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Review of Seal Designs on the Apollo Spacecraft

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The Apollo spacecraft required a variety of seal designs to support human spaceflight to the moon and to return the crews safely to Earth. High-temperature seals were required for gaps in the thermal protection system to protect the underlying structures from the high heating environment of superorbital reentry. Reliable pressure seals were also required to prevent the loss of habitable atmosphere during missions to the moon. A review is presented of some of the seals used on the Apollo spacecraft, including the seal in the gap between the heat shield and back shell and seals for penetrations through the heat shield, docking hatches, windows, and the capsule pressure hull. A brief discussion of seal requirements for the Orion spacecraft is also presented.

I. Introduction

THE Orion Crew Exploration Vehicle (CEV) is currently being designed by NASA to replace the space shuttle for human missions to low Earth orbit (LEO) and to enable long duration exploration missions to the moon and Mars. Orion will carry as many as six astronauts to the International Space Station (ISS), where it will remain docked for up to 6 months to serve as a "lifeboat" escape capsule. At the end of its mission, the Orion spacecraft will return the crew to Earth and another Orion will carry a replacement crew to the ISS. Orion will also carry four astronauts to lunar orbit, where it will serve as a staging platform supporting human excursions to the lunar surface. Eventually, Orion may remain unmanned in lunar orbit for as long as 6 months while the astronauts reside in a permanent lunar surface base. Orion is also envisioned to serve as an Earth reentry vehicle at the conclusion of a human mission to Mars. Additional details of the mission profiles envisioned for Orion are described in [1].

The Orion spacecraft will require advanced seals to prevent the loss of habitable atmosphere to space and to prevent the ingress of high enthalpy reentry gases into penetrations through the thermal protection system (TPS). Long duration space missions require robust seals to minimize the amount of crew cabin atmospheric leakage. Missions to the moon or Mars will not be able to quickly return to Earth in case of excessive atmospheric losses, and so the crew cabin pressure seals must be reliable for long mission durations. At the conclusion of lunar exploration missions, the Orion capsule will encounter the most severe reentry environment for a human spacecraft since the Apollo program. Atmospheric reentry at the conclusion of human missions to Mars will generate temperatures exceeding those generated during lunar returns. Orion will also enter the atmosphere from missions to LEO on a trajectory less severe than lunar reentries, but still subject to high thermal loads and heat fluxes imposed upon the TPS.

Orion can be compared most closely with the Apollo spacecraft relative to other historical human spacecraft in terms of mission profile, time in space, and reentry conditions, and so the design of seals for Orion may be initiated by examining seals used on the Apollo command module. This paper presents a review of seal technologies used on Apollo. As part of this review, the authors took several photographs of seals on the Apollo/Skylab 3 command module, which was launched in 1973 and is currently on display in the Visitor Center at the NASA John H. Glenn Research Center at Lewis Field. Photographs from other command modules are also featured when these capsules are better suited to show particular details of specific seals.

II. Overview of Seals on the Apollo Command Module

The Apollo command module required seals in several locations, including pressure seals to minimize the loss of crew cabin atmosphere while in space and thermal seals to prevent the influx of high enthalpy reentry gases through gaps in the TPS and into temperature-sensitive regions of the vehicle. A description of the command module is first presented to provide the background for understanding the requirements of the seals used on Apollo. Included in this discussion is a description of the TPS and the reentry environment to which the vehicle was exposed. Seals for penetrations through the heat shield, such as gaps between heat shield components and mechanisms for attaching the command module to the service module, are then discussed. Finally, the design details of pressure seals for sealing the crew cabin atmosphere are presented.

A. Description of the Apollo Command Module and Reentry Environment

The mission of the Apollo spacecraft was to carry three astronauts to lunar orbit, to serve as a staging platform for an excursion to the lunar surface by two of the astronauts, and finally to return all three astronauts safely to Earth. The Apollo capsule was also used for missions to LEO, initially for system testing in preparation for lunar missions and later for missions to the Skylab Space Station and for the Apollo/Soyuz Test Project. An overview of the Apollo program including the Apollo spacecraft is provided in [2], and Fig. 1 shows the launch configuration of the Apollo spacecraft. The spacecraft was composed of two separate modules: the command module that housed the crew and served as a reentry vehicle for return to Earth, and the service module that housed the propulsion system and provided logistics such as oxygen and electrical power. Figure 2 shows a schematic diagram of the Apollo command module. A third

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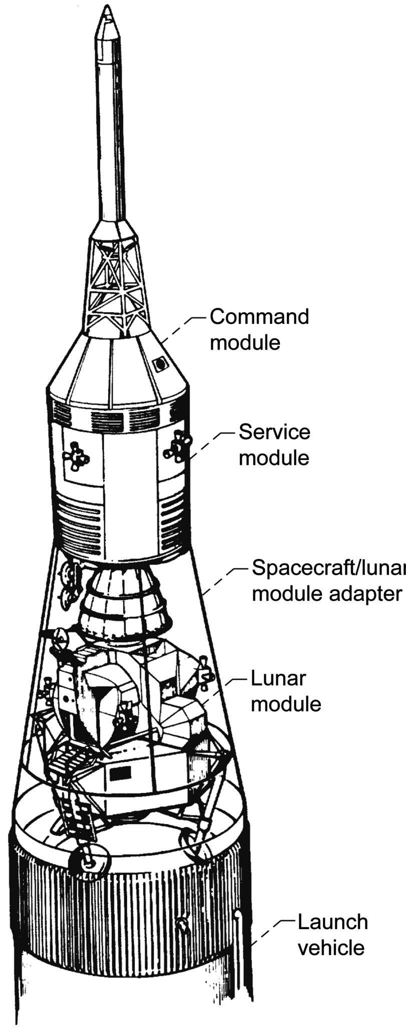

Fig. 1 Launch configuration of the Apollo spacecraft (Fig. 4-2 in [2]).

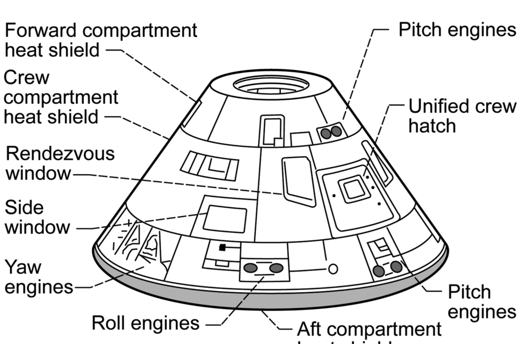

Fig. 2 Apollo Block II command module (Fig. 5 in [4]).

module, the lunar module, was designed to carry two astronauts to the lunar surface and was used for Apollo missions starting with Apollo 9 and ending with Apollo 17 (an unmanned lunar module was also flown for Apollo 5). Further details of the Apollo spacecraft can be found in [3], which used modern computer aided design (CAD) software to create a three-dimensional engineering model of the Apollo command and service modules to show how the intricate systems of the spacecraft were assembled.

The Apollo command module was subjected to the most severe reentry environment in the history of human spaceflight. The command module heat shield design was based on two entry trajectories: one that would result in the maximum total heat load to the vehicle, and one that was based on physiological acceleration limits of the human body and would result in the maximum heat flux [4,5]. As shown in Fig. 3, flow and heat transfer were not uniformly distributed over the command module and exhibited a stagnation region on the aft heat shield and both the attached and separated flow regions on the crew compartment heat shield. The crew compartment heat shield was subjected to lower heating than the aft heat shield (particularly in the separated flow region), which impacted both the design and performance of the TPS seals in this region.

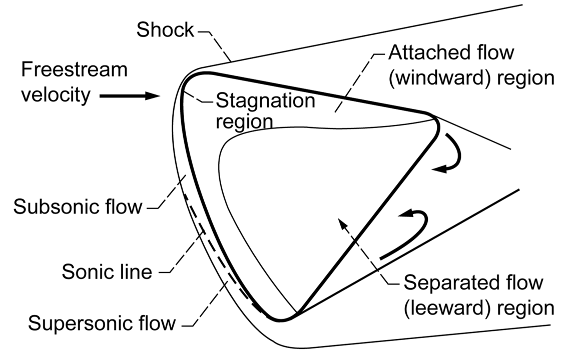

Fig. 3 Description of hypersonic flowfield surrounding Apollo command module during reentry (Fig. 1 in [6]).

Four unmanned Apollo flights were conducted to experimentally verify theoretical predictions of pressure and heat transfer on the command module. The unmanned Apollo AS-201 and AS-202 missions were flown to experimentally quantify the reentry environment from LEO. The qualitative behavior of the heat transfer measurements agreed with theoretical predictions [6,7]. Recent computational fluid dynamic (CFD) analyses of the reentry environment from LEO were performed for the conical portion of the Apollo capsule and demonstrated good agreement with the LEO flight data, enhancing confidence in the ability of CFD to predict the reentry environment of Orion [8].

Data were also gathered from the unmanned Apollo 4 and 6 superorbital flights, which entered the Earth's atmosphere at velocities typical of a direct lunar return. Flight measurements of heat transfer to the aft heat shield demonstrated good agreement with models for both convective and radiative heating. However, the heat flux measurements on the crew compartment heat shield were much lower than predicted, falling short of heat flux measurements at similar locations during reentries from LEO. This was attributed to the increased rate of growth of the boundary layer caused by upstream ablative mass injection from the aft heat shield [5,6]. Ablative mass injection during superorbital reentry affected the flight data downstream of the injection region, whereas mass injection during reentry from LEO significantly affected only the localized data on the aft heat shield.

B. Description of the Apollo Command Module Heat Shield

The Apollo TPS was made from a fiberglass honeycomb filled with AVCOAT 5026-39G ablator, an epoxy–novalac resin reinforced with quartz fibers and phenolic microballoons [9]. The TPS contained several gaps and penetrations that required thermal seals to prevent the ingestion of high enthalpy reentry gases. Figure 4 shows the aft heat shield, the crew compartment heat shield, and the forward heat shield, which constitute the three command module heat shield subassemblies. Figure 5 shows that the aft heat shield was subjected to the highest surface temperatures and heat fluxes of the three subassemblies and, as such, was designed with the greatest thickness of ablator. The crew compartment heat shield protected the pressure hull and crew cabin from the thermal environment of reentry. The forward heat shield protected the parachutes, flotation balloons, and other equipment located at the top of the vehicle and was jettisoned at the end of the mission to allow for parachute deployment.

All three sections of the heat shield (aft, crew compartment, and forward heat shields) were manufactured by first bonding fiberglass honeycomb to a stainless steel honeycomb substructure with HT-424 adhesive tape [9]. The bond line was inspected to ensure that a good bond had been achieved, after which the assembly was cured. After

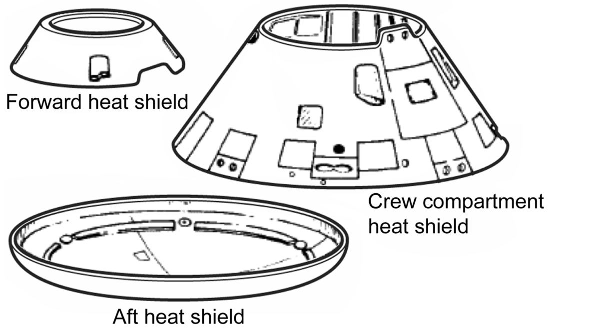

Fig. 4 Apollo command module heat shield separated into its three components (Fig. 3 in [9]).

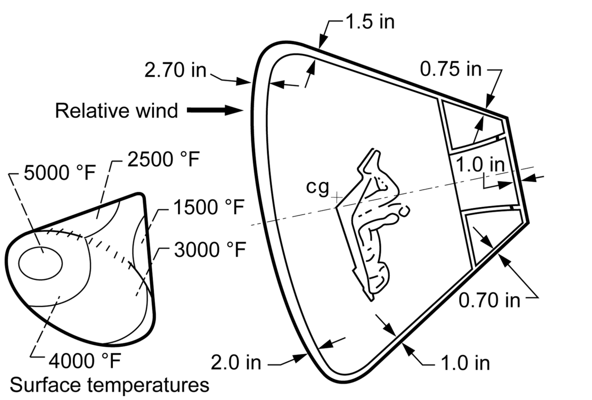

Fig. 5 Notional temperature distribution on the command module heat shield and corresponding ablator thickness (Fig. 2 in [9]).

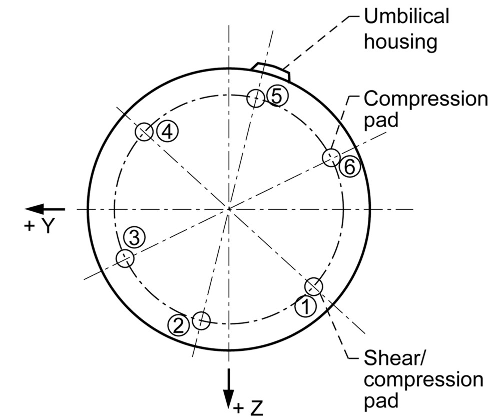

Fig. 6 View of the Apollo command module aft heat shield showing compression pad locations (Fig. 9c in [25]).

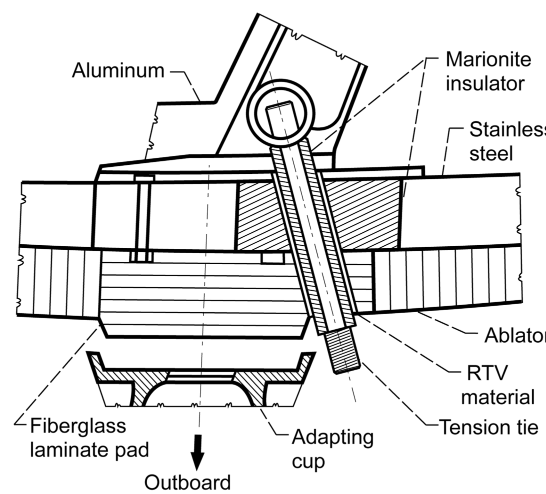

Fig. 7 Sectional view of shear pad and tension tie bolt used to transfer loads from the service module to command module (Fig. 6 in [4]).

curing, each of the approximately 370,000 honeycomb cells was manually filled with AVCOAT ablator using a device similar to a high-pressure caulking gun [10]. The filled honeycomb was furnace cured, after which it was finish machined on a numerically controlled lathe. The heat shield was x-ray inspected, and all detected voids were drilled out and refilled with AVCOAT. The completed heat shield and an underlying insulating layer were attached to the command module pressure hull using mechanical fasteners for the aft heat shield and fiberglass slip stringers for the crew compartment heat shield. The slip stringers allowed relative movement of the crew compartment heat shield and minimized loads on the seals and TPS materials between the aft heat shield and the crew compartment heat shield.

C. Seals for the Thermal Protection System of the Apollo Command Module

Penetrations through the TPS of the Apollo command module required thermal seals to prevent the ingestion of high enthalpy reentry gases. Seals for the TPS were subjected to the high heat fluxes and temperatures of the reentry environment and were constructed from high-temperature materials. The following subsections review the literature and original Apollo drawings and discuss the designs of various thermal seals for the Apollo command module aft heat shield, crew compartment heat shield, forward heat shield, and the TPS for the reaction control system (RCS) motors and access panels.

Most of the thermal seals used on the Apollo command module were composed of high-temperature silicones, including room-temperature vulcanized (RTV) silicones. High-temperature silicones exhibit ablative properties at temperatures exceeding their maximum use temperatures. As described in the following subsections, inspections of the seals on the Apollo/Skylab 3 capsule revealed evidence of ablation, particularly for seals in the high-temperature regions of the aft heat shield and the aft heat shield-to-crew compartment heat shield interface gap.

1. *Aft Heat Shield*

The aft heat shield contained several types of penetrations to allow for the attachment of the command module to the service module. Figure 6 shows the locations of six high-density fiberglass–laminate pads that were installed near the outer circumference of the aft heat shield to transfer compressive loads between the service and command modules. Three of the pads (numbers 1, 3, and 5 in Fig. 6) also transferred shear and tensile loads via steel tension tie bolts, which passed through the ablative heat shield and were fastened to the command module's aluminum substructure. A section view of a compression pad with an accompanying tension tie bolt is shown in Fig. 7. The outer circumference of the tension tie bolt was sealed with RTV silicone to prevent the ingestion of high enthalpy reentry gases, and a layer of Marionite insulation minimized thermal conduction from the tension tie bolt to the surrounding stainless steel substructure. Before reentry, explosive charges were used to break the tension tie bolts and separate the service module from the command module [11]. During reentry, the exposed tips of the tension tie bolts melted flush with the surrounding fiberglass pads, whereas temperature measurements at the bases of the bolts exhibited no significant response [4]. A photograph of a compression pad on the Apollo 11 command module is shown in Fig. 8, although it appears that the tension tie bolt was removed after recovery of the vehicle as part of the postmission inspection of the heat shield.

In addition to the fiberglass compression pad and the tension tie bolt location, Fig. 8 also shows two ablator plugs used to protect the mechanical fasteners attaching the aft heat shield to the command module structure. A section view of the ablator plug and mechanical fastener is shown in Fig. 9. The outer circumference of the ablator plug does not appear to have been sealed because of the close

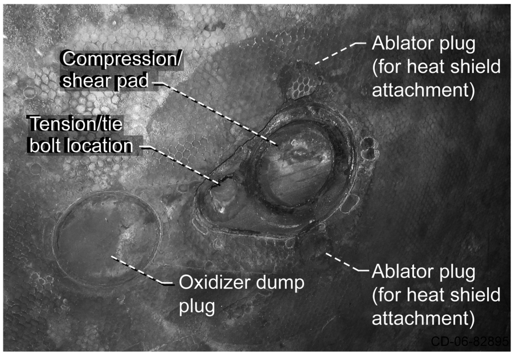

Fig. 8 Apollo 11 heat shield penetrations for the attachment of the command module to service module.

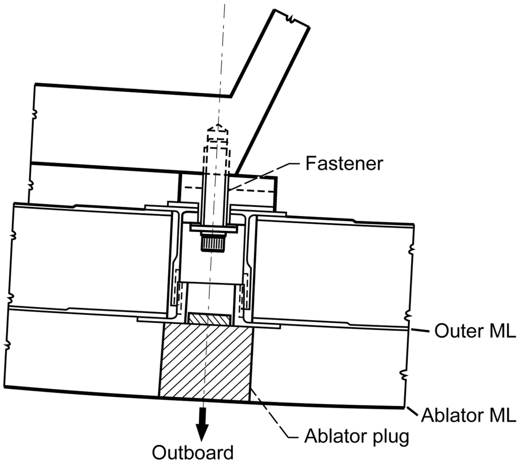

Fig. 9 Mechanical attachment of the heat shield to substructure with protective ablator plug (Apollo drawing V36-320000).

tolerance between the access hole and the ablator plug as well as the minimal flow rate through the circumferential gap due to flow stagnation at the base of the hole. Figure 10, a photograph of an ablator plug location on the Apollo/Skylab 3 command module, shows no evidence of a seal or seal material around the circumference of the hole. The penetration through the AVCOAT in Fig. 10 may represent postmission destructive removal of the ablator plug.

Each command module contained both an oxidizer and a fuel dump plug in the aft heat shield. Figure 8 shows the plug covering the oxidizer dump port on the Apollo 11 command module, and Fig. 11 shows the plug covering the fuel dump port on the Apollo/Skylab 3 command module. The gaps between these plugs and the heat shield were sealed with GE RTV 560. In the event of an abort within the first 42 s after liftoff, the oxidizer and fuel dump plugs would be jettisoned using small pyrotechnic charges [11]. The RCS monomethylhydrazine fuel and nitrogen tetroxide oxidizer would then be dumped through the ports to ensure that they would not pose a fire or chemical hazard to the astronauts and recovery crews [12–14]. Both sets of dump plug seals shown in Figs. 8 and 11 show strong evidence of ablative mass loss at their outer surfaces.

2. *Aft Heat Shield-to-Crew Compartment Heat Shield Interface Gap*

The interface gap between the aft heat shield and crew compartment heat shield was sealed with two elastomer gaskets, as shown in Fig. 12. The inner gasket (Fig. 12a) was formed first and sealed the gap between the upper stainless steel honeycomb structure and the adjoining lower connection ring. Versilube G-300 (a release agent) was first applied to the crew compartment stainless steel honeycomb surface. The aft heat shield and crew compartment heat shield were attached to the command module using mechanical fasteners and fiberglass slip stringers, respectively. Then, GE RTV 560 [15] was applied to the connection ring surface and

Fig. 10 Ablator plug hole on Apollo/Skylab 3 aft heat shield.

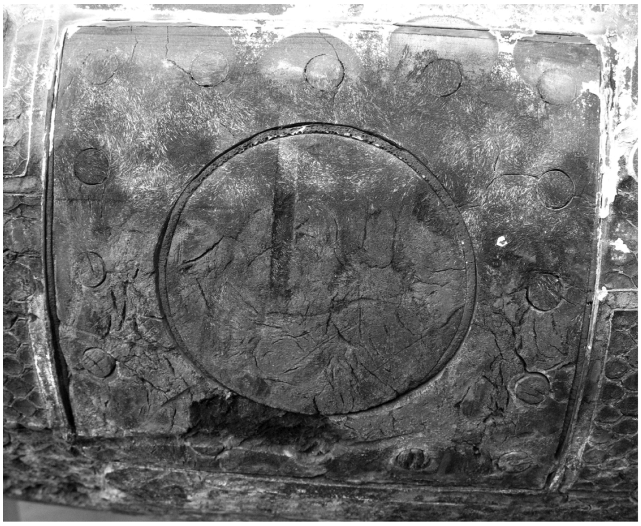

Fig. 11 RCS fuel dump plug on Apollo/Skylab 3 command module.

was allowed to cure in place. After the silicone had cured, the aft heat shield was detached from the command module, which pulled the elastomer gasket away from the crew compartment heat shield sealing surface. An identical process was used to form the outer gasket (Fig. 12b) in the gap between the ablator sections of the two heat shields. A photograph of the outside of the aft heat shield-to-crew compartment heat shield interface region including the elastomer gasket and the fiberglass closeout material is shown in Fig. 13. Of particular note is the rough appearance of the gasket outer surface caused by ablation at high temperatures.

The primary difference in shape between the inner and outer gaskets was that the inner gasket sealed around a V-shaped tooth that was machined into the crew compartment heat shield stainless steel honeycomb. This tooth served two functions. First, it provided a means of aligning the aft heat shield to the crew compartment heat shield before securing the assembly with mechanical fasteners. An accurate alignment between the heat shield structures was necessary to avoid forward- or backward-facing steps in the finished command module heat shield and the high localized heating that would result from such steps. Second, the tooth would function as a labyrinth seal and form a tortuous flow path in the event of a gasket breech.

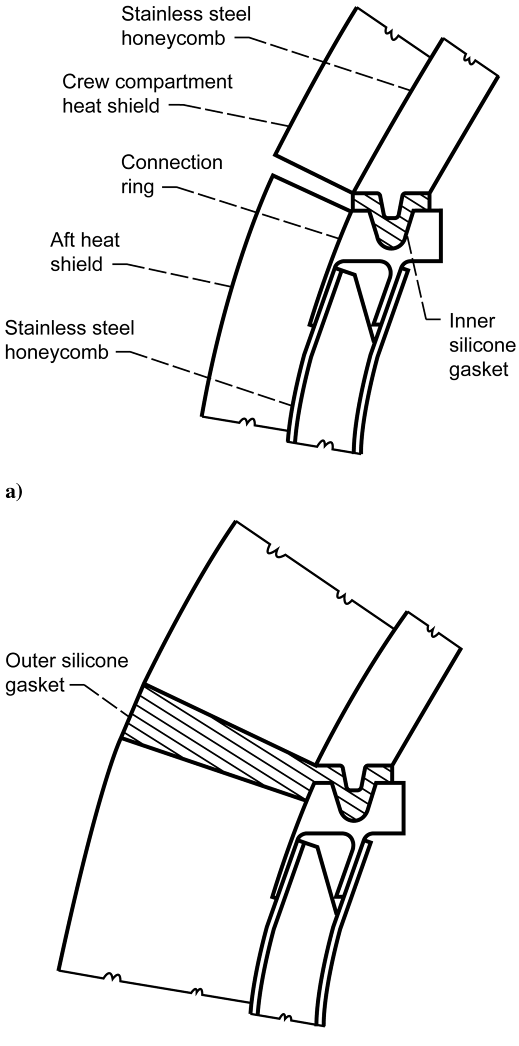

Fig. 12 Section drawings of silicone gasket used in Apollo heat shield-to-crew compartment heat shield interface gap (Apollo drawings V36-320000 and V16-320000).

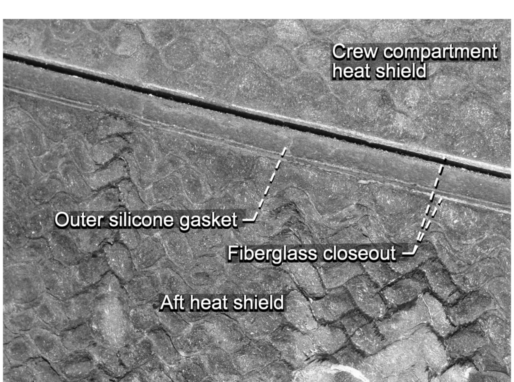

Fig. 13 Apollo/Skylab 3 aft heat shield-to-crew compartment heat shield interface region, including the outer silicone gasket seal and fiberglass closeout for the AVCOAT ablator.

3. Crew Compartment Heat Shield

The crew compartment heat shield contained several penetrations, both for access to the interior of the vehicle and for the RCS motors. After the crew compartment heat shield was attached to the command module, RTV 560 was poured into the gaps around the access panels and the RCS nozzles, where it was allowed to cure in place [4]. A photograph of one of the Apollo/Skylab 3 RCS roll motors and its RTV seals is shown in Fig. 14, whereas the location of the RCS roll motors on the Apollo capsule can be seen in Fig. 2. The RCS motor was mounted into an access panel that also included RTV seals around its perimeter. Figure 15 shows a close-up view of the corner of a similar access panel. The outer seal appears to have been cut with a razor along its inner perimeter for postflight servicing and inspection of the internal components. Unlike the silicone-based thermal seals located on the aft heat shield and the aft heat shield-to-crew compartment heat shield interface gap, the silicone seals on the crew compartment heat shield exhibit little evidence of ablation and qualitatively demonstrate the relatively benign thermal environment imposed upon the crew compartment heat shield. The surrounding AVCOAT material also exhibits little evidence of charring or ablation.

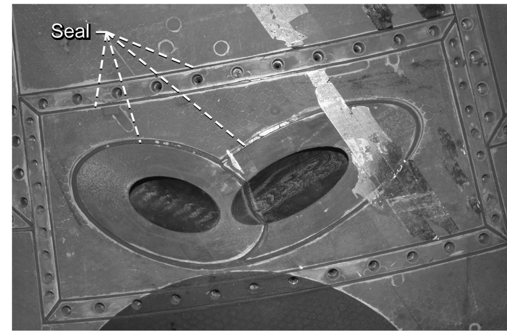

Fig. 14 Apollo/Skylab 3 RCS roll motors showing silicone thermal seals.

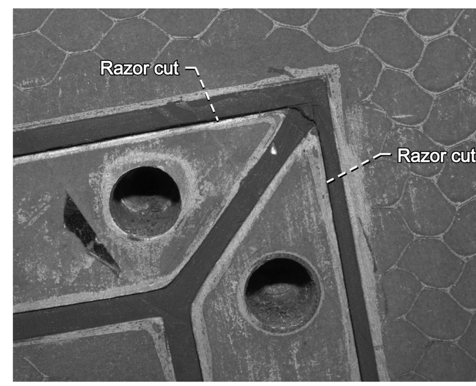

Fig. 15 Apollo/Skylab 3 access panel corner emphasizing silicone thermal seal. The seal contains razor cuts to allow for panel removal.

4. Forward Heat Shield

The forward heat shield was separated from the crew compartment heat shield by a small gap that required seals to prevent the ingestion of reentry gases. Because the forward heat shield was jettisoned before parachute deployment, it could not adhere to the crew compartment heat shield. However, the low heat transfer rates measured on the forward heat shield mitigated the adhesion concerns. Most of the gap circumference between the two heat shield subassemblies was sealed with an elastomer bulb seal believed to be heat vulcanized elastomer gum stock conforming to MIL ZZ-R-765. The bulb seal is shown on the right-hand side of Fig. 16, a downward-looking photograph of a portion of the forward compartment of the Apollo/Skylab 3 capsule. The groove outboard of the seal appears to have served as a seating location for the forward heat shield.

Figure 16 also shows the side of the upper RCS pitch motor, which was housed in the forward compartment of the command module. The forward heat shield included a conformal notch that fit around the perimeter of the upper RCS pitch motor, as shown in Fig. 4. Both sides of the RCS motor housing were sealed with silicone gaskets, and the lower corner of the motor appears to have been sealed with molded or injected silicone.

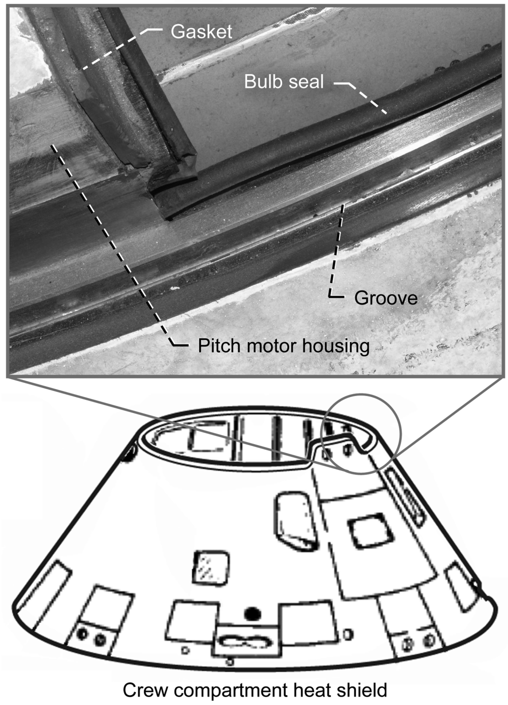

Fig. 16 Downward-looking photograph of top of Apollo/Skylab 3 vehicle showing forward heat shield mounting location and seals.

Finally, it should be noted that the seals in Fig. 16 appear to have been exposed to low heat loads, as evidenced by the apparent lack of thermal damage on their outer surfaces. This is expected in light of the low heating measurements on the forward heat shield during unmanned test flights of the command module [5–7].

D. Seals for Penetrations of the Apollo Command Module Crew Cabin

The Apollo command module pressure hull contained several penetrations that required seals to prevent the loss of habitable cabin atmosphere. The leakage rate of each command module was carefully measured before its mission, and enough spare oxygen was carried in the service module to account for any losses. All the Apollo command modules and lunar modules were leak tested on the ground to confirm a specified maximum allowable leakage of 4.8 lbm/day of air [16].

The following subsection first discusses the atmosphere in the crew cabin pressure hull to describe the environment against which the seals had to function. Descriptions of the seals used to contain the pressure in the Apollo crew cabin are presented next, including the RTV seals used along the riveted and bolted joints, seals for the two hatches, and seals for the telescope and sextant assembly.

1. Description of the Apollo Command Module Crew Cabin Atmosphere

For lunar missions, the cabin atmosphere of the Apollo command module was composed of 100% O_2 at a pressure of 5 psi [17], which is slightly higher than the partial pressure of oxygen at a standard temperature and pressure (STP) of roughly 3.4 psi but below the pressure at which oxygen toxicity becomes a concern (Skylab missions used a 5 psi atmosphere composed of 26% N_2 to reduce the risk of fire [18]). The low cabin pressure provided several benefits to the Apollo capsules. First, the additional weight of inert gases (e.g., nitrogen) as well as the associated tanks, plumbing, and other support structures for additional gases did not have to be carried into orbit, thus reducing the overall vehicle launch weight. Also, the walls of the Apollo command module and lunar module could be made lighter than the designs for a cabin pressure of 14.7 psi. Finally, the 100% oxygen environment had precedent in that it had been flown on the Mercury and Gemini missions. The capsule atmosphere mixture during launch was changed to 40% nitrogen in response to the Apollo 1 fire, and the excess nitrogen was allowed to leak to space after launch until it was replaced with the nominal 100%, 5 psi oxygen atmosphere [17].

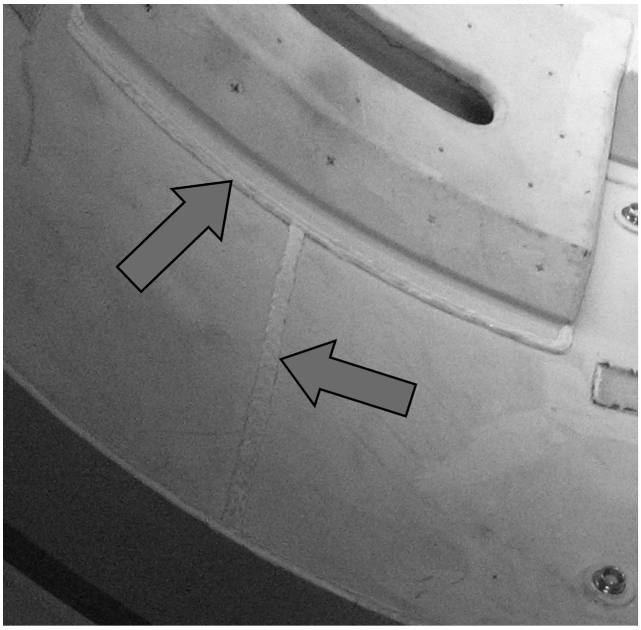

Fig. 17 RTV-sealed aluminum joint inside the Apollo/Skylab 3 forward tunnel.

The cabin atmospheric leakage from the Apollo capsules was qualified on the ground before flight. The capsules were pressurized to 5.1 psig of air to simulate the 5 psi differential pressure that would drive seal leakage in space, and the subsequent pressure decay was recorded over a period of time. The leakage measurements from the ground tests were higher than the leakage measurements while in space; this was due to the increased cabin atmospheric density resulting from the elevated absolute pressure for ground tests (∼20 psia for ground tests vs 5 psia in space) and the fact that the critical pressure ratio across the leakage paths was exceeded while the capsule was in space and thereby resulted in choked flow [16].

2. Riveted and Bolted Joints

Aluminum panels in the Apollo command module were riveted or bolted together to form portions of the pressure hull and were sealed with RTV. A typical RTV-sealed joint between two aluminum panels in the Apollo/Skylab 3 forward tunnel can be seen in Fig. 17. It is thought that RTV-sealed joints such as the one shown in the figure accounted for the majority of unplanned atmospheric losses from the Apollo command module [16].

3. Unified Crew Hatch

The Apollo unified crew hatch (UCH) was designed and implemented in response to the inability of astronauts Grissom, White, and Chaffee to quickly egress from the Apollo 1 fire. The newly designed hatch combined the previously separated pressure hatch and heat shield hatch into a single, outward-opening hatch. The new hatch could be opened in 3 s, and all three astronauts could egress in under 30 s [19]. A schematic drawing showing the overhead view of a partially open UCH is shown in Fig. 18 and illustrates both the pressure seal and the thermal seal used on the hatch. The location of the UCH on the Apollo capsule can be seen in Fig. 2.

A thermal lip seal was included to prevent the ingestion of reentry gases into the gap around the hatch perimeter, although the UCH was located on the leeward side of the capsule during reentry and was therefore subject to low thermal loads. The Apollo/Skylab 3 mission command module UCH and its high-temperature silicone thermal seal is shown in Fig. 19. The thermal seal was in contact with the hatch frame at a contact angle such that it was angled toward the outboard side of the capsule. Air in the cavity between the pressure

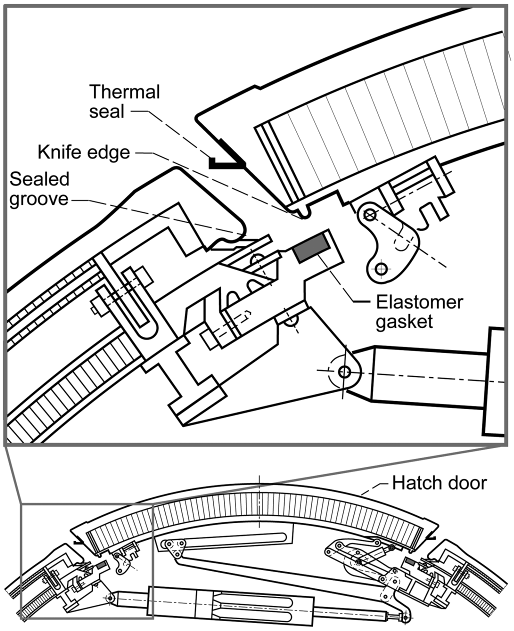

Fig. 18 Schematic drawing (top view) of the Apollo unified crew hatch (Fig. 6 in [19]).

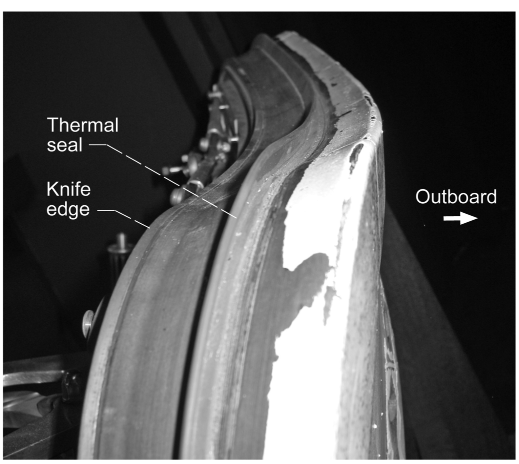

Fig. 19 UCH hatch thermal seal on Apollo/Skylab 3 command module.

seal and the thermal seal could escape during ascent across the thermal seal because the differential pressure would reduce the contact pressure of the seal. The cavity pressure therefore decayed to near-vacuum conditions during a mission. During reentry, the external pressure on the seal would increase, thereby increasing the contact pressure of the seal against the hatch frame. This enhanced the effectiveness of the thermal seal.

Figure 18 also shows the location of a sealed groove near the base of the hatch frame. This groove, also visible in the command module hatch frame in Fig. 20, separated the heat shield from the pressure vessel and allowed movement of the heat shield due to thermal expansion and pressure loads. The groove was sealed with what appears to be the same silicone material as the thermal seal and prevented hot gases from entering the volume separating the heat shield and pressure vessel.

The pressure seal on the Apollo UCH was composed of an elastomer gasket attached to the command module hatch frame with RTV and an adjoining knife edge formed into the UCH perimeter. The knife edge can be seen on the outer perimeter of the hatch door in Fig. 18 immediately outboard of the latches and linkage mechanism, and the gasket can be seen in Fig. 20. The knife edge embedded into the elastomer gasket when the hatch was fully closed, forming an effective pressure seal. A line of discoloration can be seen on the gasket where the hatch knife edge came into contact with the gasket surface.

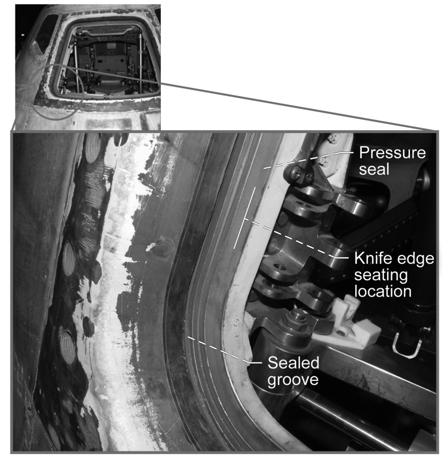

Fig. 20 Hatch frame on the Apollo/Skylab 3 command module. A residual discoloration can be seen where the UCH knife edge engaged into the elastomer gasket.

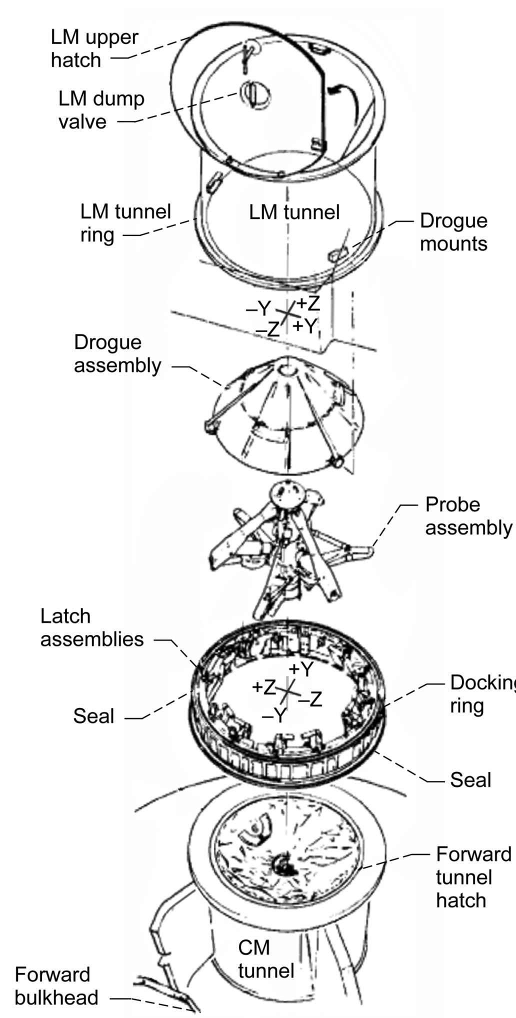

Fig. 21 Apollo docking assembly (Fig. 9 in [20]).

4. Command Module Forward Tunnel and Docking Ring

Figure 21 shows a schematic diagram of the forward tunnel assembly used to dock the command module to the lunar module. The docking ring was attached to the command module tunnel ring and served as a mounting structure for the latches, electrical connections, and probe assembly for docking with the lunar module. The docking assembly contained several seals: a pressure seal and a thermal seal on the forward tunnel hatch, a pressure seal at the junction

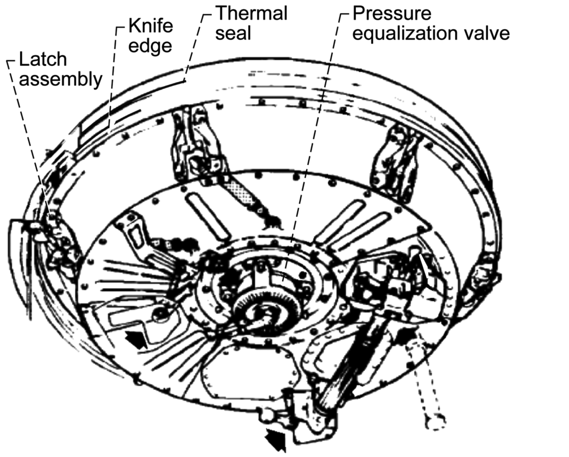

Fig. 22 Drawing of the inboard side of the Apollo command module forward tunnel hatch (Fig. A-1 in [20]).

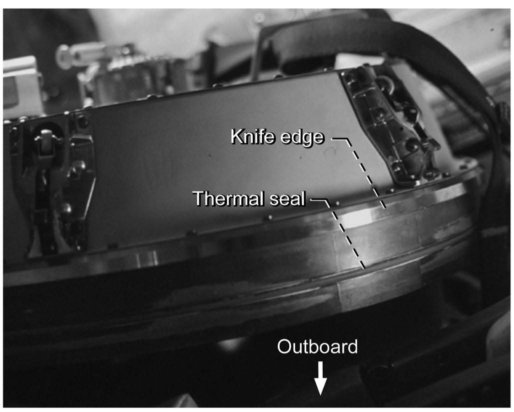

Fig. 23 Stowed forward tunnel hatch from Apollo 17 (NASA photograph AS17-162-24054).

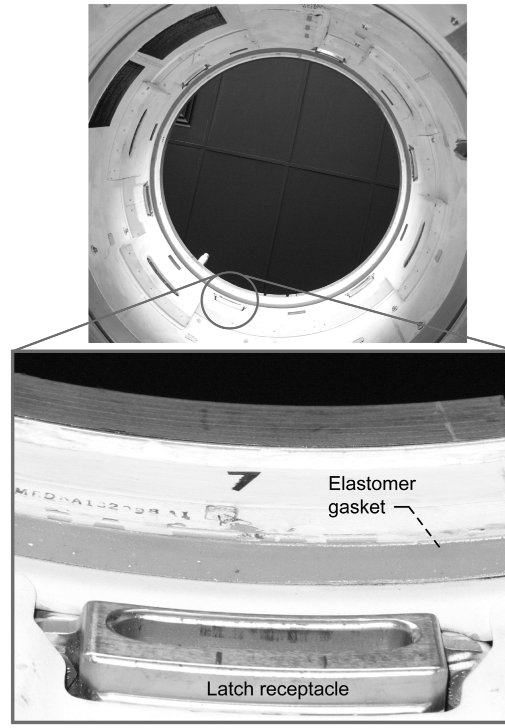

Fig. 24 Forward tunnel and pressure seal on forward tunnel of Apollo/Skylab 3 command module.

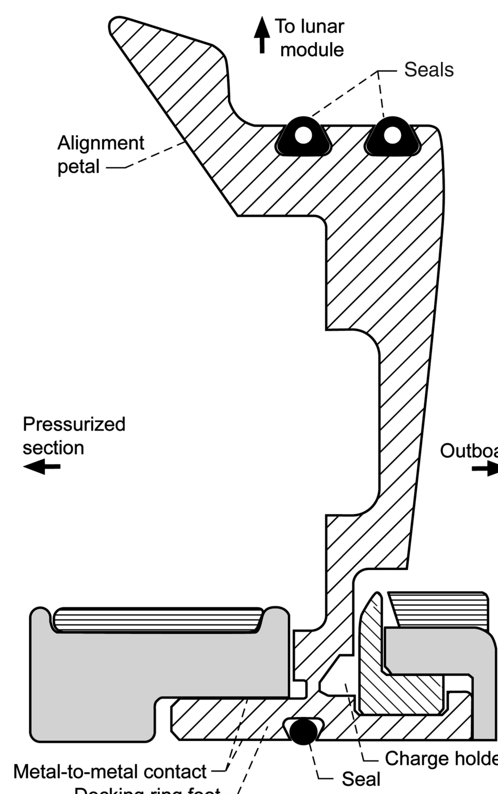

Fig. 25 Section view of Apollo/Skylab 3 command module docking ring (Apollo drawing V36-316290).

between the command module tunnel ring and the docking ring, two pressure seals at the junction between the docking ring and the lunar module tunnel ring, and a pressure seal on the lunar module hatch.

Figure 22 shows a diagram of the inboard side of the forward tunnel hatch, which includes call outs to an outboard thermal seal and an inboard knife edge that constitutes part of the pressure seal. The thermal seal prevented the ingestion of high enthalpy reentry gases into the gap around the hatch. Figure 23, a photograph of the stowed hatch taken during the Apollo 17 mission, shows the thermal O-ring seal. The thermal seal was compressed against the forward tunnel wall near the location denoted with the number 7 in Fig. 24, a photograph of the forward tunnel in the Apollo/Skylab 3 command module. The thermal seal was not as large as that of the UCH because the thermal environment at the apex of the conical portion of the command module was minimal and did not impose a heavy thermal load onto the seal.

The forward tunnel hatch also contained a pressure seal similar to the UCH knife edge denoted in Fig. 22, which embedded into an elastomer gasket attached circumferentially around the forward tunnel. The elastomer gasket can be seen in the Apollo/Skylab 3 forward tunnel in Fig. 24. When the outboard side of the hatch was exposed to vacuum conditions (e.g., the command module was not docked to the lunar module), the pressure differential across the hatch served to provide a positive engagement of the knife edge into the elastomer gasket and therefore improved the performance of the seal. The pressure equalization valve shown on the hatch in Fig. 22 allowed the docking ring tunnel to be pressurized after the lunar module had docked to the command module. Once the internal and external pressures had been equalized, the latches were disengaged and the hatch was removed and stowed inside the command module [20].

Figure 21 shows the sealed surfaces between the docking ring and the command module tunnel ring and also between the docking ring and the lunar module tunnel ring. Figure 25 presents a section view of the docking ring, including one of the alignment petals, and provides the best understanding of the docking ring seals. The “foot” of the

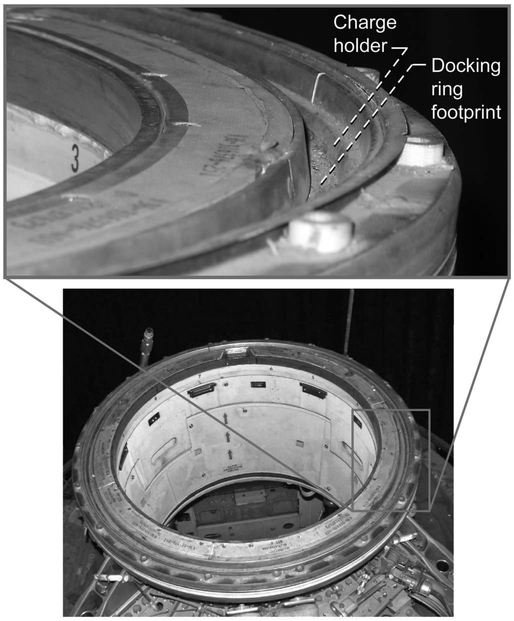

Fig. 26 Photograph of Apollo/Skylab 3 command module tunnel ring.

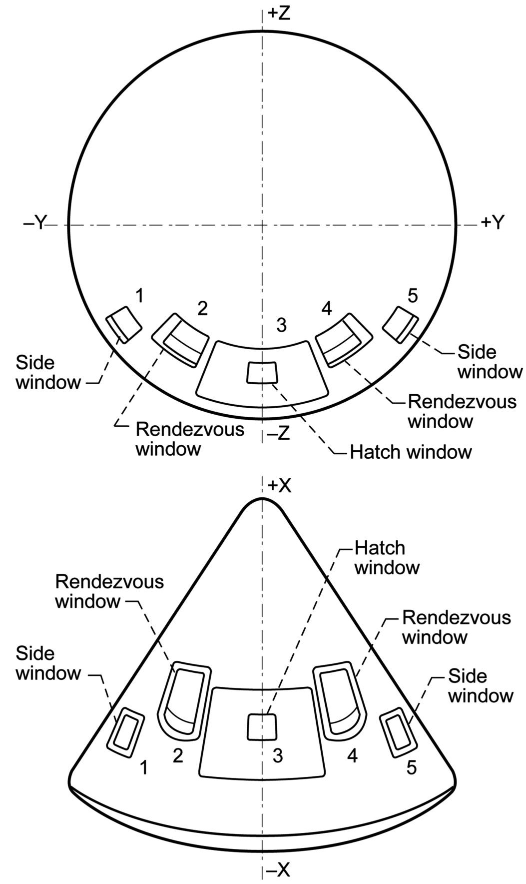

Fig. 27 Window locations on the Apollo command module (Fig. 1 in [21]).

docking ring was bolted into the command module tunnel ring and contained a single permanent pressure seal believed to be either an O-ring or bulb seal. Any leakage around the docking ring foot would have to travel through a tortuous path including two metal-to-metal contact surfaces upstream of the pressure seal and several metal-to-metal contact surfaces downstream of the seal. Figure 25 also shows the location of the charge holder that housed the pyrotechnic used to separate the docking ring from the command module after the return of the lunar module from the lunar surface and subsequent jettison of the lunar module [11,20]. Figure 26 shows the Apollo/Skylab 3 tunnel ring and, in particular, the groove where the docking ring was installed. A remnant footprint of the docking ring is visible in the groove, along with the charge holder. Based on Fig. 25, the permanent pressure seal was installed directly underneath the docking ring footprint.

Figure 25 also shows the location of the two bulb pressure seals that mated to the lunar module tunnel ring. The petal structure visible in Fig. 25 provided the centering alignment between the lunar module tunnel ring and docking ring when, after hard capture by the probe assembly, the lunar module would be retracted into the docking ring to compress and engage the seals. The seal design provided large resilience for offsets in the docking alignment caused by differences in thermal growth or manufacturing tolerances while also ensuring that the seals would be retained in the docking ring when the lunar module undocked to land on the lunar surface.

5. *Command Module Windows*

The Apollo command module included five windows, as shown in Fig. 27. The side and hatch windows were used for general observation and photography, whereas the rendezvous windows (windows 2 and 4) were oriented in the forward direction ($+X$ in the figure) and provided visual guidance for docking.

Figure 28 shows the construction of each of the three types of windows, including the seals necessary to prevent both cabin atmosphere loss and reentry gas ingestion. The windows were made of two aluminosilicate glass inner pressure panes and a fused amorphous silica outer heat shield pane. Each of the inner window panes was coated on both sides with an antireflective coating to reduce glare. The outer pane was coated on the outside with a magnesium–fluoride coating and on the inside with a blue–red coating to block both infrared and ultraviolet solar radiation [21,22].

The seal around the pressure windows was formed by injecting RTV 560 around the perimeters of the two inner panes and allowing the silicone to cure in place. The RTV was held in place while it was curing by heat-molded silicone elastomer dams that were installed around the perimeters of the windows [21]. Once the silicone had cured, the cavity between the inner windows was evacuated and backfilled with 7.0 psia nitrogen gas. A multilayer silicone resin-impregnated fiberglass insulator with an RTV 511 coating was bonded with RTV 511 [21] to the outboard perimeter of the inner window panes to minimize the heat conduction to the inner windows during reentry. The outer heat shield window was attached using a glass cloth reinforced heat-molded silicone rubber that was bonded in place with RTV 560 [21].

Window 1 and its associated seals and insulation layer from Apollo/Skylab 3 are shown in Fig. 29. A portion of the outer RTV 511 coating was damaged, exposing the fiberglass insulation. Also, the outer heat shield silica pane is missing from the capsule and may have been removed after recovery of the vehicle.

6. *Sextant and Telescope*

An assembly consisting of a sextant and a scanning telescope, shown in Fig. 30, was installed on the windward surface of the crew compartment heat shield of the Apollo command module. The inclusion of the sextant represented a significant sealing challenge. The sextant penetrated both the pressure hull and the crew compartment heat shield on the windward side of the vehicle. The sextant was free to rotate and was capable of some movement along the axis of rotation. The sealing challenge was overcome using the seal design shown in the schematic diagram in Fig. 31. The flexible thermal seal prevented the flow of high enthalpy reentry gas into the cavity between the cabin and the TPS wall while allowing movement of the sextant TPS with respect to the cabin [4]. Additionally, the slip ring seal around the sextant prevented high enthalpy gas flow along the outside circumference of the sextant and into the cabin. The slip ring seal also minimized habitable atmospheric losses from the crew cabin along the outer circumference of the rotating optics.

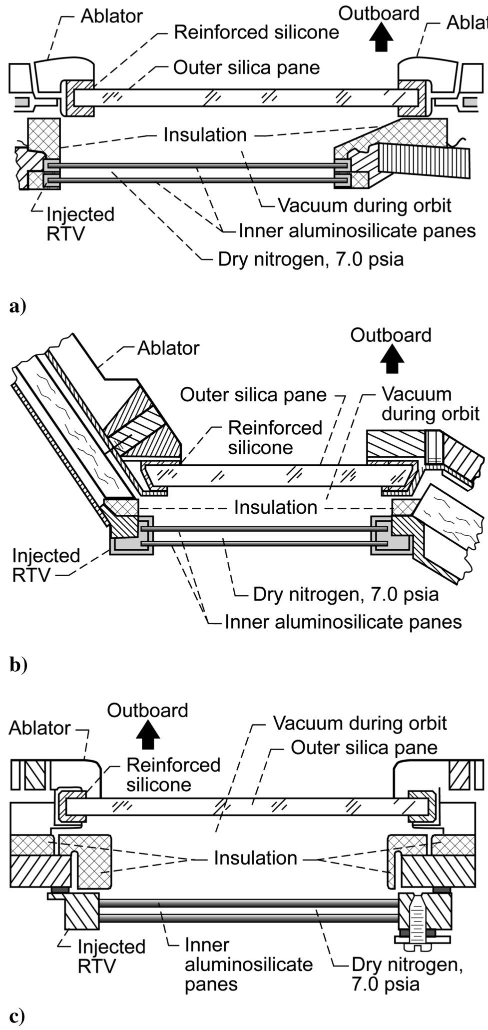

Fig. 28 Apollo command module windows: a) side windows 1 and 5 (Fig. 2 in [21]), b) rendezvous windows 2 and 4 (Fig. 3 in [21]), and c) hatch window 3 (Fig. 4 in [21]).

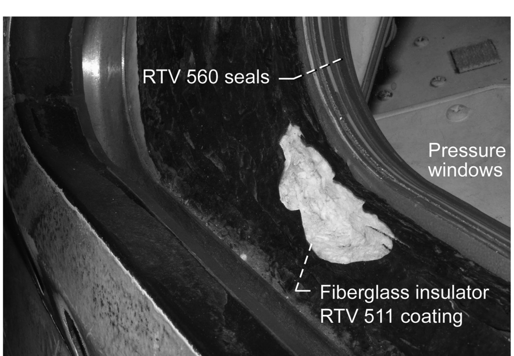

Fig. 29 Window 1 on Apollo/Skylab 3. The outer heat shield silica pane is not present.

III. Challenges for Orion Seal Design

The seal designs used on Apollo provide a good starting point for those that will be used on the Orion spacecraft because the Apollo seal designs were employed successfully in the environments in which Orion will operate. However, as Orion will differ from Apollo both in terms of design and in mission profile, the seal requirements for Orion are somewhat different than those of Apollo. The following subsections briefly discuss the starting points for the design of seals for the Orion spacecraft and how the sealing needs for Orion differ from those of Apollo.

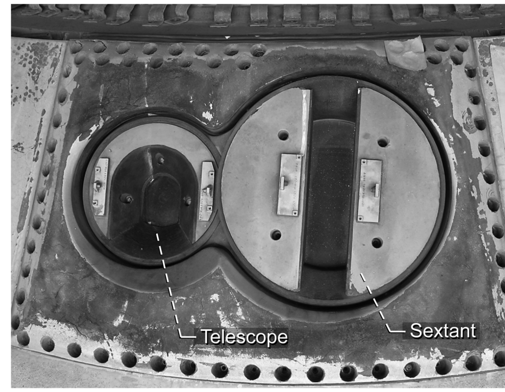

Fig. 30 Sextant and telescope assembly on Apollo/Skylab 3.

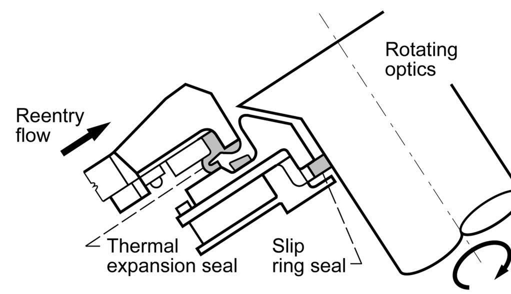

Fig. 31 Sectional view of Apollo command module sextant port (Fig. 7 in [4]).

A. Seal Needs for the Orion Spacecraft Thermal Protection System

The Orion spacecraft will require advanced seals for its TPS to account for its larger size, updated lunar reentry trajectories, and Mars reentry trajectories. The Orion spacecraft will have a heat shield diameter of 16.5 ft, more than 25% greater than that of Apollo. The larger Orion heat shield size will result in a decreased convective heating rate and an increased radiative heating rate during reentry [23]. The larger Orion heat shield also introduces the potential for increased deflections at sealing interfaces due to both thermal expansion and loading from pressure and inertial forces. The larger heat shield also presents the potential for larger manufacturing tolerance stackups, which may result in variable TPS gap sizes as well as misalignments of the TPS carrier structures during vehicle assembly. The presence of variable TPS gap sizes and increased gap deflections requires the use of seals that are more resilient than those used in similar locations on the Apollo heat shield so that they can follow the changes in gap sizes and remain in contact with adjacent sealing surfaces throughout a mission. Finally, the Orion TPS may be subjected to a more severe reentry environment than Apollo. For example, a Mars reentry trajectory would have an increased reentry velocity over lunar returns and would subject the Orion TPS seals to greater heat flux and heat load than those imposed on the Apollo spacecraft.

B. Seal Needs for the Orion Spacecraft Crew Cabin

The mission requirements for Orion differ from those of Apollo, and so the Orion vehicle will require the development of advanced seals to prevent the loss of cabin air. The allowable leakage from Orion will be less than 0.33 lbm/day [1], more than an order of magnitude less than the 4.8 lbm/day allowable leakage from Apollo [16]. The reduced leakage limit is due to several factors and can be achieved by improved construction techniques, such as welded panels (instead of riveted and bolted joints) [16], as well as improved seal designs.

The leakage limit for Orion is less than that for the Apollo spacecraft for several reasons. First, the missions anticipated for the Orion spacecraft are expected to last as long as 6 months [1]. By comparison, Apollo 17 was in space for only 14 days for its lunar mission and Apollo/Skylab 4 (the longest-duration mission for an

Apollo capsule) was exposed to the LEO space environment for 84 days. Second, the crew cabin pressure of Orion is anticipated to be 14.7 psia for missions to the ISS and 9.5 psia for lunar missions [1]. Leakage across seals is driven by the pressure gradient, and nearly doubling (or tripling, for missions to the ISS) the Orion crew cabin atmospheric pressure over that used for Apollo will scale the potential for leakage accordingly. Meanwhile, the increased size of the Orion capsule provides a greater exposed surface area, requiring the use of welded structural connections and very low leakage seals [16].

The increased Orion mission duration necessitates the use of more effective seals on Orion than those used on Apollo. Longer missions increase the time for the crew cabin atmosphere to leak into space. They also increase the amount of time that the Orion crew cabin seals will be exposed to the space environment, including solar radiation, atomic oxygen (for LEO missions), and micrometeoroids and orbital debris [24]. Effective sealing of the crew cabin may become a challenge in areas where the seals are exposed to these conditions for long periods of time.

IV. Conclusions

The Apollo command module incorporated a wide variety of pressure and thermal seals to prevent both the loss of crew cabin atmosphere and the ingestion of high enthalpy reentry gases into gaps in the TPS. Bolted and riveted joints used to assemble the pressure hull, as well as the command module windows, were sealed with RTV. The two access hatches were sealed with metal knife edges embedded into elastomer gaskets and also incorporated thermal seals to prevent the ingestion of high enthalpy reentry gases. Thermal seals throughout the vehicle, including boundaries between different heat shield components, access panels, and RCS motors, were composed primarily of high-temperature RTV silicones. The highest temperature regions of the command module, including both the aft heat shield and aft heat shield-to-crew compartment heat shield interface gap, incorporated silicone seals and gaskets. Inspections of seals near the aft heat shield of the Apollo/Skylab 3 capsule revealed some evidence of ablation of their outer surfaces. Thermal seals on the crew compartment heat shield and forward heat shield were exposed to lower temperatures, and visual inspections of the lower temperature seals on the Apollo/Skylab 3 vehicle did not reveal significant evidence of ablation.

A review of the seal designs used on the Apollo spacecraft provides a starting point for seal development for the Orion spacecraft; however, the Orion spacecraft poses several additional sealing challenges over the Apollo spacecraft that necessitate lower leakage seal designs than those used for Apollo. TPS seals on Orion must be capable of forming effective seals while subject to increased overall heat flux from flying different reentry trajectories, including Mars return trajectories, and must conform to gaps with variable sizes due to potential stackups in manufacturing tolerances resulting from the larger-sized spacecraft. Crew cabin seals on Orion must be more effective than those on Apollo to account for Orion's increased crew cabin pressure; increased mission duration, which increases both the total leakage and potential for seal degradation due to the space environment; and increased exposed surface area, on which leaks may form.

Acknowledgments

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