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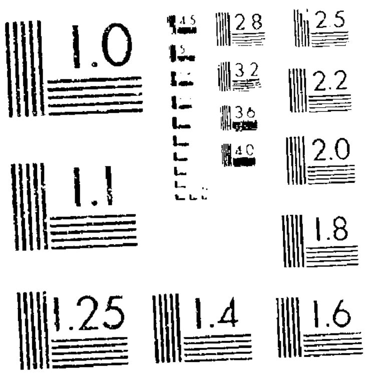

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THE PREVENTION OF ELECTRICAL BREAKDOWN AND ELECTROSTATIC VOLTAGE PROBLEMS IN THE SPACE SHUTTLE AND ITS PAYLOADS

PART II - DESIGN GUIDES AND OPERATIONAL CONSIDERATIONS

National Aeronautics and Space Administration

LYNDON B. JOHNSON SPACE CENTER

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PART II - DESIGN GUIDES AND OPERATIONAL CONSIDERATIONS

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PART II: DESIGN GUIDES AND OPERATIONAL CONSIDERATIONS

1.0 INTRODUCTION

This part of the report addresses the specific electrical discharge problems that can directly affect the Shuttle vehicle and its payloads. General design guidelines are provided to assist flight hardware managers in minimizing these kinds of problems. Specific data are also included on workmanship practices and, most importantly, system testing while in low-pressure environments. Finally, certain electrical discharge problems that may be unique to the design of Shuttle vehicle itself and to its various mission operational modes are discussed.

2.0 DESIGN PROCEDURES FOR THE PREVENTION OF ELECTRICAL BREAKDOWN IN THE SPACE SHUTTLE AND ITS PAYLOADS

2.1 GENERAL DESIGN GUIDES

2.1.1 Operating Voltage Levels

Under the proper conditions, corona can occur at any voltage level. However, there are three voltage ranges that can be conveniently used to categorize the different problems and procedures. These are 0 to 50 volts, 50 to 250 volts, and over 250 volts. The following is derived from Dunbar (ref. 12).

2.1.1.1 Zero to 50 volts peak.- The first voltage range is 50 volts and below. Field stresses normally will be below 2000 V/mm because the insulation is normally thicker than 0.025 millimeter. Corona caused by gaseous ionization will not exist in air or nitrogen atmospheres between commonly used metallic surfaces at temperatures below 250° C. In addition, tracking is not expected in this voltage range provided the following good workmanship practices are followed during design, packaging, and assembly.

- Avoid contamination on surfaces of conductors and their insulations.

- Select materials and dimensions that can withstand the worst-case voltage gradients around the energized conductors.

- Avoid short air gaps between thinly insulated or bare conductors.

- Select insulating materials with maximum resistivity and dielectric strength and with low dielectric constant.

- Apply the Paschen Law curve as modified for nonuniform fields.

- Base all calculations on the instantaneous peak "abnormal overvoltage" of the system.

- Select materials with suitable outgassing properties.

- Select packages with adequate sealing or venting.

Strict observance of these items will assure that gaseous breakdown will not occur at temperatures below 250° C.

The type of problems that can be expected if proper care is not taken are as follows.

- Low-voltage tracking where the extremely low current (nanoamperes) will eventually char the insulation.

- Metal migration can occur over extended operating times. This results in a short circuit when the metal from one electrode bridges the gap between electrodes.

- Contamination resulting from salt spray, outgassing residues from other spacecraft equipment, structure, and controlled emissions.

- Short circuits resulting from workmanship (caused by fingerprints and oils that create localized critical pressures that may affect nearby high-voltage circuitry).

2.1.1.2 <u>50 to 250 volts peak</u>.- The second voltage range is between 50 and 250 volts peak. In this range, besides the previously stated good workmanship practices and precautions, the following practices will minimize the probability that corona will occur.

- Eliminate dielectric discontinuity; that is, avoid a sudden increase in voltage stress between insulators resulting from use of insulators with large difference in dielectric constant.

- Recess terminals and encapsulate them with void-free, well-bonded surfaces, and potting materials.

- Use nontracking insulations.

- Prevent condensations of moisture and other liquids before and during operation.

- Lengthen flashover paths when practical with skirts, grooves, et cetera.

- Avoid pointed electrodes.

- Provide excellent bonds between conductors and insulators.

- When hermetic sealing is required, pressurize with a suitable dry gas with a high dielectric strength in a thoroughly dry enclosure.

- Use low dielectric constant insulators.

- Dampen inductive switching surges.

- Design for abnormal fault and transient voltages.

- Waterproof insulating surfaces.

- Complete coating of critical electrodes may eliminate electrode-to-electrode breakdown but the spacing must be sufficient to prevent corona for dc voltages.

- Avoid multipactor breakdown by having a high frequency-times-spacing product.

- Arrange conductors so that high- and low-voltage groups are separated.

- Provide rounded corners on electrical conductors and ground planes next to energized circuits.

- Use at least 0.25-millimeter insulation between rounded electrodes and 1.25-millimeter insulation between flat surfaces.

Typical problems that can occur in this voltage range are as follows.

° Corona may be enhanced by gases such as helium, argon, neon, and hydrogen, if they should mix with the pressurizing gas in pressurized containers during such operations as leak detection.

° Be careful in the use of solvents such as alcohol, benzene, et cetera, the outgassing products of which enhance corona.

° Creepage and tracking can cause increased temperatures in localized areas and eventually lead to surface flashover.

° Voltage transients may cause surface flashover to occur. Between 6 and 10 flashovers will form tracking and eventually voltage breakdown.

2.1.1.3 Voltages over 250 volts peak.- The third voltage range is all voltages above 250 volts peak or those with rf in the multipactor range. In addition to the good workmanship practices and precautions stated in sections 5.1.1.1 and 5.1.1.2, some design features that are recommended to inhibit corona for voltage above 250 volts are as follows.

° Avoid multipactor region.

° Eliminate large air gaps between insulated conductors. An example is a twisted pair wires having an end flare as they enter the terminal ports. As voltage is increased, corona will first appear at the widest separation in the low-pressure systems (below 1.33×10^{-1} N/m^2).

° Application of transverse magnetic fields to raise the sparking voltage at pressures below the critical pressure. Because the effect is to increase the gap length caused by spiraling of electrons, breakdown voltage can be lowered, rather than raised, below the critical value of the parameter, pressure times spacing dimension.

° Avoid the entry of ionized particles or electrons into the circuitry from the surrounding environment. The importance of the presence of such particles is evident from the OSO-I and OSO-II experiments which used open photomultipliers. Any electric field that may extend from openings in the enclosure will attract charged particles of one polarity. Suitable shielding grids and/or traps must be provided. Also, high voltage on conductors in the vicinity of the openings must be avoided if possible.

o Voids in encapsulants are especially bad and should be vented or kept pressurized. When poorly vented voids or gas enclosures are encapsulated in an insulation, the gas pocket will eventually reach critical pressure and electrical breakdown will occur in the void. In time, insulation deterioration will occur and the insulation integrity will be destroyed, resulting in the loss of equipment.

o The use of semiconducting coatings on high-voltage surfaces and around stranded wiring can be used to control uniformity of fields.

o Use electrode materials that are conditioned and polished to most effectively decrease the voltage gradients within the insulation.

Above 5000 volts, hermetic sealing may be required for some circuits that must operate at pressures greater than 7.5 X 10^{-4} mm Hg. In this case, it is advisable to use a gas with a high dielectric strength rather than oil. With oil, bubbles can form in zero g, which results in momentary dielectric breakdown and tracking. Pressurization is important above 10,000 volts to prohibit critical pressures caused by slowly outgassing materials and nearby equipment. Material compatibility is very important at these very high voltages.

Typical problems that can occur in this voltage range are as follows.

o Incomplete bonding of materials.

o Insufficient outgassing of potting compounds during vacuum impregnation.

- Insulation cracking during thermal/mechanical stressing.

- Gaseous ionization and partial discharges within small voids and cracks.

- Creepage and tracking.

- Flashover.

- Insulation treeing on long missions.

2.1.2 Designing for Breakdown Without Damage

Occasional corona discharge or arcing often will not permanently damage the high-voltage equipment. However, it may result in serious interference with the operation of or even serious damage to the other equipment in the spacecraft. Examples have been given of spurious pulses that have caused random stepping of commutators in encoding systems, and of components such as transistors being burned out by high-voltage spikes. These pulses can be carried on the low-voltage power distribution lines including the ground returns. The filter capacitors on the high-voltage power supply can store considerable energy that is released with the occurrence of a sparkover. Only part of this energy is dissipated as heat in the spark. The remaining energy is propagated away as a steep wave front or impulse on all neighboring conductors. Energy can be transferred to other circuits either through direct ionic conduction or by inductive and capacitive coupling.

It is very difficult to completely eliminate occasional corona discharge or arcing in high-voltage equipment. Also, there are cases of inadvertant turn-ons that can cause considerable damage. This might happen if venting were being used to produce the high dielectric strength of vacuum and the high-voltage supply was turned on near the Paschen minimum by accident. For these reasons, it is best to design equipment so damage does not result from corona discharge or arcing.

High-voltage power supplies should be designed with current-limiting characteristics. This way, no components are overloaded in the event of corona discharge or arcing. Current-limiting resistors should be placed between the output filter capacitors and the loads. Also, some power supplies are designed to limit current at their output.

The equipment should be packaged in such a way that all the high-voltage wiring is isolated or shielded from other circuits to avoid transfer of energy. One approach is to enclose the entire high-voltage circuit in a conducting envelope with just a shielded coaxial cable to the circuit it supplies.

When high- and low-voltage circuits are on the same printed circuit or terminal board, the common boundary should be minimized. A ground bus should be located between high- and low-voltage circuitry to prevent possible creepage currents or arcs. An example of these design principles is shown in figure 5-1. Where high-voltage exists on both sides of the printed circuit or terminal board, the ground bus should be on both sides, preferably superimposed one above the other.

2.1.3 Soldering

Proper soldering can reduce the electric field intensity and thus reduce the chances of corona. Also, sharp points left by improper soldering can cause tears in the insulation, which, of course, can lead to insulation breakdown. Some sketches of acceptable and unacceptable soldered terminations are shown in figures 5-2 to 5-4.

Standoffs and feedthroughs should be solder-balled as shown in figure 5-5. This will probably require a waiver from the NASA solder specifications. The solder ball is made after the connection is soldered per the appropriate NASA specification. Dunbar (ref. 12) states that "The radius of the solder ball facing the ground plane should be at least 1/6 of the value of the spacing between the solder ball and ground plane or

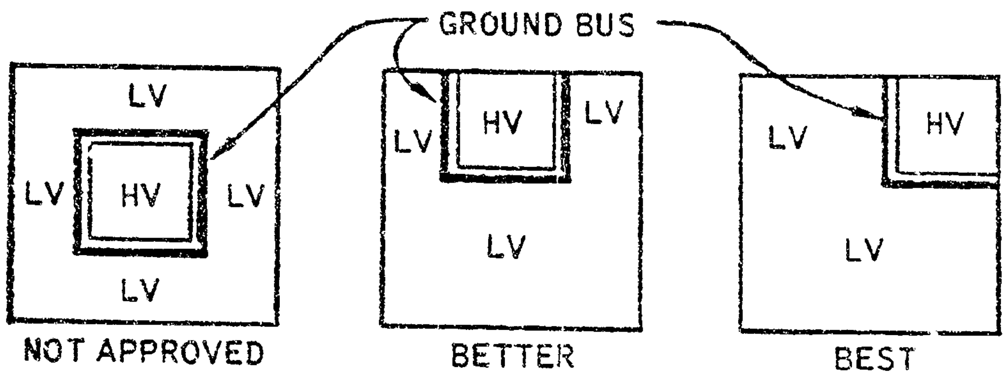

Figure 2-1.- Common-boundary high- and low-voltage circuits.

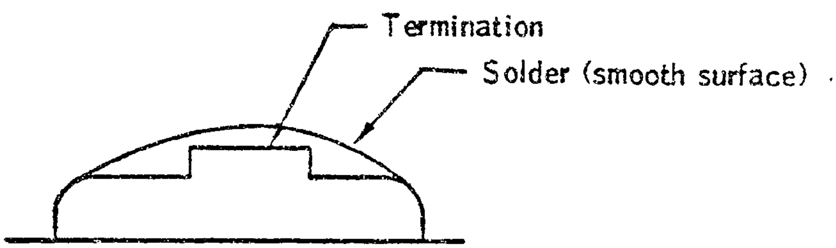

Figure 2-2.- Acceptable soldered termination.

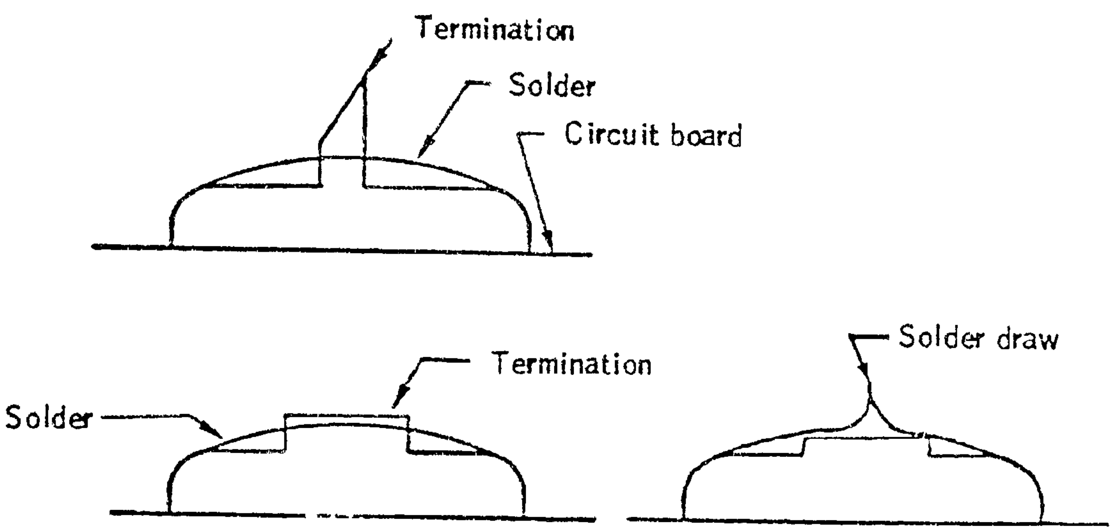

Figure 2-3.- Unacceptable soldered terminations.

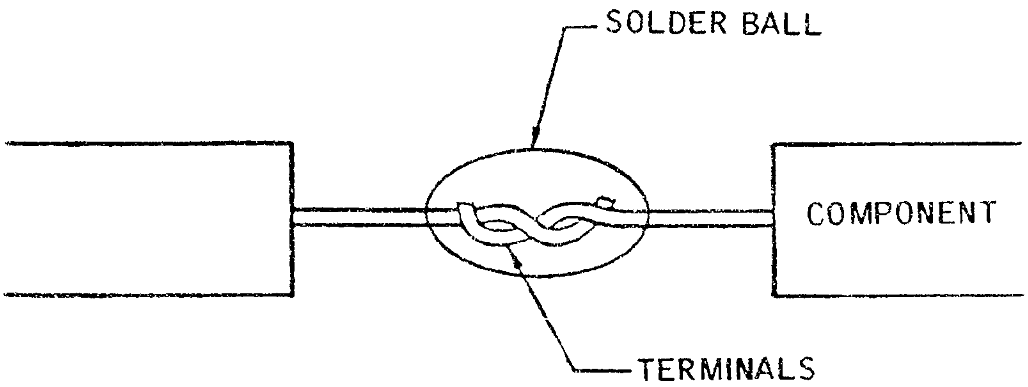

Figure 2-4.- Acceptable components interconnection.

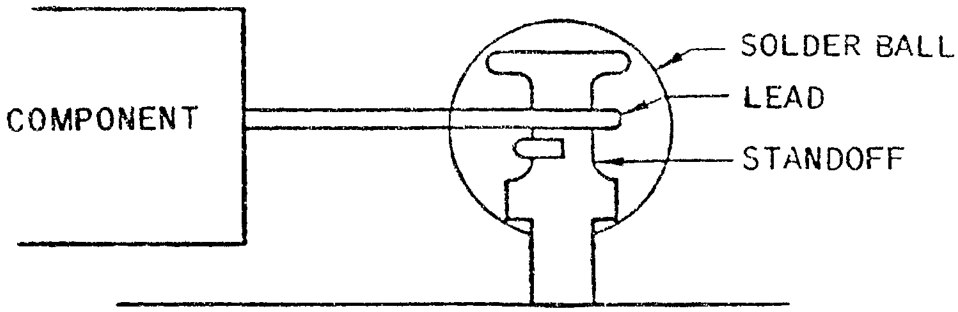

Figure 2-5.- Acceptable standoff connection.

adjacent high voltage circuit. This low ratio decreases the voltage gradient at the surface of the solder ball and decreases the probability of corona. When large spacings are involved the solder ball should have at least 3.1 millimeters (0.125 inch) diameter. These solder balls must be properly secured to eliminate any dynamic vibration and acoustic problems."

2.1.4 Testing Philosophy

Proper design of electronic equipment is essential for corona-free operation. However, it is not sufficient. Testing is a must. From the standpoint of corona detection, many test plans are inadequate (ref. 39). Indeed, some test plans seem to take no notice of the possibility of corona. These plans do not address the need to prove that instrument function is free from corona degradation. In many cases, there is not even any corona-detection equipment used. The experiment equipment itself is regarded as the corona detector. This meets with varying degrees of success. The power supplies may be heavily filtered and any effects of corona within the power supply would be masked. If the output of the experiment is in digital form, corona would again be masked.

Many experiments are operated only intermittently in thermal vacuum tests for relatively brief periods. Yet, corona onset may only occur after days into a test. The pressure and temperature time profiles usually are chosen for factors other than corona detection. Most acceptance thermal vacuum tests are entirely too short to reveal latent corona problems. Qualification test profiles are better, but in some cases do not follow mission profiles. Unfortunately, mission-length acceptance testing is usually a departure from normal procedure. However, no better way is known to gain confidence that a given unit will not experience corona-induced malfunctions.

The testing of prototype, qualification, and flight equipment should be differentiated. Dunbar's philosophy is quoted as follows.

"Testing and Detection - Generally, the test philosophy for electronic parts and hardware should be that flight parts and engineering, development, prototype and qualification equipment may and should be thoroughly and extensively tested and stressed repeatedly to establish the applicability and design margin of the design. Qualification equipment should first be tested to acceptance levels to verify workmanship and to identify infant mortality reasons for failure. Flight equipment should never be stress tested or be electrically tested repeatedly. One test of flight equipment will verify workmanship and expose infant mortality conditions. Electrical stress, a cumulative condition, can jeopardize the imposed operating life of a flight device."

2.1.5 Design Review Checklist

A checklist can be quite helpful in the reviewing of a design. Smith and Aptaker (ref. 40) have published a very extensive list of questions relating to aerospace systems. The following was compiled by Paul and Burrowbridge (ref. 2). It includes only those questions relating to electrical breakdown that are omitted from the literature or that require special emphasis.

"1. Are any hollow core resistors used?

"2. If hollow core resistors are used, are they adequately sealed or vented to avoid internal glow discharge?

"3. Are any solid state circuit elements so located that voltage gradients (electric fields) of sufficient magnitude to damage them can be imposed in either normal or faulty operation?

"4. Are solid state circuit elements protected against damage from excess reverse current in the case of an electrical breakdown?

"5. In transformers, chokes, and tuning coils, is the voltage between turns safely below the breakdown threshold?

"6. In transformers, chokes, and coils, is insulation adequate to prevent electrical breakdown in the critical pressure region?

"7. In transformers, are current limiting design features adequate to prevent loss of function resulting from an electrical breakdown?

"8. In connectors and plugs, if used, is adequate venting provided?

"9. In connectors and plugs, if used, are the insulating materials chosen for low susceptibility to tracking and treeing?

"10. Is the use of connectors and plugs in the high voltage side confined to the minimum number compatible with the intended application?

"11. Are large potential gradients possible between exposed adjacent connections on printed circuit boards?

"12. Does the design guard against transients large enough to initiate breakdown in both "make" and "break" operations?

"13. Are bleeder resistances incorporated with all capacitors that could store enough energy to cause breakdown?

"14. Are current limiting features of all circuits adequate to prevent both self-damage and neighbor-damage in the event of electrical breakdown?

"15. Are test points readily accessible for corona detection tests?

"16. Can every conceivable electrical breakdown fault be detected by tests?

"17. Will catastrophic failure result if test points are grounded?

"18. Is cabling insulation adequate for planned operations and for operation through the critical pressure region?

"19. Is cabling properly arranged to avoid trapping of gas?

"20. Are sharp points and sharp edges completely avoided?

"21. Are arc suppression features for both make and break adequate?

"22. Are appropriate steps taken to avoid the existence of ions in regions of large potential gradients?

"23. Are potting and coating materials chosen so that mechanical stress on parts is kept small?

"24. Are the possible effects of aging of potting and coating materials provided for?

"25. Are both individual and combined effects of environmental factors such as temperature, vacuum, penetrating radiation, ions, and outgassing taken into account in the design?

"26. Are provisions made to prevent inadvertent turnon of high voltage?

"27. Has electrical stress analysis been done on all circuits for both normal and breakdown operation?"

2.2 POSSIBLE ELECTRICAL BREAKDOWN PROBLEMS WITH THE SPACE SHUTTLE

2.2.1 Possible Exposed Electronic Systems

Hypersonic and reentry vehicles usually use instrumentation wire to transmit small voltage signals from sensors measuring temperature, vibration, and strain. These signals may be recorded, telemetered, or displayed for pilot information. It is important, even critical, that the wires transmit these signals with a minimum additional error. This is especially important where the vehicle safety depends upon the signal integrity. If there are such sensors on the

Shuttle, they will be exposed to extreme environmental conditions, probably temperatures over 1000° F. These extreme conditions can be expected to cause some signal error to be generated within the instrumentation wire.

The other area of concern would be the electronic bays 4, 5, and 6 located in the aft section of the orbiter (fig. 5-6). The electronics contained in these bays is shown in figures 5-7 to 5-9, respectively. The identification numbers and letters for the units are given in table 5-I. The dc power levels (ref. 7) are 28 V dc nominal with 24- to 34-volt steady-state limits. The main ac power in 400 hertz, 115/200-volt, three-phase, four-wire, wye-connected.

2.2.2 Possible Problems During Launch

Because the voltages of concern (28 V dc and 115 V ac) are well below the Paschen minimum for air, it would seem that no voltage problems would exist. However, experience has shown that even 28 V dc can break down under the right conditions. In fact, Vance and Chown (ref. 41) have produced arc discharges in the laboratory at 28 V dc in a plasma environment. The plasma environment is produced in spacecraft by either arc discharge or the rocket exhaust.

The Agena Program was plagued for many years by an occasional short circuit occurring at or near the time of separation from the booster (ref. 42). All these short circuits involved very large current flows. Some of these currents stopped as mysteriously as they started. Others have even burnt out circuitry so that the completion of the mission was impeded or even prevented. Some of the breakdowns were identified as happening in the 28-volt, 400-hertz regulators and pyro-power supplies. The breakdowns occurred at separation from the booster. The plasma environment was believed to be produced by the retrorockets that were used to decelerate the booster after staging from the Agena.

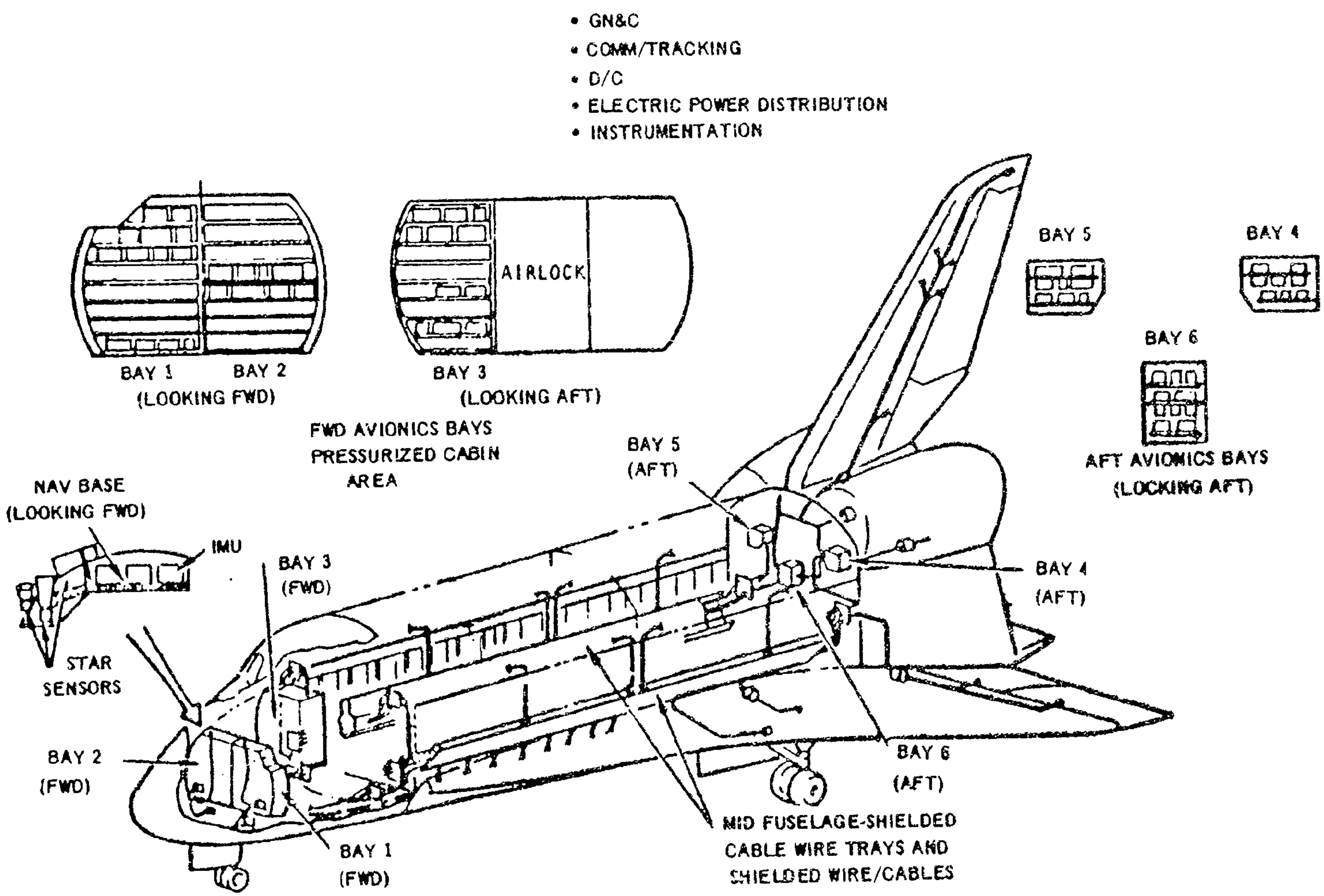

Figure 2-6.- Orbiter avionic system installation configuration.

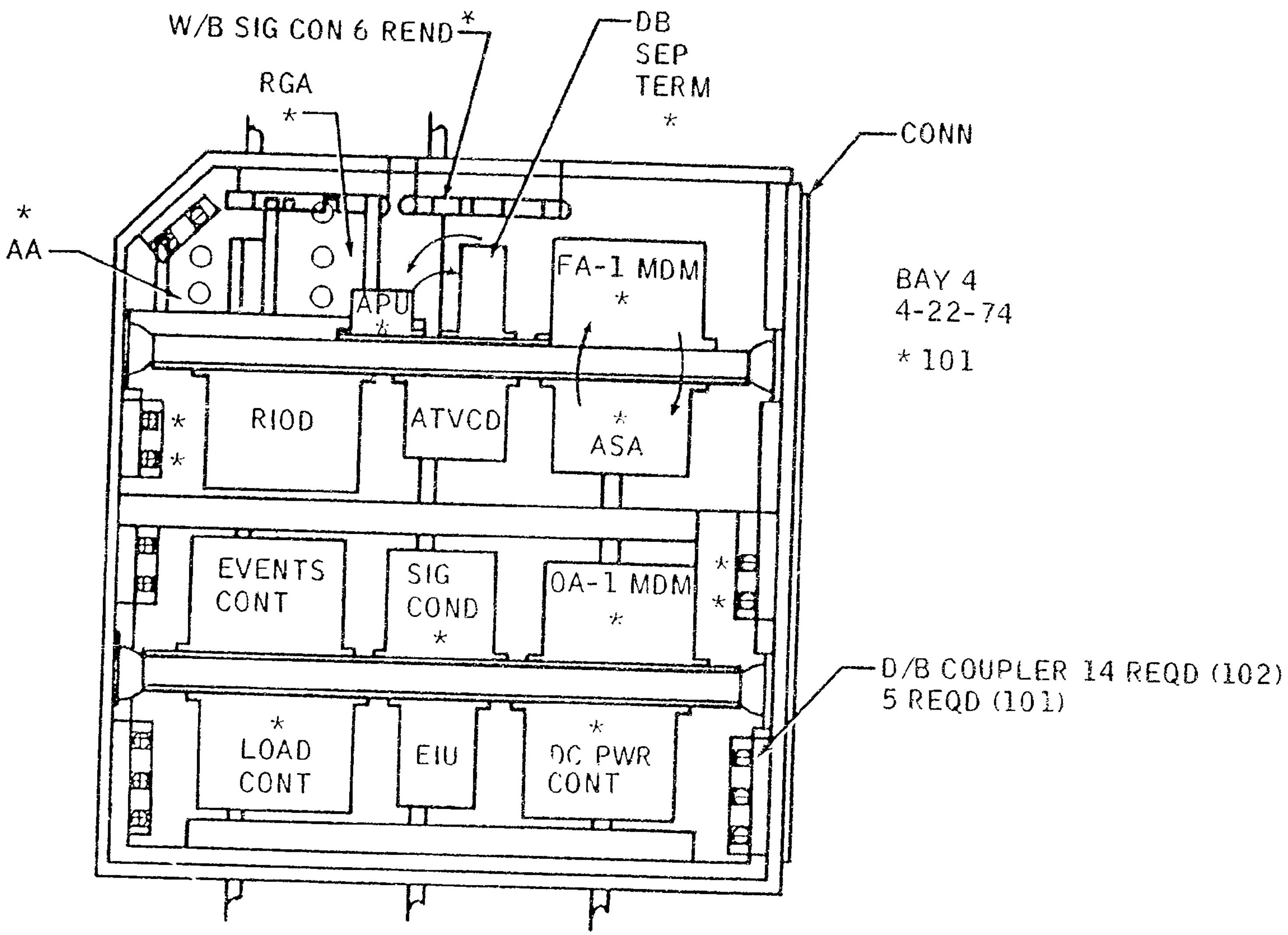

Figure 2-7.- Electronic equipment contained in bay 4.

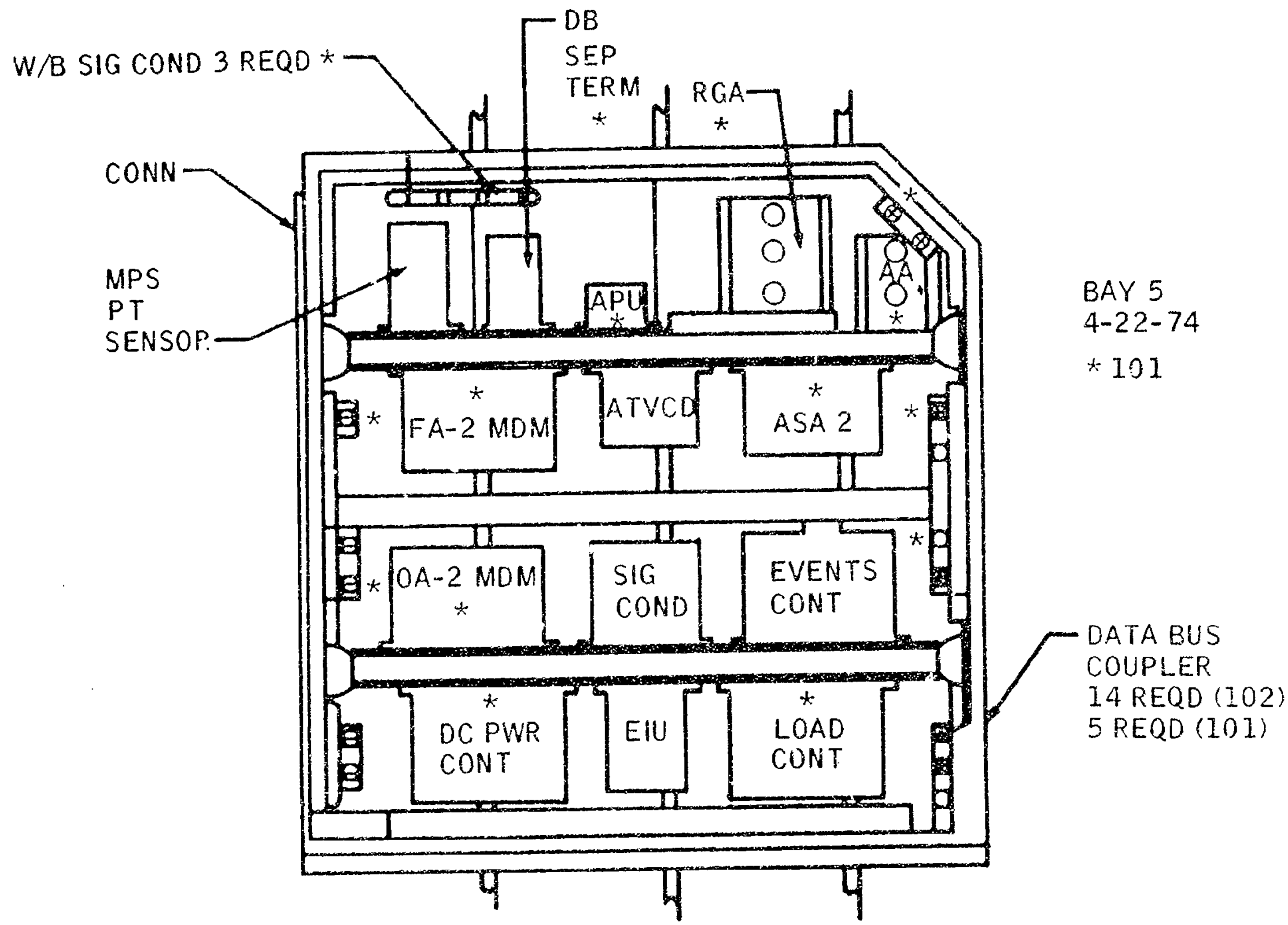

Figure 2-8.- Electronic equipment contained in bay 5.

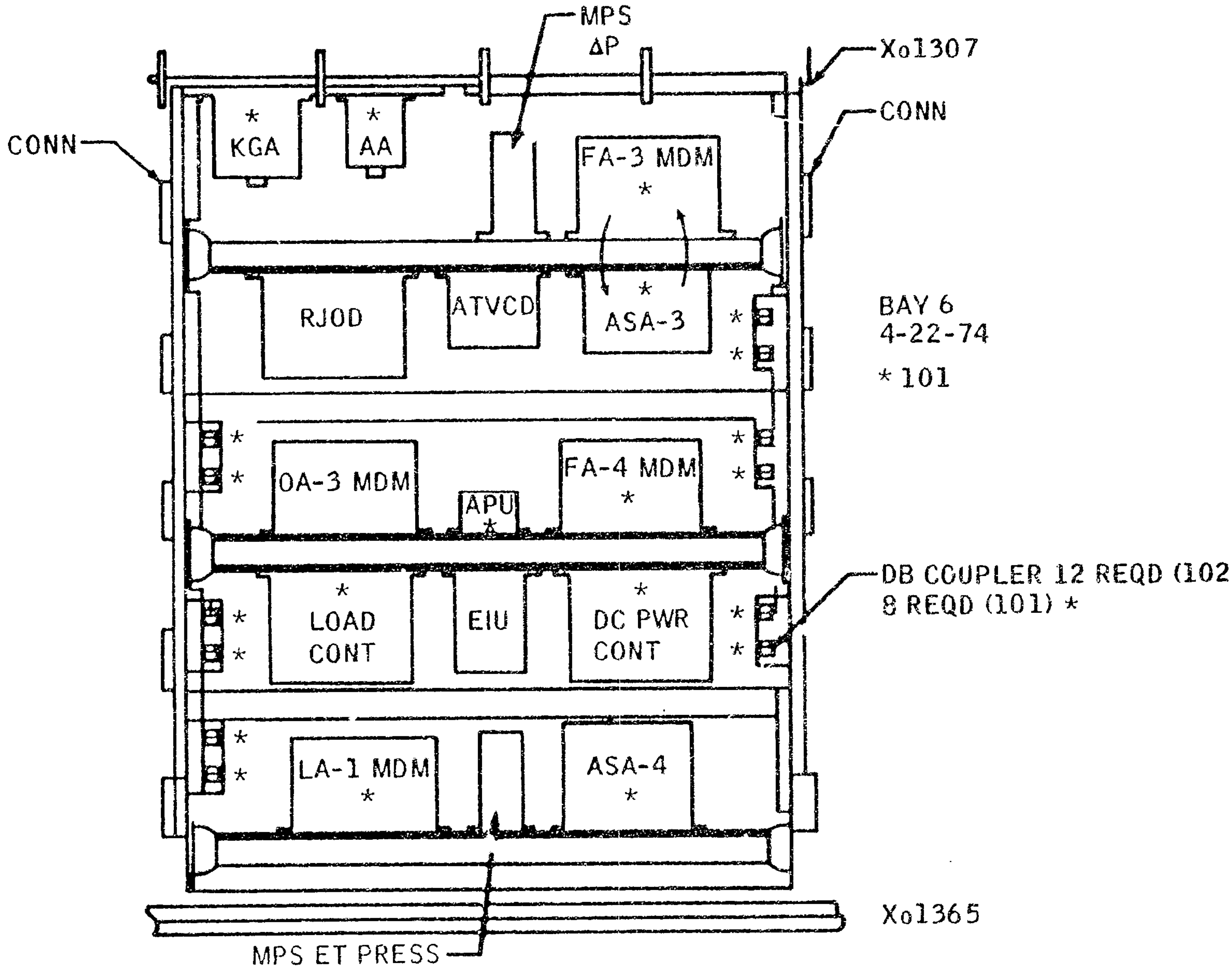

Figure 2-9.- Electronic equipment contained in bay 6.

TABLE 2-I.- EQUIPMENT IDENTIFICATION NUMBERS AND ABBREVIATIONS FOR ELECTRONICS EQUIPMENT

[Taken from SD74-SH-0120-06-1, March 15, 1974]

SC. Interface Unit Type Identification Number. A digit number uniquely identifying the following interface unit types.

01: General Purpose Computer (GPC)

02: Mass Memory (MM)

03: Display Electronics Unit (DEU)

04: Multiplex/Demultiplex FF (MDM FF)

05: Multiplex/Demultiplex FA (MDM FA)

06: Multiplex/Demultiplex LF (MDM LF)

07: Multiplex/Demultiplex LA (MDM LA)

08: Multiplex/Demultiplex PF (MDM PF)

09: Display Driver Unit (DDU)

10: Forward Events Controller (FEC)

11: Aft Events Controller (AEC)

12: Engine Interface Units (EIU)

13: PCM Master Unit (PCM)

14: Manipulator Controller Interface Unit (MCIU)

15: Performance Monitor Annunciator Panel (PMAP)

16: Multiplex/Demultiplex OT (MDM OT)

17: Multiplex/Demultiplex OF (MDM OF)

18: Multiplex/Demultiplex OA (MDM OA)

19: Multiplex/Demultiplex LL (MDM LL)

TABLE 2-I.- EQUIPMENT IDENTIFICATION NUMBERS AND ABBREVIATIONS FOR ELECTRONICS EQUIPMENT - Continued

20: Multiplex/Demultiplex LR (MDM LR)

SD. Interface Unit Type Abbreviation. The abbreviation of the interface unit type corresponding to the interface unit type identification number shown in SC.

SE. Interface Unit Number of Type. A two-digit number designating a particular unit of a common interface unit type.

SF. Equipment Identification Number. A four-digit number uniquely identifying the following equipment.

SG. Equipment Type Identification Number. A four-digit number uniquely identifying the following equipment types.

100. General Purpose Computer (GPC)

101. Input Output Processor (IOP)

102. Mass Memory (MM)

103. Display Electronics Unit (DEU)

104. Multiplexer/Demultiplexer FF (MDM FF)

105. Multiplexer/Demultiplexer FA (MDM FA)

106. Multiplexer/Demultiplexer LF (MDM LF)

107. Multiplexer/Demultiplexer LA (MDM LA)

108. Multiplexer/Demultiplexer PF (MDM PF)

109. Display Driver Unit (DDU)

110. Forward Master Events Controller (MEC EF)

111. Aft Master Events Controller (MEC EA)

112. PCM Master Unit (PCM)

113. Manipulator Controller Interface Unit (MCIU)

TABLE 2-I.- EQUIPMENT IDENTIFICATION NUMBERS AND ABBREVIATIONS FOR ELECTRONICS EQUIPMENT - Continued

114. Performance Monitor Annunicator Panel (PMAP)

115. Multiplexer/Demultiplexer OT (MDM OT)

116. Multiplexer/Demultiplexer OF (MDM OF)

117. Multiplexer/Demultiplexer OA (MDM OA)

118. Multiplexer/Demultiplexer LL (MDM LL)

119. Multiplexer/Demultiplexer LR (MDM LR)

120. Air Data Transducer Assembly (ADT)

121. Inertial Measurement Unit (IMU)

122. Startracker Unit (STU)

123. TACAN Receiver/Transmitter (TAC)

124. Radar Altimeter (RDA)

125. Microwave Scan Beam Landing System Receiver Transmitter (MLS)

126. Master Timing Unit (MTU)

127. Network Signal Processor (NSP)

128. Controller Altitude Director Electronics (CAD)

129. Rotation Translation Control Electronics (RTC)

130. Normal Lateral Accelerometer (NLA)

131. Reaction Jet Driver Forward (RJDF)

132. Rendezvous Radar Electronics (RRE)

133. Load Control Assembly Forward (LCF)

TABLE 2-I.- EQUIPMENT IDENTIFICATION NUMBERS AND ABBREVIATIONS FOR ELECTRONICS EQUIPMENT - Continued

134. Load Control Assembly Aft (LCA)

135. Brake Skid Controller (BSC)

136. TACAN Control Panel (TCP)

137. Speed Brake Hand Controller (SBHC)

138. Rotation Hand Controller (RHC)

139. Translation Hand Controller (THC)

140. Attitude Director Indicator (ADI)

141. Alpha Mach Indicator (AMI)

142. Master Thrust Controller (MTC)

143. Altitude/Vertical Velocity Indicator (AVVI)

144. Horizontal Situation Indicator (HSI)

145. Total Air Temperature Indicator (TAT)

146. Engine Interface Unit (EIU)

147. Rudder Pedal Transducer Assembly (RPTA)

148. Angular Accelerometer (AA)

149.

150. Ascent Thrust Vector Controller (ATVC)

151. Aerosurface Servo Amplifier (ASA)

152. Orbiter Rate Gyro Assembly (RGO)

153. Left Hand SRB Rate Gyro Assembly (RGL)

154. Right Hand SRB Rate Gyro Assembly (RGR)

155. Reaction Jet/OMS Driver (RJOD)

TABLE 2-I.- EQUIPMENT IDENTIFICATION NUMBERS AND ABBREVIATIONS FOR ELECTRONICS EQUIPMENT - Continued

156. Alpha-Temperature Probe Assembly (ATP)

157. Pressure-Static Probe Assembly (PSP)

158. Heater-Motor Controller (HMC)

159.

160. Battery (BAT)

161. Fuel Cell (FC)

162. Electrical Power System (EPS)

163.

164.

165.

166.

167.

168.

169.

170. RCS Forward Module (RMF)

171. RCS Aft Right Module (RMR)

172. RCS Aft Left Module (RML)

173. RCS Engine Door Left (REDL)

174. RCS Engine Door Right (REDR)

175.

176.

177. Main Gear Left (MGL)

TABLE 2-I.- EQUIPMENT IDENTIFICATION NUMBERS AND ABBREVIATIONS FOR ELECTRONICS EQUIPMENT - Continued

178. Main Gear Right (MGR)

179. Nose Wheel (NW)

180. Main Engine Controller (MEC)

181. Main Propulsion System (MPS)

182.

183.

184.

185. External Tank (ET)

186.

187.

188.

189.

190. Thermal Protection System (TPS)

191. Orbital Maneuvering System (OMS)

200. Payload Bay Door Forward (PLBDF)

210. Solid Rocket Booster (SRB)

220. Hydraulic System (HYD)

230. Launch Umbilical Door (LUD)

231. External Tank Door (ETD)

232. Deceleration Chute Door (DCD)

240.

250. Liquid Hydrogen Tank (LH2 TK)

TABLE 2-I.- EQUIPMENT IDENTIFICATION NUMBERS AND ABBREVIATIONS FOR ELECTRONICS EQUIPMENT - Concluded

251. Liquid Oxygen Tank (LOX TK)

252. External Tank Main Bus (EL BUS)

253. Gas Detector (GAS DE)

260. Network Signal Processor (NSP)

261. Payload Signal Processor (PSP)

262. EVA Signal Processor (ESP)

263. Doppler Extractor (DE)

264. S-Band Antenna Switch Assembly (SAS)

SH. Equipment Type Abbreviation. The abbreviation of the equipment type corresponding to the equipment type identification number shown in SG.

SJ. Equipment Number of Type. A two-digit number designating a particular unit of a common equipment type.

Goudy (ref. 43) has found that separation of a connector carrying a large amount of current (20 to 24 amps) can cause secondary arcing. The initial arcing occurs from the female to the male pin when the connector is separated. The ionized gas remaining at the face of the connector then initiates an arc or flashover from female to female pin.

In the Apollo 7 mission (ref. 18), the crew reported two ac bus 1 failure indications and one ac bus 1 and 2 failure indication. Postflight tests indicated that the cause was associated with corona arcing of the ac power within a motor-operated cryogenic fan switch located in the service module. A leak in the environmental seal caused the pressure to drop to the threshold for corona arcing when the controls were opened to turn off fan power.

Some of the anomalies in launches of the Titan III-C rocket were felt to be due to rocket-exhaust initiation of conduction in connectors (ref. 44). These anomalies are of especial interest because both the Titan III-C and the Shuttle have two solid rocket motors (SRM) for boosters, and the altitude for SRM separation is about the same for both vehicles (25 miles). Thus, anomalies associated with staging for the Titan III-C may give indications of possible problems for the Shuttle. When the SRM's are jettisoned, two rockets (exhausts directed toward the Titan I stage) are activated to move the solid, strap-on rockets away from the main vehicle. The operation of the jettison rockets bathes the Titan vehicle in exhaust products. The sensors that gave indication that this occurs were located (ref. 29) on the top of the rocket. This would indicate that the entire rocket would be covered with rocket exhaust. Thus, if the Space Shuttle uses retrorockets to jettison the SRM's, any open connectors or circuits would be bathed in rocket exhaust. Whether this exhaust plasma would reach the electronics in bays 4, 5, and 6 depends on many factors. If it is possible for the plasma to enter through the bay doors and reach the electronics, then all circuits should be protected by suitable potting materials.

2.2.3 Possible Problems in Orbit

One possibility is the production of an unsuitable atmosphere for the electronics by degassing of surfaces and organic solids. This should be checked.

2.2.4 Possible Problems During Reentry

The vehicle's safety during reentry depends upon signal integrity. A false bit of data or information fed to the guidance computer could lead to serious results.

If there are sensors for measuring temperature, vibration, and strain, then they will probably be exposed to extreme environmental conditions. In the design of the B-2707, it was estimated (ref. 19) that instrumentation wire up to 20 feet in length would be exposed to temperatures up to 1800° F from aerodynamic heating. This can be expected to cause some signal error to be generated within the instrumentation wire, but this error can be minimized by using high-insulation-resistance and low-resistance-conductor wires. Because the Shuttle is expected to generate these very high temperatures upon reentry, similar considerations would apply. The type of wire needed for temperatures over 1000° C is discussed in section 3.4.7.3. Also discussed are the effects of high temperature on insulation.

The next question is: How hot will it be for the electronics in bays 4, 5, and 6? If there are no plans for cooling the bay, then the temperature could become quite high. At high temperatures (above 500° F), rapid deterioration of the insulation sets in as described in section 3.4.7.3. When this happens, corona will set in. Besides accelerating the degradation of the insulation, the corona could generate false bits of data for the computer. Eventually total voltage breakdown would occur. The false bits of data could possibly be screened out by clever software, but total voltage breakdown would be disastrous.

To predict the possibility of corona in bays 4, 5, and 6, a reasonable estimate must be made of the temperature and the type of atmosphere to be expected upon reentry. The existence of contaminants (section 3.4.7.4) and plasma could be crucial. If the environment is severe, then proper encapsulation procedures must be taken.

2.3 POSSIBLE ELECTRICAL BREAKDOWN PROBLEMS WITH SHUTTLE PAYLOADS

Almost all electrical discharge problems for the payloads can be avoided by following the instructions in section 5.1 and other parts of this manual.

For experiments that are to be operated in a "shirt-sleeve" atmosphere aboard the orbiter, pressurization of the high-voltage container might be an answer to corona problems. With the right choice of gas and pressure, the voltages obtainable could be well above the COV of air at sea-level pressure. Also monitoring and stabilization of the gas pressure would be comparatively simple.

However, oil-filled containers are not recommended. Bubbles can form in oil at zero g. These bubbles can then cause momentary dielectric breakdown and tracking.

Every space vehicle has an atmosphere of ions. Thus, a hard vacuum never exists close to a spacecraft. For this reason, venting is not recommended as a procedure when the experiement is to be conducted near the orbiter. If the experiment is delivered to orbit and then left, however, then venting could be considered.

3.0 POSSIBLE ELECTROSTATIC VOLTAGE PROBLEMS WITH THE SPACE SHUTTLE

3.1 POSSIBLE PROBLEMS DURING LAUNCH

3.1.1 Electrostatic Charging of the Thermal Protection System

The orbiter will have a thermal protection system (TPS) using tile as an outer heatshield. Because these tiles are nonconductive, a large amount of electrostatic charge can build up on them. A rocket with a metal skin is effectively kept discharged above 4000 feet by the rocket plume (section 4.5). This occurs even in the presence of precipitation charging.

However, if the orbiter were to encounter precipitation charging, the tiles would not be discharged by the rocket plume and they could build up a potential of hundreds of thousands of volts. Just how large this potential would be is hard to estimate.

The Boeing 707 built up a voltage of over 300,000 volts in an encounter with precipitation containing ice (section 4.5). The electrostatic voltage on an airplane is limited to the potential at which corona takes place (unless the charging rate is higher than the discharging rate). This potential is determined by the altitude and the radius of curvature of the discharging point. On an airplane, there are numerous places (edge of the wing, etc.) where the radius of curvature is small. This keeps the potential on the airplane from becoming too large. On the orbiter, however, each tile will have to discharge separately. Because this would be a discharge from a plane surface (essentially infinite radius of curvature), the corona potential could conceivably be millions of volts.

The charge will accumulate on the surface until the potential gradient along the surface is large enough to support a streamer discharge over the tile surface to a metal structure nearby, or until the dielectric strength of the insulator is exceeded and the charge is relieved by a spark discharge that punctures the dielectric and travels to an underlying conductor. Thick dielectric surfaces, such as the tiles, backed by metal are particularly susceptible to energetic streamer discharges because the thick dielectric can support very high voltages and the metal backing increases the effective capacitance of the surface. Streamer discharges, like spark discharges, seek the easiest path to the vehicle structure.

Thus, at best it would seem that the tiles would cause very energetic streamers that would interfere with guidance computers and communication equipment; and at worst the tiles themselves would be destroyed.

The Shuttle is being designed as a reusable vehicle. Thus, the design parameters for the tiles are for the tile to withstand a temperature of up to 1500° F without any appreciable change of physical structure. The electrical conductivity is not expected to change much after reentry.

Because of the extreme heat of reentry, there may be no electrostatic discharge problem during the reentry phase, and thus the problem may exist only during the launch.

Many different conductive coatings have been developed to cover dielectric surfaces on airplanes (e.g., ref. 36). The tiles could be coated with one of these conductive coatings. This would prevent the streamer discharge during launch.

Even if the streamer discharges are stopped by the improved conductivity of the tiles, there will probably still be corona discharge. The tiles will still probably not be discharged by the rocket plume but will have to discharge in the same way as an airplane. If this turns out to be the case, then it would seem worthwhile to investigate the use of dischargers. These dischargers would have to be retractable because they would otherwise be burnt off during reentry.

Without the dischargers, the corona bursts may be energetic enough to interfere seriously with the guidance computer and with communications.

3.1.2 Electrostatic Charging of the Windshield

The windshield structure is shown in figure 6-1. Each pane is about 35 to 37 inches in diagonal measurement. The size is comparable to the 747 windshield. The outboard pane takes the thermal load and the inboard pane, the pressure load. The redundant pane is made of thick (compared with outboard pane) fused silica so that it can pick up the pressure load if the inboard pane breaks and/or the thermal load if the outboard pane breaks.

3.1.2.1 Puncture problems.- The orbiter windshield does not have a deicer. It is felt that because of its unique flight plan there will be no condensation on the windshields. During launch, the air leaking out will be warmer than the ambient. In orbit, the slow leakage will not cause condensation. The windshield is expected to be hot up to an hour after landing, so no condensation is expected during reentry or landing.

The absence of a deicer almost eliminates the possibility of puncture. When the windshield discharges, it will almost certainly do so to the air frame.

3.1.2.2 Visibility and rf noise problems.- Because the windshield is a nonconductor, there will almost certainly be streamer effects during the launch period. These streamers will probably be fairly energetic and could cause some visibility problems and almost certainly will cause some rf noise problems. If this rf noise is coupled into the data-transmission lines or the communications, the results could be serious. With airplanes, a transparent conductive coating is put onto the windshield to increase the conductivity. Any coating on the windshield of the orbiter, however, would be burned off during reentry.

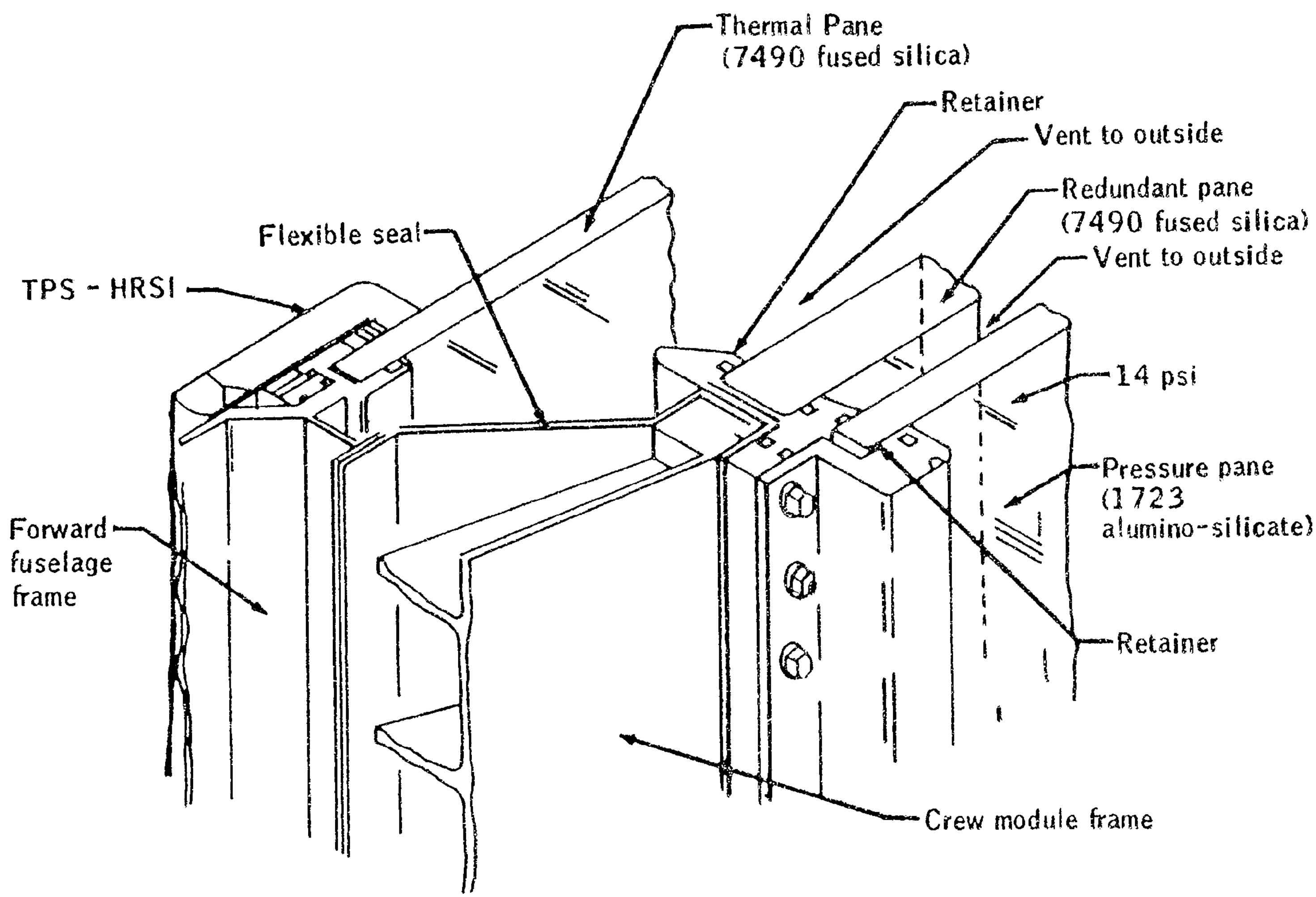

Figure 3-1.- Orbiter windshield construction.

However, there may be no streamer discharge problem from the windshield during reentry because of the extreme heat. If this were the case and protection against streamers were a problem only during the launch phase, then a coating could be applied before each launch. Of course, the coating should be chosen to obviate deleterious effects as a result of its burning off during reentry.

3.1.3 Pyrotechnic Devices

The premature firing of a pyrotechnic device could be disastrous. As discussed in section 4.4, these [illegible]es can be set off by an electrostatic discharge. It would seem to be prudent to examine the relevant devices on the Space Shuttle as was done for the Apollo spacecraft (ref. 38).

3.2 POSSIBLE PROBLEMS IN ORBIT

3.2.1 Electrostatics and Contaminant Behavior

At one time it was felt that, if there was an electrostatic voltage difference between two separate orbiting vehicles, there could be a problem when they docked. It was felt that a spark could jump from one vessel to the other to equalize the potentials just before docking. However, every spacecraft has an atmosphere of its own and, when the atmospheres of the craft make contact, the voltages balance in a civilized exchange of charge.

This very atmosphere, which prevents a harmful electrostatic discharge, tends to degrade many experiments; for example, collection of ions on the lens of a telescope. Electrostatic charge plays a very important role in this contamination.

A study should be made of the effect of electrostatic charge on contaminant behavior for the Shuttle and its payloads. A similar study was made by Beaver and Ellison (ref. 45) for the Skylab.

3.2.2 Electrostatic Potential of Satellites

Because of photoemission and other processes, satellites will acquire an electrostatic potential. This potential can seriously interfere with the satellite's function. Some satellite potentials (ref. 46) are given in table 6-I. One satellite, ATS-5, has charged up to the amazing potential of -12,000 volts in eclipse and several hundred volts in sunlight (ref. 47).

3.2.3 Biological Shock

There are many sources of possible biological shock in a spacecraft. Many materials are insulators and, when two insulators rub together, there is usually a separation of charge that, of course, produces an electrostatic potential. The discharge of this potential can have serious consequences. Ignition of solid combustibles and interference with biomedical sensors are two dangers. Other hazardous effects would be interference with communications or telemetered data and the involuntary reflex movements associated with discharge of a spark from a body.

Potter and Baker (ref. 48) investigated possible electrostatic discharges in the Apollo and Skylab spacecraft. Among other things, they found that the lockers would accumulate charge and that the lithium hydroxide canisters in the command module acquired a large electrostatic voltage (above 40,000 volts) when removed from the storage lockers. The latter item is mentioned because the canisters are expected to be present on the Space Shuttle. The space suits were also producers of large electrostatic discharges.

TABLE 3-I.- SOME MEASUREMENTS OF SATELLITE POTENTIAL

Satellite	Launch date	Experiment	Satellite potential and comments (a)
Sputnik 3	05/15/58	Ion traps	Negative to -6 volts
Explorer 8	11/03/60	Ion and electron traps	Normal; no solar cells, some effect from rf probe
Discoverer 32	10/13/61	Ion trap	Normal
Cosmos 2	04/06/62	Langmuir probe and ion traps	Negative potential increased by positive potentials on outer grids of traps
Air Force Satellite	04/17/62	Ion trap	Negative to -20 volts
Ariel 1	04/26/62	Langmuir probes	Normal up to -1.0 volt
Explorer 17	04/03/63	Langmuir probe	Normal up to -1.0 volt at night
Tiros 7	06/19/63	Langmuir probe	Normal; negative solar cells
IMP A (Explorer 18)	11/27/63	Electron trap	1 to 2 volts positive; positive solar cells
Explorer 20	08/25/64	Langmuir probe	Negative to -8 volts; postive solar cells
OGO 1	09/05/64	Ion and electron traps; mass spectrometer	Negative to -15 volts; positive solar cells
IMP B (Explorer 21)	10/04/64	Electron trap	1 to 2 volts positive; positive solar cells
Explorer 22	10/10/64	Langmuir probe	Negative, exceeding -4 volts at times; some positive solar cells
Explorer 27	04/29/65	Langmuir probe	Negative to -8 volts; some solar cell terminals coated
IMP C (Explorer 28)	05/29/65	Electron trap	1 to 2 volts positive; positive solar cells
OGO 2	10/14/65	Ion and electron traps; mass spectrometer	Negative to -3 volts; solar cell terminals coated

(a) Normal means a few tenths of a volt negative near the Earth.

3.3 POSSIBLE PROBLEMS DURING REENTRY

3.3.1 Upper Atmosphere

The orbiter is expected to heat up in excess of 1000° F. This very high temperature and the plasma created by it will probably sweep all charges off the outside of the orbiter. Thus, there would seem to be no problem with electrostatic discharge in the upper atmosphere.

3.3.2 Lower Atmosphere

As the orbiter begins to slow and cool, there might be a period before landing where electrostatic discharge could again be serious. The voltage buildup may not be as serious as during the launch period because of the elevated temperatures, but the electrostatic voltage could get high enough to be troublesome. Retractable dischargers that could be extended in the lower atmosphere may be of some help.

The windshield could also cause problems if it becomes cool enough to hold a charge. Streamers from it could interfere with the guidance computer at a very critical time.

Measurements of charging versus temperature and of temperature versus time should be made on the windshield and on the tiles. Realistic estimates of potential dangers could then be made.

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