 140°C (see Figure B5). Consulting the Delta-T model NC-441 data sheet, we find that a temperature differential of $140^{\circ} - 85^{\circ}\text{C}$ will allow 100 watts to be dissipated by natural convection (Figure B1), so we conclude reasonable designs are feasible.

(2) Silicon Controlled Rectifier Contacts:

SCR's are most severely limited by their thermal fatigue ratings, which limit the number of short term extreme temperature excursions of the junction to typically 100 to 500 times per contact lifetime. Fortunately, design procedures which eliminate such excursions by either placing the SCR in series with current limiting switches or by proportionally controlling the "On" time of the SCR as a power limiting measure have been developed. Large SCR switches pass through their active region in approximately one micro-second. Because the number of times it must switch, even when being used for current limiting, is limited to 400 times per second in 400 cycles per second systems at currents which the power limiting circuitry will limit to about 10 times rated current, it can be assumed that the power consumed by the SCR during switching is:

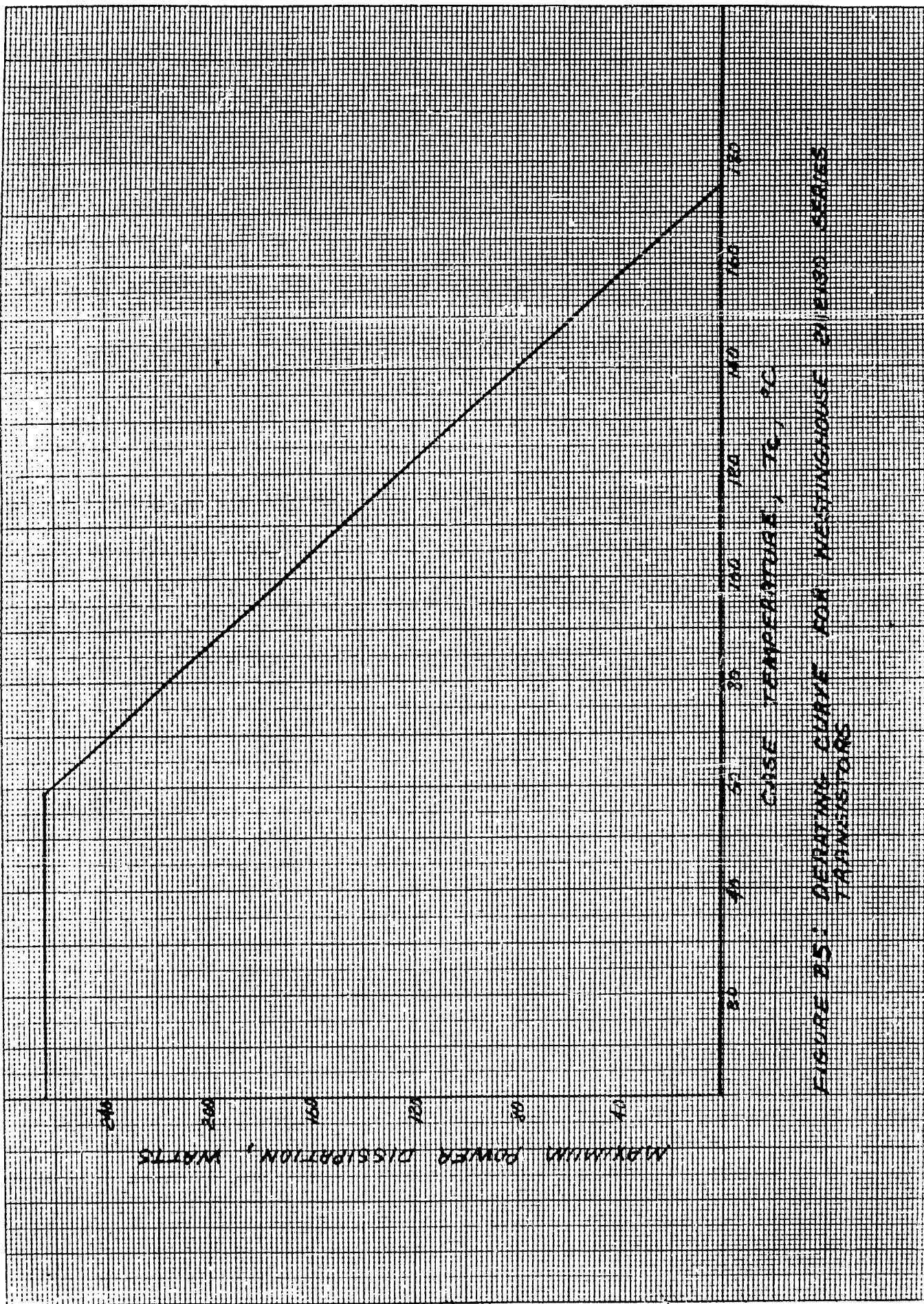


FIGURE 25: OPERATING CURVE FOR WESTINGHOUSE 2N1550 SERIES TRANSISTORS

$$P_{SW} = 1/2 (nt) V_{max} I_{max} \quad (B7)$$

(based on each power pulse generated by switching through the active region being very close to the area of a triangle equal to 1/2 the area of the rectangle $V_{max} I_{max}$). This power will be negligible compared to the continuous power which is given by:

$$P = 1/2 V_A I_A$$

For example: Given a power contact in which $I_A = 10$ amperes, $V_A = 1$ volt, $V_{max} = 300$ volts, $I_{max} = 100$ amperes, $t = 1 \times 10^{-6}$ seconds, $n = 400$ cycles per second.

Power dissipated due to switching is:

$$\begin{aligned} P_{SW} &= 1/2 (400)(1 \times 10^{-6}) (300)(100) \\ &= .6 \text{ watts} \end{aligned}$$

Continuous power dissipated is:

$$P = 1/2 (1)(10) = 5 \text{ watts}$$

Total dissipated power is 5.6 watts

From this, the preceding discussions on determining the maximum ratings allowable in steady-state operations under the headings of "Integral Heat Sink", "Current Limiting Contacts," "Transistor Power Contacts" are directly applicable, except that the temperature allowable from sink to ambient will be larger as no allowance need be made for power pulses. Therefore, the sink can be much smaller.

LIST OF SYMBOLS

R_{CS}	-	Saturation Resistance of a Transistor
P	-	Power Consumed
I_C	-	Collector Current
V_{CE}	-	Voltage, Collector to Emitter
I_B	-	Base Current
V_{BE}	-	Voltage, Base to Emitter
β_S	-	Beta Used To Insure Good Saturation Characteristics
θ	-	Thermal Resistance in $\frac{^{\circ}C}{W}$
θ_{JC}	-	Thermal Resistance From Junction To Case
C_{JC}	-	Thermal Capacitance From Junction To Case in $\frac{\text{Watt Seconds}}{^{\circ}C}$
θ_{SA}	-	Thermal Resistance From Sink To Ambient
P_{SW}	=	Power Consumed in Switching
V_A	=	Average Voltage
I_A	=	Average Current
n	=	Number of Operations per Second
T	=	Temperature
t	=	Time
γ_t	=	Transistor Thermal Time Constant

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c. Appendix C - Compatibility Chart for Electromechanical Components vs. Contactless Switching Concepts

The following compatibility chart lists the aircraft system characteristics; gives the specification requirements of the characteristics for conventional electromechanical relays, switches and circuit breakers as applicable; and gives the present capability or realistic requirement where specification requirements are nonexistent for contactless switching concepts such as power contacts, logic and signal sources as applicable. This chart will serve as a quick reference to show the compatibility of contactless switching concepts with electromechanical components.

APPENDIX C

COMPATIBILITY CHART

SPECIFICATION REQUIREMENTS

CHARACTERISTICS	ELECTROMECHANICAL (TYPICAL)			CONTACTLESS SWITCHING		
	RELAY	SWITCH	CKT BKR	POWER CONTACT	LOGIC	SIG SOURCE
Voltage (volts)						
Bus Switching						
Steady-state						
AC	240 rms	240 rms	240 rms	240 rms	--	--
DC	30	30	30	30	--	--
Transient						
AC	1800 rms (1.0 sec)	1000 rms (1.0 sec)	1500 rms (1.0 sec)	430 rms	--	--
DC	2500 (1.0 sec)	1400 (1.0 sec)	2500 (1.0 sec)	± 1.00	--	--
Load Switching						
Steady-state						
AC	120 rms	120 rms	120 rms	120 rms	--	--
DC	30	30	30	30		
Transient						
AC	1800 rms (1.0 sec)	1000 rms (1.0 sec)	1500 rms (1.0 sec)	220 rms	--	--

APPENDIX C (cont'd)

COMPATIBILITY CHART

SPECIFICATION REQUIREMENTS

CHARACTERISTICS	ELECTROMECHANICAL (TYPICAL)			CONTACTLESS SWITCHING		
	RELAY	SWITCH	CKT BKR	POWER CONTACT	LOGIC	SIG SOURCE
DC	2500 (1.0 sec)	1400 (1.0 sec)	2500 (1.0 sec)	+100	--	--
Contact Drop (volts)	.10 @ 10A	.10 @ 10A	.50 Max.	1.0 Max	--	--
Leakage (amperes)	.3 μ a max.	.3 μ a max.	.3 μ a max.	3.0 ma max.	--	--
Overload (amperes)	600% rated (200 ms) 50 operations	150% rated (20 ms) 50 operations	not applicable	600% rated (200 ms)	--	--
Surge (amperes)	1000% rated (200 ms)	600% rated (20 ms)	600% rated (1.0 sec) no trip	1500% rated (50 ms)	--	--
Pick-up Voltage	18.0	--	--	2.0 min	2.0 min	--

APPENDIX C (cont'd)

COMPATIBILITY CHART

SPECIFICATION REQUIREMENTS

CHARACTERISTICS	ELECTROMECHANICAL (TYPICAL)				CONTACTLESS SWITCHING		
	RELAY	SWITCH	CKT BKR	POWER CONTACT	LOGIC	SIG SOURCE	
Drop-out Voltage	18.0	--	--	1.0 max	.3 max	--	
Control Current	150 ma	--	--	50 μ a	50 μ a	--	
Turn-on Time	10 ms	--	--	100 μ s max	450 ns max	450 n sec	
Release Time	2 ms			400 μ s max	1.2 μ s max	1.2 μ sec	
Contact Bounce	10-1000 μ s	10-1000 μ s	10-1000 μ s	none	none	none	
Radio Noise	MIL-I-6181	MIL-I-6181	MIL-I-6181	MIL-I-6181	MIL-I-6181	MIL-I-6181	
Efficiency	98%	99%	98%	95%	--	25%	
Circuit Interruption	--	--	After 600% Overload for 1.0 sec	At 300% Overload and 40 ms or in 10ms over 300% Overload	--	--	

APPENDIX C (cont'd)

COMPATIBILITY CHART

SPECIFICATION REQUIREMENTS

CHARACTERISTICS	ELECTROMECHANICAL (TYPICAL)			CONTACTLESS SWITCHING		
	RELAY	SWITCH	CKT BKR	POWER CONTACT	LOGIC	SIG SOURCE
Reset Voltage	-	-	-	1.0 min.	-	-
Reset Current	-	-	-	50 μ a	-	-
Temperature						
Operating						
High	125° C	70° C	125° C	85° C	85° C	85° C
Low	-70° C	-55° C	-40° C	-54° C	-54° C	-54° C
Storage						
High				100° C	100° C	100° C
Low				-62° C	-62° C	-62° C
Shock	25G for 11 ms	50G for 11 ms	25G for 11 ms	150G for 11 ms	150G for 11 ms	50G for 11 ms
Vibration	15G to 500 cps	10G to 500 cps	10G to 500 cps	30G to 2000 cps	30G to 2000 cps	30G to 2000 cps
Acceleration	15G	15G	15G	100G	100G	50G

APPENDIX C (cont'd)

COMPATIBILITY CHART

SPECIFICATION REQUIREMENTS

ELECTROMECHANICAL (TYPICAL) CONTACTLESS SWITCHING

CHARACTERISTICS	RELAY	SWITCH	CKT BKR	POWER CONTACT	LOGIC	SIG SOURCE
Salt Spray	MIL-E-5272	MIL-STD-202	MIL-E-5272	MIL-STD-202, Cond. A	MIL-STD-202, Cond. A	MIL-STD-202, Cond. A
Humidity	MIL-E-5272	MIL-STD-202	MIL-E-5272	MIL-STD-202	MIL-STD-202	MIL-STD-202
Altitude (Feet)	80,000	70,000	70,000	100,000	100,000	100,000
Life	100,000 cycles	10,000 cycles	5,000 cycles	10,000 hrs. or 10,000,000 operations of norm. service	10,000 hrs or 10,000,000 operations of norm. service	100,000 cycles

d. Appendix D - Device Characteristics Charts for Signal Sources,
Logic and Power Contacts

The following charts list some of the devices that are considered capable of meeting the requirements for application to aircraft electrical systems. These charts list only the device characteristics that are pertinent to their application in contactless switching systems.

DEVICE CHARACTERISTICS

SIGNAL SOURCES

SIGNAL SOURCE	PRINCIPLE OF OPERATION	OUTPUT CHARACTERISTIC	ELECTRICAL POWER REQUIRED TO OPERATE	OUTPUT VALUE	TEMPERATURE STABILITY	SHOCK AND VIBRATION SENSITIVITY	REMARKS
Strain Sensitive Semiconductor	Strain Produces Change in Resistance	AC or DC Level	Medium	Low	Low	High	Requires Amplification
Piezoelectric Crystal	Sharp Force Creates Electrical Pulse	Pulse	-	High	High	Very High	Step-Down Transformer Necessary
Variable Coupling Devices							
Differential Transformer	Change in Magnetic Coupling Induces EMF	AC Level	High	Medium	Medium	Medium	Rectification Necessary
Variable Capacitor	Change in Field Permittivity Induces EMF	AC Level	High	High	Medium	Medium	Rectification Necessary
Photosensitive Device							
Transistor	Light Creates Electrical Energy	DC Level	Medium	Medium	Medium	High	Low Power Long Life Light Source Required

DEVICE CHARACTERISTICS
SIGNAL SOURCES

SIGNAL SOURCE	PRINCIPLE OF OPERATION	OUTPUT CHARAC- TERISTIC	ELECTRICAL POWER REQUIRED TO OPERATE	OUTPUT VALVE	TEMPERATURE STABILITY	SHOCK AND VIBRATION SENSITIVITY	REMARKS
Diode	Light Creates Electri- cal Energy	AC or DC Level	Low	Low	Medium	High	Low Power Long Life Light Source Required

DEVICE CHARACTERISTICS LOGIC

MANUFACTURERS	TYPE NO	APPLI- CATION	CKT CONFIG	FREQ.	FAN OUT	AVG DELAY	SUPPLY V	PWR DISS MW	WT	TEMP RANGE °C
Delco Radio Div.	SML33	NOR/NAND	DTL	100KC	4	-	6	4	-	-40 +100
	SM200	Flip-Flop	DTL	100KC	3	2 μ s	6	10	-	-40 +100
Electra Mfg. Co.	CML	NOR	RTL	-	5	-	5	-	-	-
Fairchild Semiconductor	MLF	Flip-Flop	DTL	1mc	5	50 ns	3	30	-	-55 +125
	MLG	NOR	DTL	1mc	5	50 ns	3	15	-	-55 +125
General Electric Co.	M1	AND	LLL	2mc	5	-	3	10	-	-55 +125
	M1	Inverter	LLL	2mc	5	-	3	10	-	-55 +125
	M1	Flip-Flop	LLL	2mc	5	-	3	10	-	-55 +125
Kearfott Semiconductor Corp.	21NR15B	NOR	RTL	1mc	5	60 ns	-10	-	-	-65 +125
Lear Siegler, Inc.	-	AND/OR	DTL	5mc	5	-	6	-	-	+125
	-	Inverter	DTL	-	5	-	6	-	-	+125
Minneapolis-Honeywell	-	NOR	DTL	1mc	-	-	-	-	-	-
	-	Flip-Flop	DTL	1mc	-	-	-	-	-	-
Motorola	MECL	NOR/NAND	LLL	-	6	4 ns	5.2	35	-	-55 +125
	MECL	Flip-Flop	LLL	-	6	-	5.2	-	-	-55 +125
Pacific Semiconductor, Inc.	PCF101	Flip-Flop	TCL	3mc	4	-	3	-	-	-55 +125
	PCG101	NAND	TCL	5mc	4	-	3	-	-	-55 +125
Philco Corp.	H7004	NOR	RTL	-	3	-	11	110	-	-55 +125
	H7005	Flip-Flop	RTL	-	2	-	11	100	-	-55 +125
Radio Corp. of America	DMC100	NOR/NAND	DTL	10mc	-	18 ns	7.5	14	-	-55 +125
Texas Instruments	SN510	Flip-Flop	RTL	1mc	4	-	3 or 6	7	-	-55 +125
	SN512	NOR/NAND	RTL	-	5	75 ns	3 or 6	7	-	-55 +125
	SN514	NOR/NAND	RTL	-	5	-	3 or 6	7	-	-55 +125
	SN515	NOR/NAND	RTL	-	5	-	3 or 6	7	-	-55 +125

DEVICE CHARACTERISTICS LOGIC (Continued)

MANUFACTURERS	TYPE NO	APPLI- CATION	CKT CONFIG.	FREQ.	FAN OUT	AVG DELAY	SUPPLY V	PWR DISS MW	WT gm	TEMP RANGE °C
Walkirt	MM10383	AND	DL	10mc	-	-	6	-	4 gm	-54 +125
	MM10423	OR	DL	10mc	-	-	6	-	4 gm	-54 +125
	MM10443	Flip-Flop	-	10mc	-	-	+18	-	4 gm	-54 +125
Westinghouse Electric	WM2101	NAND	DTL	-	5	55 ns	3	10	-	-55 +125
	WM2102	Flip-Flop	DTL	-	4	50 ns	3	24	-	-55 +125

ABBREVIATIONS:

DCFL - Direct-Coupled Transistor Logic

DL - Diode Logic

DTL - Diode Transistor Logic

LLL - Low Level Logic

RCFL - Resistor Capacitor Transistor Logic

RFL - Resistor Transistor Logic

TCL - Transistor Coupled Logic

DEVICE CHARACTERISTICS
POWER CONTACTS

PART NO.	VOLTAGE (volts)	CURRENT (amperes)	CONTACT DROP (volts)	LEAKAGE AT RATED VOLTAGE AND TEMPERATURE (ma)	TEMPERATURE (°C)
Transistors					
2N1721	100	.750	1.0 V @ .1A	.5 @ 60 V	-65 to 175
2N1050	120	.500	1.0 V @ .1A	.35 @ 30 V & 150°C	-65 to 200
2N2580	325	5A	.75 V @ 5A	5 @ 125°C	-65 to 150
2N1015E	250	7.5	.6 @ 5A	2 Typ	-65 to 150
2N1016E	250	7.5	.6 @ 5A	2 Typ	-65 to 150
2N2227	100	10	1.0 @ 2A	20 (Max)	-65 to 150
2N2228	150	10	1.0 @ 2A	20 (Max)	-65 to 150
2N2229	200	10	1.0 @ 2A	20 (Max)	-65 to 150
STC1751	200	20	1.0 @ 8A (Max)	20 (Max)	-65 to 200
109B	100	20	1.0 @ 7A (Max)	8 (Typ)	-65 to 175
109C	150	20	1.0 @ 7A (Max)	8 (Typ)	-65 to 175
109D	200	20	1.0 @ 7A (Max)	8 (Typ)	-65 to 175
STC1730	100	20	1.0 V @ 8A (Max)	20 (Max)	-65 to 200
STC1731	100	20	1.0 V @ 1.3A (Max)	20 (Max)	-65 to 200
STC1732	100	25	1.0 V @ 1.6A (Max)	20 (Max)	-65 to 200
STC1733	100	30	1.0 V @ 1.8A (Max)	20 (Max)	-65 to 200
STC1734	100	30	1.0 V @ 2.3A (Max)	20 (Max)	-65 to 200
2N2131	100	30	.72 @ 25A	8 (Typ)	-65 to 175
2N2132	150	30	.72 @ 25A	8 (Typ)	-65 to 175
2N2133	200	30	.72 @ 25A	8 (Typ)	-65 to 175
STC1735	150	20	1.0 V @ 8A (Max)	20 (Max)	-65 to 200
STC1736	150	20	1.0 V @ 1.3A (Max)	20 (Max)	-65 to 200
STC1737	150	25	1.0 V @ 1.6A (Max)	20 (Max)	-65 to 200
STC1738	150	30	1.0 V @ 1.8A (Max)	20 (Max)	-65 to 200
STC1739	150	30	1.0 V @ 2.3A (Max)	20 (Max)	-65 to 200

DEVICE CHARACTERISTICS
POWER CONTACTS

PART NO.	VOLTAGE (volts)	CURRENT (amperes)	CONTACT DROP (volts)	LEAKAGE AT RATED VOLTAGE AND TEMPERATURE (ma)	TEMPERATURE (°C)
SCRs USN2N683	100	16	.86@16A	6.5	-65 to 125
USN2N689	500	16	.86@16A	3.0	-65 to 150
USN2N1596	100	1.6	.75@.2A	<1.0	Storage
USN2N1599	400	1.6	.75@.2A	<1.0	-65 to 150
USN2N172A	100	7.0	.75@4.7A	4.5	-65 to 150
USN2N1778A	500	7.0	.75@4.7A	<1.0	-40 to 125
USN2N1911	100	110	.80@70A	6.5	-65 to 150
USN2N1916	400	100	.80@70A	4.0	-65 to 150
USN2N2025	100	110	.80@70A	6.5	-65 to 150
USN2N2030	400	110	.80@70A	<5.0	-65 to 150

DEVICE CHARACTERISTICS
POWER CONTACTS

PART NO.	VOLTAGE (volts)	CURRENT (amperes)	CONTACT DROP (volts)	LEAKAGE AT RATED VOLTAGE AND TEMPERATURE (ma)	TEMPERATURE (°C)
C36M	600	10	2.0@10A	3.0	{ -40 to 100 Storage
C36S	700	10	2.0@10A	3.0	{ -40 to 125
C50M	600	110	.80@70A	4.0	{ -40 to 125
C80M	600	235	1.3 @ 235 A	6.0	{ -40 to 125 Storage
					{ -40 to 150

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SUMMARY

The investigations conducted during Phase I of the Contactless Switching Program have determined the factors that must be considered in the development of new or improved contactless switching devices and assemblies that will meet aircraft electrical system requirements. These factors, such as voltage ratings, current ratings, thermal characteristics, contact drop, noise, etc., have been enumerated and given absolute values necessary to be compatible with aircraft electrical systems requirements.

The development factors were determined by investigative engineering studies and analyses which considered the present and anticipated aircraft electrical systems requirements, the interpretation of these requirements in light of contactless switching systems, and a compatibility analysis of device and assembly characteristics determined feasible within the present state-of-the-art in semiconductor development.

Investigations to establish the aircraft electrical system requirements were conducted in the areas of generation, distribution, utilization and control. These investigations consisted of a review and interpretation of MIL-STD-704, MIL-E-5088, MIL-I-6061, the F-8C (F8U-2) schematics and the characteristics of typical utilization equipment.

Investigations to establish the contactless switching concept requirements were conducted in the areas of bus switching and protection, load switching and protection, and control. These investigations considered all of the established aircraft electrical system requirements in light of the contactless switching system's advantages and limitations.

The investigations and analyses to determine the compatibility of devices and assemblies with the established requirements considered the areas of signal sources, control logic and power contacts. These investigations included the consideration of devices that are feasible within the present state-of-the-art as well as those that are presently available in production.

ACKNOWLEDGMENTS

The Contractor would like to give credit to the following companies for information and data which was useful in establishing compatibility requirements.

1. Birtcher Co., The, Monterey Park, Calif.
2. Blinn, Delbert Co., Pomona, Calif.
3. Clark Semiconductor Corp., Clark, N. J.
4. Clevite Electronic Components, Bedford, Ohio
5. Delco Radio Div., Kokomo, Ind.
6. Delta-T Semiconductor Cooling Div., Wakefield Engineering, Inc., Wakefield, Mass.
7. Fairchild Semiconductor, Mountain View, Calif.
8. Fansteel Metallurgical Corp., Chicago, Ill.
9. General Electric Co.,
 - a. Rectifier Components Dept., Auburn, N. Y.
 - b. Semiconductor Products Dept., Syracuse, N. Y.
10. Hoffman Electronics Corp., Semiconductor Div., El Monte, Calif.
11. Hughes Aircraft Co., Semiconductor Div., Newport Beech, Calif.
12. International Electronic Research Corp., Burbank, Calif.
13. International Rectifier Corp., El Segundo, Calif.
14. Leach Corp., Compton, Calif.
15. Motorola Semiconductor Products, Inc., Phoenix, Arizona
16. North American Electronics, Inc., W. Lynn, Mass.
17. Pacific Semiconductors, Inc., Lawndale, Calif.
18. Philco Corp., Lansdale, Penn.
19. Radio Corporation of America, Semiconductor & Materials Div., Somerville, N. J.
20. Silicon Transistor Corp., Carle Place, N. Y.
21. Solid State Products, Inc., Sepulveda, Calif.
22. Texas Instruments, Inc., Transistor Products Div., Dallas, Tex.
23. Transitron Electronic Corp., Wakefield, Mass.
24. Tung-Sol Electric, Inc., Newark, N. J.
25. United Transformer Corp., New York, N. Y.
26. Vap-Air, Div. of Vapor Corp., Chicago, Ill.
27. Walter Kidde & Co., Inc., Belleville, N. J.
28. Westinghouse Electric Corp., Semiconductor Dept., Youngwood, Penn.

REFERENCES

The following specifications and standards were used to establish compatibility requirements.

MIL-E-5272

MIL-I-6181

MIL-W-5088

MIL-STD-202

MIL-STD-704