SPACE SHUTTLE CONNECTOR DEVELOPMENT

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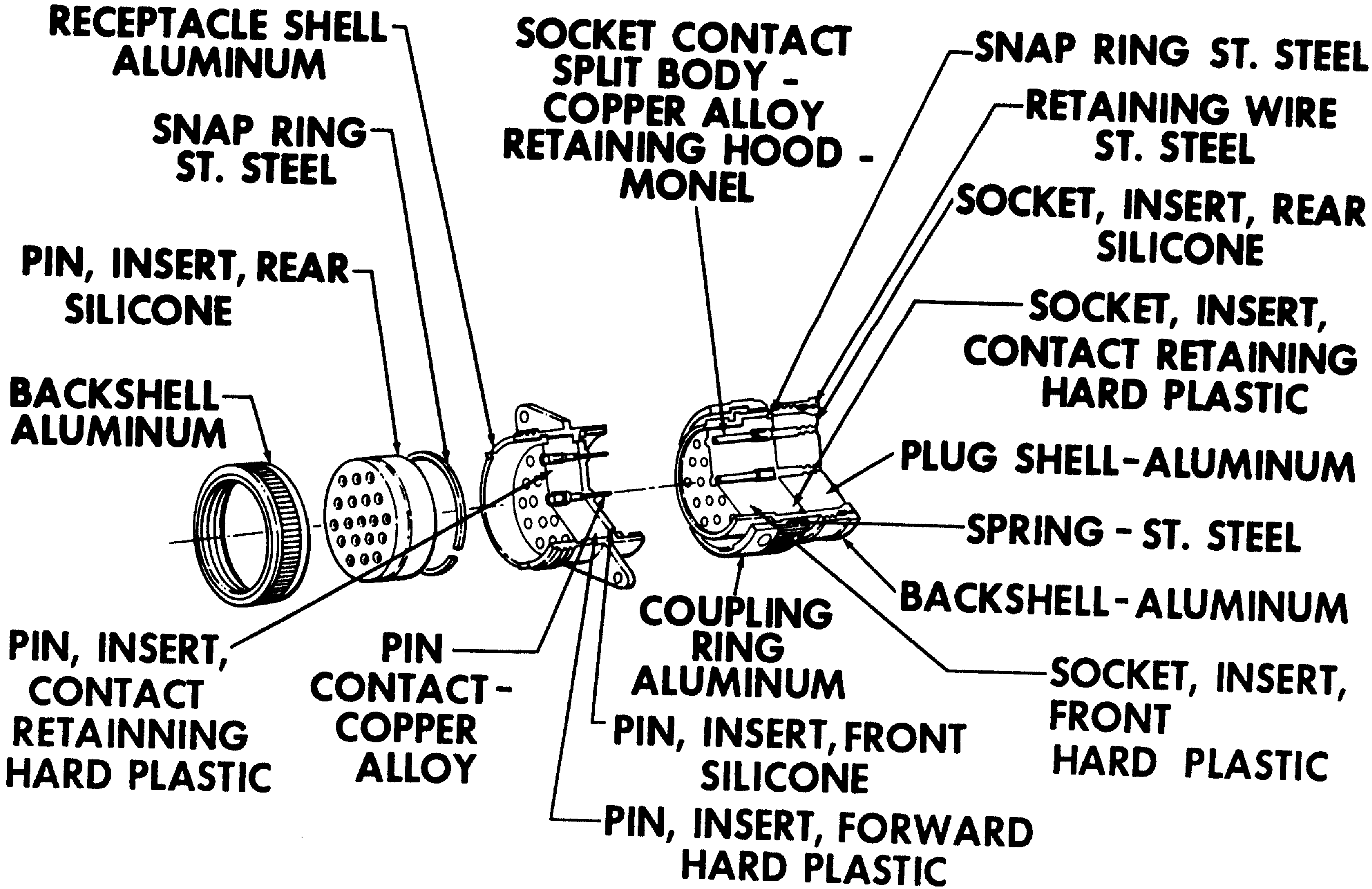
Standard and upgraded MIL-C-26482 and MIL-C-5015 connectors were the workhorses for the Saturn launch vehicle, Mercury, Gemini, and Apollo spacecraft. All of these were relatively successful space vehicles. However, they were not free from exasperating day to day problems. It has often been said that problems with the electrical wiring harness and its component parts were one of the more serious concerns with all of these vehicles. Electrical connectors presented more than their appropriate share of these troubles. Some of these problems are delineated below:

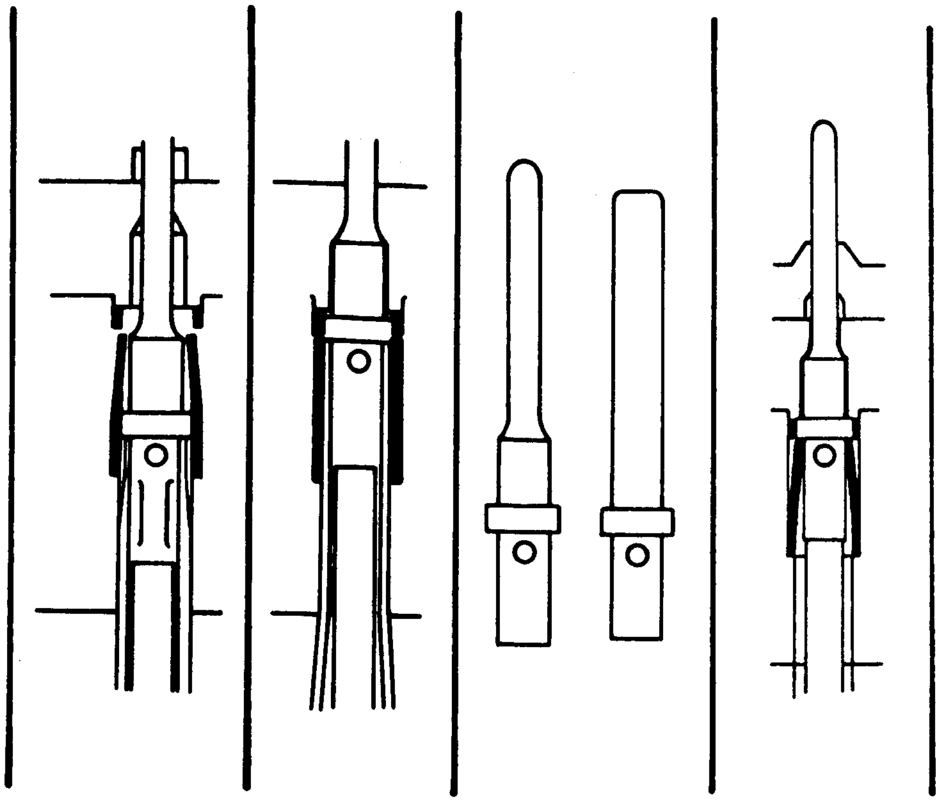
- Recessed contacts
- Recessed inserts
- Bent pins
- Torn or cracked grommets
- Dinged contacts
- Corroded contacts
- Intermittent socket contacts
- Cracked contacts (due to crimping)
- Scratched or scarred pins
- Scratched or chipped or corroded finish
- Coupling ring spring failures
- Loose threaded parts
- Splayed contacts

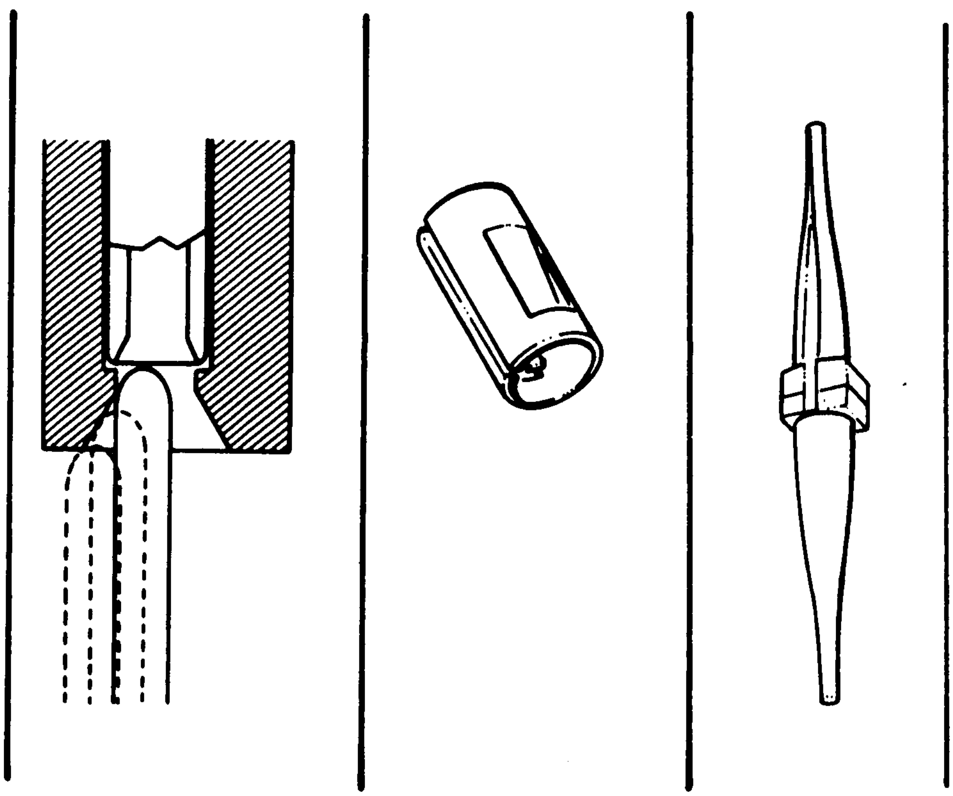
MSFC Specification 40M39569 type connectors are the mainstream or workhouse connectors for the Skylab space vehicle. These connectors are an upgraded NAS1599 type, selected and modified by NASA/MSFC to meet the more stringent and peculiar requirements of Skylab. This connector has solved many of the recurring problems that were common during the Saturn program. Design features of this connector and some of the problems solved are presented below:

- Silicone rubber instead of neoprene rubber for extended temperature and sealing capabilities.
- Insert retained by snap ring and bond between shell and insert.
- Rear contact release system has a stamped metal retaining clip captivated by molded-in shoulders in the hard plastic insulator. This method of contact retention prevents recessed contact problems.
- A rear-inserted plastic tool expands the lines beyond the contact shoulder, releasing the contact.
- The expendable plastic insertion/extraction tool is supplied with each connector. This flexible tool minimizes damage to contact, insulator or grommet.
- Simpler, stronger contact design offers greatly improved resistance to bending or damage. Contacts have a single holding shoulder and no undercuts. Probe-proof sockets have chamfered entry to aid in mating.
- Interfacial seal on pin insert is bonded to hard dielectric. Tapered raised barriers around each pin contact interlock into lead-in chamfers on socket insert, assuring individual contact sealing.
- Hard dielectric closed entry socket insert has lead-in chamfers, providing for realignment of any bent or misaligned pin contacts. For example, a #20 pin bent approximately one diameter from the position will be realigned to mate with the socket. If the pin is severely bent, the hard plastic will stop the pin and prevent mating instead of allowing puncture and uncontrolled pin contact to the outside of the socket barrel.
- Reduced clearance between contact and hard plastic insulator wall provides contact stability and prevents splayed contacts.
- Wire moisture sealing is accomplished by multiple riser design in rear silicone grommet.
- Simplified socket contact design eliminates intermittant circuit problem inherent with multipiece socket contact configurations.
- Meets Skylab outgassing requirements.

MSFC 40M39569 (MODIFIED NAS1599) CONNECTOR



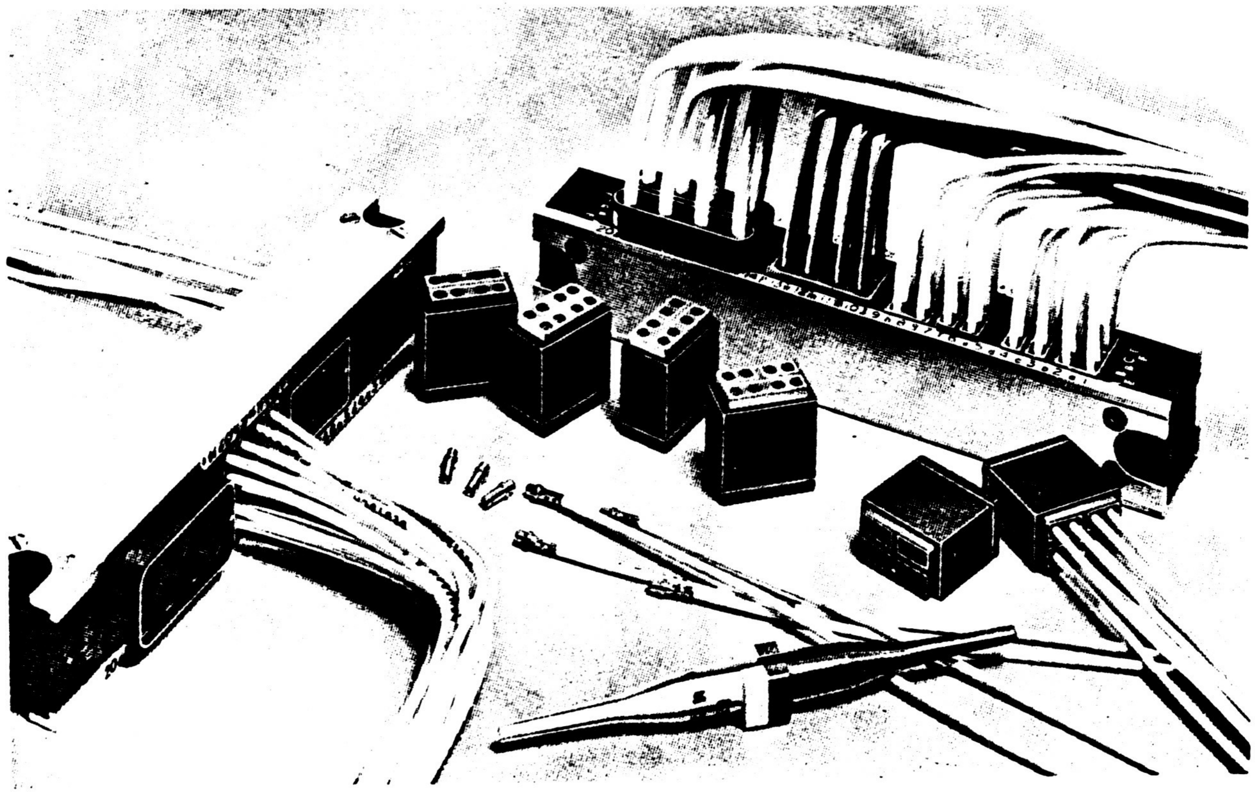




Termination devices meeting MSFC Specification 40M39589 for distribution, bussing, and interconnection are used on Skylab. These devices are a tremendous improvement over the terminal strips, solder terminals, and junction boxes formerly used and offer:

- Enclosed, environmentally protected busses and junctions.
- Removable crimp contacts.
- Standard contact crimp dimensions common with 40M39569 (Mod. NAS1599) connector.
- Standard crimp tools.
- Standard contact insertion and removal tools.
- Easy assembly with fewer tools.
- Meets extended temperature range common with 40M39569 connector.
- Meets stringent Skylab vacuum outgassing requirements.
- Minimized system weight.
- Easy installation in confined areas.
- Circuit design modifications easily accomplished.

DISTRIBUTION AND BUSSING TERMINATION DEVICES



The Zero-G Electrical Connector is also used in addition to the 40M39569 (modified NAS1599) type on Skylab. MSFC Specification 40M39580 defines this connector. The Zero-G Connector is the first electrical connector of major usage specifically designed to meet NASA's needs. Other major NASA connector types evolved from standard or modified connector designs such as MIL-C-26482, MIL-C-5015, or NAS1599 which were established to meet general purpose military and aerospace requirements. The Zero-G Connector was developed by the Bendix Corporation working with Marshall Space Flight Center and McDonnell Douglas Astronautics Company, Western Division. The Zero-G Connector is a handle operated, over-center lock, environmentally sealed unit with removable crimp type contacts. The development of the Zero-G Connector design was aimed to most effectively accomplish the following objectives:

A. Environmental

The connector must be capable of withstanding the hostile environments of space. It must give reliable service and operation in a space cabin atmosphere of humidity and oxygen. The connector materials and finishes must withstand effects of such corrosive contaminants as might be present in earth or space cabin atmospheres.

B. Performance

The design of the connector was selected to satisfy the following performance requirements:

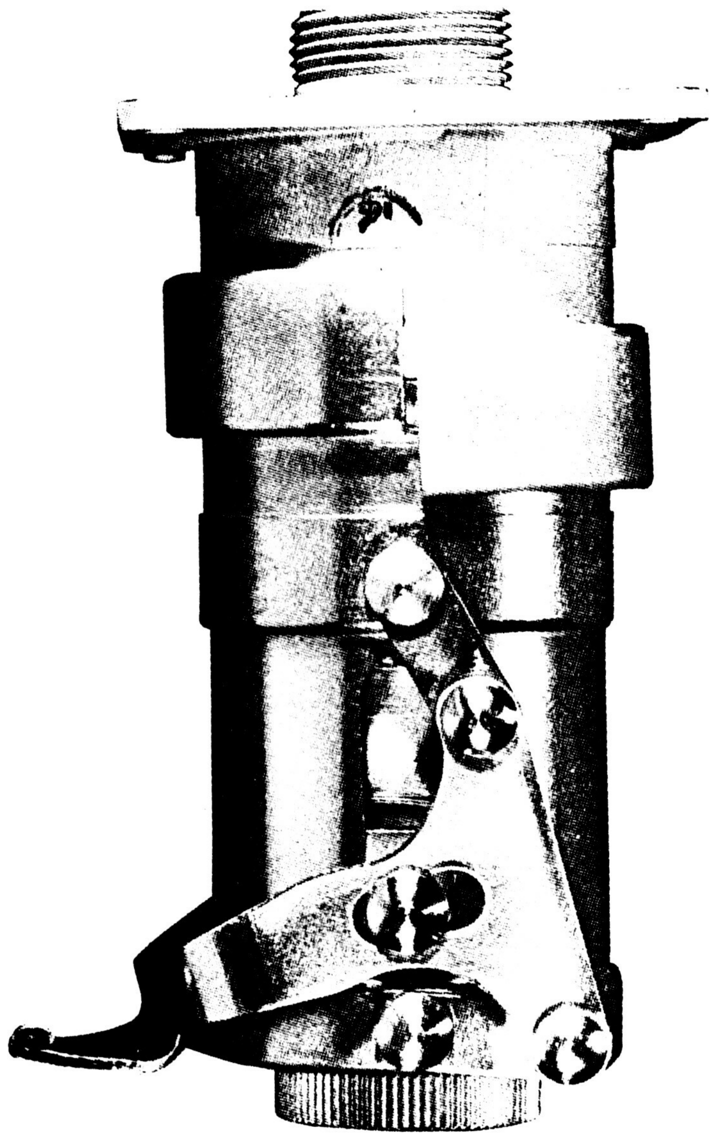
Ignition-proof operation under electrical load conditions in a highly combustible atmosphere.

The connector materials must not support combustion in an oxygen rich atmosphere nor outgas toxic or other objectionable matter in a space cabin environment.

Reliable, maintenance-free service over its intended lifespan, making maximum use of proven design concepts and minimum use of complicated mechanisms.

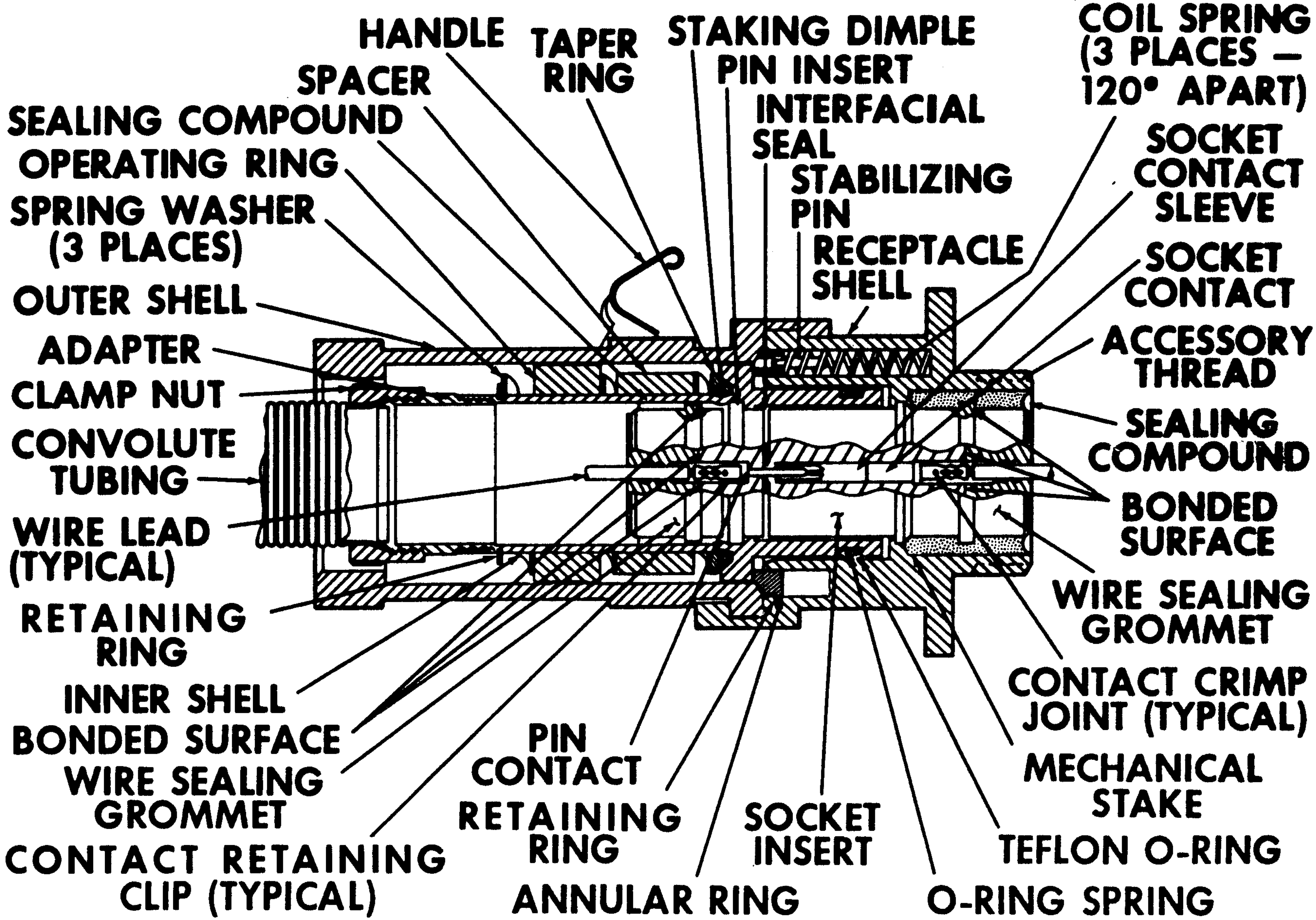
C. Astronaut Operation

The design was selected to achieve a simple one, two, three, one-handed mating or unmating sequence. The "hook-and-lip" method of shell engagement (see detail design section) and the handle operated locking feature (see mating sequence and configuration section) enables the astronaut to achieve connector engagement and disengagement with minimum effort. The Zero-G Connector design eliminates the 90° rotation and initial alignment search of conventional circular connectors; the design is especially adapted for operation in a space suit where physical movement and vision are limited.



SKYLAB ZERO-G CONNECTOR

SKYLAB ZERO-G CONNECTOR DESIGN FEATURES



D. Detail Design

To utilize already proven concepts of connector design, the insert assembly (insulator, contacts, retention clips and grommet seals) utilizes the same physical design as MIL-C-38999 for LJT connectors. The deep barrel, short contact concept gives the desired contact protection and enhances the ignition-proof characteristics of the connector.

E. Contact Retention

The contact retention system is the rear insertable, rear release, clip retained method developed by industry for the NAS1599 connector. The rear release method of contact removal increases alignment stability in that broad clearances around the contact periphery at the mating interface is not required for entry of a front release tool.

F. Insert Dielectric

The hard dielectric insulation material of the insert assembly is a glass fiber filled epoxy resin (Epiall 1288-BX) well known for its superior strength, low moisture absorption, nonoutgassing, nontoxic, and nonflammable characteristics. The chamfered lead-in feature of the hard face socket insert aligns and guides the entering pin contact into its mating socket. It also provides the "Cork-in-bottle" individual contact seal when the interfacial seal with the raised donuts surrounding each pin contact is compressed between the interface of the mated pin and socket inserts.

G. Contacts

The electrical contacts are a high conductive copper alloy, plated with 100 microinches of hard gold over an underplate of soft gold. This type of plating eliminates the undesirable features of silver or nickel underplates, improves plating adhesion and porosity, decreases contact resistance, and results in a longer contact life over an extended operating temperature range. Size 20 and 16 socket contacts are the one piece slotted segment design for improved reliability. The size 12 socket contact utilizes a discrete spring member of substantial size and securely attached within the socket barrel. The spring member portions of all socket contacts are enclosed in a stainless steel sleeve for protection of the contact springs and exclusion of oversize diameter pins or probes.

H. Seals

The wire sealing grommets and interfacial seals are a silicone rubber compound for extreme low temperature use, which enables the connector to remain environment resistant.

It further precludes the need for potting operations and greatly enhances connector maintainability.

The main gland seal (O-ring) is a U-shaped circular seal of virgin TFE teflon with an internal spring member to maintain constant seal between male and female shells and still allow pressure relief when mating or unmating. The teflon seal further retards the rapid escape of burning gases should ignition occur within the confines of the connector.

I. Shells and Housings

The connector shells are an aluminum alloy which exhibits excellent stability over the temperature extremes, has good strength characteristics, and is readily available to the manufacturer.

The plating of all shells and aluminum parts is chromium over nickel. This results in a tough, durable, electrically conductive finish with superior resistance to corrosion from salt spray and other contaminants present in earth or space cabin environments.

J. Operating Mechanism and Springs

The operating handle and linkage are corrosion resistant stainless steel for strength and improved wear characteristics. All spring members are either stainless steel or beryllium copper alloys with proven capabilities to operate over the required temperature range.

The annular ring is a circular spring loaded metal ring located in the shell interface of the connector receptacle. Its purpose is to provide friction to hold the plug and receptacle shells together in alignment until the operator pushes the handle mechanism forward to engage the contacts and latch the connectors.

K. Ignition-Proof Design

The ignition-proof design of the connector is achieved by (1) the outer shells of the plug and receptacle being mechanically interlocked around the entire connector periphery (by two 180° concentric hook-and-lip configurations), (2) the movable male shell of the plug extends into the fixed female shell of the receptacle approximately 1/2 inch; this forms a labyrinth of overlapping metal parts which slows the escape of burning gases and at the same time exerting a tremendous quenching, or cooling, effect to dissipate energy before reaching the outside atmosphere. An arc can occur at the connector contacts should they be engaged or disengaged in a power-on condition; however, before the atmosphere outside the connector would ignite, the following chain of events must occur. Assuming the atmosphere internally and externally of the connector is an explosive mixture and an arc occurs at one or more contacts, then:

1. The energy level of the arc must be sufficient to offset the quenching effect of the surrounding electrodes (male and female contact) and ignite the gas in the minutely small chamber formed by the contacts and the insulator (approximately 1.6×10^{-6} in^3 volume).

2. The energy from the initial detonation must then escape into the main chamber of the connector formed by the separation of the contact interfaces (approximately 8.9×10^{-3} in^3 volume, worst condition) with a sufficient energy level to offset the quenching effect of all the surrounding contacts and metal shells and ignite the gaseous mixture of this chamber. Should this event occur then:

3. The energy from the second detonation must be sufficient to force burning gases through the labyrinth of metal baffles formed by the connector shells, offsetting their quenching effect and have sufficient energy to ignite the external mixture.

To obtain the required data for discrete calculation of all the variables encountered in the operation of the Zero-G Connector would require a lengthy and expensive laboratory study program; therefore testing has been performed under worst case conditions to verify the ignition-proof design.

This has been successfully accomplished in the laboratories of McDonnell Douglas.

L. Mating Procedure

The mating interfaces of the plug and receptacle shells are identical (i.e. morph-riditic) with a 180° lip extending around the outer periphery of the shell and continuing into a hook around the remaining half of the shell periphery. To engage the connectors, the plug and receptacle are brought together such that they physically meet with the hook on the plug resting in a position above the lip on the receptacle.

Next the connector halves are moved together with the hooked lips engaging until the opposing hooks on the outer periphery butt and the connector halves are concentric. At this point, the connectors are in proper alignment for engaging the contacts and are held in this position by pressure from the annular ring.

Then the handle is brought forward by thumb action, which moves the inner shell of the plug forward into the receptacle shell, first locking the connector halves together and forming a peripheral O-ring seal. Finally, the inner shell comes to rest with the insert interfaces butting together to compress against the interfacial seal to form an individual seal around each mating contact. To unmate the connectors, the handle is moved back until it locks in the "rear lock" position. The connector halves are then moved apart by a slight twisting action to override the annular ring pressure at the mating shell interfaces. The handle mechanism has two over-center lock positions; one at the extreme rear position to lock the movable plug insert in its full unmated position to prevent its interference with the initial engagement of the outer shells; the other over-center lock at the extreme forward position locks the connector halves together.

Spring pressures for the lock positions are derived from 3 wave spring washers surrounding the inner shell. The wave washers also provide constant spring pressure against the mating insert interfaces to compress the interfacial seal and maintain environmental resistance.

The environmental seal at the rear of each connector plug and receptacle is achieved by compression of the sealing glands in the wire sealing grommet against each individual wire. If all wire holes are not used, then teflon sealing plugs of the same nominal diameter as the wire are inserted into the unused holes and the entire connector is sealed.

M. Astronaut Compatibility

Crew Systems analysis for astronaut performance has been implemented into the design and development of the Zero-G Connector.

The prime considerations were that the connector be operated by an astronaut in a pressurized suit under a zero-g environment, while exerting a minimum amount of physical effort and movement.

The configuration of the handle, the length of travel, the operating forces involved, and the length and diameter of the connector shells were included in the analysis.

Polarizing pins and grooves have been included in the design to prevent cross-plugging where such a requirement might exist. Large letters denoting polarizing positions are stamped on each side of the hook and lip such that a quick glance at the letters during the mating sequence will confirm if the plug and receptacle are identically polarized.

The connector shells are so designed that by sliding the two halves of the Zero-G Connector together until the shells form a concentric circle, automatic alignment is assured. No rotational search to locate alignment keys is required.

Recent investigations have been in the area of electrical connector basic materials. Some of the areas being studied are:

- Electrical contact materials and platings
- Connector shell and housing materials and platings
- Structural dielectric materials
- Elastomeric seal materials

One of the more significant studies is that of elastomeric seal materials.

The applications of elastomers for use as sealing members in basic connector designs normally fall into two categories. All connectors suitable for exposure in harsh environments require a main seal to keep that environment from penetrating between the two halves of the connectors. In its simplest form, this is an O-ring or a flat gasket. It is placed in compression when the two halves are mated, forming a barrier for moisture, air, or contaminants.

The second critical sealing area is the rear of the connector where the wires are soldered or crimped to the contacts. Here a seal must be maintained around each wire as well as to the back face of the insert to isolate the contacts from each other and from the metal shell. This has been accomplished in the past either by potting with a liquid resin or elastomer or by use of a molded grommet. This study has been limited to materials for the latter.

The basic properties required for these applications are the same; low compression set at all temperatures, high resilience, and adequate resistance to the mechanical and thermal conditions encountered.

The difference is largely that of fabrication of a simple item compared with a complex one. While O-rings, despite their simple shape, provide unique problems in manufacture, they certainly in no way approach the difficulties innate to connector grommet designs. Quite obviously, the material which produces a completely acceptable O-ring can be dismal failure in a grommet mold with its thin walls and severe undercuts.

A major improvement in connectors was accomplished when silicone elastomers were developed to replace neoprene elastomers. However, with new and more stringent requirements, the capabilities of silicone are being stretched to the limit.

Present and anticipated requirements seem to indicate the need for a change from silicone to some new elastomeric compound for connector seals. Flammability requirements in oxygen environments, vacuum outgassing requirements, and expected severe temperature extremes, when considered along with all other requirements, emphasize the need to develop new compounds. Many of the methods used in the Skylab program to meet crew area flammability requirements impose a tremendous penalty. Development of connector materials and electrical wire that will meet the flammability requirements without the massive coverings used in Skylab will bring about a tremendous weight, volume, cost, and time savings.

Therefore a major goal was established to find an elastomer or elastomers which would be suitable for use in electrical connector main joint seals and wire sealing grommets with particular attention to the following:

- Temperature extremes of -200 °C to + 200°C.
- Nonflammable or self-extinguishing in oxygen atmosphere.
- Negligible outgassing in space environments.
- Manufacturable, reasonable priced, readily available material.
- Other characteristics typical of general connector requirements.

Compounds based on fluorocarbon rubbers such as du Pont Viton or 3M Fluorel provide chance of overall compliance with requirements because of their proven flame resistance in oxygen atmospheres.

At the same time the fundamental shortcomings of these materials also have now become evident, notably poor moldability, poor resilience, cold temperature weakness, and recent indications of susceptibility to moisture degradation.

Further investigation into the fluorocarbon rubbers available indicated two more Fluorel materials worthy of study. These are Mosites #1087-JJ and Raybestos Manhattan L-3583-2. Both these materials are in the 55-60 durometer range necessary for grommets. Data is incomplete, but they appear comparable with du Pont's Viton VS 2001.

An abbreviated study confirmed suspicions relative to moldability. Molding was confined to simple molds and still there was difficulty in obtaining acceptable samples. Greatest problem seemed to be from inability to get a proper cure as parts were inclined to be porous and contain blisters. More familiarity with the material might overcome this as far as simple moldings such O-rings or gaskets are concerned. The material is much too hard for use in connector grommets. Earlier parts were molded with Fluorel L-2231 from Raybestos Manhattan with no difficulty encountered on simple parts but with tearing of webs on standard grommets.

The whole fluorocarbon elastomer family as represented by 3M's Fluorel and du Pont's Viton have been rapidly improving. Disregarding flame resistance for the moment, the major inpetus has been in compression set. Both companies have been able to reduce compression set at all temperatures. For example, Viton E-60C has about the same set after 1000 hours at 392°F as the original Viton A had after 70 hours. Fluorel 2160 is comparable. As a result of these achievements, new specifications have been issued specifically to cover these materials. These are MIL-R-83248 and AMS 7280 and mark a major advance in state-of-the-art recognition.

Du Pont also has a modified Viton designated LD-487 having lower temperature characteristics than the standard materials. Brittle point is -60°F approximately and TR-10 is 31°F, compared with -40°F and -5°F for Viton A. These are still a long way from -200°C but do represent a substantial improvement.

Because there has been so much progress in these materials, including success in developing Viton connector insert and grommet materials, it seems logical that they could be further improved in those directions considered advisable. This would be a main effort suggested for further investigation.

The alternatives to these materials are unsuitable in one area or another when compared with present guidelines. The organic rubbers as a whole are all unsatisfactory from a temperature standpoint. Temperature resistance also eliminates the CNR or Nitroso rubbers developed by Thiokol which appear to be equal to the fluorocarbons in flame resistance in oxygen atmospheres. However, CNR is also listed in NASA 50M02442 "ATM Material Control for Contamination Due to Outgassing" as an "unacceptable material".

The Dexsil materials developed by Olin Matheson appear to have the heat resistance required but difficulties in manufacture have pretty well curtailed their progress to production status. These materials are reported capable of withstanding temperatures considerably higher than the silicone. Outgassing in hard vacuum was reported minimal, tests for 72 hours at 155°C yielding only 49 ppm total organics and less than 5 ppm carbon monoxide. The materials was also self extinguishing in air, and flash and fire points are extremely high. Flammability tests conducted by NASA showed the samples tested were not self-extinguishing in 16.5 psia oxygen.

Both of the above materials had a further disadvantage, price, with the CNR rubbers at approximately $600 per pound and Dexsil at $100 per pound. No chance of their utilization in connectors at their present status is anticipated.

Beyond these lie even newer polymers in various stages of development such as the perfluoroalkylene triazines and copolymers of tetrafluoroethylene and prefluoro (methyl vinyl ether), the former under investigation by Hooker Chemical and the latter by du Pont. These are materials of the future, warranting close observation as they progress but hardly likely for serious consideration at this date.

The materials most commonly used in high performance electrical connector grommets and seals have been silicone rubber compounds. Both fluorinated oil resistant silicones, non-fluorinated silicone, and blends of both have been used.

Properly formulated silicone rubbers are capable of long life at 200° C with minimum effects on mechanical and electrical properties. In general, they are also low in outgassing in vacuum or air at these temperatures. However, it is still necessary to assure absence of low molecular weight fractions and other volatiles which may be characteristic of specific compounds. As a rule this can be accomplished by high temperature curing, in extreme cases under vacuum.

At sub-zero temperatures, they range in brittle point from -90° F (-68° C) for the fluorinated stock to -178°F (-116°C) for the best low temperature materials. While this is still well above the -200°C requirement, it is considerably below the best temperature recorded for the fluorocarbon rubbers. The brittle point does not by itself categorize the material as unsatisfactory at -200° C. Tests on actual connectors employing both Viton and certain silicones in liquid helium and liquid nitrogen have failed to cause any permanent damage although some fluorinated silicones have cracked during this exposure.

The main obstacle to use of silicone rubbers remains flame resistance in oxygen atmospheres. While the basic polymers, even the fluorinated ones, have no inherent flame resistance, progress is being made through the use of additives. Prompted by Boeing Specification BMS 1-59 and McDonnell-Douglas DMS 2012, Dow Corning, General Electric, and Union Carbide have all produced rubbers which are flame retarding and quickly self-extinguishing in air.

Dow Corning Silastic 2351 and related compounds and General Electric CE5537 are not only flame resistant in air but also have other properties important to connector grommet design. These materials are not fluorosilicones and consequently have no substantial resistance to common oils and fuels.

Most recently Arthur D. Little, Inc., in a NASA development program has succeeded in producing silicone formulations having oxygen index ratings as high as 0.60. More usable compounds have oxygen index ratings from 0.40 to 0.50 and were self extinguishing in NASA tests in 50% oxygen at 10 psia. They were also slow burning in 100% oxygen at 6.2 psia. These compounds utilize decabromodiphenyl (DBDP) as an additive to conventional silicone compounds such as General Electric SE-517. At the present time, this additive is an experimental product, and results are dependent on high purity. Mechanical properties of these flame resistant silicones are reduced some by the additive but, from the limited data now available, might be usable. Tensile strengths over 700 pounds per square inch and elongations over 450% are quite typical and certainly within the parameters needed for grommets. Low temperature resistance does not seem to be affected significantly by the additive, but heat aging data is not sufficient to indicate whether it causes any detrimental effects.

In general, it appears that Arthur D. Little Inc., has made a substantial contribution to flame resistant silicone rubber technology and that considerably more remains to be done before the optimum material is developed. Their work has been limited at this time to one basic silicone reinforced gum, GE SE517, and one catalyst, 2,4-dichlorobenzoyl peroxide. Other gums and catalysts could be expected to provide improvements in some of the other properties which appear to be borderline with the present compounds incorporating DBDP.

These materials do not appear to be nearly as flame resistant as the Viton and Fluorel materials but are substantially better than the silicones now in use. They warrant a very serious consideration for use in grommets.

One other very feasible approach would be provision of a flame resistant face on the exposed surface of a silicone rubber grommet. This face would most logically be one of the Fluorel or Viton formulations. Such a combination could give us the best of both material systems at some sacrifice in size and cost.

The various Viton and Fluorel compositions could be further investigated. This would be largely a study of design adaptability with moldability being the chief factor. Web design of the grommet holes is expected to be crucial because of the low elongation of these materials.

At the same time a formulation program should continue to provide an improved grommet material. This would be a two directional study, on one hand attempting to improve the shortcomings of the fluorocarbon materials while retaining their flame resistance, and on the other hand improving the flame resistance of the silicones without losing their desirable attributes.

Digital Efficiency:

Investigation is presently being conducted concerning digital efficiency or the effects of interconnect systems on the transfer of high speed digital signals.

The digital pulse is the controlling parameter in such digitized equipment as computers, guidance systems, and multiplexing systems as to their ability to receive, store, retrieve, and display information in large quantities at rapid rates within reasonable equipment physical size and weight limitations.

An effort has been made to determine if present or future digital pulse information is or will be deleteriously affected by interconnects, such as cable-connector combinations, in the following parameter areas:

A. Wave Form Distortion With Respect to:

- Rise Time Characteristics
- Pulse Width
- Fall Time Characteristics
- Repetition Rate
- Phase Shift
- Amplitude Changes

B. Signal Change Due to Short Term Discontinuities

C. Circuit to Circuit Crosstalk

D. Limitations on Integrated Circuit Fan-out Capabilities

Through literature searches and information obtained from digital equipment suppliers, it has been established that to increase the capabilities of digital controlled systems, efforts are being made to shorten the rise time and width of the digital pulse. At the same time efforts are being made to increase the repetition or clock rate pulse chains to meet future needs.

The losses in transmission lines and electrical interconnecting mechanisms affect the fidelity of transmitted pulses, and these losses increase with increasing frequency. In particular it is evident that as pulse rise times and widths continue to decrease, the conventional pin and socket multipin connectors will prove to be too lossy to serve as digital system interconnects.

At the same time it is evident that presently available test methods are marginal for test work in the sub-nanosecond and picosecond time range.

Thus the limitations of an electrical connector and its suitability for a specific digital application cannot now be determined in advance with certainty.

The conclusions derived from the study reported here indicate that further consideration is needed in the following specific areas:

- Development of test methods suitable for establishing the limits of operation for interconnects in digital systems.

- Measurement of multi-channel connector impedances in circuits handling fast digital pulses.

- Measurement of pulse rise time, duration, and repetition rate capabilities of multi-channel connectors currently in use in circuits dealing with fast digital pulses.

- Evaluation and determination of acceptable levels of cross-talk in multi-channel connectors currently being used.

- Determination of ageing effects on the parameters determined in above statements.

At the completion of this task, if so dictated by the work outlined above, further effort should be directed toward the development of specific multi-channel connectors which are capable of dealing with anticipated rise times, signal levels, and pulse repetition rates in future applications.

A continued effort in the investigation of digital interconnects should:

- Determine if interconnect problems exist in present system pulse transfer techniques.

- Determine if interconnect pulse transfer problems will be aggravated in future systems.

- Outline a detailed follow-on program for actual measurement and evaluation of connectors in use on present digital systems.

- Outline an evaluation of proposed connector materials for their electrical properties as to their future application in improved design digital connectors.

The ability of a particular digital system to originate a defined pulse shape. Transfer the pulse shape, and receive the pulse shape, meanwhile maintaining the pulse's integrity, can be defined as the digital efficiency of the system. The origination, transfer, and receive functions within a system will repeat many times during operation so that a loss of digital efficiency, though minor in nature on a one time basis, could, if repeated often enough, result in a complete degradation of the pulse shape to the point where system error or malfunction would result.

In order to increase the capabilities of digital controlled systems, designers have been attempting to shorten the rise time and the pulse width of the digital pulse, while at the same time increasing the repetition or clock rate of pulse trains.

Prior to the advent of the present integrated circuit (IC) technology, pulse generation was limited in the 1930's to 1940's by inherent properties of vacuum tubes, mechanical switches and relays, and their related discreet component circuitry. The digital pulse in most cases was defined as to time parameters in milliseconds. They could be classed as hertz or kilohertz systems with respect to circuit pass band and wave length limitations.

The transistor and diode-resistor networks began to replace the earlier vacuum tube and mechanical devices by the mid-1950's. As the types of transistors multiplied, their rise time was less limited due to improvement in junction forming technology. The digital pulse generation capabilities had reached the microsecond range and was approaching the nanosecond range by the late 1950's. Most circuits consisted of discreet components. Even with the advent of printed circuit board techniques, the systems could be classified as megahertz systems.

Semiconductor technology continued to improve to the point where frequency generating capabilities within the junction approached a 4 gigahertz gain-pass band property. This made possible pulse rise time in the nanosecond time range. The semiconductors failed to achieve their capabilities consistently due to losses introduced by the hermetic packaging and necessary circuit connecting wires to the various semiconductor junctions. This was undoubtedly the first evidence of interconnect limitations on digital pulse generating systems.

The IC technology which became practical in the middle 1960's aided in reducing junction interconnect limitations by making possible shorter wiring techniques and also better control as to placement of interconnects. Compensation could be designed into the IC circuit to overcome many of the IC interconnect wiring losses and impedance mismatch losses. At the same time tunnel diode pulse generating devices in a chip form gave theoretical performance capabilities of 7 to 10 picosecond rise times. When placed in their operational environment the actual rise times were increased to approximately 20 picoseconds. The above technology improvements made possible a gigahertz generating system.

From the mid 1960's to the present time articles in trade and professional journals began to appear warning of cable-connector problems associated with the transmission of microwave frequencies necessary to assure the integrity of these picosecond or sub-nanosecond pulse rise times.

During this time interval more and more digital functions were being incorporated on a single chip resulting in the use of many medium scale integrated (MSI) systems to make up a complete digital operated system, such as a computer. The shift to MSI systems, has reduced the number of conventional cable-connector system interconnects within a functional digital system, but has not eliminated them. Interconnects will be required until systems such as a complete operational computer can be placed on a single chip, achieving the ultimate in large scale integration, (LSI). Some authorities feel the practicality of such an LSI system will not be achieved until the 1980's.

The MSI systems of today and in the next decade use the mother-daughter board concept to package the digital circuitry, making necessary the use of some form of cable-connector combination to marry the various board configurations into a complete digital system. In addition, cable-connector combinations are necessary to tie interface hardware such as remote programmers and readout devices to the digital system. The interface hardware cable-connector in some form will undoubtedly always be necessary even with the successful advent of complete LSI digital systems.

The study indicated that there are two areas in a digital system where interconnects will be a problem in the next 10 to 15 years. These areas are:

A. Where cable-connectors will be necessary to interconnect circuit boards within a system to facilitate function changes, ease of assembly, and serviceability.

B. Where cable-connectors will be necessary to interconnect a given digital system to its remote interface hardware.

The problems and solutions related to digital pulse transmission will be similar in both areas, with the former being more severe in nature in the immediate future.

A digital pulse whose shape is represented by Figure 1 has a rise time of T_1 to traverse an amplitude change of 10% to 90% of its maximum amplitude. As T_1 approaches zero, the number of frequencies which must be generated and transmitted approaches infinity. Since T_1 has a finite value, a relationship between a particular rise time and its upper frequency component exists.

$$FT_1 = K \tag{1}$$

where F is the upper frequency in MHz,
T_1 is the rise time in microseconds,
K = .35, where the rise time overshoot must be limited to 2 or 3 percent of the maximum. Table 1 was calculated from equation 1 and shows presently used and future possible digital pulse rise times and their upper frequency components. The electrical length of an interconnect device is,

$$\lambda = \frac{\dfrac{300 \times 10^6}{F}}{E_R} \tag{2}$$

where:
λ = wave length in meters
300×10^6 = velocity of light, in meters/second
F = frequency in hertz
E_R = relative dielectric constant of medium

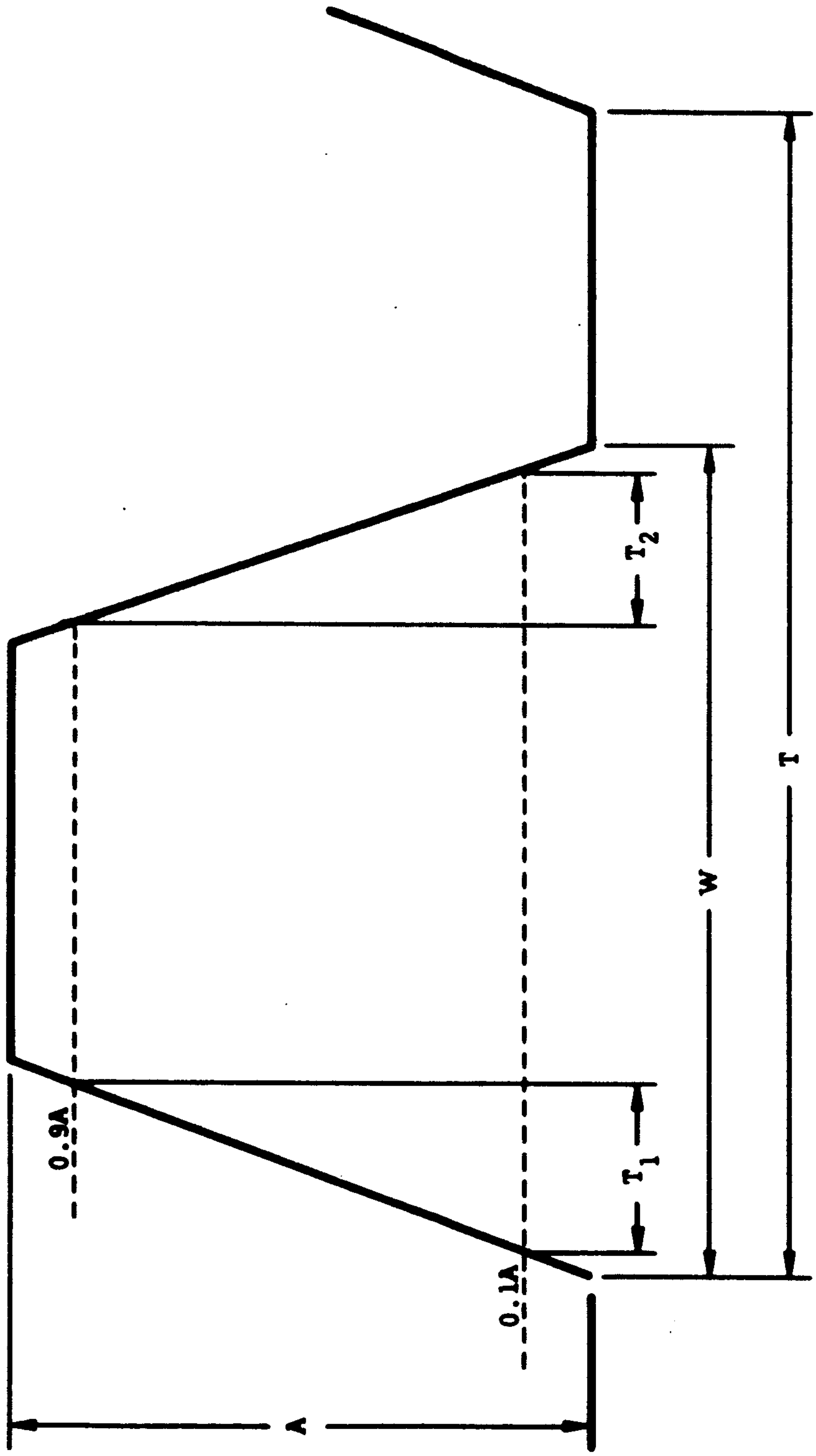


FIG. 1 DIGITAL PULSE DIAGRAM

Table 1

Rise Times Vs. Frequency & Wavelength

Rise Time - T_1	Upper Frequency - F	Wave Length λ = meters in air (E=1)
10 microseconds	35 khz	8580 meters
1 microsecond	350 khz	858 meters
100 nanoseconds	3.5 mhz	85.8 meters
10 manoseconds	35 mhz	8.58 meters
1 nanosecond	350 mhz	.858 meter
100 picoseconds	3.5 ghz	.0858 meter
10 picosecond	35 ghz	.00858 meter
1 picosecond	350 ghz	.000858 meter

Present digital rise times appear to fall between a maximum of 5 microseconds to a minimum of 10 nanoseconds. This means the upper frequency which must be transmitted undisturbed is from 70 KHz to 35 MHz.

The present average relative dielectric constant in most transmission mediums is 4.0. (See Table 2 for various dielectric material parameters.) This means the wavelength, or one electrical length, for transmission interconnects will be between 214 to 4.18 meters, or 700 to 13.7 feet. If cable-connector lengths have had physical lengths which were much less than one quarter of these electrical lengths (175 to 3.4 feet), then degradation of digital pulses due to influences introduced by mismatch and changes in velocity constant would have been minimal. Also the effects of capacity loading due to interconnects would be less a factor at the above 35 MHz frequency limit. When rise times approach 1 nanosecond and less, then cable-connector electrical lengths decrease to fractional parts of an inch, and the effects on pulse shape with respect to velocity constant and electrical parameters, such as distributed capacity, inductance, and AC resistance of the interconnect must be considered.

The future rise time goals within the next 5 to 10 years show that rise times are expected to be between 3 nanoseconds to 1 picosecond. The 1 picosecond goal is from one company who is presently achieving 100 picosecond rise times. This same company has performed their own development on connectors for digital pulses, recognizing an existing problem.

As pulse times decrease, the present circuitry now in use appears to limit their amplitude. The normal digital pulse today is 5 to 8 volts in amplitude. Future pulse amplitudes are trending to millivolt and in some cases, microvolt levels. This will undoubtedly place limitations of pulse fanout capabilities assuming complementary improvements in line driver capabilities. Losses or vibration induced noise from connectors would be more noticeable to these low level pulse signals.

Cables:

The coaxial cable is the preferred way to transmit picosecond-time digital pulses, followed closely by stripline transmission lines. They may in the future be replaced for some applications by laser beam transmissions.

As a point of interest, experimental work with laser beam transmission has progressed to the point where scientists have observed laser pulses as short as 1 picosecond in duration. Their application to digital pulse transmission systems in some form is certain to appear in the future.

The losses in present coaxial transmission lines affect the fidelity of the transmitted pulse. These losses appear as conductor or copper losses and as medium or dielectric losses and are as follows:

$$\text{Copper loss } A_{cu} = \frac{0.434}{Z_O} \quad \frac{1}{d} + \frac{1}{D} \quad F^{1/2} \qquad \text{db/100 FT} \tag{3}$$

$$\text{Dielectric loss } A_d = 2.78\, E_R^{1/2}\, R_P \quad F \qquad \text{db/100 FT} \tag{4}$$

Where
- D = diameter of inner surface of outer conductor, inches
- d = diameter of outer surface of inner conductor inches
- F = frequency, megahertz
- E_R = relative dielectric constant at frequency F
- R_P = power factor of dielectric at frequency F
- Z_O = characteristic impedance of coaxial cable in ohms.

A study of Equations 1, 3, and 4 shows that losses within a coaxial line will increase as pulse rise times decrease and their upper frequency components increase. Both losses increase with increasing frequency. The effects of these losses on pulse shape is to attentuate the higher order of frequency components necessary to form and maintain the rise time slope. The result is a delay in or a longer rise time. For example, one foot of RG-9/u cable will increase an ideal (zero rise time pulse) to 20 picoseconds, while 8 to 10 feet of RG-58/u cable will increase the same ideal pulse to 1 nanosecond. Furthermore, the rise time does not necessarily vary linearly with length.

Connectors:

The amount of degradation to the digital pulse contributed by the connector in the interconnect system has not been clearly defined by any literature studied or companies contacted in this program. Several reasons for this lack of information on connectors can be advanced, and are as follows:

A. Some companies have stated that connectors were a problem in their digital circuits, but when questioned further, could not define these problems such that a separation of electrical from mechanical problems could be determined. Most companies do not use methods of test to determine source and cause of component failures. They generally rely on "in circuit" testing and "debugging" on a system by system basis.

B. The connector has not been a culprit on most digital systems to date, as its electrical length has been short relative to the resulting pulse induced wave lengths.

The second reason appears the more valid of the two since the connector, while subject to the same loss factors as the cable, is several orders of magnitude physically smaller than most cable systems in use today. Where connector loss and impedance mismatch problems have been severe, high quality single circuit coaxial connectors are employed. Some typical coaxial connectors in use are the Amphenol precision 7-mm type APC-7, the General Radio GR type 874, and the 3-mm OSM connector.

Multipin connectors are in use in various forms for multi-interconnecting digital circuit boards and also to interface hardware. These connectors consist of the cylindrical MS and Pygmy types, the rectangular printed circuit, rack and panel, flat cable, dip socket, and TJS terminal junction system types. Most have appeared with one or more coaxial contacts installed in place of some of their normal pin and socket arrangements. These have been introduced at specific digital user requests where certain circuits passing through a particular connector must be controlled for losses due to the dielectric or impedance mismatches. The coaxial system also minimizes circuit to circuit crosstalk.

Multipin Connectors - Pin and Socket:

As pulse rise times decrease the conventional pin and socket multipin connectors will prove too lossy to serve as digital interconnects. These losses will occur mainly in the form of dielectric losses and pin to pin impedance mismatch losses. These losses will make it impossible to achieve narrower pulse widths and also increased repetition rates when they reach the picosecond rise time range. The common forms of pin and socket arrangements within their dielectric inserts will increase their circuit crosstalk potentialities.

Some typical dielectrics used in connector inserts are shown in Table 2 along with their relative dielectric constants and dissipation factors measured at 1 megahertz.

Table 2

Insert Dielectrics

Material	Die. Const.	Diss. Factor
Phenolic Mineral Filled	9-15	.07 - .20
Melamine Glass Fiber Filled	6.5-7.5	.013-.015
Alky D Glass Filled	5.2-6.8	.008-.023
Diallyl Phthlate Glass Filled	3.4-4.5	.009-.014
Silicone Glass Fiber Filled	3.2-4.7	.002-.020
Polycarbonate Glass Filled 10-40%	3.0-3.4	.007-.008

As stated in Equation 4, the dielectric loss at a given frequency is a function of the materials relative dielectric constant, E_R and its power factor or dissipation factor, R_p. The materials shown in Table 2 are mainly composite or filled materials whose mix proportions can vary. These mix variations are known to affect their electrical properties at the normal low frequency (1 MHz) measurement ranges. Very little is known about their behavior in the microwave frequency range. Physical arrangements of the contacts within the dielectric can give an infinite number of combinations of characteristic impedance for pair arrangements within a connector shell as shown by Equation 5 and Figure 2. A balanced shell shielded contact pair is used for example purposes.

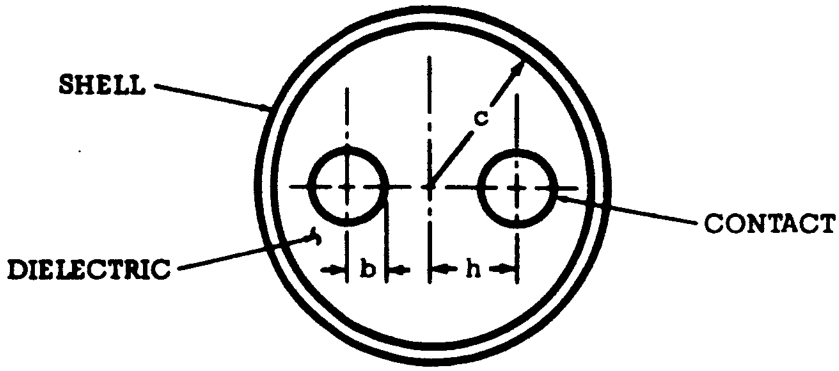


FIG. 2 SHIELD PAIR BALANCED 2 CONTACT CONNECTOR

Equation 5 shows that the characteristic impedance of two contacts within a multipin connector is not only dependent upon the dielectric constant of the insert material, but also upon the contact's diameter, their spacing from each other, and their position distance from the inner diameter of the connector shell.

$$Z_O = \frac{120}{E_R} \quad 2.303 \text{ LOG} \quad 2V\frac{1-\sigma^2}{1+\sigma^2} - \frac{1+4V^2}{16V^4} \quad 1-4\sigma^2 \qquad (5)$$

Where: E_R = Relative Dielectric Constant of the Insert

$$V = \frac{h}{b}$$

$$\sigma = \frac{h}{c}$$

Variations of Equation 5 for cylindrical and rectangular type connectors versus various pair diameters, spacing, and position could be performed on a computer and would result in a large number of impedance values in today's more common connectors.

This exercise would yield nothing other than their inadequacy if an attempt were made to use them to transmit picosecond pulses where they must be impedance matched into 50, 75, 93, and 300 ohm source and detector pulse circuitry.

Another area where connectors of this type may prove their pulse transfer inadequacy is in the typical physical design areas of a pin and contact arrangement. Equation 5 assumes that radius b is constant throughout its length. This is not true of most pin and socket contacts. There are diameter undercuts on most, used for contact retention within the dielectric. There are also diameter changes at the mating areas of the pin to socket which vary in length, dependent upon insertion tolerances. These diameter variations can be as long as .250 inch in length for a size 20 contact. A time domain reflectometer (TDR) measurement using a 28 picosecond rise time pulse would show these diameter changes as impedance discontinuities along the length of the contact.

Pulse Measurement and Standards:

As this study was pursued several additional factors pertaining to picosecond rise time generation became apparent. These factors were

- lack of a rise time standard for calibrating test equipment, and
- a scarcity of test equipment capable of measuring and displaying picosecond rise time.

The National Bureau of Standards has been working for two years on a rise-time calibration service (Page 43 E.D.N. March 1, 1970). The standard for this service will be a sampling scope whose response has been evaluated in the frequency domain. Its amplitude response was measured to 18 GHz, and its phase response to 9 GHz. Pulse voltage down to 1 volt amplitude will be measured from 20 picoseconds (at about 25 percent uncertainty limit), to 100 picoseconds (at better than 5 percent uncertainty limit) and on up (with 2 to 3 percent uncertainty limit). The pulse width will be limited to 300 picoseconds.

Realtime oscilloscopes such as the Hewlett-Packard model 183A has a band width of 250 MHz, and is the widest gain-band width oscilloscope on the market to date. The rise time of these scopes is 1.5 to 3.5 NS. The rise time measurement (T_1) is limited by the square root of the sum of the squares of pulse generated (T_G) and the pulse received (T_R).

$$T_1 = T_G^{2} + T_R^{2}$$

For this reason these oscilloscopes would not be adequate for viewing picosecond pulses.

Sampling scopes with band widths in the gigahertz frequency range are available for pulse measurement. A 50 picosecond pulse rise time would have to be measured with a sampling scope whose band width was at least 7 GHz to meet the requirements of Equation 1. The sampling scope is limited by the fact that the pulse must be repetitive, although with some scopes, the repetition need not be periodic. Also, jitter and drift can be limiting factors.

For component evaluation to pulse response, such as interconnects, the time domain reflectometer (TDR) is considered by most authorities in the field as the best instrumentation available today. Present state of the art TDR instrumentation can produce 35 picosecond pulse rise times. They can differentiate circuit impedance discontinuities as short as .250 inch.

Conclusions:

A. Connectors have not been a severe source of digital pulse degradation where pulse rise times, pulse widths, fall times and repetition rates have been greater than 1 nanosecond in duration. This is due to the fact that operating wave length has been considerably larger than the connector electrical length.

B. The losses in pulse forming and receiving circuitry have exceeded those in connectors until the recently new advances in MSI technology which may alter this situation.

C. Connectors of future digital circuit technology will prove a limiting factor in signal transmission in both the area of circuit interconnects and the area of interface hardware interconnects. These limiting factors are as follows:

- Slowing the pulse rise times by their losses.
- Limiting the shorter pulse width capability.
- Increasing pulse fall time.
- Limiting faster repetition rates.
- Pulse distortion may occur due to amplitude changes and jitter caused by contact movement from shock or vibration which may introduce transients or "glitches" on the incoming pulses.
- Phase shift may occur through the connector due to impedance shifts from reactive impedance changes through the connector.
- Fan-out of signals may be limited, where connectors introduce excessive losses to low level millivolt or microvolt pulse signals.

Detailed Recommendation:

A. Introduction

As a result of the work conducted by the Electrical Components Division of The Bendix Corporation under the sponsorship of the Marshall Space Flight Center on Phase 1 of the Materials Investigation and Tests for the Development of Space Compatible Electrical Connectors, it is evident that problem areas associated with the digital efficiency of connectors are eminent. As the need to deal with digital data at higher speeds increases, the digital efficiency of multi-channel connection mechanisms must also increase. Very little work has been conducted in industry on the problem of the digital efficiency of connectors and, in general, test methods have been confined to "in circuit tests". This approach, although satisfactory for existing needs, does not lend itself to establishing limits of operation in multi-channel connection mechanisms until problems become apparent.

It is, therefore, proposed that the task of developing test methods to define these limits be undertaken. Having established these limits, testing on selected types of connectors will then be conducted to determine where these devices are no longer serviceable with respect to rise time, pulse duration, and pulse repetition rate.

B. Problem Statement

The final report pertinent to Task V, Phase 1 of the Materials Investigation and Tests for the development of Space Compatible Electrical Connectors indicates that, within the next 5 to 10 years, rise times in the order of picoseconds are expected in digital circuits. Due to this very fast rise time, pulse amplitudes will be restricted to 1 volt or less. The ability of existing multi-channel electrical connection mechanisms to deal with these speeds and amplitudes has not been clearly defined due to lack of available information. It also appears to be doubtful if existing connectors are capable of dealing with pulses having such parameters.

In dealing with pulses having sub-nanosecond rise times, small amplitudes and fast repetition rates, test and calibration equipment is extremely scarce. Some manufacturers do, however, sell equipment which is just adequate to observe and test the transmission of these fast pulses through networks.

It is, therefore, felt that further work should be conducted to develop test methods and techniques which can be used to define limiting parameters associated with the digital efficiency of existing connectors.

Although the above referenced report indicates that problems due to mechanical shock and vibration can exist in connectors handling fast digital pulses, it is felt that such problems would, by virtue of the relatively large mechanical masses associated with connectors, exhibit themselves by much longer duration effects such as completely missing portions of the signal for periods of time approaching or exceeding a millisecond duration. Such absence of signal would be apparent in connectors currently in use. The limitations of existing equipment to measure discontinuities are presently in the nanosecond range and further advances on these capabilities are limited by the state of the art. It is, therefore, felt that any test on these parameters would not provide satisfactory limits and conclusions. For these reasons, it was decided to omit testing in these areas.

In this portion of the work, it is proposed that test methods be established to determine impedances, rise time capabilities and cross talk limitations of existing connectors. It is further proposed that these specific tests be conducted on selected samples of connectors which are currently being used in circuits dealing with fast digital pulses in order to determine their limitations.

As this work progresses, observations will be made concerning the limiting factors and, if necessary, recommendations will be made as to how these frequency limitations can be improved in future connectors.

C. Planned Approach:

In this effort, it is planned to reference the work to three areas of testing as follows:

- Impedance measurement which will be accomplished by frequency domain techniques.
- Pulse rise time measurement as indicated by time domain testing.
- Cross talk as determined by signal level detected on inoperative lines.

Having established test procedures and specific connector types, test fixturing and hardware will be designed and manufactured to facilitate the test program outlined above.

During the test portion, each test will be adequately documented. At the completion of all testing, this data will be reduced and evaluated using applicable techniques. From these results, limits of rise time, pulse duration, pulse repetition rate, and cross talk will be established.

Analysis of these results will then be made and further necessary brief tests will be conducted to indicate, in a broad sense, what connector design parameters need to be modified to improve the digital efficiency of multi-channel electrical connection mechanisms.

Future R&D Connector Activity:

The shuttle environments as now defined will introduce certain new connector requirements brought about by the combination of aircraft and space type flights. As a result of this, it is envisioned that certain key connector activities will be necessary.

A. Material Development

Continued effort is anticipated in electrical connector material development.

B. Digital Efficiency

Continued effort is anticipated concerning the effects of interconnect systems on the transfer of high speed digital signals.

C. New High Density Connector Approach

An effort is anticipated to establish a family of connectors with extremely high density contact spacing using a new approach to an all dielectric insert. Connectors with all dielectric inserts have exhibited severe problems with contact retention, ease of assembly, inspection and other weaknesses in the past. Many of these problems have been solved by metal clip contact retention devices in connector designs such as the 40M39569 (Modified NAS 1599) connector. However, the presence of the conducting metal retention devices severely restricts the close spacing of contacts in connector inserts. This new family of connectors could possibly include the following types:

1. Circular

2. Rectangular

3. Distribution, Bussing and Termination Devices

4. Zero-G Coupling Version

5. Above connectors to have common features:

   - Standard insert retention design
   - Standard materials
   - Standard contacts
   - Standard contact crimp tools
   - Standard contact insertion-extraction tools

D. R. F. Connectors

Explore and establish a family of R. F. Connectors to handle digital pulsing and R. F. applications.

E. Flat Conductor Cable Connectors and Termination Devices

Develop a reliable termination system for flat conductor cable usage.

F. Engine Harness Connectors

Explore and establish electrical connectors that will meet special or unusual engine area requirements.

G. Maintenance and Inspection

Establish connector designs or modifications that will assure ease of maintenance and inspection of assembled, installed connectors.

H. Umbilical and Remote Access Connectors

Explore and establish umbilical and remote access connectors.

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