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Apollo Meteoroid Shielding Design and Analysis at the Manned Spacecraft Center

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1.0 Introduction

The Apollo program drove the development of spacecraft meteoroid protection in the U.S. and provided the core technology used on succeeding space programs. The uncertain likelihood of a mission-ending collision with a meteoroid and the unknown consequences of a collision with particles at the very large speeds typical of meteoroids made it crucial to better understand the risk of meteoroid impact. While there are extensive records of the design and analysis of the Apollo spacecraft meteoroid shielding, the information is spread across a variety of archives and personal files. This is the first report to assemble the sources into a technical history.

As in most technical developments, there was prior work – some of which was known and used by Apollo engineers and some unknown to them. The first meteoroid impact risk assessments that U.S. engineers made were for the artificial Earth satellite preliminary design study performed at RAND Corporation in 1946 [1], [2], [3]. The invention[1] fundamental to spacecraft meteoroid protection was also made at that time [4]. Perhaps the most important prior technical developments were the hypervelocity impact test facilities built from 1955 to 1962 for Department of Defense anti-ballistic missile programs. These facilities enabled the later design and qualification of the Apollo shielding. There were prior manned spacecraft meteoroid impact risk assessments made at National Aeronautics and Space Administration (NASA[2]) in 1960 for Mercury [5, Chapt. IX, footnote 55] and circa 1963 for Gemini [6]. However, the Mercury and Gemini analyses were performed at nearly the same time the Apollo meteoroid impact risk analyses were started. The first Apollo meteoroid impact risk assessment known was B.G. Cour-Palais' February 1962 analysis of the Lunar Module (LM) preliminary design for the Apollo contract statement of work (SOW).

The Apollo meteoroid shielding design and analysis beginning and ending points roughly correspond to the contract awards and the critical design reviews (CDRs). The prime contract awards were made from late 1961 to late 1962. North American Aviation (NAA) was selected as the Command and Service Module (CSM) prime contractor on November 28, 1961, with A.J. Richardson and A.H. McHugh performing the analyses at NAA. Hamilton Standard (HS) was selected as the space suit prime contractor in April 1962; however, Manned Spacecraft Center (MSC) retained the responsibility for the meteoroid protection design. P. Burbank, W. McAllum, and B.G. Cour-Palais designed and evaluated the space suit at MSC.

After the space suit prime contract award, the Houston General Electric (GE) Apollo Support Department was established in August 1962. GE had a contract with NASA Headquarters to provide Apollo vehicle reliability and quality assurance studies, analysis and integration of the complete Apollo vehicle, and ground equipment for vehicle checkout. GE also performed specialty analyses for MSC (such as the meteoroid analyses) by task order. C.J. Eardley and E.A. Lang performed many of these tasks for MSC.

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[1] The invention was originally called the meteor bumper; however, J. Crews and B.G. Cour-Palais led a campaign in the mid 1980s that was successful at renaming it the Whipple shield.
[2] Appendix B is a list of acronyms, and their definitions, used in this report.

Grumman Aircraft Engineering Corporation (GAEC) was selected as prime contractor for the LM on November 2, 1962. A. Shreeves and his group managed the meteoroid analyses at GAEC.

Between the contract awards and CDRs, the MSC meteoroid protection engineering went through two significant reorganizations. The first was the consolidation of the meteoroid protection and environment modeling work in the Meteoroid Technology and Optics Branch (MTOB) in early 1964. The next major organizational change was the creation of the Apollo Meteoroid Protection Subsystem Office at MSC circa January 1965[3] with B.G. Cour-Palais, manager, from 1965 to 1967.

The capstone events for Apollo meteoroid protection design were the CDRs for the Block II CSM, which finished in December 1965; the LM CDR, which finished in January 1966; and the space suit (i.e., Extravehicular Mobility Unit (EMU)) integrated thermal meteoroid garment (ITMG) CDR, which finished in September 1967. CDR is the culmination of the development phase of a program. The contractor must have 90% of the drawings released by CDR for review. NASA and the affected contractors reviewed the drawings during a CDR and raised review item discrepancies to the review board as necessary. The review board was then responsible for overseeing the resolution of all discrepancies before declaring the CDR closed. The Command Module (CM) thermal pane meteoroid shield was the only CSM/LM shielding design change started after CDR, and it was withdrawn when the meteoroid environment design specification was changed. The EMU ITMG design was the exception. The ITMG design was changed 10 months after the ITMG CDR.

In July 1965, GE released their CSM meteoroid protection CDR analyses [7]. (NASA used this report during CDR to compare with the NAA analysis.) In August 1965, North American released the CSM meteoroid protection CDR analyses [8] for the December 1965 system CDR. While contractor hypervelocity impact developmental testing in support of the CSM design was primarily completed by the CDR, test data analyses continued after the CDR. At least two technical interchange meetings between MSC and NAA were held to coordinate analyses following the CDR. By May 1966, agreement [9] was achieved on how to analyze the pitting of glass by meteoroid impact, but at that time the two organizations were still using different analysis methods to evaluate which meteoroid impacts would lead to Service Module (SM) propellant tank leaking or rupture. Test data analyses and meteoroid protection analyses continued through 1966 and were completed during the last quarter of 1967.[4]

The last GAEC meteoroid risk assessment was performed in October 1965 for the January 1966 LM CDR [10]. In September 1966, MSC submitted a request to have GAEC evaluate a proposed change (Request for Engineering Change Proposal (RECP)) to update the LM meteoroid analysis for certification. GAEC responded with the cost of the proposed analysis but also reported that Shreeve's meteoroid analysis

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[3] The Apollo Meteoroid Protection Subsystems Office was created in early January 1965 [107]. The other subsystem offices were established in late 1963 to increase the Apollo Spacecraft Program Office (ASPO) control over subsystem development, chiefly to get the more advanced Block II Command Module under way. J.F. Shea, ASPO program manager, asked M. Faget, chief of the MSC Engineering and Development (E&D) Directorate, to select experts in the engineering branches to act as subsystem managers. The managers were directed to oversee their components from design through manufacture and test. They were responsible for cost, schedules, and reliability [34, Chapt. 5, footnote 36].

[4] The last CSM analysis in the GE list of Apollo reports (Appendix D) is dated May 1970; however, this is an analysis of the CSM in its substantially different configuration for the Skylab mission.

group had been disbanded to work more pressing issues.[5] When the change came up at the MSC Apollo Spacecraft Project Office (ASPO) Configuration Control Board (CCB) J. Shea had to decide whether to approve the change and slow down resolution of the "more pressing issues" or to defer/reject the change. Shea sided with Grumman and decided to defer the change. After the passage of 8 months (June 1967), Cour-Palais returned to the CCB with a revised change proposal that would have GE do the LM certification analysis [11], Low[6] approved this change and GE delivered the analysis for LM-4 (the Apollo 10 LM) during February 1968.

Appendix A shows a timeline of the previously written events. The following three sections give further chronological details of the protection requirements, protection analysis results, and the MSC hypervelocity impact test program. These three topics were chosen based on the author's experiences with the International Space Station (ISS) meteoroid and orbital debris protection. As the authors wrestled with deriving requirements during the ISS systems requirements phase, a common question was, "What did they do on Apollo?". That was difficult to answer in 1989 when most of the reports were on microfilm and in personal files. Now the reports are digitized and cataloged[7] and it's possible to write a history of the Apollo meteoroid protection requirements.

The final three sections of this report describe the as-flown design for the CSM, LM, and EMU, respectively. The design is referenced extensively in the Apollo Shielding Requirements, Apollo Meteoroid Protection Analysis Results, and The Manned Spacecraft Center Hypervelocity Impact Test Program sections of the report. These sections also describe the critical items and their failure criteria.

Whereas the large initial estimate of the meteoroid flux drove many of the decisions made between 1962 and 1966, a discussion of how the flux was measured and incorporated into a design specification would lead this report into tangents that would detract from its focus on spacecraft shielding. For this reason, the changing understanding of the meteoroid environment's severity is not discussed at any length in this report.

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[5] Disbanding the GAEC meteoroid risk assessment group may have been in work a year before the RECP, which would place it around the time of the completion of the CDR analysis. A contract's letter from MSC to Grumman dated September 21, 1965, identifies Cour-Palais as the MSC focal on meteoroid protection and requests that MSC be notified of his Grumman counterpart [109]. Cour-Palais was made meteoroid protection subsystem manager 9 months previously and should have well known by September who his counterparts at NAA and GAEC were. It seems more likely to the authors that Shreeves had told Cour-Palais he was reassigned and that Cour-Palais had MSC contracts write a letter to ask Grumman management to make their intentions explicit. The GAEC CDR analysis was given as a verbal report during the January 1966 CDR, which is another indication that the group had been disbanded since it was no longer available to write a report. The written report followed CDR by 10 months in November 17, 1966; possibly an attempt to satisfy the September RECP.

[6] Joseph Shea was reassigned to Headquarters on April 7, 1967, and George Low replaced him as ASPO program manager.

[7] Appendix C is a bibliography of reports released by MSC and Appendix D is a bibliography of reports released by GE.

2.0 Apollo Shielding Requirements

The Apollo shielding requirements were an outcome of the desired system reliability. Although reliability analyses were new to many aerospace engineers in 1958, they were becoming more familiar because the U.S. Air Force was pushing their contractors to use reliability analyses on their Intercontinental Ballistic Missile (ICBM) programs. These techniques were instituted at NASA when Deputy Administrator Richard Horner brought in a small staff of mathematicians and statisticians during the summer of 1959 [5, p. 178-183]. When the techniques were first applied to the Mercury program, heritage National Advisory Committee for Aeronautics (NACA) and Army Ballistic Missile Agency (ABMA) engineers were resistant. Both organizations were experienced at developing rockets and had their own quality procedures. However, by the summer of 1960 all parties agreed on a consensus procedure [5, Chapt. IX, p. 265]; therefore, reliability analyses were an accepted part of the requirements for the following Gemini and Apollo programs.

The initial reliability requirements for Apollo were set in the CSM SOW released in December 1961. The SOW [12] required a better than 0.90 probability of mission success and a better than 0.999 probability of not exceeding the emergency limits during a 14-day mission.[8] The Saturn V booster was required to have a probability of 0.95 or better of mission success, leaving 0.95 for the Apollo CSM and what was then called the Lunar Excursion Module (LEM).

The meteoroid protection reliability requirement could have been allocated out of the 0.95 reliability requirement for the Apollo CSM and LEM. However, there was such limited knowledge of the meteoroid environment in 1961 that the meteoroid impact risk would have rendered the estimated reliability of the Apollo system so uncertain that a reliability analysis would not be able to select between competing design concepts. Therefore, the SOW was released with a model of the meteoroid environment to be used for design (para. 3.2.6.2.2.3), a requirement to provide meteoroid protection (para. 3.4.2.6), and a reliability requirement that explicitly excluded meteoroids and radiation (para. 3.2.1.3). Thus the SOW did not require a numerical value for the probability of no loss of mission due to meteoroid impact.

By 1963 the Headquarters Office of Manned Space Flight (OMSF) system specification [13] stated “the CSM and LM shall be designed for a 0.999 probability of not aborting a mission due to meteoroid penetration.” The contemporaneous MSC Block II specification [14] stated, “the design of the CSM will be based on a probability of 0.99 of not aborting the mission due to meteoroid penetration” – a significantly less stringent requirement. The less demanding MSC mission success requirement reflected the growing awareness that Apollo could not meet the OMSF requirement. This was illustrated by GE Apollo Support Department E.T. Chimenti’s December 1964 analysis that reported [15] it would take 1,155 to 2,986 lbs of shielding to meet the 0.999 requirement and 226 to 1,413 lbs to meet the 0.99 requirement. He suggested changing the SM propellant tank failure criterion as well as changing the analysis method to preclude a weight increase with the 0.99 requirement.[9] The MSC and Headquarters requirements were in sync by March 1, 1966. Concurrently, the NASA OMSF Apollo program

[8] See Ref. [108, p. 168] for the origin of the 0.999% requirement. The chance of not exceeding the emergency limits was later referred to as probability of crew safety.

[9] Prior analyses assumed that any perforation of the SM honeycomb skin would spray the propellant tanks with meteoroid and SM skin fragments that would perforate or rupture the tank wall. If the failure criterion was changed to damage to the wall, but no leaks, then the weight increase could be avoided.

specification [16] called out a 0.99 requirement for both the CSM and LM, which the MSC ASPO apportioned as a 0.995 requirement for the CSM and a 0.995 requirement on the LM.[10] More requirements relief must have been needed because by the Block II specification's January 1969 release [17], the CSM requirement had decreased from 0.995 to a probability of 0.992 of not requiring an abort during a Design Reference Mission (DRM) IIA 8.3-day mission.

The 1963 and 1964 versions of the Block I CSM specification [14] were written without a meteoroid impact risk requirement. Even without a requirement, NAA was evaluating the Block I spacecraft for risk of meteoroid impact and reporting the results [9]. But an analysis for crew safety was never necessary because program delays resulted in the Block II Apollo's availability for the first crewed mission.

The EMU requirements underwent a similar series of changes. The first record the authors have of an EMU requirement is dated December 9, 1964 [18]. In the memo, Ed Smylie, assistant chief for Apollo Support, Crew Systems Division (CSD) states that the requirement is 0.9999 for 18 man-hours. But he also wanted the MSC MTOB to evaluate requirements of 0.995, 0.999, and 0.9999 probability of no loss of mission and exposure times of 9, 12, 15, and 18 man-hours. Smylie requested the evaluation of both the current EMU meteoroid protection design concept of a separate meteoroid protection garment (MPG) and an external thermal garment (ETG) where the ETG is worn outside the MPG. Smylie also requested a trade study to evaluate a design where the astronauts disposed of the MPG prior to ascent from the lunar surface to save weight. This would require having an integrated ETG and a thinner MPG for contingency extravehicular activity (EVA) transfer from the LM to the CSM. The design was required by mid-February 1965 (i.e., 2 months) so the contractor could deliver an MPG for evaluation by spring and have qualifiable units by December 1965.

A CSD memo for the record [19] dated 1 month later reported that the requirement would be reduced to 0.999 for 18 man-hours. It further recorded that the MPG and ETG were now a single garment (named the thermal meteoroid garment (TMG)) and was to be stored in a canister on the descent stage where the EVA astronauts would don the TMG.

Later, as the MPG was integrated into the ETG to produce the TMG, the TMG was integrated into the pressure garment assembly (PGA). This new TMG configuration was called the ITMG. ITMG testing revealed it significantly restricted the astronaut's mobility. In February 21, 1968, the Astronaut Office [20] requested that the EMU Design Review Board evaluate the requirements for the thermal/micrometeoroid garment to remove layers from the ITMG to improve mobility. The astronauts suggested that recent meteoroid environment measurements would allow a relaxation of the design meteoroid environment requirement. However, this had already been factored into the design by 1968, so the only alternative was to relax the protection requirement. When the requirement was relaxed from a 0.999 probability of no leak to a 0.999 probability of no leak larger than 50 ml/min, one of the two neoprene-coated ripstop layers could be removed from the ITMG. The final ITMG meteoroid protection

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[10] The March 1, 1966, date is an upper bound on when the OMSF and ASPO requirements were in sync. August 1964 is a lower-bound date and comes from a memo within Maynard's memo of that date [31] stating that NAA had been put onto the contract to design the CSM to 0.995 probability of mission success with the Block II letter contract change of some prior date.

requirement was a 0.999 probability of no leak larger than 50 ml/min within 24 hours of exposure (two suits performing four 3-hour EVAs) [21].

In the end, the OMSF goal of a 0.999 probability of mission success for the CSM and LM proved too difficult to meet. However, with the design meteoroid environment reduced dramatically and the duration of exposure shortened from 14 to 8.3 days, meeting a 0.99 requirement was proved possible. Similarly, the 0.9999 requirement for the EMU also proved too difficult; however, with the same environment reduction, a reduction of the protection requirement to 0.999, and the allowance for small leaks, it was proved possible to design an EMU protective garment that allowed acceptable mobility and met the meteoroid protection requirement.

3.0 Apollo Meteoroid Protection Analysis Results

Designing to operate in the meteoroid environment was new and difficult for the contractors. The expected number of spacecraft impacts was uncertain [22] when the contract was awarded and the assumed 30 km/s closing speeds between meteoroids and the spacecraft made estimating the consequences of an impact problematic.[11]

NASA pursued an energetic program to characterize the meteoroid environment using ground-based radars and impact sensors flown on spacecraft. The progress in this program was marked by at least two micrometeoroid program reviews: one in May 1961 and one in April 1963 [23]. By February 22, 1964, G.E. Mueller said in a NASA news release, “Data from the Explorer XVI satellite and ground observations indicated that meteoroids would not be a major hazard” [24, p. 139].

By early 1964, meteoroids were no longer a potential program-ending technical issue for Apollo, but meteoroid protection was still a weight threat. The CSM was struggling to meet a 0.999 probability of mission success, but was having difficulties because of the propellant tanks underneath the SM honeycomb skin panels. The tanks were susceptible to violent explosions if impacted by a meteoroid and required heavy meteoroid shielding to meet the probability of mission success requirement. In March 1964, NAA was authorized to perform trades on shielding weight for both the CSM and LM, which quickly became trades on requirements, failure criteria, and shielding weight [25]. A contemporaneous April 15, 1964, GE CSM analysis [26] assumed that any perforation of the SM honeycomb skin would result in a failure of the underlying propellant tank. GE reported a 600- to 1,400-lb weight increase was needed to meet the OMSF 0.999 requirement. At an April 23, 1964, meeting at MSC, NAA reported their trade study results. NAA recommended adding a bumper on the interior of the SM, changing the propellant tank failure criterion to impacts producing more than a 50% reduction in the propellant tank thickness, and shortening the mission duration. At the same meeting, MSC E&D presented a design for a bumper of 0.015-inch thick aluminum alloy and 1 inch of foam that would be spaced 1.375 inches off the

[11] See [108, p. 113] for an anecdote concerning CSM meteoroid protection from the NAA bidder’s presentation to the Apollo Evaluation Board on October 11, 1961.

SM structure.[12] MSC E&D thought the additional shielding would weigh 240 lbs [27]. As a result of this meeting, C.H. Perrine, the ASPO flight technology manager, led a team to review the alternatives. The study began with a request in May 1964 to have NAA and GAEC perform a second set of weight trades to evaluate critical item shielding that could be installed on the interior of the CSM and LM [28]. Midway through the trades on June 11, 1964, Cour-Palais [29] notified the program that three shields were needed in the Block II spacecraft: an SM shield between the honeycomb shell and the Service Propulsion System (SPS) oxidizer and fuel tanks, an extension of the SM aft heat shield, and thicker Electrical Power System (EPS) and Environmental Control System (ECS) radiator tubes.[13] When the trades finished in August 1964, Perrine reported the conclusion to the Chief of ASPO System Engineering Owen Maynard: 200 to 400 lbs of shielding were needed for the CSM to meet a 0.99 probability of mission success [30]. The internal shields for the SM fuel and oxidizer tanks were designed and 2/3 of the drawings were released by May 1966 when they were overcome by events [9]. First, the meteoroid environment for design was factored down based on data from the Pegasus meteoroid detection satellite. Second, NASA Headquarters agreed to reduce the CSM mission success criterion to 0.99. Third, both NAA and MSC thought that a realistic failure criterion would allow some damage to the SPS propellant tanks.

In the end, no meteoroid shielding was added to the CSM. However, 400 lbs for shielding was carried in the mass properties report as a weight threat until 1966. At that time, the design meteoroid environment was reduced and it was possible to eliminate the weight threat; however, the same was not true for the LM.

The NAA and GAEC weight trades of June and July 1964 mentioned that the LM had similar difficulties meeting a 0.999 requirement and that 200 lbs of shielding were needed to meet a 0.99 requirement.[14] Maynard reported the CSM and LM results to the ASPO manager during August 1964; however, only a draft memo documenting the recommend solution [31] is available with no documentation of what Shea decided. It does seem likely though that the decision was to continue with the CSM internal shield design as a kit that could be installed if needed and to accept the programmatic risk to the LM design in anticipation that further work on the environment model and further hypervelocity impact testing would eliminate unnecessary conservatism and lower the risk estimates.

This contention is supported by an April 1965 GE analysis that showed the LM met its requirement with a 0.006-inch thick aluminum thermal shield covering the ascent and descent stages. GE concluded that no additional weight for LM meteoroid shielding was necessary [32].

Regardless of this achievement, the LM meteoroid shield issues continued. During the summer of 1965, a Grumman management review (Super Weight Improvement Program (SWIP)) of all the released drawings started attempted to reduce the growing weight of the LM. The thermal/meteoroid shields were an inviting target for weight reduction because the thermal analysis group had concluded that only the

[12] Perrine wrote that the E&D shield "would be spaced 1-3/8 inches outboard of the present structure." Perrine might have been referring to the SPS tanks, but the primary structure was the fore and aft bulkheads, the center tunnel, the radial panels, and the honeycomb skin.
[13] These results were well known to management by this time because, on the same date, North American was authorized to begin designing meteoroid shields for the SM [24, p. 188].
[14] Without the 200 lbs of extra shielding, MSC E&D was reporting that the LM thermal design would only provide a 50% probability of mission success in the meteoroid environment [113].

Multilayer Insulation (MLI) blankets were needed as thermal protection; therefore, the aluminum thermal/meteoroid shields could be eliminated. In November 1965, GE completed an analysis [33] that studied the consequences of replacing the 0.008-inch thick aluminum thermal shield with MLI and reported that 1,092 lbs would have to be added by thickening the LM primary structure to achieve the same meteoroid protection afforded by the thin aluminum thermal shield. In the end, the aluminum shields were retained on the ascent stage and eliminated from the sides of the descent stage [34, Chapt. 7, footnote 20]. The sides of the descent stage propellant tanks were enclosed by the primary structure, which was effective protection. Only the propellant tank domes were exposed through the primary structure. The aluminum thermal shields were retained on the upper and lower decks perhaps for the extra meteoroid protection of the descent stage tank domes that they provided. Further weight reductions resulted from reducing the aluminum thermal shield thickness to 0.004 inch at various locations [35].

Thus, while the LM meteoroid protection began as the thermal protection for the spacecraft, by the end of 1965, the ascent stage aluminum shields were retained only because they provided meteoroid protection.

The meteoroid protection status was summarized in the ASPO Weekly Management Report for July 8 to 15, 1965, to NASA Headquarters:

> The Structures and Mechanics Division (SMD) [of the MSC-ASPO] presented meteoroid protection figures for the CSM. (During April, GE had developed [32] reliability estimates for the LEM, based on revised design criteria, for the 8.3-day reference mission. The probability for mission success, GE had found, was 0.9969.) SMD's figures were:

Module	Block I 14 day earth orbital flight	Block II 8.3 day lunar mission
CM	0.99987	0.99989
SM	0.9943	0.9941
LM		0.9969
Total	0.9942	0.9909

> The division consequently placed the meteoroid protection for the entire mission at 0.99417 (Block I, CSM only) and 0.99089 (Block II, CSM and LEM). Apollo's goal was 0.99.
> All of the above figures, both GE's and SMD's, were derived from the inherent protection afforded by the spacecraft's structure. Thus no additional meteoroid shielding was needed. (Meteoroid protection would still be required, of course, during extravehicular operations.)[36, p. 169]

The meteoroid protection for extravehicular operations referred to in the ASPO weekly report was the TMG. Before January 1965, the TMG was two separate garments: the MPG and the ETG. MSC MTOB engineers P. Burbank ,W. McAllum, and B.G. Cour-Palais developed the initial design for the meteoroid protective garment in April 1964. They calculated the meteoroid protective garment would protect a person from a meteoroid with the same kinetic energy as a 1/64-inch diameter glass sphere traveling at 6 km/s and would have to protect from lunar ejecta with the same kinetic energy as a 1/8-inch glass sphere traveling at 200 m/s [37] to achieve a 0.9999 reliability for 16 hours of exposure. The result of the testing was a design weighing 0.096 g/cm^2 (28.3 oz/sq. yd) and measuring about 1 inch thick.

The TMG Preliminary Design Review (PDR) was held on June 10, 1965. On September 29, 1965, GE delivered a TMG analysis [38] to the Apollo meteoroid protection subsystem manager that concluded a TMG weighing 20.5 oz/sq. yd (0.0695 g/cm^2) was needed to meet a requirement of 0.995 probability of no leak during 18 hours of exposure. GE also reported that a 32-oz/sq. yd (0.108 g/cm^2) garment was required for a probability of no leak of 0.999 and a garment with a mass-per-unit area of 57 oz/sq. yd (0.193 g/cm^2) was required for a 0.9999 probability of no leak. Each of these probabilities was considered for alternative EMU probability of no leak requirements.

An updated analysis [39], released on February 14, 1966, reported a TMG weighing 28.75 oz/sq. yd (0.0975 g/cm^2) would have a 0.9973 probability of no penetration during 24 hours of exposure. Penetration was defined as a perforation of the TMG (but not the PGA) or a perforation of the Portable Life Support System (PLSS) fiberglass case. The updated analysis used the same meteoroid environment and penetration equation for the TMG as the 1965 analysis and differed only by the mass-per-unit area of the TMG used and the inclusion of the PLSS in the assessment of probability of mission success.

A month later, GE wrote up a task description [40] to develop a new EMU probability of mission success requirement (or a new TMG design) based on a 0.99 total CSM, LM, and EMU probability of mission success. The task description listed the due date as the last week of July 1966. No final report from such a task is extant.

The last report of the EMU probability of mission success is from a May 16, 1967, memo from Cour-Palais [41] that reported the EMU probability of mission success as 0.99958. The duration of exposure was 24 hours and the risk assessment did not include the helmet or the PLSS. The TMG was integrated with the PGA and called the ITMG. The ITMG CDR was scheduled for September 7, and 8, 1967. This is the last update of the EMU probability of mission success known by the authors.

Risk analyses for the Apollo CSM/LM lunar mission continued from 1965 to 1967. The last extant system-level risk assessment is a November 1967 memo from B.G. Cour-Palais [42] to G.E. Low, the recently appointed manager of the ASPO. Cour-Palais reported the probabilities of mission success listed in the second column of Table 1 for the DRM IIA. (DRM IIA was the 8.3-day mission mentioned in the Apollo Shielding Requirements section and was similar to the G mission flown by Apollo 11.)

Evidence does not show that Headquarters or the MSC ASPO ever managed the meteoroid risk for the Apollo program as a whole. However, it is possible to estimate the overall system risk from the available data. The DRM IIA risk estimates of Table 1 can be adjusted to reflect current estimates of the meteoroid flux and closing speed. To arrive at a total system risk, the DRM IIA risk estimates can also be adjusted by factoring the DRM IIA mission duration up to the actual mission durations flown for two Earth orbital and the seven lunar missions flown. The result of this calculation is a 0.085 probability of mission failure during one or more of the 11 Apollo missions. (The complement of the 0.9149 probability of no loss of mission is listed in the last row of Table 1.) If the last three J missions had been finished and flown, then the probability of loss of mission would have been 0.118. The program requirement was 0.90 probability of no loss of mission, per mission, or a 0.31 probability of no loss of mission during 11 missions. Thus the loss of mission risk due to meteoroid impact was about 12% of the total system risk; therefore, it was a significant factor, but not the largest factor.

Table 1. Comparison of the 1967 Design Reference Mission IIA Assessment with an Estimate of the Overall Apollo Program Risk

Module	Probability of Mission Success	
	DRM IIA	Apollo 7 to 17
CM	0.99950	0.9960
SM	0.99580	0.9673
LM	0.99400	0.9547
EMU	0.99958	0.9947
Total	0.98890	0.9149

4.0 The Manned Spacecraft Center Hypervelocity Impact Test Program

At the beginning of Apollo, the NASA expertise in terminal ballistics resided at Ames Research Center. Alex Charters had nurtured the development of the two-stage light gas gun as a hypervelocity launcher at Ames starting in January 1952, culminating in the development of the accelerated reservoir two-stage light gas gun in 1958 [43]. In March 1961, he moved to the General Motors Defense Research Laboratories (GMDRL) in Santa Barbara to build an even larger 4-inch bore two-stage light gas gun [44]. Pat Denardo, Robert Nysmith, and James Summers continued the terminal ballistics work at Ames.

Ames engineers performed the early hypervelocity impact testing of SM honeycomb panels and ablative materials. C.H. Perrine, ASPO Flight Technology Division, monitored the progress of the Ames testing for MSC [45]. Results were also communicated through the Meteoroid Technology Advisory Working Group, which had reached its fifth meeting by December 1963 [46].

At the same time that Ames was testing honeycombs [47], [48], MSC was able to fund testing through the NAA Apollo contract and directly through purchase orders.[15] NAA had written into their CSM proposal a 465-shot-test matrix that MSC negotiated down to a 257-shot program. The contract was let with GMDRL and was under negotiation on October 30, 1962. It started around that time [49] and ran until July 1965. MSC purchased tests of space suit fabrics and SM honeycomb directly from Utah Research and Development Corporation (URDC), the Illinois Institute of Technology Research Institute (IITRI), and Avco before 1965. The space suit material testing occurred before April 1964 and involved shooting very small projectiles because of the suits' small surface area and short duration of exposure to the meteoroid environment [50], [37]. The SM honeycomb testing shot various honeycombs [51] before July 1964.

The NAA test program at GMDRL produced perhaps its most significant result in June 1964 [52] when GMDRL reported that one could not extrapolate the Ames results to meteoric speeds because of the melting and vaporization of the projectile and shield materials during hypervelocity impact. Projectile melting and vaporization changed the honeycomb rear face sheet failure mechanism from cratering to rupturing by impulsive loading. The impulsive load was spread over a larger area than the individual fragment impacts and hence was less efficient at perforating the rear face sheet. Eventually GM developed an analytical relation for the impulsive failure mode that MSC requested GE to use in their meteoroid protection analyses during the December 1964 to April 1965 timeframe.

Around July 1964, MSC directly contracted testing with GMDRL. This work focused on developing penetration equations for double sheet structures such as the SM honeycomb. The initial phase of the contract ran until June 1965. The contract was renewed at least once and was complete in November 1966. This work was reported in the nine NASA contractor reports (CRs) listed in Table 2 and in the seventh Hypervelocity Impact Symposium, and was summarized in two chapters of Reference 53.

[15] Appendix F is a list of hypervelocity impact testing purchase orders and contracts let by MSC.

Table 2. Contractor Reports Produced for NASA Contract NAS9-3081

Reference	GMDRL No.	Title	Authors	GM Release Date
NASA-CR-295	TR 64-61	Thin sheet impact (also presented at 7th Hypervelocity Impact Symposium)	Maiden, C.J.; McMillan, A.R.; and Sennett, R.E., III.	11/01/64
N/A	TR 65-05	Structural response of beams and rings to impulsive loading	…	02/01/65
NASA CR-65039	TR 65-08	Structures 1. The Response of Beams and Rings to High-Intensity, Short-duration Loading	Sennett, R.E. and Skaar, D.E.	02/01/65
N/A	TR draft	Spacecraft hull thickness requirements for protection against meteoroid penetration	Maiden, C.J., McMillan, A.R., and Sennett, R.E.	04/01/65
NASA-CR-65222	TR-65-48	Experimental investigations of simulated meteoroid damage to various spacecraft structures Summary report	Gehring, J.W.; Maiden, C.J.; McMillan, A.R.; Sennett, R.E.	07/01/65
NASA-CR-65223	TR-65-51	Impact of rod projectiles against multiple-sheet targets	Christman, D. R.; McMillan, A.R.	07/01/65
NASA-CR-92088	TR 66-63	Computer analysis of clamped circular plate response to axisymmetric impulsive load	Sennett, R.E. and Skaar, D.E.	10/1/66
NASA-CR-915	TR-66-67	Final report on experimental investigations of simulated meteoroid damage to various spacecraft structures	McMillan, A.R.	11/01/66
N/A	TR-66-85	TEDDY - a two-dimensional Lagrangian code for determining the wave propagation in elastic-plastic media	Jones, A.H. and Kriech, C.E.	12/1/66

Cour-Palais convinced management that MSC needed a 30-caliber two-stage light gas gun, which they purchased from GMDRL in late 1963 and had installed by early 1964. Hypervelocity impact testing with the MSC light gas gun started around June 1964. This gun, as it was when it was originally installed at Ellington Air Force Base (AFB), is shown in Figure 1. During the first half of 1967, the gun was moved to the gun hall in room 1028 of Building 31 at MSC.

Testing at the MSC hypervelocity impact facility proceeded at a rate of about 1,000 shots a year[16] from 1965 through 1967. Though not all the tests occurred on the 30-caliber two-stage light gas gun, they averaged 4 shots a day, which is a rigorous pace. By the end of 1966, hypervelocity impact testing at MSC for the Apollo lunar mission was for the most part finished. There were several accomplishments during this period:[17]

1. The development of the Gemini G4C space suit meteoroid protective cover for Gemini IV c. October 1964.
2. Modifications to the Gemini meteoroid protective cover for Gemini VIII and following c. 1965.
3. Development of the initial Apollo meteoroid protective garment c. January 1965.
4. Demonstration that a protective cover for the Lunar Visor Assembly was unnecessary c. February 1965 [36].
5. Development of the LM meteoroid shield evaluation methodology for lunar ejecta c. April 1965 [32].
6. Development of the SM honeycomb and propellant tank evaluation methodology for meteoroid impact c. July 1965 [7].
7. Development of the CM ablator evaluation methodology for meteoroid impact c. May 1966 [54].
8. Development of the LM meteoroid shield evaluation methodology for sporadic meteoroids c. December 1967 [55].

[16] Appendix E is list of test numbers, dates, and test descriptions for tests performed at the MSC hypervelocity impact range.
[17] The dates and references are to the GE analysis reports where the methodologies were first used. The CM and LM window and the LM ascent and descent stage shield methodologies were developed in their final form in 1967.

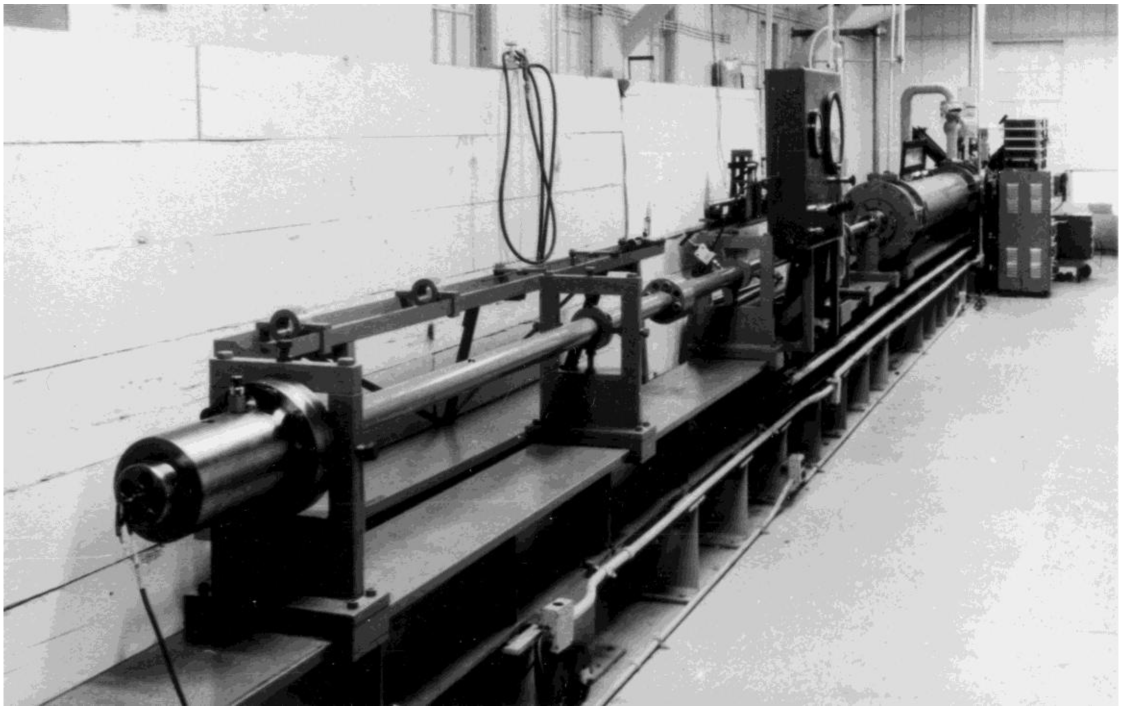

Figure 1. Manned Spacecraft Center 30-caliber two-stage light gas gun. S64-6213.

While the July 1965 MSC design methodology was similar to what GMDRL developed, it predicted significantly smaller meteoroids would perforate the SM honeycomb. The GMDRL researchers had shown that for some impact conditions the honeycomb outer face sheet would melt and vaporize the meteoroid, resulting in a blast loading of the inner face sheet. Hence, they expended considerable effort developing computer programs to calculate the motions of the inner face sheet from blast loads. (These programs are described in GMDRL technical reports TR 65-04, TR 65-08, and TR 66-85 referenced in Table 2.) However, the MSC gas gun testing convinced MSC engineers that the conditions leading to blast loads were too narrowly constrained to significantly affect the probability of mission success. As a result, they developed a methodology that they concluded was applicable to a greater range of impact conditions and required NAA, GAEC, and GE to analyze the probability of mission success with that methodology.

5.0 Command and Service Modules

The Apollo CSM is shown in Figure 2. The conical structure at the top of the figure is the CM that is pressurized and crewed. The lower cylindrical structure provided most of the electrical power, propulsion, and thermal control for the mission.

The largest contributors to the Apollo CSM design spacecraft impact risk [54] are listed in order of importance:

1. SM propellant tanks
2. CM ablator
3. SM Reaction Control System (RCS) propellant tanks
4. The EPS or ECS radiator fluid lines
5. CM windows

The impact risk calculations concluded SM propellant tank leak or rupture was 88% of the total risk, the CM ablator perforation was 7%, the SM RCS prop tank rupture was 4%, and the remaining risk was spread over the SM radiator fluid lines, the CM windows, and the SPS engine nozzle.

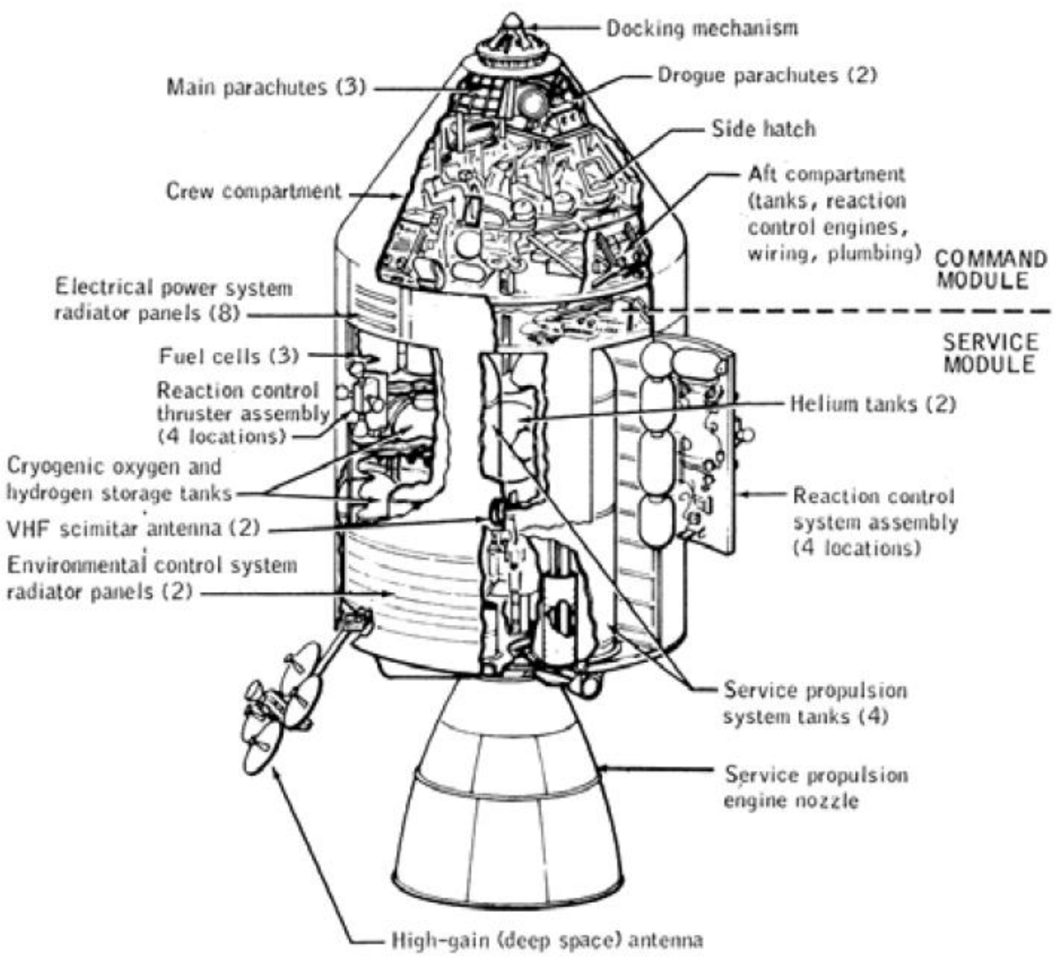

Figure 2. Command and Service Module.

North American typically analyzed more components for their risk of failure due to meteoroid impact, but their collective contribution to the system risk was small.

5.1 Service Module Propellant Tanks

The SM propellant tanks are visible in Figure 2 through the SM center cutout and are labeled "Service Propulsion System Tanks". The SPS propellant tanks ran the full length of the SM and a portion of the tank-end domes protruded through holes in the fore and aft bulkheads. Thus, the inboard sides of the SM propellant tanks were protected by the fore and aft bulkheads, the SM center tunnel, and the radial panel primary structure. However, the aft-end domes were not covered by primary structure. Furthermore, the outboard sides of the propellant tanks where shielded only by the aluminum honeycomb skin.

The SPS tank domes are shown in a test article without the aft base heat shield installed or the SPS main engine nozzle on the right hand side of Figure 3. The SM in-flight configuration is shown on the left-hand side of Figure 3 with the aft base heat shield installed. The aft base heat shield was the only meteoroid impact protection for the aft SPS propellant tank domes.

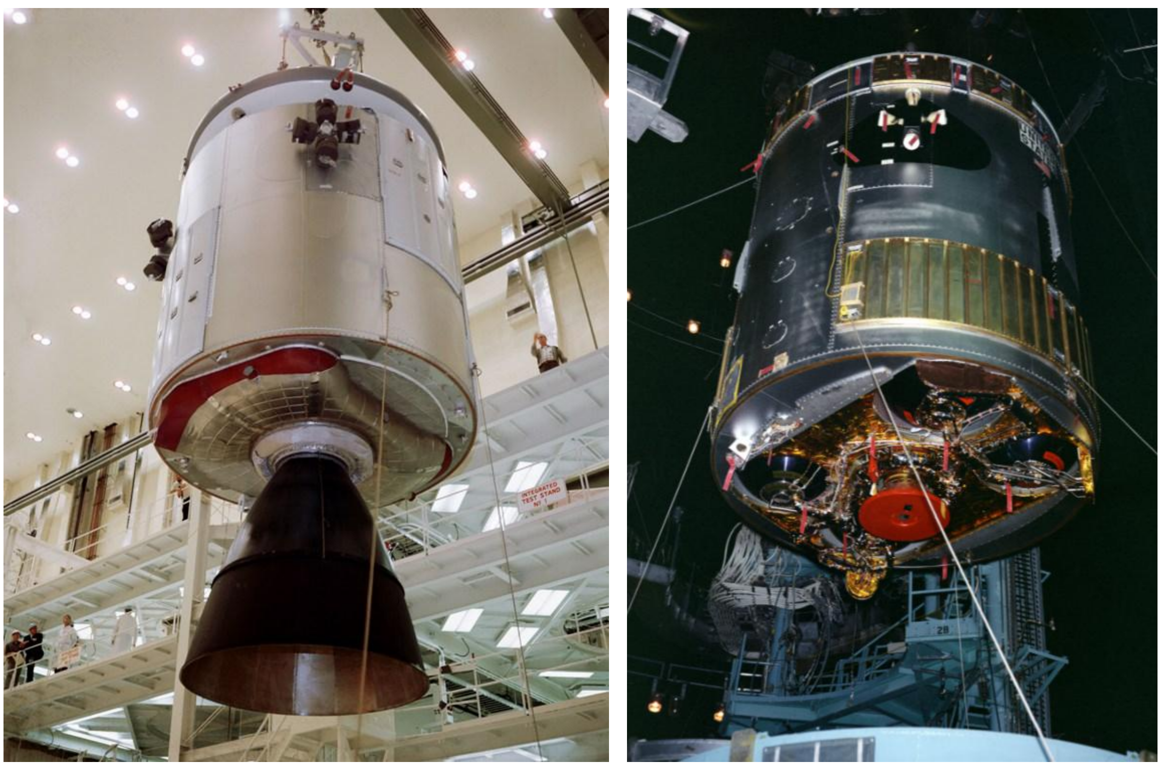

Figure 3. Views of the Service Module aft end with the aft heat shield (right photo) and without the aft heat shield, exposing the Service Propulsion System propellant tank domes (left photo). S67-15704 and S68-28791.

The aft base heat shield was made up of a 0.005-inch thick sheet of nickel spaced 1.25 inches from a 0.054-inch fiberglass panel. Eardley's analysis [54] of 1966 showed that 35% of the SPS propellant tank risk was through the tank-end domes, yet the tank-end domes accounted for only 20% of the exposed area.

By 1961, scientists knew that two sheets of aluminum spaced some distance apart stopped meteoroids more effectively than a single sheet of aluminum with the same total thickness. This was one of the reasons the SM honeycomb skin panels were used to protect the outboard sides of the propellant tanks. The use of honeycomb skins was mandated by the amended November 27, 1961, CSM SOW [56, p. 122].

The Block I SM honeycomb outer face sheet was 0.016 inch thick and made of 7075-T3, the honeycomb was 1 inch thick, and the inner face sheet was 0.010 inch thick and made of 7075-T3. The Block II SM honeycomb skin panels used 2024-T81 face sheets to provide greater high temperature strength. The material change required increasing the face sheet thicknesses [57].

Figure 4 shows a cross section of a 2-inch thick honeycomb test article for an advanced SM shield following hypervelocity impact testing. The projectile entered from the top of the figure. The original failure criterion for the SPS propellant tanks was perforation of the SM honeycomb skin panels. Because the failure criterion was too stringent to meet the desired probability of mission success, engineers considered an alternative. If the original criterion had remained, the test shown in Figure 4 would have been an SPS tank failure.

Figure 4. Service Module honeycomb panel hypervelocity impact test article in cross section.

To select a new criterion, one approach was to design intermediate shields between the honeycomb skin panels and the SPS propellant tanks. A 0.010-inch thick aluminum shield was designed for the oxidizer tanks and a 0.012-inch thick aluminum shield was designed for the fuel tanks [9]. These shields were kits that could be installed or removed as needed. Another approach was to determine how tolerant the SPS tanks were to pitting caused by hypervelocity projectile and honeycomb fragments from a skin perforation. After some development, NAA and NASA engineers reached a consensus that the tanks would not fail if the fragments from the perforation did not penetrate deeper than 25% of the SPS tank wall thickness. This change in failure criterion, coupled with the decreased meteoroid flux design specification, proved enough to allow the CSM to meet its meteoroid protection requirements. At this point, the intermediate shield kits were dropped from the program. The impact conditions that would produce failure of the SPS tanks were typically analyzed by adding 25% of the tank wall thickness to the honeycomb inner face sheet thickness.

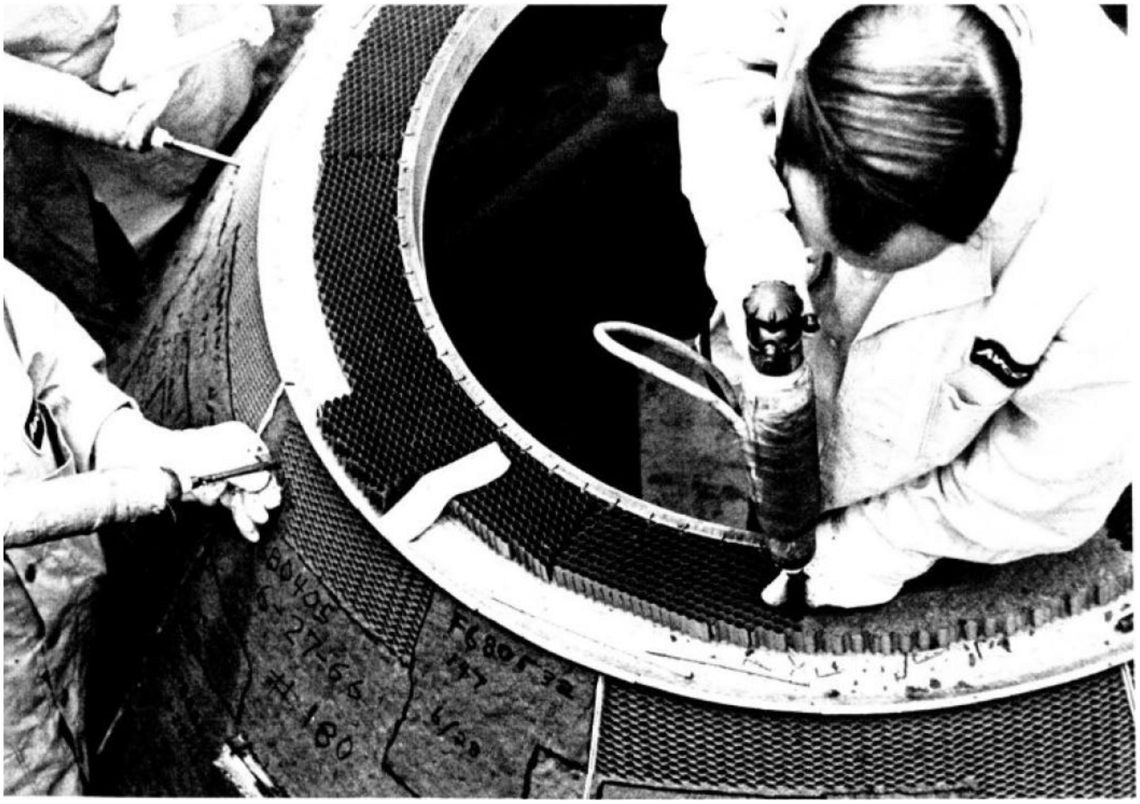

Figure 5. Technicians gunning ablator into phenolic honeycomb bonded to the Command Module aero shell.

5.2 Command Module Ablator

The CM ablator was composed of a phenolic honeycomb with a 3/8-inch cell bonded to the CM aero shell with Avcoat 5026-39G ablative material gunned into the cells. Technicians are shown gunning ablator into the apex of the aero shell in Figure 5 from Reference 58. There were about 370,000 cells to be filled on the CM. The ablative material was porous and was composed of an epoxy-novalac resin reinforced with quartz fibers and phenolic micro-balloons. The bulk density of the ablator was about 0.5 g/cm^3.

The ablator thickness varied over the CM aero shell. The 1965 GE meteoroid impact analysis [7] for the lunar mission reported that the heat shield thickness ranged from 3/4 inch to 2 inches. The 1966 analysis [54] reported that the ablator thickness varied from 2/3 inch to 1.4 inches and the GE analysis [59] for the Skylab Earth orbit missions reported that the thickness varied from 2/3 inch to 1.2 inches. Many of the details of the ablator design were classified confidential at the time and hence are missing from the unclassified meteoroid impact analysis reports.

The failure criterion selected for the Lunar and Earth orbit missions was penetration through the ablator and the outer face sheet of the stainless steel honeycomb aero shell. NAA was using this as a failure criterion by July or November 1964 [60], whereas GE was using a perforation of both face sheets of the aero shell honeycomb in July 1965 [7]. GE began using the NAA criterion by May 1966 [54].

Figure 6 shows a picture of a specimen that has been tested by hypervelocity impact and then sectioned. Hypervelocity impact test campaigns were conducted for NASA at Avco [61], the Naval Research Laboratory [62], and the MSC. The MSC and NAA ablator impact test campaigns started in 1964 and were completed by December 1965 and April 1966. Cour-Palais and Richardson both recollected that impacted specimens were arc-jet tested. Cour-Palais stated, "Hypervelocity impact tests were conducted to create craters of various depth to diameter ratios that were subsequently exposed to re-entry heat in an arc-jet facility. None of the craters tested in the arc-jet resulted in failure of the bond" [63]. Richardson also recalled that the tests penetrated two thirds of the ablator thickness and passed the arc-jet testing.[18]

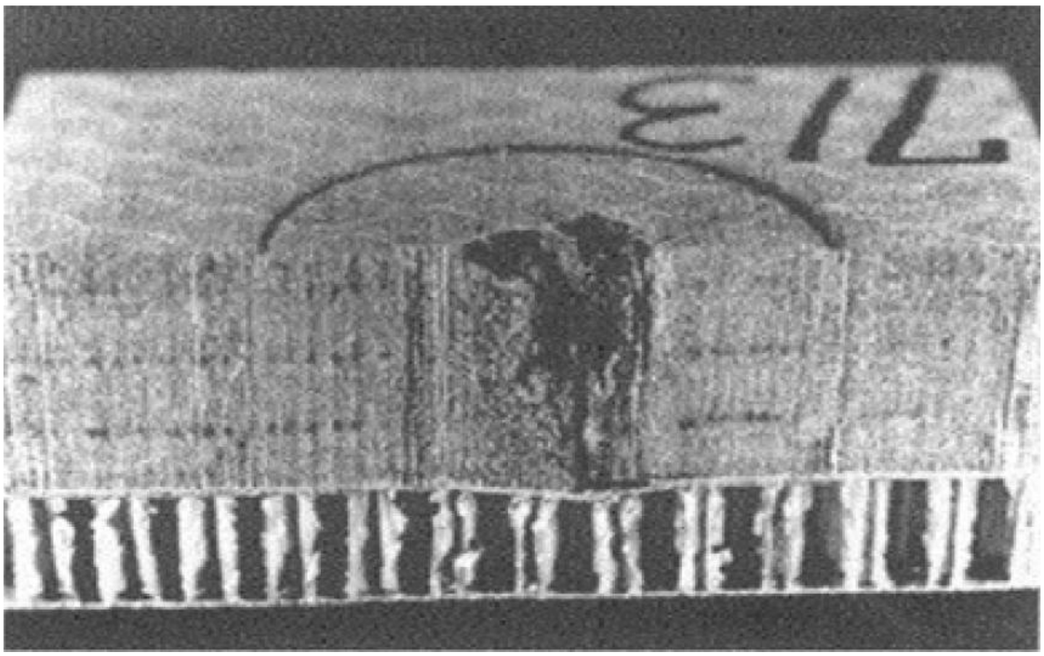

Figure 6. Command Module ablator hypervelocity impact test article in cross section. Tested c. 1965.

Ablator impact tests were also performed for the Avco ablator design subcontract with NAA. Their June 15, 1962, test plan outlined a test program to determine whether a bumper was needed to protect the ablator. Ten tests in the 10-megawatt arc jet test facility were planned to occur from June through August 1962 [64]. Testing was performed at Avco and at IITRI in Chicago. Tests were performed at room temperature, -100˚ F and -260˚ F˚, and a ballistic limit equation was developed from the data. Engineers then analyzed the probability of mission success and concluded that probability was 0.973 for a 14-day Earth orbital mission [65]. In the same monthly report, Avco engineers summarized the results of a calculation indicating that a penetration of the ablator down to the back shell face sheet at the midpoint on the windward side would result in burn-through for the analyzed trajectory. Further test results were reported the next month; however, the work was terminated before the arc jet testing was started. It is

[18] Personal communication. A.J. Richardson 2008

unclear how this early work factored into the later testing performed for MSC. The testing at Avco Space Systems Division [61] performed in 1965 makes no mention of the earlier design subcontract testing.

5.3 Command Module Windows

The CSM requirements drove the window design to a single exterior thermal pane and redundant interior pressure panes. However, rising concerns with the meteoroid threat prompted NAA engineers to recommend a meteoroid pane to protect the thermal pane. NAA engineering review board circa September 1965 accepted this technical recommendation. The meteoroid pane and its frame added 23 lbs to the CM weight [36, p. 203].

Figure 7 shows the NAA-recommended 1965 Block II lunar missions design. NAA analysis concluded that the probability of mission success per DRM IIA mission would decrease from 0.9998 with the 0.35-inch thick meteoroid pane to only 0.422 without the pane. This estimate was based on a flaw with a length of 0.0050 inch produced by meteoroid impact during the mission growing under the re-entry heating until the 0.70-inch thick thermal pane split in two.

North American Rockwell[19] (NAR) engineers submitted an engineering change in October 1967 to evaluate removing the meteoroid pane, and before the first Block II CSM flight (Apollo 7, October 1968), the outer meteoroid pane was eliminated from the design.

NAR testing had shown that a pit 0.005 inch deep at the thermal pane's edge (produced by removing a thermocouple bonded to the test article) could lead to complete fracture of the pane under simulated re-entry heating conditions [66]. This test anomaly prompted an NAR engineer analysis that concluded a high confidence that the panes would not develop a complete fracture upon re-entry; it was necessary to preclude flaws 0.001 inch to 0.060 inch long depending on the pane and the location of the pane. (Large flaws could be tolerated at the center of the pane and only small flaws could be tolerated at the edge of the pane near the window frame.) Later, NAR engineers decided the CM could survive re-entry with a cracked thermal pane because the frame would hold the pieces in place. The final failure criterion was two or more 0.050-inch flaws formed in a single pane by meteoroid impact. Cracks growing from two flaws during re-entry might intersect, leading to a piece of the window falling out. If this occurred, the opening would allow hot re-entry gases to impinge on the pressure panes resulting in window failure or window frame failure or both and loss of mission.

[19] North American merged with Rockwell in March 1967

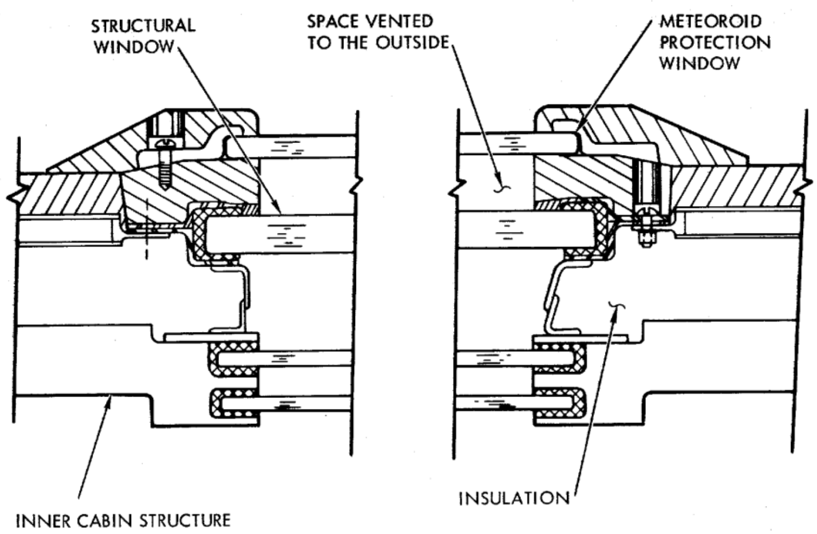

Figure 7. North American Rockwell meteoroid pane design c. 1965 to 1967. Not the design actually flown.

6.0 Lunar Module

Figure 8 shows a drawing of the LM. The figure shows the ascent stage in the upper unshaded portion and the descent stage in the lower shaded portion. The largest contributors to the Apollo LM design spacecraft impact risk that were identified in the 1968 GE analysis [67] are listed in order of importance:

1. Ascent stage cabin
2. Ascent stage aft equipment rack
3. Ascent stage tanks
4. Descent stage propellant tanks
5. Ascent stage windows
6. Descent stage quad tanks
7. Descent stage engine nozzle

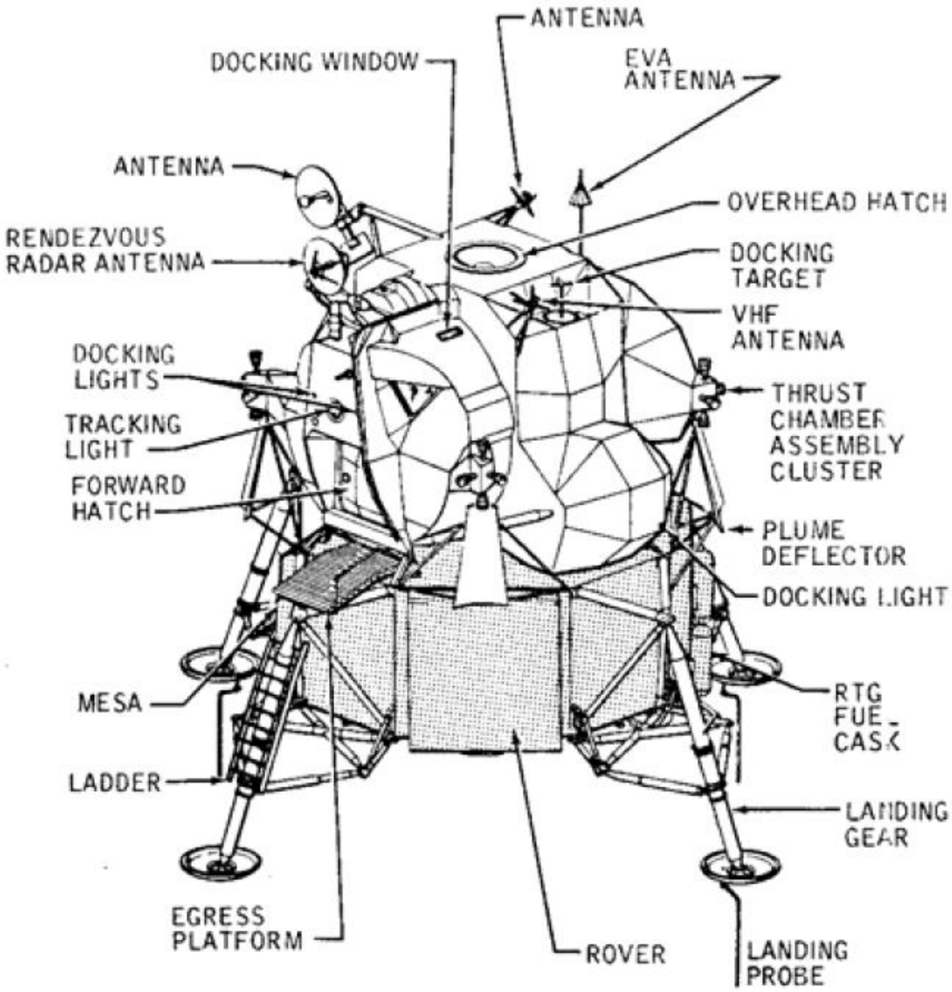

Figure 8. Lunar Module.

6.1 Ascent Stage Thermal/Meteoroid Shields

The passive thermal protection provided meteoroid protection to the LM ascent stage. The ascent stage shield was 0.004 to 0.008 inch of 2000 series aluminum alloy spaced 2 inches from the pressurized crew cabin or the fuel tanks. A 25 or more layer MLI blanket was attached to the secondary support structure by clips. An aluminum frame supported the MLI around the fuel tanks. The areas of the aluminum bumper that were near the RCS nozzles had a layer of Inconel, Inconel mesh, and nickel foil protecting the exposed bumpers from the RCS plumes [68].

Figure 9 shows the LM ascent stage on a work stand in the Grumman manufacturing area. The secondary support structure is visible over the aft equipment bay[20] and the starboard oxidizer tank. The secondary support structure tubes follow the edges of the polygons defined by the thermal/meteoroid shields with occasional cross bracing.

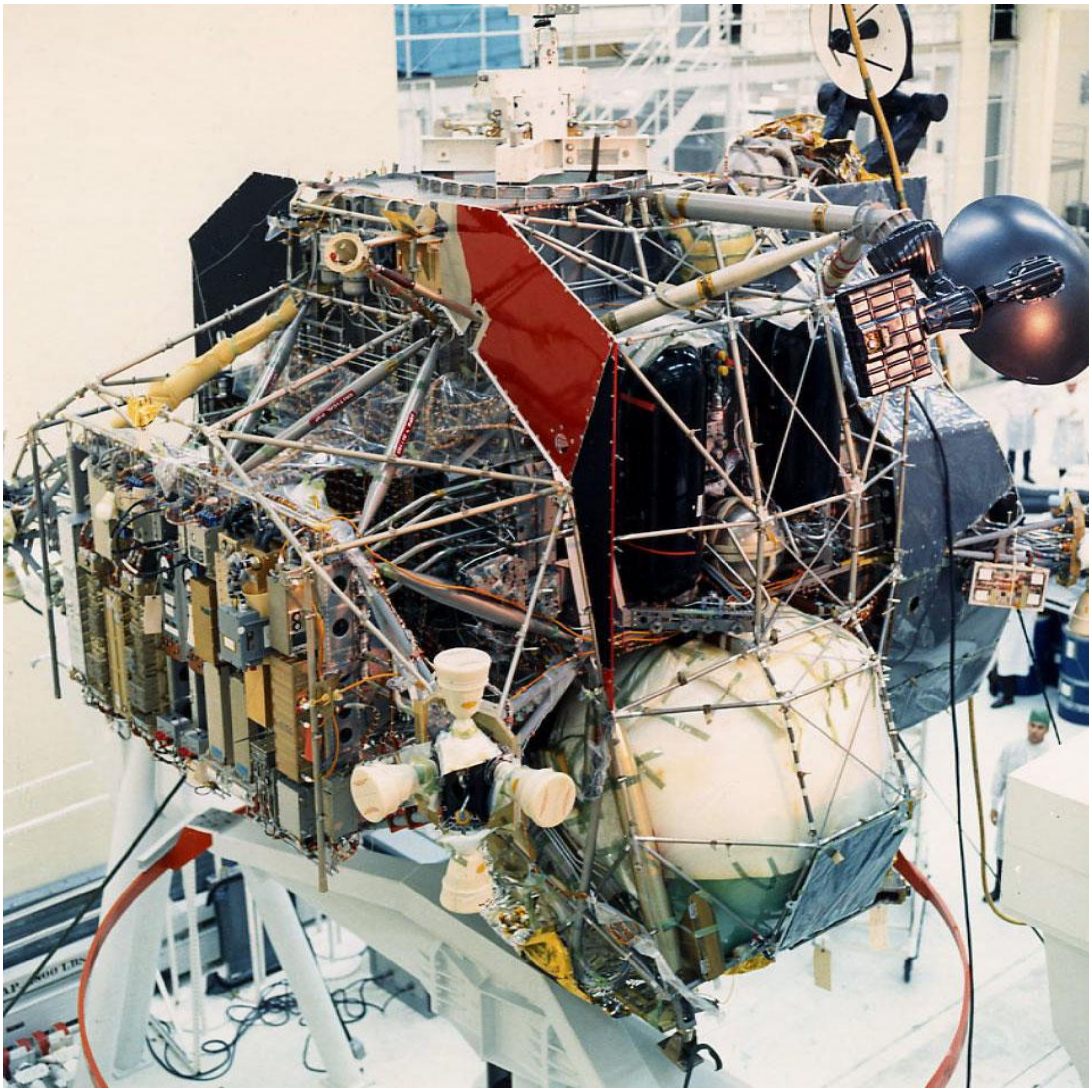

Figure 9. Thermal/meteoroid shield secondary support structure.

Figure 10 shows the LM at a later stage of the assembly. Close inspection of the photo shows that the MLI is attached to the exterior of the support structure and that there are small tabs connecting the aluminum shield to the support structure.

[20] The aft equipment bay contained two ECS oxygen tanks and two helium tanks for pressurizing the ascent stage propulsion system, batteries, and inverters.

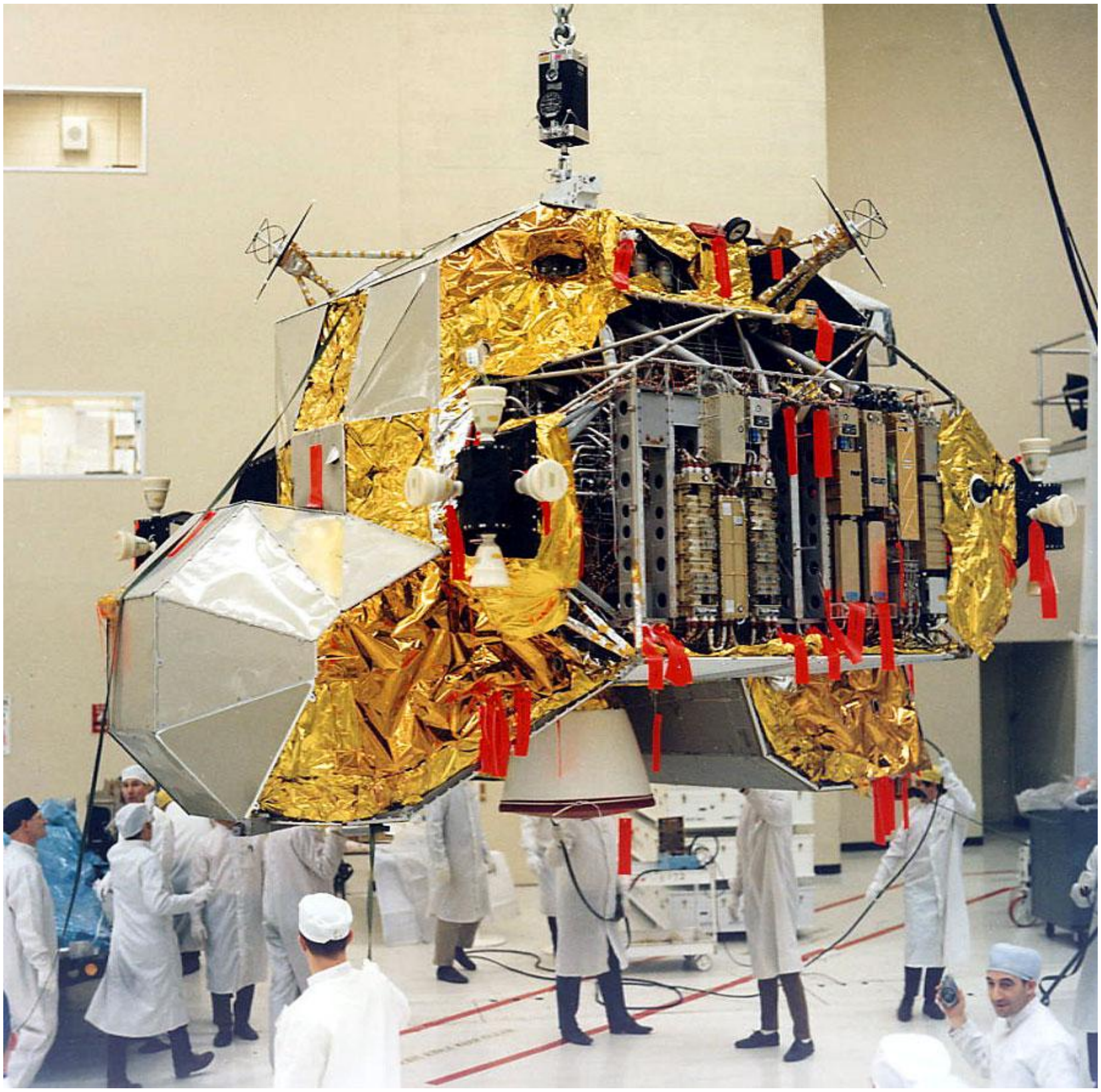

Figure 10. Thermal/meteoroid shield attachment.

The ascent stage crew cabin failure criterion was perforation of the shielded crew cabin wall. The crew cabin was the only pressure vessel on the ascent stage[21] that was not analyzed with the more conservative criterion of no penetration greater than 25% of the pressure vessel wall. This was done because the crew cabin was only pressurized to 5 psi and engineers thought that the stored energy was too small to burst the cabin following a meteoroid impact.

[21] There were 14 pressure vessels on the ascent stage. Two water tanks pressurized to 48 psi, two RCS fuel tanks pressurized to 250 psi, two RCS oxidizer tanks pressurized to 250 psi, two RCS helium pressurization tanks pressurized to 3,500 psi, one ascent engine fuel tank pressurized to 250 psi, one ascent engine oxidizer tank pressurized to 250 psi, two ascent engine helium pressurization tanks pressurized to 250 psi, and two gaseous oxygen tanks pressurized to 1,000 psi.

Although the ascent stage thermal/meteoroid shields were a low-strength, light-weight, secondary structure, only one incident involving the shields was recorded. At the Apollo 16 lunar lift-off, four vertical meteoroid/thermal shields on the aft equipment bay tore loose from the lower standoffs and remained attached only at the upper standoffs as shown in Figure 11. The most probable cause of the failure was ascent engine exhaust entering the aft equipment rack [69]. Figure 12 shows a cross section of the lower edge of the shields.

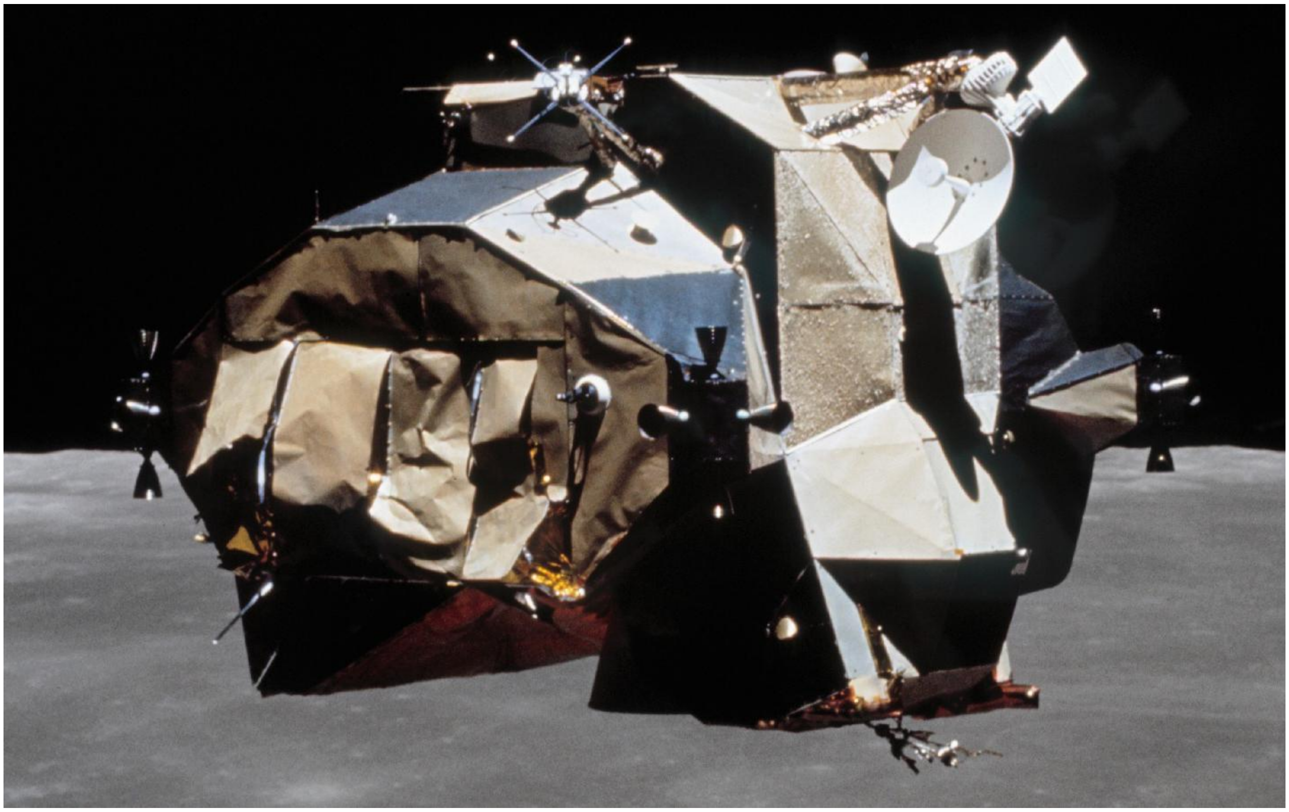

Figure 11. Apollo 16 ascent stage meteoroid bumper damage. AS16-122-19533.

The problem started with inadequate venting of the aft equipment bay MLI. Air trapped in the MLI during ascent from the Earth's surface caused the MLI to balloon outwards and press on the aft equipment bay shields until they were loosened from their supports. The loosened shields are visible in Apollo photo AS16-113-18331 taken on the lunar surface.[22] During ascent from the lunar surface, the meteoroid/thermal shield that extended below the support tube, shown in Figure 12, trapped exhaust gases on the closure shield until the pressure built up and ruptured the closure shield. The exhaust then entered the aft equipment bay and blew out the shields at the lower supports. Engineers precluded a recurrence on Apollo 17 by improving the venting of the aft equipment bay MLI and redesigning the closure shield to prevent trapping exhaust. The redesign closure shield is shown in Figure 13.

[22] The Apollo astronaut photographs are available from the online Apollo Image Atlas of the Lunar and Planetary Institute at http://www.lpi.usra.edu/resources/apollo/.

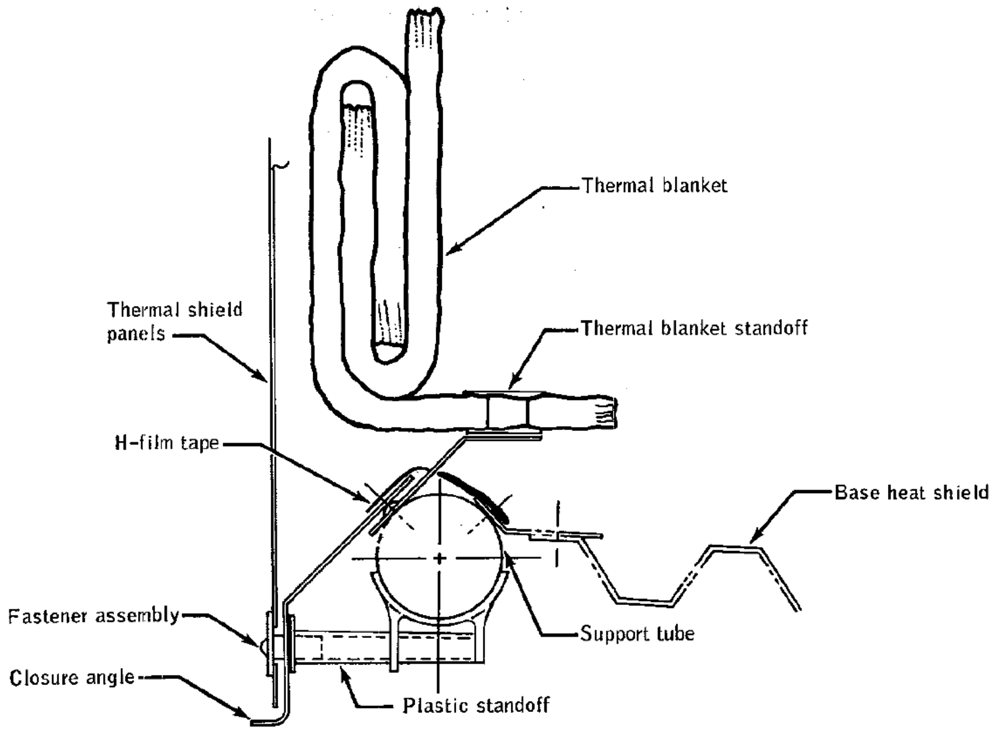

Figure 12. Cross section of the lower aft equipment bay meteoroid bumper.

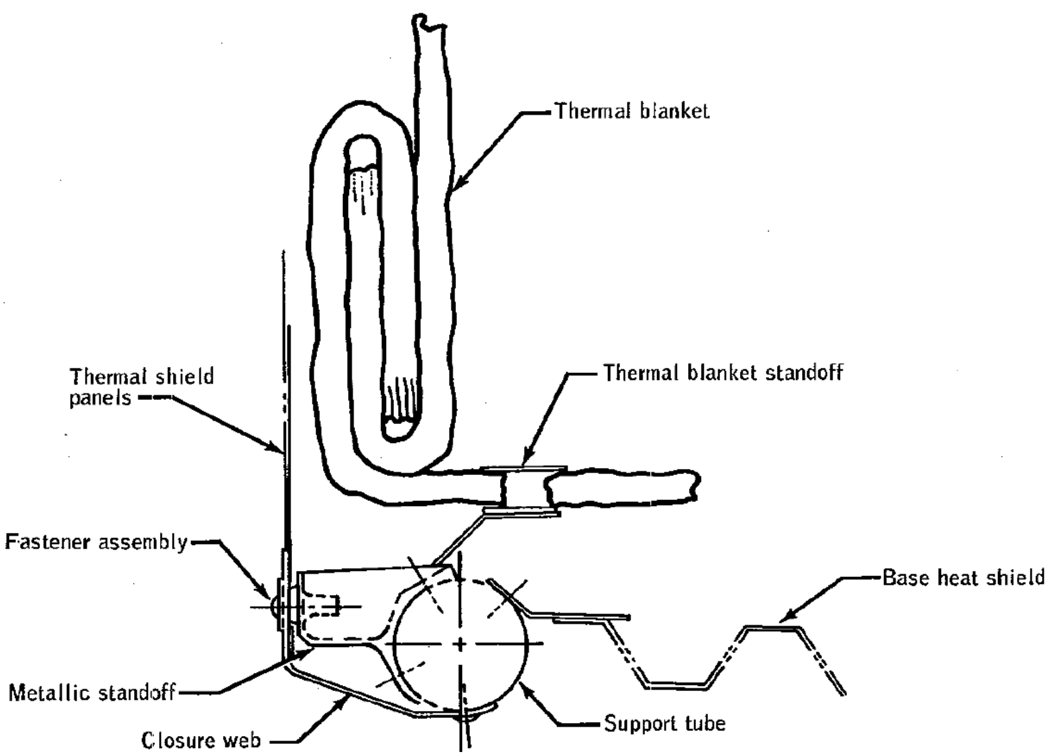

Figure 13. Redesigned lower aft equipment bay meteoroid bumper for Apollo 17.

6.2 Descent Stage Meteoroid Protection

The primary structure provided meteoroid protection for the descent stage propellant tanks. Fifty-seven percent of the exposed tank cylinder section was covered by primary structure between 0.006 to 0.007 inch thick, 25% was covered by structure between 0.010 and 0.018 inch thick, and 17% was covered by structure 0.023 or 0.032 inch thick [70].

The tank domes protruded through the primary structure upper deck, as shown in Figure 14. The ascent stage covered most of the descent stage upper deck for the duration of the mission. Only the aft oxygen tank upper dome and the starboard fuel tank upper dome were partially exposed (300 and 332 sq. inches, respectively). The upper deck thermal shield varied in thickness from 0.003 to 0.040 inch [55], [70]. The tank domes also protruded through the lower deck of the descent stage. These were covered by the base heat shield, which provided thermal protection for the structure and tanks while the descent stage motor was firing. The base heat shield was 0.010 inch thick over the lower tank domes.

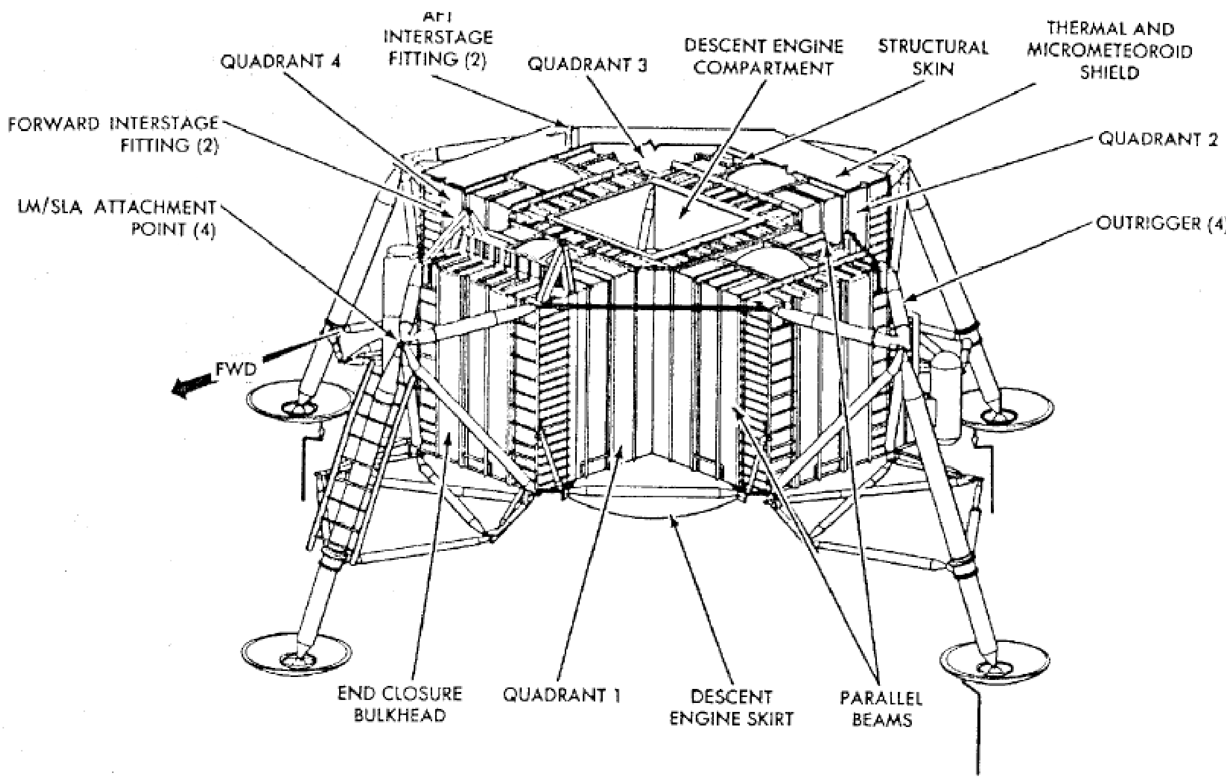

Figure 14. Lunar Module descent stage primary structure.

The total exposed area of each lower tank dome was 504 sq. inches. The meteoroid impact risk analysis of the lower domes was performed assuming the base heat shield thickness added to the thickness of the tank dome and that a 25% penetration of the tank dome thickness was allowable.

The descent stage contained four tanks on the exterior of the primary structure: a water tank for drinking and coolant in quad 2, a helium tank for starting descent stage propulsion propellant flow, a super critical helium tank for feeding the helium tank, and an oxygen tank for cabin pressurization in quad 3. (The quad locations are labeled in Figure 14.) The water and oxygen tanks needed to function up to but not including ascent, whereas the helium tanks' function was completed at touchdown. The maximum operating pressure of the water tank was 48 psi, the helium tank was 1,750 psi, the supercritical helium tank was 1,710 psi, and the oxygen tank was 3,000 psi. The tanks were behind a 0.00125-inch thick Inconel foil thermal shield on the exterior of the descent stage MLI. The Inconel protected the MLI from the RCS plumes and gave the descent stage MLI its characteristic black color. The Inconel foil was determined equivalent to a 0.004-inch thick aluminum shield, which reduced the risk of perforation meteoroids to an insignificant value.

The water tank was in the upper half of quad 2. The water tank was shadowed from below by the scientific equipment (SEQ) bay in which the Apollo lunar surface experiments package (ALSEP) was transported to the Moon. The SEQ bay had doors, covered in MLI with an Inconel foil outer layer, that were to be closed after the ALSEP was extracted [71].

The J missions added a geology equipment pallet over the three tanks in quad 3. The bump-out for the pallet deflected the RCS plume away from the descent stage, so the Inconel foil was eliminated from the side (but not top) of quad 3.

6.3 Windows

GAEC originally intended to make the forward viewing windows of Chemcor chemically tempered glass. However, hypervelocity impact testing performed at MSC [72] showed that an impact would completely shatter a tempered pane, leaving nothing in the window frame. Hypervelocity impact tests of Vycor (GE trade name for fused silica) showed that comparable impacts would not break out the window, so the decision was made to use an outer pane of Vycor for meteoroid protection and an inner pressure pane of Chemcor tempered glass. Figure 15 is a cross section of the edge of the forward window frame and the two panes of glass. The cavity between the two panes was vented to space to prevent condensation between the panes. The outer meteoroid pane was clamped to the window frame, whereas the inner pressure pane was floating (simply supported) mounted on a seal constructed from a metallic spring surrounded by a Teflon jacket [73].

The authors are uncertain of the dimensions of the panes. Cour-Palais described the initial design as two panes of Chemcor glass spaced 1 inch apart [74]. Johnson describes the revised design as a 0.125-inch thick Vycor meteoroid pane [75] and Cour-Palais said the Chemcor pressure pane was 0.085 inch thick [74]. The failure criteria Johnson evaluated were a cracked but not perforated meteoroid pane and a perforated meteoroid pane with a 1-cm hole. The final failure criterion appears to have been an impact of the meteoroid pane that spalls the rear side of the pane but does not perforate the meteoroid pane.

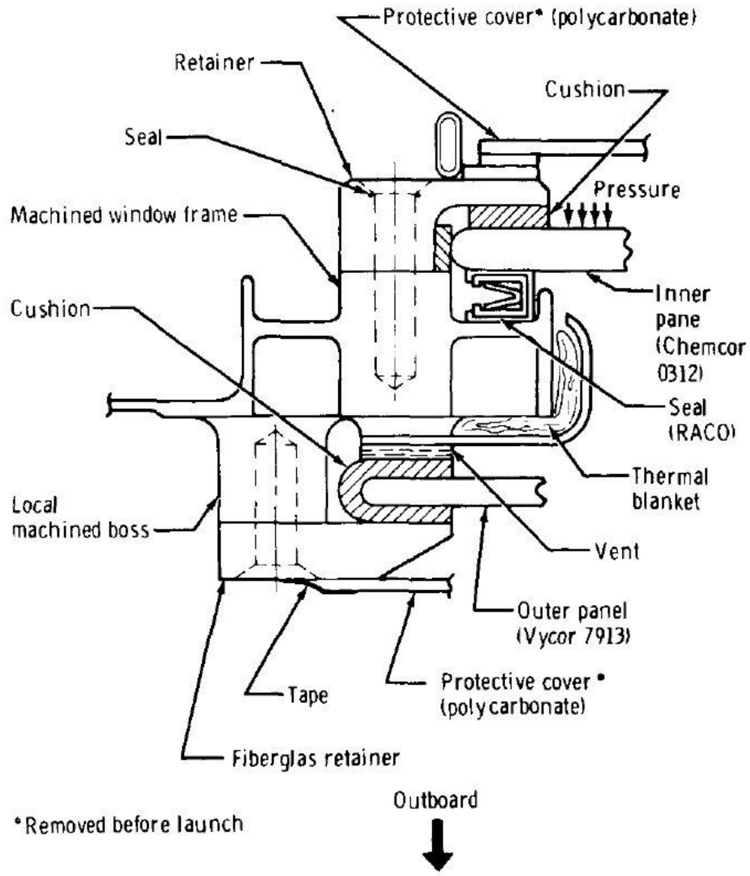

Figure 15. Lunar Module forward window Vycor meteoroid pane.

6.4 Designing the Lunar Module for the Lunar Ejecta Environment

The LM had to operate on the lunar surface as well as in cislunar space where the CSM operated. Besides the different thermal environment and the questions about whether the surface would support the LM, Ames and US Geological Survey researchers, Gault and Shoemaker, had raised the possibility that the lunar surface was shrouded in a cloud of crater ejecta fragments from meteoroids impacting the lunar surface [76]. While they thought there were 10,000 times more ejecta particles than meteoroids at any give volume of space near the lunar surface, they argued that the ejecta fragments were launched at such small speeds that they did not pose a significant risk to manned spacecraft.

The thinking at Ames is further illustrated in an article on the Ames lunar ejecta test program that appeared in the January 14, 1963 issue of Aviation Week. The Aviation Week author reported that the risk of penetration of a lunar spacecraft by ejecta was perhaps a hundredth or a thousandth the risk of penetration by meteoroid impact, but that the risk of penetration of a lunar EVA astronaut's EMU by ejecta was as large as it was for penetration by meteoroids [77].

The first LM meteoroid impact risk analysis by GE reported that the ejecta risk was negligible [15], similar to the result published in Aviation Week. However, by 1968 the risk assessment had flipped; lunar ejecta were thought to be 30% of the LM risk of penetration [55] [80] and a negligible component of the EMU risk of penetration [39]. This turn of events occurred when the ballistic limits of the EMU TMG and the LM structure were actually measured at the small impact speeds typical of lunar ejecta. The average impact speed of lunar ejecta is about 200 m/s [78], well below the 26,000 m/s impact speed of meteoroids. Measurements of the TMG's ballistic limit showed it could stop ejecta traveling at this speed [79]. However, the Whipple shields on the LM were more susceptible to penetration by small speed projectiles than they were to hypervelocity projectiles.

7.0 Extravehicular Mobility Unit

The ITMG laced to the EMU PGA protected the EMU from meteoroid impact. Figure16 shows the A7L suit that was worn on Apollo 11 with the PGA/ITMG assembly on the left and the PGA on the right. The ITMG was made of 14 layers of materials: some to maintain the PGA at a constant temperature and some to reduce the risk of a PGA leak from meteoroid impact. The ITMG layers are listed from outside to inside:

1. Teflon-coated Beta yarn (i.e., Beta cloth)
2. Two layers of gridded aluminized Kapton film/Beta marquisette laminate
3. Five layers of aluminized Mylar alternating with five layers of non-woven Dacron (the basic thermal insulation)
4. Rubber-coated nylon (ripstop)

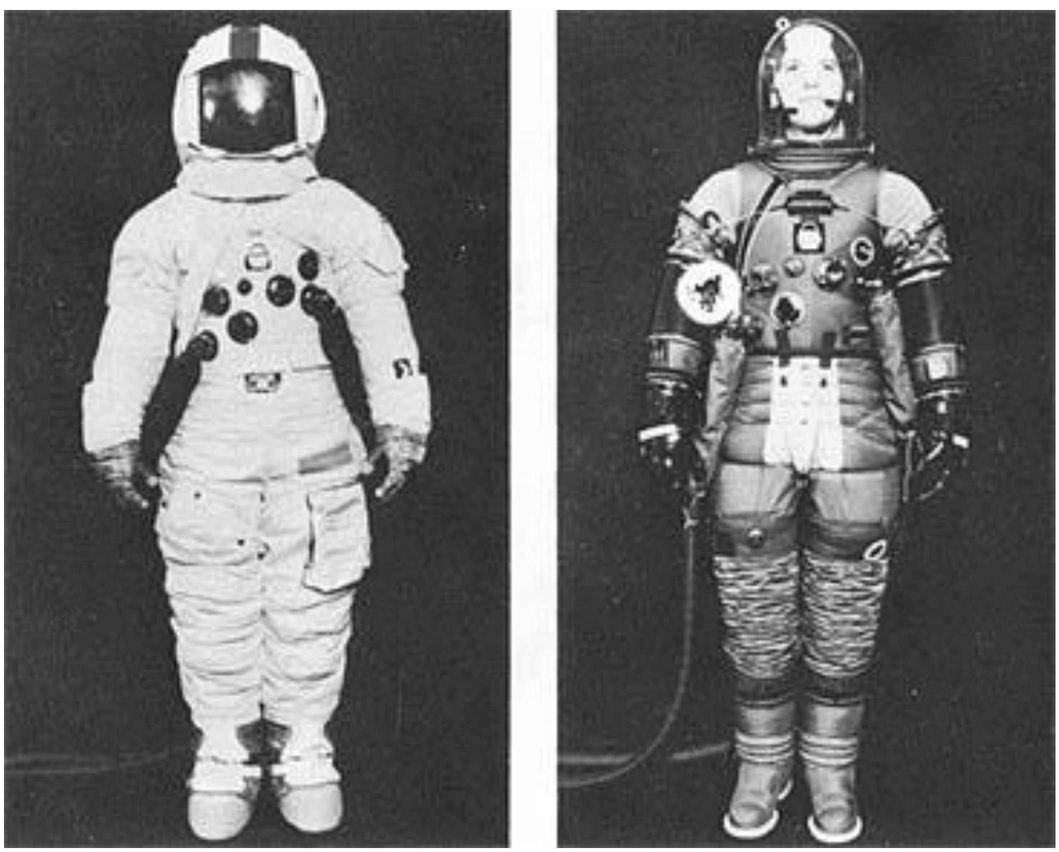

Figure 16. Apollo A7L integrated thermal/meteoroid garment (left photo) and the pressure garment assembly (right photo).

This construction was incorporated into the A7L suit used on Apollo 10 to 14 [81, Section VI - Chapter 6] and the A7LB suit [82] used on Apollo 15, 16, and 17.

The helmet and the PLSS meteoroid protection underwent fewer design changes than the ITMG. Early on, engineers determined the helmet and the PLSS structure were inherently resistant to micrometeoroid impact. Figure 17 shows the PLSS construction. The PLSS mechanism was mounted to the blue fiberglass frame shown on the left in Figure 17. This frame was on the exterior of the PLSS and would receive the initial strike of a micrometeoroid impacting the PLSS. The fiberglass frame was robust; the risk of a micrometeoroid perforating the frame so that debris from the impact would strike the PLSS mechanism was estimated in February 1966 as an order of magnitude less than the risk of an ITMG perforation [39].

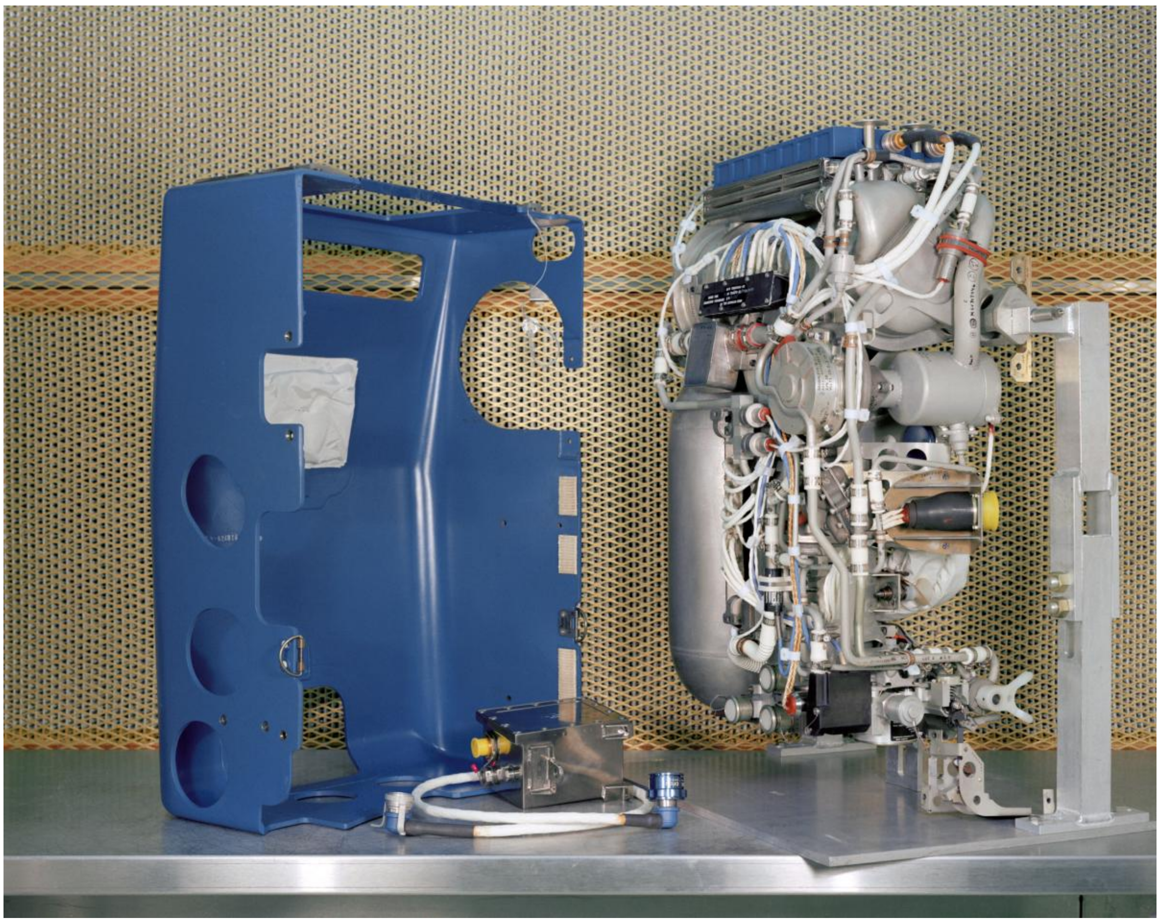

Figure 17. Portable Life Support System. S68-34580.

The development of the Apollo EMU meteoroid protection started in 1964 with the design of the Gemini EVA space suit MPG. Initially, MSC engineers used a powder gun to perform low-speed tests until the two-stage light gas was installed. IITRI performed the first soft goods hypervelocity impact tests for MSC under purchase order before April 1964 [83]. The IITRI test engineers were unable to reliably separate the sabot from a single 1/64-inch diameter projectile, so several projectiles were loaded in the sabot and a 1/2-inch aluminum plate with a small hole was used to filter all but one projectile. The ITTRI tests impacted a concept from the Gemini space suit SOW, which was composed of the following lay-up (outside to inside) and weighed a total of 8.81 oz/sq. yd.:

1. One layer of high temperature (HT-1) Nylon fabric
2. Seven layers of ¼-mil Mylar, aluminized, for thermal insulation
3. Seven layers of unwoven Dacron spacers between the ¼-mil Mylar
4. One Nylon layer

The testing determined that a fabric would stop the same size hypervelocity projectile as a 0.0117-inch thick sheet of 2024 aluminum. Based on this equivalency, McAllum concluded that the Gemini cover layer needed to weight 0.0807 g/sq. cm (23.8 oz/sq. yd) to meet the Gemini risk requirement. The final design for the G4C space suit protective cover designed for Ed White's Gemini IV spacewalk on June 3, 1965, was composed of the following layers:

1. One layer of HT-1 Nylon cloth
2. One layer of HT-1 Nylon felt
3. Seven layers of aluminized Mylar separated by seven layers of unwoven Dacron spacers. (i.e., MLI)
4. Two layers of HT-1 Nylon cloth

This design weighed 0.096 g/cm^2 and proved to be quite bulky. The bulk intentionally came from the HT-1 Nylon felt.[23] The felt was referred to as an absorber and provided the spacing between the outer HT-1 Nylon layer bumper and the inner two layers of rear wall. MSC engineers qualified this design for 135 minutes of exposure in the engineering criteria bulletin one (EC-1) meteoroid environment.

The Gemini IV protective cover impact testing development schedule can be further refined from the available sources. As mentioned above, the initial testing started with the MSC powder gun and ITTRI performing a few hypervelocity tests in early 1964. The low-speed testing was concluded when the MSC two-stage light gas gun was operational [63], [83], [84]. The hypervelocity testing with the MSC two-stage light gas gun began in July 1964 and continued through September 1964 (See Appendix D). Developmental impact testing finished before November 1964 [85]. Engineers communicated the design to the suit contractor in time for a prototype G4C suit with a thermal/meteoroid cover layer to be delivered to the NASA CSD on December 28. Zero-g tests in an aircraft were performed during January. The astronauts determined that the suit was too awkward due to the cover layer. As a result, the cover layer was redesigned to remove excess bulk and was retested in February when it was pronounced satisfactory [86, Part II (B)]. The Gemini IV space walk followed on June 3, 1965.

The Gemini protective cover layer development was ongoing and it was improved for the next EVA scheduled to be performed during Gemini VIII in March 1966. The improved protective cover layer was composed of the following layers:

1. One layer Nylon cloth
2. Seven layers of ¼-mil Mylar (with seven spacers) thermal insulation
3. Two layers of Neoprene on ripstop

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[23] HT-1 Nylon is now called Nomex.

The improved cover layer design weighed 0.075 g/cm^2 (22.1 oz/sq. yd), but more importantly it was thinner and hence less bulky. This design was used for the remainder of the Gemini program.

The thermal and meteoroid protection for the Apollo EMU was originally conceived of as garments that the astronaut would don before an EVA. Figure 18 shows one such garment circa August 1964 from Reference 87. The photo shows astronaut Walt Cunningham evaluating the EMU and mobility aids at the Big Obsidian Flow in the Newberry National Volcanic Monument near Bend, Oregon.[24] This is one of the sites used then to represent the lunar surface. Another representative site was sandy. This particular garment met the current thermal requirements, but did not meet the meteoroid protection requirements [88].

Testing to determine how many extra layers were needed for the meteoroid protection started with low-speed powder gun tests, like the Gemini protective garment design. The low-speed tests were directly relevant to the Apollo garment because of the low-speed lunar ejecta threat. MSC performed powder gun tests and also contracted low-speed tests with URDC. McAllum [84] lists the MSC results from testing at 350 m/s, URDC compressed air gun results at ~200 m/s, and URDC results from their 22-caliber powder gun.

Figure 18. AX3H-024 thermal meteoroid garment.

[24] http://www.fs.fed.us/r6/centraloregon/newberrynvm/trivia-bof.shtml

The MSC two-stage light gas gun was available in June 1964. By January 1965, the baseline lay-up for the Apollo meteoroid protective garment was composed of the following materials [19]:

1. Dacron fabric outer layer
2. MLI (seven layers)
3. Dacron fabric liner
4. 0.5-inch thick Tri-Lock
5. Nomex felt
6. HT-1 Nylon fabric
7. Nomex felt
8. HT-1 Nylon fabric

The mass-per-unit area of the garment was 46.2 oz/sq. yd (0.157 g/cm^2) and the total thickness was 1 inch. It was designed for the new, smaller, 0.999 probability of mission success requirement and reduced exposure duration of 18 hours in the EC-1 meteoroid environment. This MPG needed to stop a meteoroid with a kinetic energy equivalent to a 1.6-mm glass sphere traveling at 6.5 km/s [89], hence the large design thickness.

Other changes were also under way. On February 18, 1965, the MSC CSD rebaselined the ETG and the MPG as a single garment: the TMG. The division also deleted the requirement for a separate meteoroid visor because MSC impact testing had shown the thermal and glare visors provided ample protection against meteoroids as well [90].

There was push back from the MSC ASPO Systems Engineering Division that questioned whether the weight and storage volume requirements could be met with a TMG [91]. Johnston emphasized, if for any reason the integration scheme proved impracticable, the division could still return to the concept of separate thermal and micrometeoroid garments [92]. Ultimately CSD obtained agreement to go to a TMG and Johnston was authorized to request a contract change proposal on April 21, 1965 [93].

The TMG PDR was held on June 10, 1965, when the TMG was again divided into separate thermal and meteoroid garments. One of the outstanding issues from the prior month's discussion on thermal and meteoroid garment integration was providing thermal protection during a contingency EVA from the LM to the CSM in lunar orbit following ascent from the lunar surface. This was resolved at the PDR by MSC directing HS to integrate the thermal layers with the second A5H suit. MSC management desired to retain the meteoroid protection as a separate garment because engineering might change the meteoroid protective garment design due to new test data and a recent reduction of protection requirements [94].

A change in meteoroid protective garment design was in store because of the data returned by the Pegasus 1, 2, and 3 meteoroid detection satellites. The satellites were launched on February16, May 25, and July 30, respectively, and showed that the micrometeoroid environment was significantly smaller than the EC-1 design environment. The total fluence for the 24-hour Apollo EVA was now thought by MTOB engineers to be smaller than the design fluence for the 135-minute Gemini EVA. This meant Gemini VIII's previously developed protective cover layer was sufficient for the Apollo mission [95].

This was made official on January 3, 1966, when MSC directed International Latex Corporation (ILC)[25] to use the Gemini VIII protective cover layer lay-up to fabricate the A6L TMG [36, p. 243].

The Block II EMU Design Reviews (based on the A6L suit) were completed nearly a year later during November and December 1966. Because of the bulk of the space suit, astronaut mobility on the lunar surface was a continuing problem. Hoping that some of the suit layers could be removed, the program requested additional tests with every change. One example, from January 18, 1967, is a request for testing a PGA with an added cover layer of HT-1 for intravehicular activity (IVA) snag protection with a meteoroid protective garment with one of the neoprene-coated nylon rip-stop layers removed [96]. The HT-1 Nylon layer was significantly thinner than the neoprene rip-stop and would have improved astronaut mobility. This request was overcome by events with the Apollo 1 fire on January 27.

The Apollo 1 fire prompted numerous EMU revisions. During the Apollo 1 fire, the HT-1 Nylon outer layer burned in a pure oxygen atmosphere, so the HT-1 was replaced with Beta cloth – a cloth woven from Teflon-coated glass fibers that will not burn. Another change included attaching the meteoroid protective garment to the PGA to protect the astronaut from fire whenever wearing the space suit. The TMG would now be called the ITMG to reflect its new construction. The fire protection was further enhanced by replacing the outer two layers of Mylar MLI with two layers of Kapton sandwiched with layers of Beta fabric marquisette. The remainder of the MLI still consisted of five layers of aluminized Mylar sandwiched with Dacron scrim and two layers of neoprene-coated nylon rip-stop [87].

The replacement of the Nylon bumper layer with Beta cloth caused the program to question the new ITMG's ability to meet the meteoroid protection requirements. The ASPO requested impact tests of the new lay-up, and the MSC Meteoroid Sciences Branch[26] conducted a 12-shot test campaign whose results were summarized in a May 16 memo [41]. The testing revealed that the revised ITMG lay-up had a 0.99958 probability of no penetration for a 24-hour exposure in the January 24, 1967, DS-21 Rev. A environment.

The ITMG CDR was held on September 7 through 8, 1967, at ILC Dover using this design, and a prototype ITMG was installed on suit A6L-009 for review [97], [98]. The first article configuration inspection was scheduled for October 13, 1967 [98].

With the EMU revisions, the astronauts continued to have issues with the ITMG restricting mobility. On February 21, 1968, the Astronaut Office requested the ITMG design and requirements be reevaluated to improve mobility [20]. The EMU Design Review Board requested on March 18, 1968, that the Meteoroid Sciences Branch test an ITMG with only one layer of neoprene-coated nylon rip-stop. The first results were reported on April 19, 1968 [99], and further results were reported on June 12, 1968 [21]. The conclusion was that this design could meet only a 0.999 requirement if the requirement were changed from a 0.999 probability of no leak to a 0.999 probability of no more than one leak at a rate above 60

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[25] Because of ongoing issues between Hamilton Standard and ILC, the provider of the PGA, MSC assumed the EMU integrator role on November 5, 1965, when the EMU contract was divided between HS and ILC. HS was to provide the PLSS and ILC was to provide the PGA [36, p. 199-201].

[26] The Meteoroid Sciences Branch was formed from the former Meteoroid Technology and Optics Branch in January 1967. Cour-Palais was now branch manager and Burbank was promoted to division deputy manager.

ml/min. This change required buy-in from the Medical Directorate whose position on the requirements change was requested by May 31, 1968 [100].

The final result of these changes was an ITMG constructed of the following material:

1. One layer of Teflon-coated Beta yarn (i.e., Beta cloth)
2. Two layers of gridded aluminized Kapton film/Beta marquisette laminate[27]
3. Five layers of aluminized Mylar alternating with five layers of non-woven Dacron (the basic thermal insulation)
4. One layer of rubber-coated nylon (ripstop)

This construction was incorporated into the A7L suit used on Apollo 10 to 14 [81, Section VI - Chapter 6] and the A7LB suit [82] used on Apollo 15, 16, and 17.

8.0 Epilog

Neil Armstrong and Buzz Aldrin successfully piloted Apollo 11 to the lunar surface on July 20, 1969. The spacecraft crew cabin in which they traveled was engineered to protect them from meteoroid impact using thin aluminum shields. When walking on the lunar surface, the astronauts were protected by their space suits made from layers of materials designed to stop meteoroids and lunar ejecta. The spacecraft waiting in lunar orbit, and which would return Armstrong, Aldrin, and Mike Collins to the Earth, consisted of a honeycomb skin that had been, in part, selected to protect the propellant tanks from meteoroid impacts.

However, the mission also was possible without two types of shielding initially designed for the spacecraft. The large uncertainty over the design meteoroid environment led to the inclusion, by June 1964, of 400 lbs of meteoroid shielding between SM honeycomb skin and the SPS propellant tanks. The environment situation became clearer with the launch of the Pegasus meteoroid detection satellites in February, May, and July 1965. Pegasus showed that the design environment was too severe, and the SM propellant tank intermediate shields were eliminated in 1966. The second shield types eliminated were the meteoroid window panes that covered the CM thermal panes. The NAA Engineering Review Board approved the meteoroid panes in September 1965 adding 23 lbs to the CM weight. However, with a refinement of the failure criterion, it proved possible to eliminate the meteoroid panes in October 1967.

With the application of significant NASA and contractor engineering resources between 1963 and 1966, MSC was able to retire the programmatic risk posed by meteoroid impact and close the requirements with the design. However, the requirements had evolved during design. The original CSM SOW was released with a requirement to design meteoroid protection, but with no required probability of aborting a mission due to meteoroid impact. By 1963, Headquarters set a goal of 0.999 probability of mission success, but MSC analyses showed that 0.999 was unobtainable. The requirement was eventually set at a 0.99 probability of mission success by March 1966, and this remained the requirement until the end of the program.

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[27] 2-inch griding with Polyemite tape is employed in the arm and knee areas; 4-inch griding is provided in all other areas.

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Appendix A: Meteoroid Protection Timeline

1961

25 May: President Kennedy announces the goal of landing an American on the Moon before the end of the decade.

28 November: North American Aviation awarded the CSM contract.

1962

April: Hamilton Standard awarded the EMU contract.

August: GE Apollo Support Department office set up in Houston [34, p. 119].

7 November: Grumman awarded the LEM contract.

November: Two-stage light gas gun testing of Apollo CSM components begins at GMDRL under contract to NAA. (Contract negotiations were underway 30 October, 1962 [49].)

1963

February: Space Environment (Division) formed at MSC.

April: NASA TN D-1767 by Gault and Shoemaker released detailing the lunar ejecta environment [76].

9-10 April: Office of Advanced Research and Technology, Headquarters (OART) meteoroid meeting at which Cour-Palais presents the current MSC environment model. (Different from EC-1.)

8 November: EC-1 meteoroid environment published. (Available from the NASA Technical Report Server as Ref. [101] and [102].)

1964

January: MSC 30-caliber two-stage light gas gun installation at Ellington AFB under way. [50]

April: Block I CSM Mockup Review Board [34, p. 138]. Similar to a PDR.

June: Testing starts on the MSC two-stage light gas gun.

11 June: North American authorized to add meteoroid protection to the Service Module.

July: GMDRL placed under contract to develop penetration equation for SM honeycomb.

29 September: Block II CSM Mockup Review Board [34, p. 140].

5-8 October: LM M-5 mockup review board. (Last of the LM mockup reviews [34, p. 161-162].)

1965

January: EMU meteoroid protective garment and external thermal garment combined into a thermal meteoroid garment.

5 January: MSC ASPO meteoroid protection subsystem office established.

16 February: Pegasus 1 meteoroid detection satellite launched. Pegasus 2 launched 25 May and Pegasus 3 launched 30 July.

18 February: Requirement for an EMU visor assembly meteoroid cover eliminated.

10 June: Thermal meteoroid garment PDR [94].

July: First GMDRL report on SM honeycomb penetration equation produced under MSC contract NAS9-3081.

July: GMDRL completes the NAA test program.

12 July: GE completes Block II CSM CDR meteoroid analysis.

August: NAA completes Block II CSM CDR meteoroid analysis.

September: NAA adds a meteoroid pane to the CM windows.

September: GAEC removes the aluminum thermal/meteoroid shields from the LM descent stage [34, p. 175, footnote 20].

October: GAEC finishes LM CDR analysis. (Analysis was presented verbally at the January 1966 CDR.)

5 November: EMU contract split between ILC (PGA and TMG) and Hamilton Standard (PLSS).

December: Block II CSM CDR completed. Subsystem CDRs started around February.

December: NRL completes the light gas gun testing of Apollo heat shield materials.

1966

3 January: ILC directed to use the Gemini VIII protective cover layer design for the Apollo TMG.

January: LM Critical Design Review for LM-4 completed [103].

April: Avco completes the light gas gun testing of Apollo heat shield materials.

5 May: Last GE Block II CSM meteoroid analysis for a lunar mission. (This was followed by a 24 May heat shield meteoroid analysis and an 18 October SM RCS subsystem analysis.)

15 August: Change orders SCN 3-9 and 3-10 to Headquarters environments document M-D E 8020.008B are approved. This change incorporated the Pegasus meteoroid detector satellite results as a single segment fit.

7 October: Block I CSM Design Certification Review held at NASA HQ.

12 October: Change DS-21 REVA to the MSC meteoroid environment started. (Kessler was the originator, org EF421. Incorporated the Pegasus meteoroid detector satellite results as a three-segment fit.)

November: Last GMDRL test and analysis report produced under contract NAS9-3081. (Released as NASA CR-915 in January 1968.)

17 November: GAEC submits LM CDR analysis. (Analysis was performed in October 1965.)

1967

first half: MSC gas gun moved from Ellington AFB to the recently opened Building 31.

January: Meteoroid Sciences Branch establish (TG2).

27 January: Apollo 1 fire.

7-8 September: ITMG CDR.

5 October: Master Change Record A4264 signed eliminating the meteoroid pane from the CM windows [66].

1968

February: GE delivers LM-4 meteoroid analysis.

6 March: LM-3 Design Certification Review held at MSC. (LM-3 was flown on Apollo 9. A delta DCR was held on 7 August to close out action items.)

June: ITMG requirement changed to a probability of no leak greater than 50 ml/min to allow the second layer of neoprene-coated nylon ripstop to be removed from the ITMG.

10-11 July: Block II CSM Design Certification Review held at MSC. (Action items closed by 13 August.)

8-9 October: OART Meteoroid Impact and Penetration Workshop, Houston, TX.

Appendix B: Acronyms

ABMA	Army Ballistic Missile Agency
AFB	Air Force Base
ALSEP	Apollo lunar surface experiments package
ASPO	Apollo Spacecraft Project Office, Manned Spacecraft Center
CCB	Configuration Control Board
CDR	critical design review
cm	centimeter
CM	Command Module
CR	contractor report
CSD	Crew Systems Division, Manned Spacecraft Center
CSD	Criteria and Structural Development, North American Aviation
CSM	Command and Service Module
DRM	Design Reference Mission
EC-1	engineering criteria bulletin one
ECS	Environmental Control System
E&D	Engineering and Development
EMU	Extravehicular Mobility Unit
EPS	Electrical Power System
ETG	external thermal garment
EVA	extravehicular activity
GAEC	Grumman Aircraft Engineering Corporation
g/cm^2	grams per square centimeter
g/cm^3	grams per cubic centimeter
GE	General Electric
GMDRL	General Motors Defense Research Laboratories
HS	Hamilton Standard
HT-1	high temperature Nylon
ICBM	Intercontinental Ballistic Missile
IITRI	Illinois Institute of Technology Research Institute
ILC	International Latex Corporation
ISS	International Space Station
ITMG	integrated thermal micrometeoroid garment
IVA	intravehicular activity
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
km/s	kilometers per second
lb	pound
LEM	Lunar Excursion Module
LM	lunar module

mil	thousandths of an inch
ml/min	milliliter/minute
MLI	Multilayer Insulation
MPG	meteoroid protection garment
m/s	meters per second
MSC	Manned Spacecraft Center
MTOB	Meteoroid Technology and Optics Branch
NAA	North American Aviation
NACA	National Advisory Committee for Aeronautics
NAR	North American Rockwell
NASA	National Aeronautics and Space Administration
NTRS	NASA Technical Report Server
OART	Office of Advanced Research and Technology, Headquarters
OMSF	Office of Manned Space Flight
oz/sq. yd	ounces per square yard
PDR	Preliminary Design Review
PGA	pressure garment assembly
PLSS	portable life support system
psi	pounds per square inch
RCS	reaction control system
RECP	Request for Engineering Change Proposal
SEQ	scientific equipment
SLA	spacecraft/lunar module adapter
SM	service module
SMD	Structures and Mechanics Division, MSC ASPO
SOW	statement of work
SP	special publication
SPS	Service Propulsion System
sq	square
SWIP	Super Weight Improvement Program
TIR	technical information release
TMG	thermal meteoroid garment
TN	technical note
URDC	Utah Research and Development Corporation
U.S.	United States

Appendix C: Manned Spacecraft Center Reports

1. Burton G. Cour-Palais, "Meteoroid Environment and Structural Reliability," NASA Working Paper No. 1077, NASA Manned Spacecraft Center, Houston, TX, June 12, 1963.
2. "Particle Accelerators for Hypervelocity Impact Investigations," MSC Internal Note No. 64-EA-4, NASA Manned Spacecraft Center, Houston, TX, January 31, 1964.
3. Paige B. Burbank, Burton G. Cour-Palais, and William E. McAllum, "Application of the Meteoroid Environment to the Apollo Mission," Internal Report MSC IN 64-EA-18, NASA Manned Spacecraft Center, Houston, TX, April 9, 1964.
4. William E. McAllum and K. Kotila, "Preliminary Low Velocity Tests for Armor Space Suit Configuration," Internal Report MSC IN 64-EA-25, NASA Manned Spacecraft Center, Houston, TX, April 10, 1964.
5. Paige B. Burbank, Burton G. Cour-Palais, and William E. McAllum, William E., "A Meteoroid Environment for Near-Earth, Cislunar, and Near-lunar Operations," NASA General Working Paper No. 10,017, NASA Manned Spacecraft Center, Houston, TX, May 11, 1964.
6. William E. McAllum, "A Rudimentary, Empirical Relationship of Hard and Soft Suits to the Meteoroid Environment," Internal Report MSC IN 64-ET-41, NASA Manned Spacecraft Center, Houston, TX, July 14, 1964.
7. Burton G. Cour-Palais, "The Ballistic Limit and Impact Efficiency Factors of the Apollo Service Module and Alternative Structural Configurations," Internal Report MSC IN 64-ET-46, NASA Manned Spacecraft Center, Houston, TX, July 24, 1964.
8. William E. McAllum, "Preliminary Low Velocity Tests of Space Suit Materials," Internal Report MSC IN 64-ET-49, NASA Manned Spacecraft Center, Houston, TX, July 29, 1964.
9. Donald Kessler and Robert E. Patterson, "Determination of the Critical or Design Meteoroid Mass for Major Streams and Sporadics," Internal Report, MSC IN 64-ET-48, NASA Manned Spacecraft Center, Houston, TX, August 5, 1964.
10. Paige B. Burbank, Burton G. Cour-Palais, and William E. McAllum, "A Meteoroid Environment for Near-Earth, Cislunar, and Near-lunar Operations," National Aeronautics and Space Administration, Washington DC, NASA TN D-2747, April 1965.
11. William E. McAllum and Paige B. Burbank, "Development of Meteoroidal Protection for the Extravehicular Gemini Space Suit," Internal Report, MSC IN 65-ET-30, NASA Manned Spacecraft Center, Houston, TX, July 28, 1965.
12. Burton G. Cour-Palais, "Meteoroid Environment Model - 1969 [Near Earth to Lunar Surface]," National Aeronautics and Space Administration, Washington DC, NASA SP-8013, March 1969.
13. Donald G. Kessler, "Meteoroid Environment Model - 1970 [Interplanetary and Planetary]," National Aeronautics and Space Administration, Washington DC, NASA SP-8038, October 1970.
14. Robert E. Flaherty, "A Study of low-velocity impacts into thin-sheet aluminum and nylon cloth," National Aeronautics and Space Administration, Washington DC, NASA TN D-6324, May 1971.

Appendix D: General Electric Reports

The following is a list of the meteoroid impact risk reports written by GE under a task order contract with MSC.

1. TIR 545-I-20-001. Service Module Radiator Analysis Environmental Control System and Electrical Power System. February 7, 1964.
2. TIR 545-G-185. Service Module Tanks Analysis: Propellant Tanks and Cryogenic Tanks. April 15, 1964.
3. TIR 545-S05-4000. Preliminary Estimates of the Probability of Crew Safety (LEM). 20-November 20, 1964.
4. TIR 545-S03-4002. Analytical Optimization of the Meteoroid Shielding Weight for Space Vehicles. November 20, 1965.
5. TIR 545-OP01-4004A. Study of the Meteoroid Protection Requirements for Command/Service Module and Lunar Excursion Module. December 4, 1964.
6. TIR-545-S05-4001. LEM Meteoroid Protection Optimization. December 15, 1964.
7. TIR 545-S05-5002. LEM Parametric Studies and Analysis. April 22, 1965.
8. TIR 545-S2.5-5002. Preliminary Estimate of the Mission Success Probability for Block I and II Command and Service Modules. July 13, 1965.
9. TIR 580-S-5106. Meteoroid Analysis of the Command Module Windows. August 11, 1965.
10. TIR 580-S-5117. Interim Report on Meteoroid Confidence Level Evaluation Task. September 30, 1965.
11. TIR 580-S-5138. Preliminary Meteoroid Analysis of the Thermal-Meteoroid Garment (TMG). September 30, 1965.
12. TIR 580-S-5141. Apollo Meteoroid Design Evaluation Curves. November 2, 1965.
13. TIR 580-S-5142. Preliminary Meteoroid Analysis of the LEM Windows. October 5, 1965.
14. TIR 580-S-5186. Meteoroid Analysis of the LEM with no Aluminum Thermal Shield. November 15, 1965.
15. TIR 580-S-5186 Addendum A. Meteoroid Analysis of the LEM with Aluminum Thermal Shield Removed. November, 19, 1965.
16. TIR 580-S-6007. Evaluation of the Relative Meteoroid Hazard to the Windows of the Mercury Gemini and Apollo Spacecraft. January 11, 1966.
17. TIR 580-S-6018. Preliminary Estimate of the Probability of Astronaut Safety during Exposure to the Lunar Surface Meteoroid Environment. February 14, 1966.
18. TIR 580-S-6048. Proposed LEM Meteoroid Failure Criteria. March 16, 1966.
19. TIR 580-S-6056. Meteoroid Analysis of Block II Service Module Radiators. March 18, 1966.
20. TIR 580-S-6058. Investigation of the Velocity Exponent in Hypervelocity Penetration. April 21, 1966.
21. TIR 580-S-6060. Task Description (Meteoroid Effects Analysis). April 4, 1966.
22. TIR 580-S-6078. Meteoroid Analysis of Proposed Block I CM Hatch Windows. April 18, 1966.
23. TIR 580-S-6088. Meteoroid Analysis of the Block II Command and Service Modules. May 5, 1966.
24. TIR 580-S-6101. Apollo Heat Shield Penetration Probabilities using the NAA and MSC Penetration Equations. May 24, 1966.
25. TIR 580-S-6102. Meteoroid Analysis of the LEM Descent Stage Engine Nozzle. May 24, 1966.

26. TIR 580-S-6116. Mission Success Probability Estimate of LEM Based on Primary Meteoroid Environment. June 21, 1966.
27. TIR 580-S-6128. Lunar Module Analysis for Secondary Meteoroid Hazard. July 12, 1966.
28. TIR 580-S-6129. Review of NAA Meteoroid Damage Equation. July 18, 1966.
29. TIR 580-S-6200. Meteoroid Analysis of SM RCS Tanks. October 18, 1966.
30. TIR 580-S-7203. Trip to GAEC Bethpage Long Island. December 4, 1967.
31. TIR 580-S-8006. LM Meteoroid Analysis: Assumptions and Criteria. January 11, 1968.
32. TIR 580-S-8034. Lunar Module Analysis for Meteoroid Hazard. February 2, 1968.
33. TIR 580-S-8034 Rev A. Revision of Lunar Module Analysis for Meteoroid Hazard. February 29, 1968.
34. TIR 580-S-8049. Working Data and Notes from LM 4 Meteoroid Analysis. February 9, 1968.
35. TIR 580-S-8080. The Effect of Variations in Meteoroid Penetration Criteria on Lunar Module Probability of Mission Success. March 6, 1968.

Appendix E: Manned Spacecraft Center Impact Test Requests

A rough date for the commissioning of the MSC two-stage light gas gun can be inferred from surviving test request sheets and test records. Cour-Palais's files contained a bundle of EMU test request sheets [104] from June 1964 to October 1964. They all request tests at 6 km/s, probably indicating that the light gas gun was available during that time. Burbank released a memo on October 22, 1964, requesting the experimenters write a one-page description of test goals and a test description for submission to a biweekly review panel that would set priorities [105]. This memo could indicate that testing started in October, or more likely, that the gun was already up and running but oversubscribed and required some scheduling. Patterson's October 28, 1964, Phase II test request, made only 6 days after Burbank's memo (and includes the fill-in box for priority mandated by Burbank's memo, that was missing from prior test request sheets), supports this supposition. It seems likely that Phase I of Peterson's tests occurred before October 22, 1964, to allow enough time for the tests to occur. The horizontal line in Table E-1 separates the Reference 104 test requests from the Reference 105 requests.

Table E-1. Test Request Sheets

Request Date	**Originator**	**Task Title**
Jun 1964	W. McAllum	Apollo suit
Jul 1964	W. McAllum	2.8 and 6.0 oz/sq. yd nylon bumper
Jul 1964	W. McAllum	Apollo absorber
Jul 1964	W. McAllum	Visor material
Jul 1964	W. McAllum	Exotic materials for EMU protection
Jul 1964	W. McAllum	Variable weaves
Aug 1964	W. McAllum	Gemini umbilical
Aug 1964	W. McAllum	Prototype Gemini garment qualification
Sep 1964	W. McAllum	Modified Gemini meteoroid cover layer (Gemini IV design)
Sep 1964	W. McAllum	Modified Gemini meteoroid cover layer (Kevlar ballistic cloth)
Oct 1964	T.W. Lee	Simulation of meteoroid impact in Vycor (MA-9)
Oct 1964	W. McAllum	Polyethylene EMU cover layer qualification
Oct 1964	T.W. Lee	Bumper efficiency of soft goods
	B.G. Cour-Palais	[(E/A) d/h evaluation]
	B.G. Cour-Palais	Effect of projectile shape in cratering phenomena
Oct 28, 1964	R. Patterson	Al/Nylon laminate target impact series, Phase II
Nov 4, 1964	W. McAllum	Qualification of a meteoroid detector
Nov 4, 1964	R.E. Flaherty	Determination of K-factor for LEM structures
Jan 1965	W. McAllum	Service Module tank shield
Mar 26, 1965	T. W. Lee	Preliminary test of impacts into ablative materials

The test photographs and data sheets in Cour-Palais's files have test numbers attached to them, unlike the test request sheets summarized in Table E-1. These test numbers and test descriptions are listed in Table E-2. The test numbers are prefixed with a single digit that may be an indication of the year the test was performed, or the facility in which the test was performed or the fourth digit of the shot sequence.

Table E-2. Extant Test Photographs and Data Sheets

Date	Test Engineer	Test Series	Test Title
1964	…	58, 71	absorber efficiency [85]
1964	…	107, 108, 113, 114, 116-120	space suit qualification [85]
1965	…	137-140	Plexiglas cratering
1965	…	280-282, 284	laminated soda-lime glass cratering
1965	…	313-315, 318	CR-39 cratering (Visor material)
1965	…	648, 658-660	Merlon cratering (Visor Material)
1965	…	650	Vycor testing (NAA STR 241)
1965	…	662-693	0.016 and 0.020 Whipple shield tests
3/1965	…	713	ablator tests (photo)
3/1965	…	706, 709, 711, 712, 759, 760	ablator tests (NAA STR 151)
1965	…	736-738	0.016 and 0.020 Whipple shield tests
1965	…	743, 747	further d-s plate glass window tests
1965	…	763-765	pressurized tank impacts
1965	…	801, 802, 804, 806, 809	double pane Chemcor tests
1965	…	826, 828, 831, 832	Vycor tests (NAA STR 241)
1965	…	850, 853, 856, 857, 859, 860	further d-s plate glass window tests
1965	…	921-929, 931, 933, 935, 936, 947	double pane Vycor
11/4/1965 to 11/9/1965	B.G. Cour-Palais	2-228, 2-231, 2-233, 2-240	Lunar orbiter structure impact tests for Boeing
1965	…	2-393	window test
2/24/1966 to 2/28/1966	W. McAllum	2-544 to 2-551	Apollo suit - leak or no leak
2/28/1966 to 3/8/1966	B.G. Cour-Palais	2-545 to 2-584	LEM - multilayer aluminum
3/8/1966 to 3/10/1966	W. McAllum	2-585 to 2-590	Silicone rubber tests
3/22/1966 to 3/30/1966	B.G. Cour-Palais	2-621, 2-622, 2-636, 2-640, 2-645, 2-650	Apollo window configuration
4/15/1966 to 4/19/1966	B.G. Cour-Palais	2-699 to 2-706	Apollo base heat shield
4/19/1966 to 4/22/1966	B.G. Cour-Palais	2-707 to 2-724	LEM - multilayer aluminum
1966	B.G. Cour-Palais	2-889 to 2-892	combustion of the S-IVB tank insulation by impact tests
1966	…	2-914 to 2-932	combustion of the S-IVB tank insulation by impact tests
< 5/16/1967	…	3-385, 3-388 to 3-391, 3-395 to 3-401	Modified Apollo TMG [41]
1967	…	3-793 to 3-796, 3-798,	Subsystem Test Bed

Date	Test Engineer	Test Series	Test Title
		3-802, 3-804	(spacecraft/lunar module adapter (SLA)) impact tests
1968	…	4-303, 4-306, 4-310, 4-314, 4-316, 4-350	Mariner 9 shielding for JPL
3/1968 to 4/1968	W. McAllum	8 shots	EMU leak rate tests
4/1968 to 6/1968	W. McAllum	12 shots	EMU leak rate tests
12/30/1968 to 1/8/1969	B.G. Cour-Palais	4-611, 4-613 to 4-617, 4-623 to 4-631, 4-636 to 4-644	tests for Ref. [106]
1/15/1969 to 1/20/1969	B.G. Cour-Palais	4-691 to 4-698, 4-700 to 4-706, 4-708 to 4-712, 4-714 to 4-717, 4-719 to 4-721	tests for Ref. [106]

Appendix F: Manned Spacecraft Center Impact Test Contracts

1. Purchase Order T-21565, “MA-9 impact experiment,” IITRI final report December 9, 1963.
2. Purchase Order No. unknown, “URDC low speed impacts on soft goods using an air gun and the Swift .220 powder gun,” before April 1964 [37].
3. Purchase Order No. unknown, “IITRI small size projectile impacts of Gemini space suit materials,” before April 29, 1964 [83].
4. Purchase Order No. unknown, “IITRI small size projectile impacts of SM honeycomb,” before July 24, 1964 [51].
5. Purchase Order No. unknown, “Avco small size projectile impacts of SM honeycomb,” before July 24, 1964 [51].
6. NAS9-3585 “Effectiveness of aluminum honeycomb shields in preventing meteoroid damage to liquid-filled spacecraft tanks,” URDC, Contract let before November 1964, final report December 18, 1964.
7. NAS9-3081 Contract with General Motors Defense Research Laboratory, Santa Barbara, CA, ran from July 1964 to c. December 1966. Produced the reports listed in Table 2 of this report.
8. NASA-Defense Purchase Request No. T-27872(G) NRL Problem F04-17 “Experimental Investigation of Hypervelocity Impact Damage to Ablative Materials,” Naval Research Laboratory, Washington DC, December 13, 1965. (Manuscript submitted to the printer on November 4, 1965).
9. NAS9-3404 “Study of meteoroid impact into ablative heat shield materials,” Avco Corporation, final report April 1966.
10. NAS9-6818 “The effects of hypervelocity impact on honeycomb structures,” General Motors Defense Research Laboratory, Santa Barbara, CA. Final report was released December 1967.
11. NAS9-7452 “Hypervelocity impact damage in aluminum targets,” August 14, 1967 to March 15, 1968. Douglas Aircraft Co.

Appendix G: Sources

Most of the memos referenced were obtained from the Johnson Space Center (JSC) History Collection Archives at the University of Houston, Clear Lake. An on-line catalog is located at http://www.jsc.nasa.gov/history/history_collection/uhcl.htm. The memos from the archives are referenced in this report by their history search index number in the format [HSI-XXXXX].

The other major sources of primary material that the authors of this report used are the files of Burton Cour-Palais, the Apollo meteoroid protection subsystem manager. His files are maintained in JSC's Building 267. These files contain copies of all the GE TIR reports listed in Appendix D and the memos referenced by folder number (196X-XXXX).

The NASA Technical Report Server (NTRS) was also a source of primary material. The NASA special publications (SPs), technical notes (TNs) and contractor reports (CRs) are available through the NTRS.

Figures 1, 3, 4, 6, and 17 are NASA MSC institutional photographs and are available from the JSC media center. Figure 11 is an Apollo astronaut photograph and is also available from JSC. Figures 2 and 8 were obtained from the NASA History Program Office at http://www.hq.nasa.gov/office/pao/History/diagrams/apollo.html. Figure 5 was taken from Reference 58. Figure 7 came from Reference 66. Figures 9 and 10 were downloaded from Kipp Teague's Project Apollo Archive http://www.apolloarchive.com/apollo_gallery.htm photo ids LM-NOID-18 and LM-NOID-29. Figures 12 and 13 were taken from Reference 69, Figure 15 was taken from Reference 73, Figure 16 was taken from Reference 81, and Figure 18 was taken from Reference 87.

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13. ABSTRACT *(Maximum 200 words)*

The Apollo program drove the development of spacecraft meteoroid protection in the U.S. and provided the core technology used on succeeding space programs. The uncertain likelihood of a mission-ending collision with a meteoroid and the unknown consequences of a collision with particles at the very large speeds typical of meteoroids made it crucial to better understand the risk of meteoroid impact. While there are extensive records of the design and analysis of the Apollo spacecraft meteoroid shielding, the information is spread across a variety of archives and personal files. This is the first report to assemble the sources into a technical history. This report includes sections on the Apollo shielding requirements, Apollo meteoroid protection analysis results, the Manned Spacecraft Cetner Hypervelocity Impact Test Program, Command and Service Modules, the Lunar Module, and the Extravehicular Mobility Unit.

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