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Lessons from the Lunar Module Program: The Director's Conclusions

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ABSTRACT

Half a century after the first piloted lunar landing, it is time to consider the program, lessons, and legacy of the lander that made it possible. This article does so from the perspective of Joseph Gavin, Jr., who led Apollo's Lunar Module (LM) Program from its unofficial origins as a controversial dream at Grumman in 1960, to its official inception by NASA in 1962, to its successful conclusion in 1972. He directed as many as 7500 employees in developing the LM and ultimately building twelve operational vehicles. All met mission requirements, and those that actually made a lunar landing worked every time. Developing the state-of-the-art machine required unprecedented innovations and maximization of reliability amid inherently unknown and untestable conditions. When congratulated on the success of each landing, Gavin typically replied that he would not be satisfied until his spacecraft and its crew got off the moon and arrived home safely. This process required three procedures in unison (firing of explosive bolts, severing by guillotine of wires and other connections between the descent and ascent stages, and firing of the ascent engine). Each function could be tested on Earth individually, but not under lunar conditions at systems level. Gavin drew lessons from his Grumman Corporation team and its subcontractors' experience that the author distills into eight principles:

(1) Above all, return astronauts safely to Earth; accordingly:
(2) create conditions for success,
(3) attain reliability,
(4) prioritize innovation over schedule over cost,
(5) don't complicate things unnecessarily;
(6) remove hierarchical barriers;
(7) empower individuals, and
(8) share information.

Serving in top management subsequently returned Gavin to the naval aircraft development that remained Grumman's specialty. He applied the best practices learned from LM development, particularly improving initial construction to reduce the need for tests (per principle three). Drawing on extensive interviews with Gavin and thorough examination of his personal materials, this article explores his lessons and explains how he envisioned and applied them in practice as an aerospace project engineer leading one of history's greatest engineering achievements.

1. Lunar Module program, 1962-72

Having launched his career at the inception of jet engines and carrier aircraft as a Navy reservist in the Bureau of Aeronautics (1942–46), Gavin took it to a whole new level in the space age. Gavin's aerospace project engineering leadership tracked Grumman's preparation to bid for the eventual LM contract. Before Gavin assumed management responsibilities, however, he absorbed his profession's fundamentals as a structural designer. On August 31, 1978, Richard J. Cyphers—then in charge of all Grumman's structural designers—sent Gavin a set of the company's detailed guidelines with the following annotation: "I am including a copy of 'Structural Design at Grumman.' This was done in 1965 and to this day every job applicant … if he accepts the job, on his starting day … gets this memo. All of the existing designers also receive

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it, so you can see that your own penchant for meticulousness has impacted more than a thousand designers since 1965."[1] While to the author's knowledge Gavin did not draft the memo himself, he was clearly credited with coming to embody and inculcate its ethos throughout the corporation he came to lead.

Following a decade of naval aircraft project management, as Grumman's Chief Missile and Space Engineer from 1957 to 1962, Gavin planned and directed all spacecraft and missile technical activity for Grumman and led the corporation's unsuccessful 1958 bid on Project Mercury. Heading a new organizational entity as Space Programs Director further consolidated his leadership of Grumman projects in an exciting new domain. This included Grumman's first NASA contribution: building the launch adapter and canister for *Echo 1*, the agency's first communications satellite.[2] Still more significant, and with more foundational implications for Gavin and his team, was their second NASA contract in 1960 to build the agency's first space telescope, the Orbiting Astronomical Observatory (OAO). Innovations necessitated by the OAO's unique challenges, Gavin explains, "later formed the basis for our heat disposal system on the LM."[3]

With the Soviet launch of the first artificial satellite on October 4, 1957, Gavin "was a little surprised that they got there first." On November 3, in his dayplanner, he noted: "2nd Soviet satellite." But he had anticipated possibilities for spaceflight: "At the end of my tour in the Navy, we wrote a report at the request of Senator [Harry] Truman about where the Navy should go in the future. We suggested that the Navy should be interested in navigating outside of the atmosphere. So the idea took hold of doing something [in space]. It was not a new idea." Soviet success "stimulated a lot of interest, [which] extended nationwide." NASA funded studies on reentry bodies; Grumman conducted its own: "orbital navigation was related mathematically to some of the work we had done on [the optimum flight path] of jet airplanes."[4]

1.1. I·I Launching the LM program

Four years later on May 25, 1961, inspired by the bold initiative President Kennedy announced, the Apollo Program brought Grumman, and Gavin, the opportunity of a lifetime. It was during a decade as LM Program Director that Gavin faced his greatest challenges in management of technological innovation, after Grumman won the NASA competition to build the lander that would deliver NASA astronauts Neil Armstrong and Buzz Aldrin to the moon's surface on July 20, 1969. Ten counterparts followed in five landings through 1972.

From Grumman's initial study and bid through Apollo's conclusion, Gavin led the team. As the Grumman Vice President responsible for the LM contract, he had LM engineering, procurement, manufacturing, and field operations reporting to him, and was deeply involved in all areas. He interacted extensively with major subcontractors, especially those producing the rocket engines and radio and electronic devices[5]: "I spent a lot of time on the road [and] in the air."[6] Managing subcontractors was a major responsibility. Coordinating with Radio Corporation of America (RCA), contracted in 1963 to develop rendezvous and landing radar and communications equipment for the LM,[7] proved particularly challenging: Gavin's dayplanner reflects scores of communications and dozens of visits.

Under Gavin's management, Tom Kelly, the LM Chief Design Engineer for the program's first seven years,[8] and the rest of the Grumman team succeeded with boldly-designed craft that landed on the moon and rejoined the Command Module in lunar orbit six times without mishap; while serving as a vital lifeboat and tugboat during the one aborted mission. At its peak, Gavin managed 7500 employees (including nearly 4000 engineers and 400 draftsmen) in several locations across the United States. Approximately 55%[9] of NASA contracting[10] "for development, manufacture, test and delivery of two mission simulators, 10 ground

[1] Annotated copy: R.J. Cyphers to All Structural Design Personnel, "Use of Computation Notebooks," Grumman Aircraft Engineering Corporation Structural Systems Memorandum No. 217, July 12, 1965.

[2] As Gavin noted in his dayplanner, Grumman won a contract for *Echo 2* on March 17, 1961.

[3] Richard Thruelsen, *The Grumman Story* (New York: Prager, 1976), 329.

[4] Unless otherwise specified, all quotations in this paragraph are from Brian Keegan, Interview of Joseph G. Gavin, Jr., Infinite History Project, MIT, July 17, 2007, https://infinitehistory.mit.edu/video/joseph-g-gavin-jr-'41-sm-'42. Already, in 1957, von Braun's "Proposal for a National Integrated Missile and Space Vehicle Development Program" advocated a piloted moonshot by 1970. Matthew Brzezinski, *Red Moon Rising: Sputnik and the Hidden Rivalries that Ignited the Space Age* (New York: Times Books/Henry Holt, 2007), 249. Perhaps more than anyone else, NASA administrator George Low helped tee up Kennedy's decision within a fleeting window of opportunity: "It was one of those unique moments in history when a bold idea had probably just one shot at getting through or would risk being lost forever." In April 1959, Low proposed a piloted moonshot both to NASA's Research Steering Committee on Manned Space Flight and in Congressional testimony. The committee's December 1959 Long-Range Plan for Manned Space Flight reflected Low's goal. During winter 1960–61, Low chaired a committee report with studies showing that moon landing was feasible before 1970. Low's July 9, 1960 presentation to NASA's leaders (T. Keith Glennan, Hugh Dryden, and Richard Horner) would lay the groundwork for Kennedy's endorsement the following spring. Meanwhile, it triggered important preparations: NASA's first industry planning conference (July 28), proposal request (September), receipt of fourteen bids (October 9), and awarding of three $250,000 study contracts (end of October). Richard Jurek, *The Ultimate Engineer: The Remarkable Life of NASA's Visionary Leader George M. Low* (Lincoln, NE: University of Nebraska Press, 2019), 79, 69, 55, 141, 71, 73, 75. Further background: W. David Compton, *Where No Man Has Gone Before: A History of Apollo Lunar Exploration Missions* (NASA History Series, Special Publication-4214, 1989), https://history.nasa.gov/SP-4214/contents.html; Richard W. Orloff and David M. Harland, *Apollo: The Definitive Sourcebook* (New York, NY: Springer Praxis, 2006), 37–40, 56–61.

[5] Gavin, comments handwritten in December 2001 in personal copy of Thomas J. Kelly, *Moon Lander: How We Developed the Apollo Lunar Module* (Washington, DC: Smithsonian Books, 2001).

[6] Keegan, Interview of Gavin. Numbering 376,700 in 1965, employees of Apollo contractors like Grumman and its subcontractors exceeded their NASA civil service counterparts more than ten-fold. Roger D. Lanius, *Apollo's Legacy: Perspectives on the Moon Landings* (Washington, DC: Smithsonian Books, 2019), xvi.

[7] "RCA Subcontractor to Grumman for LEM," NASA Release No. 63–143; Kelly, "Technical Development Status of The Project Apollo Lunar Excursion Module," paper presented at American Astronautical Society 10th Annual Meeting, May 4–7, 1964, 18.

[8] "Tom Kelly, the LM chief engineer, is one of the finest engineers that ever worked for me, a friend for over fifty years," Gavin recalled. "We sent Tom to the Sloan School at MIT after Apollo 12, and I called him back, temporarily, for the Apollo 13 crisis." Gavin, comments written in December 2001 in Kelly, *Moon Lander*. For Kelly's experiences in this position, which he held from 1961 to 69, see Kelly, *Moon Lander*. On April 9, 2001, Gavin inscribed in the copy Kelly sent him: "I've known Tom since he first arrived at Grumman—an exceptional talent, right from the start. A fine person to work with—one of Grumman's 'tried and true.'" See also Gavin, with contributions by Joan Kelly, "Thomas J. Kelly, 1929–2002, Elected in 1991," *Memorial Tributes, National Academy of Engineering of the United States of America*, Volume 11 (Washington, DC: National Academies Press, 2007), 179–81.

[9] Gavin, "Engineering Development of the Apollo Lunar Module," IAA-90-633, paper presented at the 41st Congress of the International Astronautical Federation, October 6–12, 1990, Dresden, GDR [Hereafter: IAC, 1990], 2.

[10] Charles Fishman, *One Giant Leap: The Impossible Mission That Flew Us to the Moon* (New York: Simon and Schuster, 2019), 253.

[Lunar Module] test articles (LTAs) and 15 flight articles (LMs)"[11] went to subcontractors that Grumman oversaw. By the program's conclusion at the end of 1972, total LM program expenditures reached $2,287,600,000.[12] Throughout, the buck stopped in Gavin's office: "we were responsible for putting it all together and making it work."[13]

According to an official NASA history, "The story of Grumman's drive for a role in manned space flight has a rags-to-riches, Horatio Alger-like quality. The company had competed for every major NASA contract and, except for the unmanned Orbiting Astronomical Observatory satellite, had never finished in the money."[14] But the upstart enterprise was nothing if not determined. "The interesting thing about Grumman at the time was that we had a core of people who had been with the company anywhere from 10 to 20 years," Gavin recalled three decades later. "These were the core of the activity, and I can't say enough for the confidence that was there."[15] Beginning in January 1961, formalizing efforts started the previous year,[16] Gavin led Grumman's self-funded study by its Space Group of a novel moon-landing technique refined and championed by NASA Langley Research Center engineer John Houbolt,[17] lunar-orbit rendezvous (LOR).[18] "We were convinced that LOR was the way to do it," Gavin explains.[19]

On May 15, 1961, ten days before Kennedy's announcement,[20] Gavin's group submitted their summary report to NASA.[21] Under his leadership, Grumman recruited subcontractors, starting with Honeywell and Space Technology Laboratories.[22] NASA requested Apollo spacecraft proposals in July.[23] Gavin and his colleagues hoped to bid as a prime contractor, which Gavin believed technically feasible. "I'm an eternal optimist, so I think we could do it, but I don't have the whole company to worry about," he stated then.[24] Ultimately, they were prevented by Grumman's management from betting the firm on such an ambitious, risky endeavor.[25] Instead, on August 2 Grumman decided to bid as a subcontractor for General Electric (GE),[26] and while Gavin learned much he encountered significant differences in corporate culture.[27] On November 28, NASA selected North American Aviation as the Apollo spacecraft contractor, precluding such a path.[28]

Seizing their final chance to join Apollo, in early December 1961, Gavin and his fellow underdogs made a pitch directly to Robert Gilruth, founding director of NASA's Manned Spacecraft Center (MSC),[29] and his colleagues. Their vision for a lunar lander coincided remarkably with NASA's own internal estimates, including regarding the weight of such a vehicle.[30]

Heading Grumman's fifty-man one-year study of LOR and the LM, Gavin instructed Kelly to "prepare a study plan and budget request for [1962], aimed at positioning [Grumman] as a prime contractor on the LM."[31] Having presented their proposed plan on January 23, 1962, they lost NASA's study competition to Convair, but persisted on Grumman funds anyway. They submitted their report in June and briefed it to Deputy Director of NASA's Office of Manned Space Flight Joseph Shea. From November 1961 through June 1962, NASA debated whether to

[11] "Development of the NASA/Grumman Lunar Module," Grumman press materials distributed at Apollo 12 launch, November 14, 1969. Because of cancellations, only twelve LM flight articles were built; of these, LM-2 and -9 were unflown backups. LM-7 was Apollo 13's lifeboat. "Apollo Lunar Module," undated Grumman pamphlet. Unless otherwise specified, undated/unidentified documents are from Gavin's personal collection.

[12] "Figure 2A: LM Program Dollar Profile," "Summary of Price Growth of the LM Program," unidentified document; Richard W. Orloff, "Apollo by the Numbers: A Statistical Reference for the Manned Phase of Project Apollo," June 1996, https://georgetyson.com/files/apollostatistics.pdf; "Appendix 7: Funding," Compiled by F. B. Hopson, Administrative and Program Support Directorate, NASA, https://www.hq.nasa.gov/office/pao/History/SP-4009/v4app7.htm.

[13] Gavin, "Introduction," Apollo Guidance Computer History Project, First Conference, July 27, 2001, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/gavin-intro.htm.

[14] "NASA-Grumman Negotiations," https://www.hq.nasa.gov/pao/History/SP-4205/ch4-7.html.

[15] Gavin, "Introduction," Apollo Guidance Computer History Project.

[16] "Development of the NASA/Grumman Lunar Module," Grumman press materials distributed at Apollo 12 launch, November 14, 1969.

[17] "John C. Houbolt, Unsung Hero of the Apollo Program, Dies at Age 95," April 17, 2014, https://www.nasa.gov/content/john-c-houbolt-unsung-hero-of-the-apollo-program-dies-at-age-95/; James R. Hansen, *Enchanted Rendezvous: John C. Houbolt and the Genesis of the Lunar-Orbit Rendezvous Concept*, Monographs in Aerospace History Series 4 (Washington, DC: NASA Headquarters History Office, January 25, 1999), https://history.nasa.gov/monograph4.pdf; William F. Causey, *John Houbolt: The Unsung Hero of the Apollo Moon Landings* (West Lafayette, IN: Purdue University Press, 2020); David Sheridan, "How an Idea No One Wanted Grew Up to Be the LEM," *Life* 66.10 (March 14, 1969): 20–27; Fishman, *One Giant Leap*, 235–46; Robert C. Seamans, Jr., *Aiming at* Targets: *The Autobiography of Robert C. Seamans, Jr.* (Washington, DC: NASA, 1996), 98–99, https://history.nasa.gov/SP-4106.pdf.

[18] The initial U.S. lunar landing concept, direct ascent, entailed sending an enormous Nova rocket directly from Earth to the moon and back. LOR saved considerable resources and development time by having a smaller rocket deliver two spacecraft to lunar orbit. The main cabin (Command Module/CM) and its supporting Service Module (SM) would continue orbiting with one astronaut while the LM separated and delivered the other two astronauts to the lunar surface with its descent stage's rockets easing the landing. Upon completing activities there, they would launch in the LM's ascent stage and re-dock with the CM. After all three crewmembers had reunited in the CM, the LM's ascent stage would be discarded. In seven attempted Apollo moon landings, the Apollo 13 mission was the exception to this rule: it was the only one not to land two astronauts on the moon, and the only one in which the LM was used as a lifeboat/tugboat after an explosion devastated the SM. In that case, the LM was finally jettisoned just prior to CM re-entry. "The Rendezvous That Was Almost Missed: Lunar Orbit Rendezvous and the Apollo Program," Fact Sheet NF175, December 1992, https://www.nasa.gov/centers/langley/news/factsheets/Rendezvous.html.

[19] Keegan, Interview of Gavin. Kelly elaborates: "We read some of [Houbolt's] early papers on that, and we checked all the calculations ourselves, and it seemed like a pretty attractive idea to us." LOR was "more economical": "The Command Module could be specialized for re-entry," while "The Lunar Module was able to be specialized for operations in space and on the moon." "The Lunar Module Story," Grumman Corporation, 1989, https://www.youtube.com/watch?v=vjDdu7WzjQw.

[20] In his dayplanner, Gavin noted an "Apollo progress presentation" on March 8, 1961; an "Apollo LM" meeting at Langley Field, VA, on May 18; and another such meeting the following day.

[21] Kelly, *Moon Lander*, 14.

[22] Ibid., 17.

[23] In his dayplanner, Gavin lists an "Apollo briefing" from July 18–21, 1961.

[24] Kelly, *Moon Lander*, 19.

[25] As Gavin explained to his team, "Our senior management thinks it's too big a job for us. We'd be risking the whole company, and the jobs of everyone at Grumman on this single project. It's not just the money involved. If the company failed before the world on this project, it would never recover. We'll have to find a berth on someone else's team." Ibid., 19.

[26] Gavin, dayplanner. Gavin's "Apollo proposal team" convened on August 3–4. He recorded an "Apollo bidders conference" from August 13–16. He made daytrips to GE on August 16 and 21. On September 7–8, he attended an "Apollo mtg on west coast." September 15 witnessed a first-draft proposal. Following the "9th dry run," GE-Grumman submitted its proposal on October 9.

[27] Ibid. 20–21. In his personal copy of Kelly's book, Gavin noted, "I found dealing with GE painfully difficult—a clash of cultures."

[28] "Design—Decision—Contract," Part 2 (E), October/November 1961, Courtney G. Brooks et al., *Chariots for Apollo: A History of Manned Lunar Spacecraft* (Washington, DC: NASA, 1979), https://www.hq.nasa.gov/office/pao/History/SP-4009/v1p2e.htm. Gavin's dayplanner reads "Apollo to N. American!!"

[29] Gilruth would lead his institution, later renamed Lyndon B. Johnson Spaceflight Center, for a decade. "Former Manned Spacecraft Center Director Dies," NASA, https://spaceflight.nasa.gov/history/gilruth/gilruth_obit.html.

[30] Kelly, *Moon Lander*, 22–23.

[31] Ibid., 23.

select Wernher von Braun's preferred approach of Earth-orbit rendezvous, or the "dark horse" approach of LOR.[32] LOR finally prevailed with von Braun's endorsement, triggering a June 4 "LEM[33] kickoff" that Gavin listed in his dayplanner before his June 5 NASA presentation; followed by a July 24 Request for Proposals.[34] Limited to 110 pages in ten-point font, every word counted.

In "the highlight of my entire career," Presentations Editor Sam Koeppel coordinated and proofed the proposal layout. At crunch time, "Joe Gavin placed the resources of the entire company at our disposal for the entire weekend … Gavin himself sat with us almost all of Saturday …. "[35] On September 4, Space Vehicle Program Manager Saul Ferdman hand-delivered 150 copies of Grumman's bid 2 h before the deadline.[36] Gavin's team then dropped everything for a "fire drill" to answer follow-up questions from NASA's Source Evaluation Board in less than 48 h. Proposals had involved addressing a set of twenty questions, to be answered in 100 pages using standard margins and type.[37] "To answer the questions, we had to postulate a design," Gavin later recalled.[38] But "NASA hadn't really bought [our] design. They thought they'd bought an engineering service."[39] "We had just passed the entrance examination, and we would have to work with [NASA's] Johnson Space Center to develop a design."[40] According to its official history, "Grumman was able to present NASA with a mountain of data, evidence that it understood the two paramount problems—weight and dependability."[41] Grumman won officially on November 7, 1962.[42] "LEM award!" Gavin exalted, double-outlining the date in his dayplanner.

In mid-November, Gavin's sixty-man team began marathon negotiations with NASA.[43] From a Houston motel whose interior remained unfinished, they worked straight through Thanksgiving and only barely made it home for Christmas, with Gavin and a colleague the last to leave. Gavin's dayplanner records a meeting with NASA's Gilruth, David Lang, and Robert Piland January 3, 1963 to discuss the "LEM contract agreement."[44] On January 14, Gavin and Gilruth resolved remaining issues in Bethpage, yielding NASA's verbal go-ahead. A formal $387.9 million contract followed in mid-March[45] for initial production of six LMs.[46] On November 11–12, 1963, Gavin recorded "start[ing] participation in a major Apollo schedule review."

Grumman gave Gavin "the shirt-sleeve management job … For his success, Gavin was made a vice president the day the contract was won. Grumman's proposal had indicated such a step might be made to assure NASA that the LEM had corporate backing … He fits the mold [President Clint] Towl has shaped for Grumman management."[47] Gavin now faced the challenge of heading "the last major portion of the Apollo program to be defined and started."[48] Kelly described his boss as "a natural leader, who, in the face of crises and confusion, remained calm and steadfast of purpose, inspiring others to rally around him."[49] He repeatedly credited Gavin's "steadying influence" with enabling focus amid extraordinary pressure and occasional withering criticism from NASA over any possible errors.[50] Selected last of all major contractors, Grumman had to assemble personnel and infrastructure rapidly. LM Management Staffer Brian Evans recalled that Gavin "provided tremendous assistance in selecting personnel to fulfill the management slots."[51] Among "highlights of my part in the program," Facilities Planning Manager Joseph Walsh credited rapid establishment of LM facilities that met NASA's demanding standards in part to "encouragement by Joe Gavin." His "most naïve" experience: "When Joe Gavin told me NASA said we will need Interface Control Documents, I said 'That's ridiculous, we don't need them. We all talk to each other.' He said, 'Well, we're going to have them anyway.' I soon became a believer."[52]

1.2. I·II Unprecedented engineering challenges and innovation

"You must remember how many things we didn't know at the very

[32] Michael J. Neufeld, "Von Braun and the Lunar-Orbit Rendezvous Decision: Finding a Way to Go to the Moon," *Acta Astronautica* 63.1–4 (July–August 2008): 540–50, https://www.sciencedirect.com/science/article/abs/pii/S0094576507003517; Academy of Program/Project & Engineering Leadership (APPEL) News Staff, "A Strategic Decision: Lunar-Orbit Rendezvous," *Insight* 5.1 (January 26, 2012), https://appel.nasa.gov/2012/01/10/5-1_lunar_orbit_rendezvous-html/; John M. Logsdon, "Selecting the Way to the Moon: The Choice of the Lunar Orbital Rendezvous Mode," *Aerospace Historian* 18.2 (Summer, June 1971): 63–70; Richard D. Lyon, "Moon Landing Craft Unveiled by Astronauts," *New York Times*, January 16, 1969, 1, https://www.nytimes.com/1969/01/26/archives/moon-landing-craft-unveiled-by-astronauts-moon-landing-craft-is.html.

[33] The LM was termed the Lunar Excursion Module (LEM) until 1967. At that time, to eliminate any "frivolous connotation," NASA's Public Affairs Office dropped the middle word and initial. Kelly, *Moon Lander*, 267.

[34] On August 10, 1962, Gavin noted: "LEM manpower estimate due."

[35] Sam Koeppel, in Ross Fleisig and Lois Lovisolo, eds., "Lunar Module Remembrances," AIAA 25th Anniversary of the First Manned Lunar Landing, Regional Conference, June 18, 1994, 27–28.

[36] Saul Ferdman, "The Last Proposal Day," in Ibid., 19.

[37] Keegan, Interview of Gavin.

[38] "The Lunar Module Story."

[39] Gavin, Interview by Rebecca Wright, NASA Johnson Space Center Oral History Project Oral History Transcript, Amherst, MA, January 10, 2003, https://www.jsc.nasa.gov/history/oral_histories/GavinJG/GavinJG_1-10-03.htm. [Hereafter: NASA Interview, 2003].

[40] "The Lunar Module Story."

[41] "Development of the NASA/Grumman Lunar Module," Grumman press materials distributed at Apollo 12 launch, November 14, 1969.

[42] "Grumman Selected to Build LEM," NASA News Release No. 62–240, 5 p.m., November 7, 1962; "NASA Selects Grumman Lunar Excursion Module Proposal: Negotiate for $350 Million Contract," *Grumman Plane News*, Special Bulletin (November 9, 1962), 1; John W. Finney, "Grumman to Build Lunar Craft; Project Will Spur L.I. Economy," *The New York Times*, November 8, 1962, 1, 14; Kelly, *Moon Lander*, 33–36. Kennedy and NASA waited until after Congress's midterm elections to announce Grumman's victory. Douglas Brinkley, *American Moonshot: John F. Kennedy and The Great Space Race* (New York: Harper Perennial, 2019), 369.

[43] "Billion-Dollar Coup for Grumman," *Business Week*, December 1, 1962, 96.

[44] Piland recalled: "We evaluated Grumman … to be … the best proposal-writer or best contractor to do the job … and took it up to headquarters, and [NASA] administrator [James E. Webb] concurred or made his selection based on that, and it was consistent with our results. We thought there was a difference between it and second place. I don't even remember who was in second place at the time, which, I guess, is some indication. Incidentally, Grumman had focused in on the LEM and that mode early on, earlier than [we had] … if you go back to the proposal that Grumman put in for the command module, the first proposal, they had an appendix to that proposal which described the whole lunar-orbit scheme, rendezvous, and so forth. So they early on were focused on it, which I'm sure aided them in writing their proposal. Grumman had very good credentials … amongst all the people involved … So we negotiated with them and finished up a negotiation again. Just before Christmas, we finished up our negotiations and sent them home to go get started …. " Robert O. Piland, Interview by Summer Chick Bergen, Edited Oral History Transcript, NASA Johnson Space Center Oral History Project, Houston, TX, August 21, 1998, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/PilandRO/PilandRO_8-21-98.htm.

[45] Kelly, *Moon Lander*, 46.

[46] Keegan, Interview of Gavin.

[47] John P. Kushnerick, "What Makes Grumman Grow," *Aerospace Management* (January 1963): 15–16.

[48] Gavin, "LEM Design Evolution," *Astronautics & Aeronautics* (April 1965): 46.

[49] Kelly, *Moon Lander*, 27.

[50] Ibid., 177. "'I've never seen a man handle the pressure and all the guff like Joe does,' an associate at Cape Kennedy observed. Mr. Gavin's wife, Dorothy, agrees. 'He does have a gift of being able to relax when given the opportunity—completely and without artificial help,' she said. 'This is what keeps a man like this going.'" "Reacher for the Moon: Joseph Gleason Gavin Jr.," *New York Times*, January 23, 1968, 10.

[51] Brian D. Evans, in Fleisig and Lovisolo, "Lunar Module Remembrances," 17.

[52] Joseph G. Walsh, Ibid., 39.

beginning," Gavin emphasized.[53] Indeed, there was no precedence, and certainly no blueprints, for a machine anything like the LM. Instantly recognizable by its ungainly appearance, it remains "unique among manned spacecraft in that it is designed solely to operate in space."[54] To Gavin, the key "unique requirements" were "pure space craft—no reentry, each mission a first flight, many features not possible to test on Earth, no post mission examination."[55] Gavin stresses: "each vehicle that was launched from Cape Kennedy was an unused, untested vehicle in every sense except electrically."[56]

The LM was then the largest U.S. spacecraft by internal volume and per-capita crew space.[57] During the mission, its gross weight would vary by a factor of ten.[58] "[T]here never had been a rocket-propelled vertical-landing machine," Gavin emphasizes, and the LM needed an unprecedented throttleable rocket to accommodate its drastic weight reduction through fuel expenditure.[59] It had to be completely reliable even though lunar conditions could not be replicated on Earth for full testing. Moreover, there were conflicting information and assessments about the suitability of the moon's surface for landing. Worst-case scenarios included Cornell University Professor Thomas Gold's theory that the LM would sink into "10 m of impalpable dust … electrostatically it'll probably just cover everything up."[60]

All this had to be overcome without today's modern electronics, computing, or employee databases. Over 50,000 engineering drawings supported the design[61] and integration of its one million parts.[62] Gavin viewed the moonlandings as a "tremendous accomplishment—even by today's standards."[63] We "were pressing the state of the art to a degree that is hard to imagine unless you know the situation at that time," he stressed.[64] Nevertheless, when asked how the LM would be designed today, Gavin readily acknowledged:

> … there are some things I'd do differently. At the time that we designed the Lunar Module, we were very restricted on where we could use solid-state devices. In fact, all of the communication gear was made up of discrete elements. And I would certainly avoid that. That was a nightmare, getting enough units that would pass test. I would also have a digital data bus, just to reduce the miles and miles of wire that we had. We deliberately went to a skinnier gauge of wire than is commonly used in aircraft in order to save weight. And we paid for it, because we had ever so many faults that came about from just plain handling the bundles of wire. So anything you could do to get rid of the old-fashioned way of wiring would be an advantage. I think that it's also quite likely that a lot of the equipment that we had [such as] the MIT-designed guidance and navigation [computer] … can all be done in a miniaturized version today that would weigh a lot less. [And positioning, navigation, and timing] in lunar orbit … is something we could do much better today. And that's probably true of almost all equipment.[65]

As things stood in the 1960s, LM design challenges forced considerable rethinking by an organization whose foundational culture was grounded in the design of naval fighters by Gavin and other "graduates of the aircraft business."[66] Unlike their aviator counterparts, he contended, the LM pilots "are really computer experts playing numbers into their computer keyboards, rather than flying the spacecraft in the conventional sense of airplanes."[67] "In defense of his bizarre creation," Gavin "reminded visiting reporters that few airplanes really achieved grace but, rather, had it thrust upon them to reduce wind resistance and improve stability in flight. … the LM would never return to earth after its job was done, thus eliminating the need for any streamlining or shielding against atmospheric friction."[68] Gavin shared a related learning experience: "I crashed one of the simulators several times for a very simple reason. If you try to translate along the surface of the moon, there's no air resistance. So in order to stop, you had to fire in the opposite direction. You don't automatically slow down."[69]

Whereas aerodynamic considerations required aircraft to be built from the outside-in, the harsh vacuum of space required a spacecraft like the ungainly LM to be built from the inside out. "[I]t became very utilitarian in appearance, and only its designers could love it," Gavin allowed.[70] Unlike aircraft, for which range can generally be traded somewhat for payload or speed, the LM's range was fixed.[71] On the plus side, "this vehicle only has to make one landing … a revelation too to somebody who's been designing airplanes … the shock-absorbing material is aluminum honeycomb in a billet. And it's good for one landing. It will take the shock and eat up the energy. It does not rebound, and you can't use it a second time, but of course, we're not using it a second time."[72]

Indeed, it took strong management backing to overcome opposition by a faction of "conservative aircraft traditionalists"[73] who believed that "these guys on the lunar module are nuts"[74] and that entering the space business threatened excessive risks. "It kind of split the company," Gavin recalled. "The confirmed aircraft people felt … that we were gambling the company. A bunch of us were still young enough and eager enough, and said: 'hey, this is where the future of engineering really is.' And I think we were right, because later on the group that had worked on Apollo kind of took over the company management. I'm an incurable optimist, and furthermore I knew that I had a great team of people … We

[53] "Part 4: The Lunar Module," *Moon Machines*, Science Channel HD documentary miniseries, June 2008, https://www.youtube.com/watch?v=f2Tc8z2xO74.
[54] Gavin, "LEM Design Evolution," 51.
[55] Gavin, notes for talk, "L.I. Apollo Anniversary," 1989.
[56] Gavin, "The Lunar Module Design and the Apollo Program," annual Lester D. Gardner Lecture, AeroAstro Department, MIT, December 3, 1996, https://infinitehistory.mit.edu/video/joe-gavin-%e2%80%9c-lunar-module-design-and-apollo-program%e2%80%9d-mit-gardner-lecture-1231996.
[57] Brooks et al., *Chariots for Apollo*, 147.
[58] Gavin, "The Apollo Lunar Module (LM): A Retrospective," IAC-02-IAA.2.3.08, paper presented at 53rd International Astronautical Congress, Houston, TX, October 10–19, 2002 [Hereafter: IAC, 2002], 2.
[59] Jennifer Bogo, "The Oral History of Apollo 11," July 18, 2019, https://www.popularmechanics.com/space/moon-mars/a4248/oral-history-apollo-11/. Updated from June 2009 issue of *Popular Mechanics*.
[60] NASA Interview, 2003. Gavin recalled: "a prominent astrophysicist assured me that the lunar surface was covered by 10 m of impalpable dust; fortunately, he was wrong!" IAC, 1990, 2. This refers to his meeting with Cornell Professor Thomas Gold on September 19, 1963.
[61] Kelly, *Moon Lander*, 96–97.
[62] John Noble Wilford, *We Reach the Moon* (New York: Bantam Books, 1969), 151.
[63] Gavin, notes for talk, "L.I. Apollo Anniversary."
[64] Gavin, "Introduction," Apollo Guidance Computer History Project.
[65] Gavin, Gardner Lecture. For earlier analysis, see Kelly, "Design Features of the Apollo Lunar Module," paper presented at AIAA 1981 Annual Meeting and Technical Display "Frontiers of Achievement," May 12–14, 1981.
[66] NASA Interview, 2003.
[67] Richard D. Lyon, "LEM Holds Key to Apollo's Success," *New York Times*, May 18, 1969, 69.
[68] Wilford, *We Reach the Moon*, 149.
[69] Gavin, Gardner Lecture.
[70] Ibid.
[71] "We've got to get from orbiting command and service modules to the moon and back," Gavin explained. Tom Buckley, "It Looks Like a Martian, It Will Land Our Men on the Moon," *New York Times*, February 23, 1969, 72.
[72] Gavin, Gardner Lecture.
[73] IAC, 2002, 2.
[74] NASA Interview, 2003.

had to recruit from the company at large … the core were a group that I had worked with for about 10–15 years."[75]

The "bug's" configuration and engineering evolved in a relentless effort to counter weight growth above 32,000 pounds while maximizing reliability under uncertain conditions in a remote environment with five-hundred-degree temperature variation, radiation, and micrometeoroids.[76] Gavin remembered weight growth as "one of our worst problems—it was with us every day for 10 years."[77] The heavy, weak, thermally-wasteful helicopter-style windshield that Gavin initially envisioned shrank to small triangular windows pressed against the faces of standing crewmembers, their seats eliminated in recognition of the flight's short duration and one-sixth gravity environment.[78] This was one of many design adjustments[79]: a knotted rope was replaced with a fixed ladder,[80] five legs reduced to four, two hatches to one.[81] To make the LM work, Grumman and its subcontractors developed history's first (1) broadly throttleable rocket engine, (2) solid-state radar, (3) 'strap-down' inertial navigation unit, and (4) fly-by-wire control system for a rocket-powered vertical takeoff and landing (VTOL) aircraft.[82] "Our original notions of the LM have undergone a striking evolution," Gavin declared in 1966.[83]

Gavin and his team faced extreme pressure to improve schedule and weight, as well as cost to some extent—all while ensuring reliability. For Gavin, the unforgiving business of management entailed constant pressure-cooker meetings and receipt of unvarnished communications. In 1967, for instance, MSC Apollo Spacecraft Program Office (ASPO) Manager for the LM C.H. Bolender wrote Gavin with strong concerns regarding weight control. He specifically proscribed "ultraconservative" design philosophy and "requested a biweekly review of weight reduction candidate changes."[84] On October 25, 1967, Gavin noted in his dayplanner, in discussion of cost, weight, and schedule challenges, NASA Apollo Manned Lunar Landing Program Director Sam Phillips declared, "You're in trouble … let's see results." So relentless was the pace of testing, astronaut Fred Haise recalled, that when seconded to Bethpage he often slept in the LM during consecutive tests stretching as long as 27 h: "There were times I'd be here a whole week and never get any further than Vito's Deli, which is just across the street …. "[85] The NASA-mandated Super Weight Improvement Program yielded soda-can-thin aluminum alloy LM walls (0.12 inch).[86]

Challenges abounded. Winter weather, and even hurricanes, disrupted operations. Crises and tragedy struck: On January 27, 1967, Gavin was at the White House witnessing the Outer Space Treaty's signing when, he recorded in his dayplanner, "astronauts [were] killed at [Cape Kennedy] in [the Command & Service Module/CSM]—Grissom, White, Chaffee." Minimizing inflammability following the Apollo 1 launchpad fire necessitated neater configuration of the LM's 40 miles of wiring[87] and additional weight in fire retardant.[88] As part of this, Gavin recounted, "we created these little baggies that went around that circuit breaker body. And then all of the other electrical connections were covered with this mud-like material … it was a very extensive redesign …. "[89] Gavin assessed that the tragedy set back not only the Apollo program overall, but also the LM program itself: "we lost a year."[90]

As part of cost control, NASA managers continually pressed Gavin and his team regarding overtime. On January 18, 1966 in his dayplanner, Gavin noted: "overtime and manhour crisis." On March 13, 1967, he wrote, "Reconvene financial wizards!" Of particular concern, "two things caused a tremendous amount of extra hours." First, "the introduction of bomb testing for combustion stability in engines doubled testing times." Second, extreme weight minimization and corrosive nitrogen tetroxide propellant made plumbing leaks a continual challenge.[91] Gavin recalled, for "one of the vehicles that was already at [Cape Kennedy, Grumman] had to send back this whole lower structure so that we could redo the seals. It was a terribly frustrating affair. And we were looking for leaks that were on the order of one cubic centimeter per year. Pretty small leak. With jet fuel, you would never worry about that."[92] As Kelly relates, "responding to pressure from NASA, Joe Gavin became involved in the leak problem."[93] Gavin explains: "The obvious cure was beefing something up, but we didn't want to beef things up more than we had to. We didn't want to spend the weight. We burned up a lot of man hours, test time, and test articles to prove that the

[75] Keegan, Interview of Gavin. Exemplifying this continuity, Gavin's dayplanner frequently notes his communications with manager Edward Nezbeda, both as an aircraft project engineer in the 1950s and as LM Program Director in the 1960s. Background: "Edward C. Nezbeda, Grumman Officer," *New York Times*, March 26, 1971, https://www.nytimes.com/1971/03/26/archives/edward-c-nezbeda-grumman-officer.html. Other era-spanning colleagues included: "George M. Skurla, 80, Grumman Executive," *New York Times*, September 6, 2001, https://www.nytimes.com/2001/09/06/business/george-m-skurla-80-grumman-executive.html; "Lawrence Mead, Jr., Aerospace Engineer for Grumman, Dies at 94," *New York Times*, September 7, 2012, https://archive.nytimes.com/query.nytimes.com/gst/fullpage-9C03E1DA133FF934A3575AC0A9649D8B63.html.

[76] Joshua Stoff, *Building Moonships: The Grumman Lunar Module* (San Francisco: Arcadia Publishing, 2004), 33.

[77] Gavin, Gardner Lecture.

[78] NASA Interview, 2003. Additional window-related considerations included pilot mobility, restraint, and suit design; as well as vehicle attitude in the terminal descent phase. Joseph G. Gavin, Jr., "LEM Design Evolution," *Astronautics & Aeronautics* (April 1965): 49.

[79] Other design choices involved the selection of widely-spaced four-legged extendable landing gear; a boxier descent stage containing fewer, larger propellant tanks matching those in the CM as well as the landing gear's geometry; doubling peak electrical power; a single, throttle-controlled descent rocket engine; and landing radar derived from that of the *Surveyor* probe. Gavin, "LEM Design Evolution," 46–51. As Gavin explained to the press in 1964, "There have been reports that the seats were removed to save weight. If I had been asked about them, I was going to say what Mark Twain said about reports of his death—greatly exaggerated. We're fighting to keep down weight but we're within our budget." Evert Clark, "Moon Landing Capsule Passes Final Design Test," *New York Times*, March 27, 1964, L7.

[80] Fishman, *One Giant Leap*, 228–31.

[81] Gavin, Gardner Lecture.

[82] For example, "In the past, there had been a tendency to let the electronics manufacturer start with the black box, without accounting for heating and cooling. We reversed this, and had the box designed around the thermal scheme. It resulted in more weight saving, and eliminated our thermal problems." Gavin, "The Design of the Lunar Module," presentation to AIAA New England Section, The MITRE Corporation, Bedford, MA, April 10, 2002.

[83] "Ready for New Strides on Pathway to Moon," *Business Week*, November 26, 1966, 84.

[84] "More Details for 1967-09-22—Apollo LM Weight Growth," http://www.astronautix.com/d/details17790.html.

[85] Fishman, *One Giant Leap*, 250.

[86] Kelly, *Moon Lander*, 122–23.

[87] Wilford, *We Reach the Moon*, 151.

[88] Kelly, *Moon Lander*, 158.

[89] Gavin, Gardner Lecture.

[90] Gavin's annotation of unidentified document "Lunar Module—Problems and Solution." Document states: "Grumman … was directed by NASA to 'Fire proof the Lunar Module' without benefit of any material flammability acceptance criteria or specifications. This rework was to be implemented with virtually no change in the LM delivery schedule."

[91] "We would chem mill down to ten thousandths...," Gavin recalled. "And we tried going to 008. And then we counted the number of grains across a 008 section and chickened out. We went to the ten thousandths. … we chem milled almost everything you can think of. Propellant tubing was chem milled, keeping the original thickness where the connectors were. … many man hours were expended in trying to save weight … an endless process." Gavin, Gardner Lecture.

[92] Ibid.

[93] Kelly, *Moon Lander*, 131.

configuration was accurate."[94]

Oversights were usually harmful but occasionally helpful. Unexpected stretching of the LM's fuel tank membranes, proportionally thinner than eggshells, accommodated 20 s' additional fuel—the margin that Armstrong had left when he landed four miles downrange of the planned site.[95] This push to the limits in the initial landing was one of the few times during an Apollo mission that Gavin was nervous to the point of holding his breath.[96] "We had very small margins," he explained. "We were all counting seconds as to how much fuel we thought remained."[97] Recalling Armstrong's confirmation of a successful landing, Gavin added, "I can't describe this to you in words, but let me tell you—there was a relaxation that I think all of us felt."[98]

Central to the difficulties in designing and proving the LM was that it could not be flight-tested, a conundrum that had no analogue in Grumman's aircraft business, wherein even a vehicle that crashed could be retrieved and examined.[99] Never before in history had a flying machine gone into service without a single test flight. Each LM had to be launched brand-new without even a comprehensive test of its propulsion system: storable propellants could not be purged fully, and ground conditions differed completely from those in space. Most critical of all was takeoff from the moon. The conditions simply could not be duplicated, precluding direct testing of the LM design as a fully integrated system. Apollo launched at Cape Kennedy following weeks of preparation by over 8000 technicians; yet 250,000 miles away, two astronauts had to launch the LM themselves.[100] In Gavin's words, "you had a limited time, you had to punch the button, and everything had to work. The ascent engine had to ignite. The explosive bolts had to explode. The guillotine had to cut the connections, and then it had to fly up. And this is something we never saw happen until the last mission."[101] Moreover, there was no way to include a backup engine. "Once you pressed the button, that was it," he added. "It was really quite tense."[102] "For all the other parts of the mission, you could find a back-out mode," he emphasized. "But when you had to take off from the moon, it either worked or it didn't work."[103] Lynn Radcliffe, whom Gavin selected to lead engine testing in White Sands, New Mexico, recounted that he and his team "had to develop a perfect engine that was fired once, then discarded."[104]

To address these challenges, Gavin and his team developed and implemented a testing regimen whose rigor far exceeded that for any aircraft or even available statistics-and-probability methodology.[105] At the time Kennedy committed America to a manned moonlanding before 1970, Gavin recalls, his notoriously skeptical science advisor Jerome Wiesner "was saying that, with the reliability available and components at that time, that it would take probably … forty attempts to make a successful landing."[106] Such a notion was obviously unacceptable to Gavin and his team, let alone their sponsors. "We … came up with the idea," Gavin explains, that "there should be no such thing as a random failure … if in running tests you find something that doesn't work, there has to be a reason for it, and if you're patient enough, you ought to be able to find out why it failed and do something about it."[107] "Gavin led a crusade to refine the design and improve reliability," Kelly recalls, "by relentlessly tracking down and correcting the cause of test failures. Gavin proclaimed throughout the program, 'There are no random failures; every test failure has a specific cause that must be found and corrected.'"[108] "We got into the business of trying to compute reliability," Gavin explained.[109] A decade of exhaustive LM ground testing[110] yielded 14,247 test failures or anomalies,[111] in a process Gavin termed "turning over every rock on the beach."[112] Only twenty-two defied analysis; the parts involved were replaced.[113] Grumman demanded similar testing from subcontractors.[114]

Exemplifying this regimen: testing for 600+ different landing conditions involving dust, brittle chalk, hard ice, slopes, and potholes;

[94] Keegan, Interview of Gavin. "Hundreds of hours of testing," Gavin hand-noted on R. Botwin, "Problem: Leaks in the Ascent and Descent Stage Propulsion Systems," undated troubleshooting summary.

[95] Unexpected lunar gravitational anomalies confused the autopilot, then Armstrong had to avoid a field of boulders. Robert C. Cowen, "The Apollo 11 Legacy: Revolution in Knowledge—The First Lunar Landing Radically Changed Scientific Theories," *Christian Science Monitor*, July 19, 1994, https://www.csmonitor.com/1994/0719/19101.html.

[96] Author's discussion with Gavin over the years and review of his public statements and annotated flight plans, especially for Apollo 11: "Had to fly manually over huge football field-sized crater with huge boulders around it. This made final landing phase longer than planned. All kind of rocks in view—landed long ~4 miles" (blank page below 3–70). See also Douglas Martin, "Joseph Gavin, Who Helped Put First Man on Moon, Dies at 90," *New York Times*, November 4, 2010, http://www.nytimes.com/2010/11/04/business/04gavin.html. Other highlights of Gavin's flight plan annotation include: Apollo 9—"This mission was a huge success!" (inset). Apollo 14: "landed [on] slope—landing gear struts evenly depressed—soft soil" (3–133). Apollo 15: "No jagged peaks—all smooth—some linear features on mountain to south—no indication of slides or flow—small fragments on surface—no problem for rover—large boulders on horizon across rille—" (3–131).

[97] "Part 4: The Lunar Module."

[98] Ibid.

[99] Author's interview of Gavin, Amherst, MA, December 11, 1998.

[100] Kelly, *Moon Lander*, 216.

[101] NASA Interview, 2003.

[102] "Part 4: The Lunar Module."

[103] "The Lunar Module Story."

[104] "Engine Tester: Lynn Radcliffe," in Tony Reichhardt, "Twenty People Who Made Apollo Happen," *Smithsonian Magazine*, June 7, 2019, https://www.airspacemag.com/airspacemag/twenty-people-who-made-apollo-happen-180972374/.

[105] See, for example, "Figure 15 Lunar Module Assembly, Installation and Test Flow," Lunar Module Subsystem Assembly and Installations (Manufacturing Engineering, Grumman Aircraft Engineering Corporation, December 1967), 36–39.

[106] Gavin, Gardner Lecture.

[107] NASA Interview, 2003. Conversely, "all failures have a cause that can be found and fixed." IAC, 1990, 2.

[108] Kelly, *Moon Lander*, 72.

[109] Keegan, Interview of Gavin.

[110] Bob Carbee, "LM Ground Test Summary," Grumman Aerospace Corporation Space Management Memorandum SMO-39-249, April 7, 1971; R.M. Carbee and A.H. Christensen, "LM Ground Test as Run," April 5, 1971, Sheets 1–5.

[111] IAC, 1990, 2.

[112] Keegan, Interview of Gavin.

[113] Author's many discussions with Gavin over many years; Dick Dahl, "Reflections on Apollo and the Next Giant Steps: The Giant Leaps Symposium," *AeroAstro Annual* (Cambridge, MA: MIT, 2008–09), 10; Kevin M. Rusnak, "NASA Johnson Space Center Oral History Project: Oral History Transcript," Cutchogue, NY, September 19, 2000, https://www.jsc.nasa.gov/history/oral_histories/KellyTJ/TJK_9-19-00.pdf, 12–40.

[114] It "required nearly all subcontractors and vendors to subject their equipment to 1 min of random vibration in each of three mutually perpendicular axes …. " Scott H. Simpkinson, MSC, "Testing to Insure Mission Success," *Aeronautics & Astronautics* 8.3 (March 1970): 52.

including ones in which the LM skidded laterally and caught its spindly legs in a crater or curb-like formation.[115] "We worried tremendously about tipping over," Gavin relates.[116] The need to finalize the landing gear well before the first *Surveyor* probes sampled lunar soil in 1966[117] led to a conservative design[118] that Gavin retrospectively believed was twice as heavy as strictly necessary.[119] Compressible legs experienced a maximum of three inches' compression out of thirty-two inches available.[120]

Two decades after Apollo 11, Gavin highlighted key dynamics "from an engineering viewpoint. What we worried greatly about but worked well—landing, takeoff, rendezvous … the problems we encountered—some expected, some surprises: weight, leaks, fire-proofing (oxygen atmosphere), crystals in the glycol, batteries, electronic equipment and systems, reaction control system contamination, propellant tank design, stress corrosion, windows."[121] Among these, Gavin cited "LM stress corrosion, fuel leaks, 'hot' drop test, glycol crystals, ascent stage takeoff, [and] analysis of landing conditions" during 1966–68 as "incidents in Grumman Corporation history that tested corporate mettle and required us to follow our principles at some risk."[122] From December 1967[123] through December 1968, Grumman's quality inspectors found multiple instances of stress corrosion. In a concerted campaign, they reviewed "all machined parts," found 1204 "potentially vulnerable to stress corrosion," "searched 359 drawings of spacecraft components … identified 45 parts as critical in terms of safety or mission success," and reinforced or replaced all items in question.[124]

1.3. I·III Safe success trumped schedule and cost

Gavin's LM leadership experience convinced him that innovation to ensure safety and reliability required flexibility in schedule and, particularly, in costs. As Program Director, he dealt intensively with NASA, subcontractors, and Grumman's own management: "You do whatever has to be done … it was a balancing act where the program director tries to keep the program on the right track despite what the internal management might think, and to some degree what NASA might think, because, after all, if [the product] doesn't work, it's our fault."[125]

NASA imposed incentives on Grumman and other Apollo contractors with a complex formula trading off fulfillment of three major objectives: (1) safety, (2) schedule, and (3) cost. "It took us about 90 days to figure out that there was no trade off," Gavin recalled.[126] The equation quickly became largely fixed. First, mission success was non-negotiable; the LM "was always an engineering program."[127] Second, schedule was important; having started a year behind the CSM, the LM faced continuous catch-up and coordination challenges.[128] Here, technology was a dominant factor: "You weren't going to advance the program by meeting a schedule if the technology wasn't right." Only the third area, cost, offered any real flexibility. Over the course of 3600 contract changes, the LM's cost tripled[129]—but with only a 12–15% overrun of cost on an evolving contract[130]—ultimately constituting approximately 10% of Apollo expenditures.[131]

Mounting expenses prompted considerable pressure from NASA and its Congressional funders. In April 1966, ASPO Manager Joseph Shea wrote to Gavin with cost-escalation concerns.[132] Following the Apollo Quarterly Program Review on July 1, 1966, Grumman appointed Brian Evans subcontract manager of an immediately established Program Control Office reporting directly to Gavin on the subject.[133] Grumman only began to receive significant incentive pay when actual missions began, then maximized it with a perfect track record. "From 1963 to 1967, very little fee was earned," Gavin recalled. "The program was always behind the desired schedule and over cost. Once the missions began, the fee situation improved; the Lunar Module 'worked' every time."[134] Grumman earned 97.7% of possible flight incentives–$17,986,000.[135]

By fall 1968, the LM had finally caught up with the rest of Apollo,[136] just in time for a spate of missions that laid the groundwork for the Apollo 11 landing in July 1969, and Apollo 12 that November. On December 31, 1969, Gavin wrote in his dayplanner, "And so ends a great year!" Five missions (with four landings) followed through 1972. Apollo 15–17 employed heavier extended-duration LMs with additional fuel,

[115] Gavin, "LEM Design Evolution," 47–48; Gavin, "A Review of Two Past Space Programs."

[116] "Part 4: The Lunar Module."

[117] "Things like pressure bags—a kind of inflatable seat cushion for it to land on—were suggested," Gavin explains, "but you have to go a long way before you get anything as efficient as plain landing struts." Buckley, "It Looks Like a Martian," 35.

[118] Slides "25-1. Landing gear parameters," "25-2. A severe landing—initial contact," "25-3. A severe landing—maximum pitch," Apollo Contractors Executive Briefing, March 1964.

[119] NASA Interview, 2003.

[120] Gavin, "A Review of Two Past Space Programs."

[121] Gavin, notes for talk, "L.I. Apollo Anniversary."

[122] Gavin, untitled notes, November 9, 1987.

[123] In his dayplanner on December 8, 1967, Gavin recorded: "stress corrosion found on vehicle struts." On December 15, he wrote, "one major task—[fix] strut corrosion by 28 Dec!"

[124] William J. Normyle, "Development Problems Resolved for First Manned Flight," *Aviation Week & Space Technology*, February 17, 1969, 44. See also "LM Fittings Changed," NASA Release No. 69-24, January 31, 1969.

[125] NASA Interview, 2003.

[126] Gavin, "Introduction," Apollo Guidance Computer History Project.

[127] Keegan, Interview of Gavin.

[128] "Grumman … benefitted in some respects, Gavin said, by having been the last Apollo module contractor selected. The company's LEM team has inherited some mission systems chosen earlier and thereby reduced its own design workload …. " William J. Normyle, "Focus of LEM Effort Shifts to Detailed Requirements," *Aviation Week & Space Technology*, April 6, 1964, 22.

[129] IAC, 1990, 2.

[130] Keegan, Interview of Gavin.

[131] First draft of IAC, 2002, dated June 25, 2002.

[132] "1966 September 28—Grumman Work on the Apollo LM Program," in "Apollo LM," http://www.astronautix.com/a/apollolm.html.

[133] "1966 Week Ending July 1," in Ibid.

[134] IAC, 2002, 3.

[135] "Slide 19—Flight Performance," D.F. Schlegel and D.J. Markarian, "Apollo Lunar Module Legacy," presentation, AIAA Meeting, Denver, CO, July 1973.

[136] Kelly, *Moon Lander*, 153, 163.

oxygen, water, and batteries; as well as an improved descent engine and enhanced thermal protection.[137] Increases in the Saturn rocket's power also allowed more scientific equipment and a lunar rover stowed in the descent stage.[138]

1.4. IV Difficult judgment calls

Gavin had to make some challenging on-the-spot decisions. One concerned the approach that Grumman would choose regarding the nozzle of the LM's descent engine, the first wide-range-throttle-controlled rocket engine. "NASA was not supposed to make the decision," Gavin recalled, "so I made the decision, and [NASA manager Maxime Faget] said, 'Fine,' and that was that."[139]

In a singular instance, meeting NASA's scheduling target was so important that Gavin bypassed normal pre-launch testing. A motor in the LM environmental control unit required replacement in a confined space that could only accommodate two people. Gavin devised a procedure whereby the best technician from the unit subcontractor (Hamilton Standard Division, United Aircraft Corporation) would replace the motor, vetted by Grumman's best mechanic. Such a judgment was only possible because of the direct interpersonal knowledge that Gavin accrued over the years within his organization.

Gavin telephoned directly Nelson J. Vosburgh,[140] whom he first met when Gavin was a very junior engineer at Grumman—"clearly the best nuts-and-bolts mechanic I have ever seen." Gavin's plan was good enough for NASA administrator George Low when he declared: "I've known this chap for over fifteen years, and he's the best mechanic I've ever seen do anything." Gavin elaborates: "we got him indoctrinated on what to look for, and we got the expert from Hamilton Standard and the two of them at [Cape Kennedy], and they went in and they changed the motor. A routine check said everything works, and on the basis of that, we launched the mission." Vosburgh had reported directly to Gavin that he could not have done it better. Gavin recalled: "And [Nelson will] never forget that, and I won't ever forget it, because it was one of the few times that we really breached the procedural testing sequence that we had set up."[141]

In yet another judgment call, Gavin required that a Rocketdyne injector be used in an engine that was otherwise built entirely by Bell—a crushing disappointment to the Bell team with whom he had worked closely.[142] As had been the case from his aircraft project engineer days, Gavin's recommendations usually prevailed, but he stuck to his principles even when occasionally a lone holdout whose position was overridden.[143]

Another important decision by Gavin concerned not technology directly but rather supporting his colleagues in developing it. In fall 1961, when he took his team to settle LM contract details, Houston was still racially segregated. Hotel after hotel would not accommodate two of their top engineers, Reaction Control System Project Leader Ozzie Williams and Guidance & Navigation Project Leader George Henderson. Being regrettably familiar with such prejudice, they volunteered to find their own rooms. Gavin, who had previously defended the engineers to ensure that Grumman's culture of equal treatment was honored without exception, insisted on keeping the team together no matter what. Under his direction, the group finally found "the one hotel [in the area] that would take the whole team," and negotiations with NASA proceeded successfully. Even the additional commuting distance proved a bonus: "in hindsight, that was the smartest thing we ever did, because it welded the team together." This was just one of many times that he had stood up for people and supported them: "in some respects, I was backing up those two guys more than once." Here Gavin led, but within the context of an enlightened workplace: "Fortunately, Grumman—from early on, from the founders—had had a very modern view of treating everybody alike, so it was easy to do within the Grumman operation."[144]

1.5. I·V Apollo 13's lifeboat

During the aborted Apollo 13 mission of 1970, the LM became a lifeboat and tugboat of last resort. This linchpin role was anticipated overall, unanticipated in some specifics, and enabled throughout by systematic preparations true to Grumman's conservative engineering philosophy.[145] While not primarily intended to provide supplemental propulsion, electricity, and oxygen in the event of a Service Module fuel tank explosion—as happened then—the LM was designed with considerable capacity and reserves.[146] NASA initiated the Grumman-led

[137] Kelly, "Design Evolution of the Apollo Lunar Module," presentation, Columbia University, New York, NY, November 8, 1972, 10; Gavin, "A Review of Two Past Space Programs"; Keegan, Interview of Gavin; *Apollo 15 Mission Report* (Houston, TX: NASA Manned Spaceflight Center, 1971).

[138] Kelly, *Moon Lander*, 245.

[139] NASA Interview, 2003.

[140] Background: "Nelson Vosburgh," Obituary, *Berkshire Eagle*, February 25, 2000, https://www.ancestry.com/boards/localities.northam.usa.states.massachusetts.counties.berkshire/2555/mb.ashx.

[141] NASA Interview, 2003.

[142] Ibid.

[143] Dayplanner example—March 1, 1967: "Everyone but JGG wants to rescale accelerometers."

[144] Keegan, Interview of Gavin.

[145] Key example: power. "The CSM/LM electrical interface was designed so that the CSM would provide electrical power to the LM during the translunar phase of the mission. The reverse condition, LM power to the CSM, was not a design requirement and was never attempted prior to the Apollo 13 problem. The LM Descent batteries were estimated to have delivered a total 1567 amp hours out of a rated total capacity of 1600 amp hr. The batteries were unevenly discharged so that some batteries exceeded the spec requirement (i.e., one battery delivered 428 amp-hours compared to the 400 amp hr spec requirement)." "LM-7 (Apollo 13)," unidentified document.

[146] Indeed, five years previously, Gavin concluded in an article on LM design development that "Without the necessity of starting over 'from scratch,' LEM appears adaptable to other lunar missions such as the logistics 'truck' as well as to Earth orbital missions which capitalize on its propulsive capacity to provide maneuverability or which make use of its compatibility with the Command Module." Gavin, "LEM Design Evolution," 51. See also "Lunar Module Derivatives for Future Space Missions," in Richard Hoagland, *Apollo Spacecraft News Reference* (Bethpage, NY and Houston, TX: Grumman Aerospace Corporation and NASA MSC), LMD-1 to −13; same title, undated brochure and drawings; "Looking Past Apollo for Future Space Missions for LEM Vehicle," *Grumman Plane News* (November 29, 1965), 5. Gavin mentioned the LM "truck" variant in his dayplanner on May 13, 1964; June 3, 1964; and June 12, 1964. He mentioned LM "TUG" on February 4, 1965. On April 25, 1969, he noted a "pitch on LM derivatives." Gavin references "LM-A" on June 12, 13, 16, and 27; as well as July 7 and 8, and August 5, 1969. He mentions "LM-B" on July 8, 1969. "We at Grumman had developed a very interesting and I think reasonable, practical program for expanding the exploration of the moon," Gavin recalled, "that … involved modifications of the Lunar Module to carry different kinds of equipment, and … the development of a rover that would be pressurized so that it could be operated under shirt-sleeve conditions, with a greater range of maneuver …. " Author's interview of Gavin, Amherst, MA, December 11, 1998.

Apollo Mission Planning Task Force (AMPTF) in 1964 "to examine the various phases of the mission and look for ways to make them safer."[147] "One major result" had been "the identification of the 'LM Lifeboat' mission," which triggered prescient increases in tank size for consumables,[148] although that role "had never been rehearsed by either the ground or flight crews or written into specific operational procedures."[149] Grumman's foresight exceeded that of NASA, whose otherwise extremely detailed contractual scenarios never envisioned a LM rescue mission; Grumman would earn no incentive rewards for saving the day.[150]

Throughout the crisis, Gavin was at NASA's Mission Control Center in Houston helping to coordinate the urgent assessment and employment of the LM's capabilities for this emergency assignment. He had previously led the normal process as he did for every LM mission:

(1) First, a major review at Grumman before the machine was shipped to the Cape Kennedy, Florida launch site.
(2) Second, "almost disassembling" the vehicle at the Cape and checking it out.
(3) Third, a three-day-prior meeting where "all principals from companies were subject to a checkout list: 'are you ready to go'?"
(4) Fourth, staying at Cape Kennedy from launch until the spacecraft was safely in orbit,[151] before flying to Houston to support the mission—normally busy but routine.[152]

On April 13, 1970, two days after LM-7 was launched as part of the Apollo 13 mission spacecraft, Gavin and several colleagues were concluding a long day in Houston at the MSC's Mission Evaluation Room (MER; the engineering support center adjoining Mission Control) with dinner and rest at their motel. It was 10:30 p.m.—typical of the challenging hours then. "We were just about to order when the motel manager leaned over my shoulder," Gavin recalled. "He said he'd heard there was a problem at Mission Control and he thought we might like to get over there. That did it for dinner." Back at MER, "They knew generally what had happened but they hadn't yet been able to figure out the exact cause or the probable chain of consequences. I started by feeling, 'It can't be this bad' and then went through a period of progressive disbelief as the reports came in through telemetry and spacecraft communications and we began to appreciate the full extent of the disaster. Finally it became clear that the mission had to be aborted and our Lunar Module was the only hope for the astronauts' survival."[153] "I think all of us had a sense of tension in those hours that we've not felt before or since," Gavin recounted.[154] Nevertheless, "The extensive preparation and analysis that's gone on tend to make the reaction to an

[147] Kelly, "A Review of the Apollo Lunar Module Program and its Lessons for Future Space Missions," 4.

[148] "While postulating the effect of various CSM failures on the outbound leg of the mission, the planners realized that a number of them could be countered by using the LM as a lifeboat and utilizing its propulsion, guidance and control, life support, and other systems to return the crew to the vicinity of the Earth's atmosphere for re-entry in the CSM. To provide this rescue capability, some of the LM consumables, such as oxygen, water, and electrical power, would have to be increased by 10–15% above that needed to perform the basic mission. Because LM then existed only on paper, we decided to make the tanks that much larger. At a later date it could be decided whether to actually load the consumables into them. Six years after it first appeared in the AMPTF's reports, this vital crew rescue mode was dramatically utilized on Apollo 13." Kelly, *Moon Lander*, 77. See also "1966 March 17—Apollo time-critical aborts due to service propulsion system failure investigated," http://www.astronautix.com/l/lmecs.html: "John D. Hodge, Chief of MSC's Flight Control Division, proposed that time-critical aborts in the event of a service propulsion system failure after translunar injection (TLI; i.e., insertion on a trajectory toward the moon) be investigated. Time-critical abort was defined as an abort occurring within 12 h after TLI and requiring reentry in less than two days after the abort. He suggested that if an SPS failed the service module be jettisoned for a time-critical abort and both LEM propulsion systems be used for earth return, reducing the total time to return by approximately 60 h. As an example, if the time of abort was 10 h after translunar injection, he said, this method would require about 36 h; if the SM were retained the return time would require about 96 h. He added that the LEM/CM-only configuration should be studied for any constraints that would preclude initiating this kind of time-critical abort. Some of the factors to be considered should be: 1) maximum time the LEM environmental control system could support two or three men on an earth return; 2) maximum time the CM electrical system could support minimum power-up condition; 3) time constraints on completely powering down the CM and using the LEM systems for support; 4) effects on planned landing areas from an open loop reentry mode; 5) stability of the LEM/CM configuration during the descent and ascent propulsion burns; 6) total time to return using the descent propulsion system only or both the LEM's descent propulsion system and ascent propulsion system; and 7) communications with Manned Space Flight Network required to support this abort."

[149] Kelly, *Moon Lander*, 226. The following claim suggests that some relevant training had occurred: "this current mission, with a loss of power in the command module, was flown many times in the simulators. When the explosion happened Monday night, the crew had started to climb into the LEM even before the flight director told them to, they were so familiar with what probably would happen." Martin Waldron, "Flight Director Is Making the Decisions," *New York Times*, April 16, 1970, 30.

[150] "Slide 32—Incentive Targets," Schlegel and Markarian, "Apollo Lunar Module Legacy."

[151] At the three-days-prior meeting for Apollo 11, Gavin recalled, "My job was to say the LEM was ready. I said it was. Then, the night before the launch, there were some questions about the loading of a critical helium tank on the LEM. I stayed at [Cape Kennedy] until about 9 o'clock to review and approve the procedures being used. Then I went back to my motel to catch a few hours' sleep, but was back at the Cape by 1 a.m." Michael Dorman, "A Giant Step for LI: Grumman's Lunar Module Ferries Astronauts on a Dangerous Mission to the Moon," *Newsday* (Long Island), June 14, 1998, A16.

[152] Keegan, Interview of Gavin.

[153] Richard Thruelsen, *The Grumman Story* (New York: Prager, 1976), 13. Gavin summarized in his dayplanner: "mid-evening CSM power failure—lunar landing aborted—desperate effort to do return mission on LM—"

[154] "Part 4: The Lunar Module."

emergency a controlled one—no lack of emotion—but you start thinking what are the alternatives, the possibilities, the priorities."[155]

Unlike its Soviet counterpart, "Apollo was a very open program." Now it was operating under an intense national and international spotlight. Gavin led with full knowledge that he had ultimate responsibility: "One thing we did think about was: 'Who speaks for the company if there is a catastrophe?' And we worked that out, and I drew the short straw. My wife quizzed me about this and asked me: 'What happens if … ?' And I said: 'Well, we've thought about it. We know what has to be done. It won't be pleasant.' But, having been in the aircraft business for quite a number of years, we'd faced disaster before … When you deal with flying machines, when you're defying gravity, you have to know that sometime you're going to have a problem. I think we had grown up with that uncertainty. And I think we had a team at Grumman that thoroughly understood this."[156]

Staring reality in the face, Gavin directed the Apollo Mission Support Center (AMSC) back at Grumman's headquarters to address the new emergency-imposed priorities: "Hoarding the consumables was first on the list. That was a fairly straightforward job of extrapolation and was already being worked on by SPAN [Spacecraft Analysis] and MER. Many of the other problems and contingencies we faced involved options which demanded considerable study and, sometimes, some trial runs on a simulator. So we had to get backup crews in the two LM test modules, one in Houston and one at Bethpage, so that we could run through the simulations of suggested procedures. Then we had to start working on problems like whether it was better to jettison the damaged Service Module or to keep it as part of the package, how the LM descent engine would perform in pushing that three-module configuration, and whether it would be wise to discard the descent section of the LM and use the ascent engine as the emergency power. They were all questions which had never been asked or answered before."[157]

It was truly an all-hands-on-deck time for Grumman. Gavin recalled Kelly and fellow LM engineer Howard Wright from year-long Boston-based industrial management courses by midnight phone call. They boarded a 2 a.m. chartered flight for Grumman's Airport.[158] As he rushed into Grumman's AMSC at 3 a.m., Kelly saw a "flood tide" of engineers entering the building, assembling spontaneously to serve as needed.[159]

Meanwhile, in Houston, Gavin was appointed to the Mission Review Council.[160] Maintaining his post atop Grumman's multiple layers of technical support,[161] "the tensest episode in my career,"[162] Gavin estimates that he only "got 2 h of sleep in that whole [four-day] mission." His leadership was particularly important in determining the sequence in which systems could be shut off to save electricity without compromising their ability to be restarted when needed. Gavin's frontline VIP room was connected by "an open line" to a nearby building, itself connected by another "open line" to Kelly and his 200-plus colleagues back in Bethpage.[163] This way, "you could get an answer on almost everything in 1–2 min" Initial worries about insufficient oxygen gave way to intangible worries about "the real problem: times that just had to go by with nothing expected to happen, where you hoped that nothing would happen."[164]

"Successful splashdown—all safe!" Gavin inscribed enthusiastically in his dayplanner on April 17. Low invited him to leave his post against the glass windows surrounding Mission Control to enter the main floor. The room "just burst into cheering … the atmosphere was … so buoyant …. "[165] "There was a sense of relief—you could feel it."[166] *The Washington Post*'s front page showed Gavin watching the astronauts' recovery with Alan Shepard, first American in space and subsequent Apollo 14 commander. Shepard clenches a cigar and claps, Gavin smiles.[167] Watching the movie *Apollo 13* in retirement, Gavin observed that it depicted neither the small American flags that people waved in celebration nor the cigars of which he declined to partake. He regretted that nobody had consulted Grumman in making the film, which he believed did not properly credit the company for how it helped to save the day.[168]

Above all, Gavin was humble and grateful: "There was a level of emotion in that group—you could cut it with a knife, because the odds of it being a successful return were pretty small. In fact, if the accident hadn't occurred at the right point, the options to go around the moon and return wouldn't have worked. A lot of us got pretty exhausted, but it

[155] Bruce Lambert Jr., "Space Medal Winner Credits Team Effort," *Newsday*, March 9, 1971.

[156] Keegan, Interview of Gavin.

[157] Thruelsen, *The Grumman Story*, 13–14.

[158] Ibid., 13–14; Gavin, "JGG Comments" regarding Kelly, *Moon Lander*, December 2001. Wright attended Harvard Business School. Kelly, *Moon Lander*, 225.

[159] Kelly, *Moon Lander*, 227.

[160] Gavin, dayplanner, April 14, 1970.

[161] Gavin was typically on post during missions. Always busy in the instrument room, he never witnessed a launch first-hand. Kelly recalls that Gavin "was liable to be [in the VIP viewing area] at any hour." Kelly, *Moon Lander*, 210. What distinguished Apollo 13 was the lack of occasional downtime to sleep.

[162] Martin Childs, "Joseph Gavin: Aerospace Engineer Who Played an Integral Part in the First Moon Landing," *The Independent*, January 1, 2011, https://www.independent.co.uk/news/obituaries/joseph-gavin-aerospace-engineer-who-played-an-integral-part-in-the-first-moon-landing-2173400.html.

[163] Kelly, *Moon Lander*, 228–29.

[164] "Part 4: The Lunar Module." Accordingly, Gavin tracked progress in his copy of the flight plan by noting days with a marker, vice his normal practice of annotating extensively during the LM portion of the mission.

[165] NASA Interview, 2003.

[166] "Part 4: The Lunar Module."

[167] "Astronauts Come Home Safely," *Washington Post*, April 18, 1970, 1. See also *Daily News* (New York), April 18, 1970, 1. Originally slated to command Apollo 13, Shepard would instead command Apollo 14 and pilot its LM *Antares* to a near-perfect landing.

[168] In particular, he considered the cameo appearance of the lead Grumman representative (himself, in real life) an unfair portrayal. Author's experience watching *Apollo 13* with Gavin upon its 1995 release at Tower Theaters, South Hadley, MA, and discussing it with him subsequently.

was a good feeling to get [the astronauts] back on the carrier."[169]

For his contribution, NASA awarded Gavin its Distinguished Public Service Medal in 1971 "as the leader and representative of the lunar module team … in recognition of the team's outstanding skill which made possible the successful use of the lunar module as a rescue vehicle for the safe return … of the Apollo 13 crew."[170] This followed his 1969 NASA Public Service Award for contributions to Apollo 11.[171] In 1971, the American Astronautical Society accorded him its Space Flight Award on similar grounds.[172] In 1974, in the highest professional distinction an American engineer can receive,[173] and one of his proudest career accomplishments, he was elected to the National Academy of Engineering "for leadership in the design and the production of the Apollo Lunar Module."[174] In 2007, he was inducted into the Long Island Technology Hall of Fame.[175] In accepting recognition, Gavin always credited these technical feats to the spirited teamwork throughout Grumman, across the nation, and around the world. In recounting Apollo, Gavin made particular effort to recognize steadfast contributors such as NASA administrator Bob Gilruth, whom he felt "should have gotten far more credit."[176]

1.6. I·VI Space apogee for Gavin and Grumman

Grumman was not nearly as successful in its subsequent space efforts. First, America's space program became a victim of its own success. With Kennedy's goal achieved, Apollo-level funding rapidly proved politically unsustainable. On February 26, 1970, following lunch with Gilruth, Gavin presciently concluded in his dayplanner: "After last Apollo, no return to the moon this century!" Many proposed LM variants were never built.[177] Air Force officials met repeatedly with Gavin regarding a Manned Orbiting Laboratory, but the program was cancelled. Grumman's "future space business outlook" also contemplated a lunar base[178] and a "space factory scheme."[179] Gavin himself advocated a "lunar polar orbit mission" and for the rest of his life championed a lunar far-side observatory shielded from terrestrial electromagnetic interference.[180] None of these projects materialized.[181]

Second, rising to management, Gavin observed the impact of politics and bureaucracy on procurement decisions: "Success does not mean you necessarily get the next job."[182] In 1968, Boeing declined to collaborate on a space station bid, and Grumman never succeeded in this area despite great effort.[183] Considering his team's lunar rover design "first-class," Gavin was disappointed when NASA selected Boeing abruptly while his company's prototype remained in testing.[184] Grumman likewise lost the bidding competition for the Space Shuttle.[185] This was despite submitting what Gavin and his team considered a superior proposal,[186] and reportedly winning the technical competition.[187] Indeed, working much unpaid overtime, "Grumman engineers had come up with a major design innovation—involving use of expendable fuel tanks—on which all final design proposals had to be based."[188]

169 "Part 4: The Lunar Module."

170 "Special Honor Awards Ceremony," NASA MSC, Houston, TX, February 1971; Bruce Lambert Jr., "Space Medal Winner Credits Team Effort," *Newsday*, March 9, 1971. This was only the seventh such award since 1958.

171 "Special Honor Awards Ceremony," NASA MSC, Houston, TX, October 2, 1969.

172 "Space Flight Award," American Astronautical Society, https://astronautical.org/awards/space-flight/.

173 "Grumman, Hedrick Get National Honors," *Grumman Plane News* 33.7 (April 15, 1974), 1.

174 Neil A. Armstrong, "Joseph G. Gavin, JR. 1920–2010," in *Memorial Tributes: Volume 15* (Washington, DC: National Academies Press, 2011), 111–14, https://www.nap.edu/read/13160/chapter/21.

175 Ross Daly, "Tech Hall of Fame Welcomes Four Newest Members," *Long Island Business News*, March 16, 2007, http://libn.com/2007/03/16/tech-bytes-46/.

176 NASA Interview, 2003.

177 "The Lunar Modules That Never Were," Chapter 6 in Stoff, *Building Moonships*, 111–20. The Air Force even considered using a modified LM to disable Soviet satellites mechanically. Ibid., 116. See also David J. Shayler, *Apollo: The Lost and Forgotten Missions* (New York, NY: Springer Praxis, 2002), 64–84.

178 Gavin, dayplanner, April 18, 1969.

179 Ibid., October 29, 1969.

180 "Space Expert Predicts Global Environmental Data System," *Grumman Plane News* (October 22, 1971), 7; Gavin's many discussions with author over many years.

181 On November 2, 1971, Gavin even noted in his dayplanner a meeting about "possible commercial space programs." As with much of his outlook: prescient, but failed to materialize in time for Grumman to execute under his leadership.

182 Keegan, Interview of Gavin.

183 "Boeing declined space station teaming." Gavin, dayplanner, November 29, 1968. Convair expressed interest in December 1968. "Both McDonnell-Douglas and Martin are willing to join in space station study." Ibid., December 3, 1968. Gavin persistently mentioned Grumman's Shuttle quest in his dayplanner.

184 Grumman's prototype was well known. For example, it was the only rover to appear photographically in the following published interview with Apollo's head. Gavin appeared on the magazine's cover discussing the LM with Low. Murray Q. Smith, "The Apollo Program and its Implications: An Interview with General Sam C. Phillips, USAF, Director of the NASA Apollo Program," *Data on Defense and Civil Systems* 14.4 (April 1969): 26–27.

185 Richard Witkin, "NASA Contracts for Development of Space Shuttle," *New York Times*, July 27, 1972, 1.

186 "1972—The Year in Review," *Grumman Plane News* 31.23 (December 21, 1972), 6–8; Otto Erbar, "Gavin Confident Grumman Will 'Zoom Back Again'," *The Long Islander*, August 3, 1972, 1, 5. Regarding Grumman's shuttle concept and other past and proposed space projects, see Gavin, Grumman Aerospace Corporation, testimony, Hearings before the Subcommittee on Manned Space Flight of the Committee on Science and Astronautics, U.S. House of Representatives, Ninety-Second Congress First Session on H.R. 3981, [No. 2], Part 2, March 4, 1971, 1109-52; Gavin, "Stockholders Meeting—Space Report," Report of Annual Meeting, Grumman, Bethpage, NY, May 16, 1972; Richard L. Kline and Andrew R. Mendelsohn, "Thermal Integration Considerations for the Space Shuttle," paper presented at the American Society of Mechanical Engineers' Space Technology and Heat Transfer Conference, Los Angeles, CA, June 21–24, 1970.

187 Richard Witkin, "Grumman Is Seeking $1-Billion in Subcontracts in U.S. Space-Shuttle Program," *New York Times*, July 29, 1972, 54.

188 Ibid.

Following Gavin's determined campaigning, Grumman was selected to build the Shuttle's wings as a subcontractor to North American Aviation.[189] In the immediate aftermath of the loss, Gavin reassured his employees: "I believe that our programs are clearly in the national interest, that our products are sound, and that with continued determination we can press on to future successes."[190] In a memo posted on Grumman's bulletin boards, he concluded, "The Lunar Module now being processed for launch at [Cape Kennedy], although the final one, should be a lasting tribute to the workmanship and dedication of the people at Grumman who were involved in this historic undertaking."[191]

For Gavin and Grumman, space development thus reached its apogee during the heady LM years. Under his subsequent leadership, Grumman would focus on traditional naval aircraft while attempting commercial diversification on Earth.[192]

2. Moonshot management: Lessons from Bethpage and beyond

A hands-on problem-solver who never took a management course, Gavin drew multiple lessons from his team's experience in developing the state-of-the-art LM and ultimately building twelve operational vehicles, of which ten flew.[193] Some he applied to Grumman's subsequent aircraft business. All he shared concisely with interested audiences, culminating with his delivery of a paper at the 2002 IAC Congress in Houston, TX: "The Apollo Lunar Module (LM): A Retrospective."[194] Written in an engineer's impersonal bulletized shorthand, its four pages of diagram-rich text constitutes Gavin's capstone public discussion of his career, the machine that made it, and the underlying principles that he internalized, exemplified, and conveyed in actions and statements. Here, the author draws on additional sources to elaborate on Gavin's conclusions and distill them into eight principles that he espoused professionally but never listed formally or sought credit for.[195]

2.1. Return astronauts safely to Earth

Above all, Gavin and his team were concerned for spacefarers' wellbeing.[196] In Congressional testimony, Gavin highlighted "several themes which run through the programs with which we have been associated and which represent the 'character' of a company developed over 40 years. The first is personal identification with the crew; the continuing priority given to the safety of the men who pilot our flying machines. We can think of no better proof of the importance of this theme than the Apollo 13 [mission]."[197] When he appeared in the *New York Times* as "Man in the News" two years before Apollo 13, his photograph was appropriately captioned, "Thinks always of safety of the spacemen." The article stressed: "… underlying all his concerns about his work is the safety of those who someday might pilot a craft he helped build."[198] President Nixon wrote to Gavin's boss: "you and your colleagues at Grumman … who were responsible for the *Aquarius* Lunar Module have reason for special pride in your work. I hope you will convey my personal appreciation to all of your employees for the brilliant engineering and painstaking execution which played so major a role in the safe return of Astronauts Lovell, Haise and Swigert."[199]

Grummanites knew that they were building the LM for real people whose lives depended on it.[200] "The team at Grumman developed a personal relationship with every one of the astronauts in the Apollo era," Gavin stressed. "We were building machines that our friends would

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[189] Kelly, *Moon Lander*, 261; David A. Adelman, "Space Contracts Given Grumman—Saving of 300 Engineering Jobs Expected on L.I.," *New York Times*, September 17, 1972, L24; Gavin, remarks as Chairman of the Board, Grumman Aerospace Corporation, Report of Annual Meeting, Grumman, Bethpage, NY, May 16, 1974.

[190] Gavin, "Holiday Message," *Grumman Plane News* 31.23 (December 21, 1972), 3.

[191] "Message by President Joe Gavin on Recent Space Shuttle Developments," News Board, Internal Communications Department, Grumman Public Affairs, July 28, 1972.

[192] Chapin A. Day, "Ups and Downs at Grumman: Despite Diversification, The Firm's Fate as a Major Aerospace Industry Hinges on the F-14," *News Day*, November 5, 1971, 3, 21. The most enduring commercial success was Grumman's development and sales of its boxy but efficient Long Life Vehicle mail truck. It is familiar to many through the 140,000 units the U.S. Postal Service has operated following a stringent competition in 1985, with similarly widespread use in the Canada Post and additional sales to Mexico and other countries. "LLV Postal Trucks," http://grummanpark.org/content/llv-postal-trucks; Nancy A. Pope, "Long Life Vehicle," National Postal Museum, Smithsonian, January 2009, https://postalmuseum.si.edu/collections/object-spotlight/llv.html. Less successful were efforts to diversify the company's products into such varied offerings as seaplanes, buses, ambulances, garbage and fire trucks, the Dormavac perishable goods transport system, yachts, aluminum canoes, and wind turbines. These either represented niche markets; and/or preceded today's focus on, and incentives for, green technologies. Gavin listed the "worst crisis" of his career as "repairing the [Flxible] buses—a design we bought from Rohr." "Gavin, Joseph G. Jr.," *50th Reunion Yearbook* (Cambridge, MA: MIT Class of 1941, June 3–8, 1991). To revamp Grumman's "money-losing" Flxible bus subsidiary, which suffered from unrevealed structural defects in the design that Grumman had purchased, Gavin was named its chairman and put in charge of it directly. James Barron, "Grumman's President Named Chairman of Flxible Bus Unit," *New York Times*, February 23, 1982, D4.

[193] Stoff, *Building Moonships*, 8.

[194] IAC, 2002.

[195] While Gavin was a key individual heading an unusually demanding program, his experiences and philosophy overlapped with other important stakeholders who together ensured Apollo's success. Low, for instance, shared Gavin's early inspiration by the fast-moving aeronautics field, including through wind tunnel research as a student. Both emphasized attention to detail, even for top managers, and walked shop floors themselves. Both worked closely with Teague to support Congressional funding. Both shared with Armstrong mutual admiration; as well as key qualities, including an emphasis on listening over talking as well as calm judgment amid real-time pressure and information overload. Low had direct input into Armstrong's selection to be first on the moon, which Gavin embraced wholeheartedly. Jurek, *The Ultimate Engineer*, 12, 52, 113, 118, 143; author's many discussions with Gavin over many years.

[196] Gavin followed the safety not only of American astronauts but also their Soviet counterparts. In his dayplanner on June 30, 1971, he recorded: "Russians announce death on return for Salyut [space station] cosmonauts." Key stakeholders across Apollo shared the Gavin-Grumman safety imperative. To Low, "every decision…[had] to be based on the knowledge that one day you [would] have to tell the [pilot]: 'I've done the best job I know how to do for you.'" Teague emphasized: "we are a lot more interested in an individual [astronaut] and his life than other countries." Reflecting Low's emphasis, NASA stated: "the safe return of the astronaut must be insured." Jurek, *The Ultimate Engineer*, 2, 52–53.

[197] Statement of Joseph G. Gavin, Jr., Senior Vice President, Grumman Aerospace Corporation, Before the Subcommittee on Manned Space Flight, Committee on Science and Astronautics, House of Representatives, Hon. Olin E. Teague, Chairman, March 14, 1972, 1.

[198] "Reacher for the Moon," 10.

[199] Richard Nixon, Letter to Llewellyn J. Evans, President, Grumman Corporation, May 26, 1970.

[200] IAC, 2002, 3.

operate, not some faceless individuals unknown to us."[201] "It was not just 'put it in a package and ship it.'"[202] While the astronauts' personalities varied greatly, all were top-caliber professionals and "their [periodic] visits to the plant made people feel that 'We're not just building something for some mysterious customer; we're building it for these people.' … that was very useful."[203]

This embodied an ethos dating back to the philosophy of the company's founder, World War I naval aviator Leroy Grumman, who "flew Navy" from 1918 to 1921 and worked for a major naval airplane builder before leading several associates to establish his firm in a Long Island garage.[204] Grumman, Gavin recalled, "had one basic direction to all of us … 'You bring the pilot back one way or another.'"[205] Gavin shared Leroy Grumman's core vision. Piloting was a path not taken for Gavin, but nevertheless informed his work on all the flying machines to which he contributed, including the LM. In 1946, at the end of his four years' service in the Naval Reserve, the Navy offered Gavin a chance to stay on and undergo flight training. He ultimately "decided I wanted to build something" instead, but brought a pilot-centered perspective to those efforts. "I think that as a designer, you have the feeling that 'I could fly this thing,' no question. 'I know it so well that I could fly it,'" Gavin later recalled. "While I had the urge [to get and maintain a pilot's license and fly], by Apollo 11 I was accustomed to saying [to the astronauts], 'It's OK to go fly it.' That's something you don't say without thinking about it."[206] Gavin and his LM team always fulfilled the critical pilot-return requirement from Grumman's founder. Kelly stressed: "Extensive analyses of potential single point failures have been conducted and, wherever technically feasible, the spacecraft has been designed so no single point failure can compromise crew safety."[207]

Below a passage in Kelly's book regarding NASA and Grumman's respective responsibility for the LM's success or failure, Gavin wrote: "I always considered Grumman to be 100% responsible."[208] Duty was reciprocated. "NASA very wisely saw to it that one or two of the astronauts would be in the plant every month," he explained. "The astronauts ended up knowing more about the [LM] than we did. The principal example is Freddy Haise … he knew the machine better than we did."[209] *New Yorker* reporter Henry S. F. Cooper, Jr., who drove out from the city to shadow Grumman's LM operations as an embedded observer, concluded in his resulting feature story that "Haise and other Apollo astronauts represent, even more than NASA does … 'the client.'"[210] During Apollo 13, Haise's experience and expertise would prove invaluable; he took the LM to its performance limits in unforeseen circumstances despite being severely ill. Whereas the automation-maximizing USSR lost four cosmonauts to orbital fatalities during the Apollo years, Gavin credited Apollo 13's survival in part to the "balance between man and automatics."[211]

On May 5, 1970, Haise and fellow crewmembers James Lovell and John Swigert "came to Bethpage to thank Grumman and the LM team for saving their lives …. "[212] Haise addressed hundreds of Grummanites: "We thought, when we were out there floating [post-splashdown], 'if we don't do anything else, let's get back up to Grumman and say 'Thanks.'"[213] Ozzie Williams, defended by Gavin nearly a decade earlier in Houston, "recall[ed] three firm handshakes and three voices saying 'thanks'" in his office. He concluded: "To paraphrase Dr. Martin Luther King's famous words, all of us Grummanites had 'been to the mountaintop' that day."[214] Gavin's other conclusions follow from this crew-safety imperative.

2.2. Create conditions for success

Gavin emphasized the factors powering Project Apollo and its LM. He cited three significant decisions: (1) President Eisenhower's establishment of NASA as a civilian organization, (2) Houbolt's promotion of the LOR concept over von Braun's initial opposition at the risk of his career by going "around his superiors,"[215] and (3) President Kennedy's bold commitment to put a man on the moon by the end of the decade. "In hindsight," Gavin assessed, putting NASA rather than one of the contending armed services (e.g., the U.S. Air Force) in charge of spaceflight "was a really wonderful decision, because it made the space effort in this country open to the public and the world, whereas the Soviets were still carrying on their efforts with the usual … secrecy, and in the long run this worked out very much to the advantage of the American effort."[216] Another great American advantage over its Soviet rival: a "dedicated team: contractors and government agency" that "push[ed the] state of the art" and "attracted real talent" and "personal commitment." "The nation, NASA, and the contractors assembled an extraordinarily talented team of people," Gavin recalled, "it was THE place for engineers to be."[217] More broadly, Gavin stressed, "A complex, demanding program needs long-term commitment and support." Apollo enjoyed "presidential long-term commitment, strong committee leadership in Congress,

[201] Childs, "Joseph Gavin." Gavin's dayplanner contains numerous references to meeting and dining with astronauts.

[202] Keegan, Interview of Gavin.

[203] NASA Interview, 2003. See also "Grumman President L.J. Evans Welcomes Apollo 11 Astronauts," Grumman Corporation Interim Report, September 30, 1969.

[204] "Grumman Course: Following the Fleet," *News Day*, November 15, 1971, 21.

[205] NASA Interview, 2003.

[206] Keegan, Interview of Gavin.

[207] Kelly, "Design Evolution of the Apollo Lunar Module," 3. For similar wording, see "Apollo Navigation, Guidance, and Control Systems," NASA-S-65-4336, 5/65, 11.

[208] Gavin's notation; Kelly, *Moon Lander*, 39.

[209] Keegan, Interview of Gavin.

[210] S.F. Cooper, Jr., "A Reporter at Large: LM," *The New Yorker*, January 11, 1969, 55.

[211] Gavin, notes for talk, "L.I. Apollo Anniversary."

[212] O.S. ("Ozzie") Williams, in Fleisig and Lovisolo, "Lunar Module Remembrances," 40.

[213] "Welcome Home!" *Grumman Plane News* 29.9 (May 11, 1970), 6.

[214] Williams, 40.

[215] Keegan, Interview of Gavin.

[216] Author's interview of Gavin, Amherst, MA, December 11, 1998. Addressing Apollo leaders in the mid-1970s, Armstrong credited the rare alignment of four peaking factors: "Leadership, Threat, Economy, and Talent." Brandon R. Brown, *The Apollo Chronicles: Engineering America's First Moon Missions* (Oxford, UK: Oxford University Press, 2019), 230–21.

[217] Gavin, "Engineering When It Had To Be Perfect," "What Matters" Column, MIT, February 28, 2001.

[a] clearly defined, understandable goal: beat the Soviets to the moon, a real challenge." This enabled "willingness to start in the face of many unknowns," principally regarding the "nature of the lunar surface" and "confidence in reliability."[218]

In 2001, Gavin concluded, "LM was part of a unique, unambiguous goal. President Kennedy made a long-term commitment. We had real competition. The Congress of the '60s had some safe seats so that some, like [Representative] Olin Teague [a Democrat serving Texas's sixth congressional district from 1946 to 78], could vote the national interest."[219] Teague chaired the House Science and Technology Committee's Manned Space Flight Subcommittee[220]; Gavin communicated closely with him and his staff.[221] At the end of his career, four years before his death, Teague wrote to Gavin: "I want to thank you for the beautiful model of the LEM … It is wonderful and I shall deeply treasure it."[222] Gavin viewed the LOR concept as a critical breakthrough: "it was a radical change, and I think it was responsible for the success of the program. I don't think the program would have succeeded on the original path of Saturn" that von Braun initially championed.[223] A product of the era that motivated its creation, the program was energized by heightened Cold War competition on the ultimate stage and sustained by President Kennedy's legacy and President Johnson's persistence.[224]

Regarding Apollo 1, Gavin reflected, "I'm not sure the program could have continued under today's situation, but then it could because we were in the midst of the superpower contest."[225]

2.3. Reliability is attainable

"A lot of people may look at the Lunar Module and say to themselves 'if I did it myself in the cellar it would be a snap'," Gavin joked. "But they forget that every piece of material must have a pedigree, that the tools must be super clean, and, above all, that there would be no instruction sheet. We had to figure it out for ourselves."[226] Grumman's immaculate clean room included stringent check-in/-out procedures, Styrofoam cutouts to reveal any forgotten tools, and a Tumbler for physically shaking debris out of finished LMs.[227] Grumman workers developed a "Glitch Detector" to handle electrical transients. As explained previously, Grumman under Gavin adopted a rigorous regimen and "integrated family of tests"[228] grounded in the principle that they must "take nothing for granted" because "there is no such thing as a random failure."[229] His "ironclad" rule: "If indeed the design has been done properly and the environment is understood, there has to be a reason for the failure which you can find and which you can fix."[230]

Gavin stressed, "This is something that only works when you have a really good team, and when they say they've done something, you can believe them."[231] He underscored: "those of us who were directly involved with the details were always very confident—otherwise we wouldn't have said we were ready to go."[232] Related Gavin axioms: "One should take absolutely nothing for granted."[233] "Never assume previous experience qualifies an equipment or a procedure."[234]

[218] Gavin, notes for talk, "L.I. Apollo Anniversary."

[219] Gavin's note, Kelly, *Moon Lander*, 266. "A great supporter of the [Apollo] program," Teague communicated with Gavin to keep "tabs on what we were doing [for] the whole ten years." After the successful jettisoning of the LM near Apollo 11's conclusion, "he put his arm around my shoulder and said, 'Joe, I'm glad it worked. You know, you've been telling me for years how it was going to work, but in my heart I wasn't really sure.' And I thought, 'Well, that's quite a compliment.'" A colorful character, Teague suffered for most of his life from wounds received heroically in the Italian campaign. "He wound up in Walter Reed [Army Medical Center] for diabetes. So what does he do but arrange for one of his staff to bring him corned beef sandwiches and a bottle of beer. I think he drove the medics wild." Keegan, Interview of Gavin. See also "TEAGUE, OLIN EARL [TIGER]," https://tshaonline.org/handbook/online/articles/fte32.

[220] "A History of the Committee on Science," https://web.archive.org/web/20060824092215/http://www.house.gov/science/committeeinfo/history/index.htm.

[221] Gavin indicates in his dayplanner meeting with Teague as early as December 10, 1962; and records scores of communications and interactions with him and his staff periodically thereafter.

[222] Teague, letter on official letterhead to Gavin, September 12, 1977.

[223] Author's interview with Gavin, Amherst, MA, December 11, 1998.

[224] Seamans testifies to this prioritization from firsthand experience interacting with both presidents in his official capacity. He reveals that Kennedy at various times considered pursuing a manned mission to Mars and a manned moonlanding by 1967 (the latter effort to go "as rapidly as possible" supported with increased funding). While persuaded by Seamans and others to modulate his ambitions, Kennedy was clearly committed to major space success. Robert C. Seamans, Jr, "Oral History Interview—JFK #1," March 27, 1964, 10–11, 14–15, 35. In a major redirection of national priorities, Kennedy ordered atmospheric nuclear testing rescheduled to create the safest environment for Walter Schirra's 1962 Mercury-Atlas 8 mission. Ibid., 24–27. For Johnson's contribution, see Robert Stone and Alan Andres, *Chasing the Moon: The People, Politics, and Promise That Launched America into the Space Age* (New York: Ballantine, 2019), 148–50. For Johnson's Congressional lobbying, see Lanius, *Apollo's Legacy*, 10.

[225] NASA Interview, 2003.

[226] Wilford, *We Reach the Moon*, 150.

[227] Fishman, *One Giant Leap*, 249.

[228] Gavin, notes for talk, "L.I. Apollo Anniversary." See also "Lunar Module: A Manual of Lessons Learned," Grumman Aerospace Corporation, undated.

[229] Keegan, Interview of Gavin. MIT's Instrumentation Lab had similar standards for the Apollo Guidance Computer. George T. Schmidt, AESS V.P. Technical Operations, emphasizes two "rules": "(1) no unexplained failures anywhere and (2) always consider other scenarios—'What if?'" Schmidt, "Inside Apollo: Heroes, Rules and Lessons Learned in the Guidance, Navigation and Control (GNC) System Development," 7.

[230] "Reflections on Apollo and the next Giant Leaps: The Giant Leaps Symposium," in Ian A. Waitz and William T.G. Litant, eds., *AeroAstro* 6 (Cambridge, MA: MIT, September 2009): 10.

[231] Ibid.

[232] Bogo, "The Oral History of Apollo 11."

[233] "Giant Leaps: Apollo 11 Alums Reflect 40 Years Later at MIT Conference," *Popular Mechanics*, October 1, 2009, https://www.popularmechanics.com/space/moon-mars/a4409/4321671/.

[234] Gavin, handwritten note on Bob Steele, "Lunar Module GN&C System," undated three-page troubleshooting summary.

"We tested at the component … assembly … [and] subsystem level [s], and of course we finally tested at the all-up level. And statistically you couldn't prove reliability of the kind we felt we had to have. So we adopted the policy that … every failure had to be examined, had to be understood, and some action had to be taken to eliminate that cause."[235]

To identify and eliminate sources of failure, Gavin and his team had to study deeply a panoply of esoteric subjects, including the properties and performance dynamics of glass and batteries. As Kelly relates, "Grumman was forced to learn more about these batteries than even the manufacturer knew."[236] Grumman rigorously tracked mission anomalies.[237] Each LM featured improved batteries redesigned per ground test results.[238] To maximize program efficiency, they used the latest systems management practices adopted by NASA,[239] including the Navy-devised Program for Evaluating and Reviewing Technique (PERT) and Air Force-devised configuration control.[240] Gavin's conclusion: "If you pay the price, reliability can be attained."[241]

2.4. Prioritize performance over schedule over cost

Gavin's experience in managing technological innovation convinced him that a requirement for breakthroughs to ensure crew safety and mission accomplishment under challenging conditions rendered schedule and cost impossible to forecast. This he termed the "basic program dilemma"[242]: "If a major project is truly innovative, you cannot possibly know its exact cost and its exact schedule at the beginning. And if in fact you do know the exact cost and the exact schedule, chances are that the technology is obsolete."[243] While there was some unavoidable overlap of related concepts, what Grumman prioritized was safety, which became equated with reliability. Accordingly, Gavin and his team prioritized performance (as measured in safety and reliability) first, schedule second, and cost a distant third[244]: "Performance was absolutely critical. Schedule [came] next, and cost was derivative of the first two."[245] In his dayplanner on February 2, 1968, Gavin underscored: "General outlook: if it isn't perfect, fix it—hang the schedule!" "Whenever you start a complex program," he explained, "it's impossible to foresee every little thing that has to be proved out."[246] The biggest surprise for Gavin? It "was the time it takes to do anything really well—it's much longer than you think."[247] Even after the final design freeze, it took an average of 2.5 years to build a LM (as many as three were under construction simultaneously),[248] with tests run constantly over most of this period—all for what was typically a three-day mission usage at most (four days for Apollo 13). Nevertheless, LM development was time-limited: following an intensive Washington meeting on September 3, 1968, Gavin inscribed in his dayplanner: "must plan lunar landing by fall of [calendar year 19]69."[249] A related factor of particular importance for the LM: weight control. "We reached the point," Gavin explained, "where we had to say, 'Look, we've got to stop the design as it now stands and squeeze some more weight out of it.' That is a very embarrassing thing to have to do in terms of delivery dates and costs, but we had no choice. We would see that if nature took its course we'd have had a vehicle that would simply have been too heavy."[250] Hence, slight schedule slippage and considerable cost growth were unavoidable tradeoffs for ultimate LM success.[251]

2.5. Don't complicate things unnecessarily

Gavin and his team found new relevance in the time-honored adage 'if it ain't broke, don't fix it.'[252] In his words: "change = risk"[253]—"the basic rule [is] that if something works, be very careful if you try to

[235] "The Lunar Module Story."

[236] Kelly, *Moon Lander*, 138.

[237] D.F. Schlegel, "Backup Information," undated presentation.

[238] Gavin, "A Review of Two Past Space Programs."

[239] Michael Getler, "Critical Design Phase Ending on Lunar Excursion Module," *Missiles and Rockets*, July 15, 1963.

[240] Kelly, *Moon Lander*, 101–03. Gavin mentions PERT and configuration control frequently in his dayplanner.

[241] Gavin, notes for talk, "L.I. Apollo Anniversary." The LM's conservative design margins and reliability proved an ideal example of Apollo's approach overall. Brown, *Apollo Chronicles*, 154.

[242] Gavin, Gardner Lecture.

[243] "Fly Me to the Moon: An Interview with Joseph G. Gavin, Jr.," *Technology Review* 97.5 (July 1994): 62. In unpublished phrasing, Gavin noted, "Political figures and business school and management wonks find it difficult to accept this idea." First draft of IAC, 2002, dated June 25, 2002. See also Gavin, "How to Sell a Program and Keep it Sold," MIT Alumni Lecture Series on Space Station Design, Cambridge, MA, September 18, 1986; Heather M. David, "NASA Struggling to Hold to 1970 Man-on-Moon Schedule," *Missiles and Rockets*, December 23, 1963, 15.

[244] IAC, 2002, 4.

[245] "Giant Leaps: Apollo 11 Alums Reflect."

[246] Wilford, "First Flight Test of Lunar Landing Craft Expected Tomorrow Afternoon," *New York Times*, January 21, 1968, 78.

[247] Wilford, "Moon Landing Craft is Unveiled by Astronauts," *New York Times*, January 26, 1969, 50.

[248] Stoff, *Building Moonships*, 8.

[249] Here Gavin inserted an eight-page document giving Grumman a multi-tiered risk-versus-incentive structure supporting multiple moonlanding contingencies, beginning with "Complete Lunar Mission on LM-4 or 5 as first attempt in late 68 early 69 with moderate 2nd increment delivery and CTR degradation." Three successive scenarios postulated deadline slippage and aborted missions. The fourth, worst-case, scenario postulated a 1970–71 landing with LM-12, beyond Kennedy's deadline. "Incentive Point Matrix," NASA-5-67-1496; Datafax transmission from F. Harding to Wayne Young, Grumman Aircraft Engineering Corporation, March 15, 1967.

[250] Wilford, *We Reach the Moon*, 155.

[251] Even as Low rode herd over Grumman to promote progress in schedule and cost, he recognized safety and reliability as the overriding imperatives. Richard Jurek, *The Ultimate Engineer*, 123–26.

[252] MIT Apollo Program Director of Mission Development Richard Battin applied similar lessons: "All of the software for all the flights, we did right up through the Skylab missions, the Apollo-Soyuz … The computer didn't change, even though by … [the early seventies], there were much better computers, much faster computers, memory, but you wouldn't want to go in there and change something that worked. If it ain't broke, don't fix it." Rebecca Wright, Interview of Richard H. Battin, NASA Johnson Space Center Oral History Project, Edited Oral History Transcript, Lexington, MA, April 18, 2000, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/BattinRH/BattinRH_4-18-00.htm. See also D.G. Hoag, Memorandum from FA/Chairman, Apollo Software Control Board, "Flight Ropes for Apollo 16 and 17," August 17, 1971; Christopher C. Kraft, Jr., Director of Flight Operations, NASA, letter to Dr. Frederick H. Martin, Technical Director, Mission Development, MIT/Instrumentation Laboratory, May 5, 1969.

[253] Gavin, notes for talk, "L.I. Apollo Anniversary."

change it, because maybe you'll get into something you don't foresee."[254] In an episode that Gavin recounted repeatedly up through his June 11, 2010 Godfrey L. Cabot Award acceptance speech less than six months before his death,[255] upgrading to a costlier, purer rust-inhibitor additive produced unexplained glycol crystals in electronic coolant fluid that no amount of exotic filtering could remove. Investigation included "us[ing] almost all the bowls in the Grumman cafeteria to have samples of glycol sitting around where people could look at it." The solution: "we reverted to the cheap stuff, and all the rest of the missions were straightforward."[256]

2.6. Remove hierarchical barriers

Gavin credits Grumman's informal, responsive, relatively flat LM program organizational structure with fostering innovation and quality control. It "operated with very little 'vertical' distance between the leaders and doers; communication routinely crossed all chart boundaries, vertically, horizontally, and diagonally," he explained. "And the organization evolved with time to meet the demands of the program."[257] Indeed, Gavin's firm long lacked an organization chart: "Roy Grumman, who founded the company, was against it, so we didn't have it for many years." Grumman finally developed a chart at NASA's request.[258]

Gavin and others regularly received reports from employees of all types who felt empowered to call anyone in the company to identify a problem or suggest a solution without fear of suppression or reprisal. "To go through designated channels was unheard of. Consequently, as an organization, it was flatter than the chart would indicate."[259] Indeed, "Grumman had … a peculiar culture … in that everybody looked at the company as 'my company,' and they were not adverse to calling anybody up to tell them what should be done differently, or what was going on."[260]

Gavin led by example. He worked to enhance communications and morale by regularly traversing different departments after lunch when not on travel: "it's amazing what you can learn just by taking an hour's walk and seeing firsthand what people are doing, and what problems they're having."[261] For two months he overlapped with the night shift.[262] A top priority: maintaining constructive relations between Grumman's engineers and skilled manufacturing-floor staff. The company ensured that they were located as close together as possible physically to maximize information flow and minimize dissonance between the disparate disciplines.[263] On May 14, 1966, Gavin noted in his dayplanner, "Spent 2 h on main assembly floor—pace slow in some areas." The benefit: "as we went through the flight readiness review, we knew that we had taken care of the things that could cause problems. This was because of the individuals and the feeling they had that they could speak up if something was not quite right … in the Lunar Module program, we didn't need laws to protect whistleblowers."[264]

2.7. Empower individuals

A major Grumman theme under Gavin was "continuing concern for making the hardware work. This has been accomplished by inculcating throughout the organization a sense of personal responsibility."[265] Gavin afforded LM managers autonomy, but gave them clear guidance. Handwritten notes reveal his directions of August 15, 1967:

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[254] NASA Interview, 2003.

[255] "2010 Eugene 'Gene' F. Kranz & Joseph E. Gavin, Jr.," Godfrey L. Cabot Award, Aero Club of New England, https://www.acone.org/content.aspx?page_id=22&club_id=779885&module_id=284133#Kranz/Gavin. Recipients are "individuals or teams who have made unique, significant, and unparalleled contributions to advance and foster aviation or space flight." See also Janice Wood, "Cabot Award Winners Named," *General Aviation News*, February 1, 2010, https://generalaviationnews.com/2010/02/01/cabot-award-winners-named/; "ACONE Presents Cabot Award to Joseph Gavin and Gene Kranz," National Aeronautic Association, http://archive.constantcontact.com/fs091/1102200709681/archive/1103512417067.html.

[256] NASA Interview, 2003.

[257] IAC, 2002, 4. "I've sometimes thought that an organization chart should look like a slowly-swirling galaxy of stars—some that are brightening and some that are dimming—because the roles tend to change as time goes by," Gavin elaborated. Gavin, Gardner Lecture.

[258] Gavin, Gardner Lecture.

[259] Keegan, Interview of Gavin.

[260] Gavin, Gardner Lecture.

[261] "[S]ome of the problems [we]re simple. I recall one where the thermostat on the heating system was stuck, and it was too hot. And apparently, the foreman had complained. Nothing had happened. Well, I made a phone call. It got fixed." Ibid.

[262] Regarding 1967–68, Gavin recalled, "It was a very tough period. I spent two months on a 1 p.m. to 1 a.m. schedule to be on hand for both day and night shifts!" Gavin's notation; Kelly, *Moon Lander*, 188. Gavin's dayplanner records other night shifts, including December 27–30, 1966.

[263] Grumman also avoided polarizing workers' identities. "The technician is a white-collar worker and doesn't consider himself a shop worker," Gavin explained. "In the electronic system center, for example, you can't tell the technologists from the technicians." Byron Porterfield, "L.I. Companies Vie for Larger Share of Space Spending," *New York Times*, October 9, 1961, 26.

[264] Gavin, address to Long Island Section, AIAA, "Twentieth Anniversary Celebration—'The First Manned Lunar Landing,'" Cradle of Aviation Museum, Garden City, NY, July 15, 1989. NASA encouraged similar outspokenness throughout Apollo. Brown, *Apollo Chronicles*, 127.

[265] Statement of Gavin Before the Subcommittee on Manned Space Flight, March 14, 1972, 1. In the early LM years, ca. 1964, "it took imagination and judgment to recognize the real requirements."

1. Supervisor's motivation—who else
2. Tight schedules—critical hardware—over hump of [Apollo 1] fire aftermath—get back to test—
3. Be professional—no casual additional work, meet your commitments, if in trouble get help—be aware of the "big picture"
4. Be a supervisor—motivate your people, outline carefully what you want done, set a date, check to make sure it will get done—don't wait till too late, set high standards—assign responsibility, demand prompt and competent work—help other groups—

"Individual responsibility is the key," Gavin also stressed, "at all levels, at all times; by example, by direction, by insistence."[266] Organizational culture empowered professionals to investigate and solve problems themselves. Gavin's favorite example involved a talented young engineer who averted potential failures by investigating, unprompted, the standard miniature toggle switches used throughout the LM, which scores of aircraft had employed for years.[267] In one-third of the cases, sectioning samples revealed loose solder pellets that could miss-set a switch in zero gravity. While it was too late to change the switch type, Grumman devised a means of identifying and rejecting the portion that was compromised. To Gavin, "this was a case … of how an inquisitive mind … led to the right thing. Nobody could have told the individual that this was something that should be done." Instead, "he said, 'You know, I am responsible … I'd better understand everything about everything.'"[268] "In looking back at some of our aircraft experience," Gavin reflected, "there are one or two crashes where I personally suspect that [the loose solder pellet] phenomenon was involved."[269]

2.8. Share information

Continuous information flow was likewise essential. Gavin emphasizes the value of stand-up meetings he held daily in his Bethpage office from 7:30–8:00 a.m. with 20–30 principals, themselves linked by telephone conference to field sites at Cape Kennedy, Houston, and White Sands.[270] Key managers such as Low, then ASPO head, participated; subject matter experts reported; problems were emphasized; and immediate action assignments ensued. It was "not a witch-hunt atmosphere." Rather, "cross talk [was] encouraged." This was "Effective in surfacing problems and extending feeling of responsibility beyond one's immediate sphere."[271] A large flowchart tracked the progress of various components.[272] This ensured shared awareness of design changes and their potential consequences ("configuration control") and helped avoid bottlenecks.[273]

3. Lunar landing legacy

Having already combined LM program management with Grumman service as a Vice President (1962–70), the Director of Space Programs, a Board Member/Director (Aerospace subsidiary), and a Senior Vice President (1970–72),[274] Gavin was elected to ever-higher leadership upon Apollo's conclusion. On July 21, 1972 he became President of the subsidiary Grumman Aerospace Corporation,[275] then served concurrently as Chairman of the Board (1973–76).[276]

On January 1, 1976, Gavin became President and Chief Operating Officer (COO) of Grumman,[277] then a Fortune 500 Company exceeding a billion dollars in annual sales and Long Island's largest employer by far.[278] In 1983, he received the Tuskegee Airmen, Inc. Distinguished Service Award for Business and Industry. In 1985, upon heading the design of a new leadership structure and reaching Grumman's mandatory retirement age,[279] Gavin concluded his management

[266] Gavin, "A Review of Two Past Space Programs."

[267] IAC, 2002, 4. Gavin mentioned "toggle switches" in his dayplanner on December 6, 1966.

[268] NASA Interview, 2003.

[269] Keegan, Interview of Gavin. Low oversaw a similar toggle switch fix on the CM. Jurek, *The Ultimate Engineer*, 136–37. Such dramatic responsibility and autonomy, freedom from bureaucratic strictures, and bottom-up contributions pervaded Apollo. Brown, *Apollo Chronicles*, 232–36.

[270] IAC, 2002, 4.

[271] "Slide 30—Daily 'Standup' Meeting," Schlegel and Markarian, "Apollo Lunar Module Legacy"; Jurek, *The Ultimate Engineer*, 96.

[272] Discussion with Joseph Gavin, III, December 29, 2019; August 2, 2020.

[273] NASA Interview, 2003.

[274] "Clint Towl Elected Board Chairman of Grumman Aerospace, Bill Zarkowsky, Vice Chairman, and Joe Gavin, President," News Board, Internal Communications Department, Grumman Public Affairs, July 22, 1972; "Grumman Corp.," *The Wall Street Journal*, July 24, 1972; "Name Gavin, Hedrick, Zarkowsky Senior VPs; Aerospace Board Also Elects 5 Vice Presidents," *Grumman Plane News*, special report (February 16, 1970).

[275] "Executive Changes," *The New York Times*, July 22, 1972; Gavin, dayplanner.

[276] "Elect Gavin Chairman of Grumman Aerospace; Towl, Schwendler Relinquish Duties in Aerospace," *Grumman Plane News* 32.8 (April 27, 1973), 1,3.

[277] "Towl Retires, Succeeded by Bierwirth as Chairman; Gavin President of Parent Firm," *Grumman Plane News* 34.19 (October 24, 1975), 1–2.

[278] Frank Lynn, "Voices That Are Heard: The Men Who Make Things Happen," *New York Times*, February 15, 1976, http://www.nytimes.com/1976/02/15/archives/long-island-weekly-voices-that-are-heard-the-men-who-make-things.html. In 1983, for example, Grumman had 21,320 employees on Long Island, more than twice that of runner-up NY Telephone with 9,700. "Top 200 Employers Provide 303,515 Jobs, 1/3 of LI's 944,000 Total," *LI/BUSINESS Newsweekly*, July 27–August 2, 1983, 6.

[279] Kenneth N. Gilpin and Todd S. Purdum, "Business People; Grumman Picks Officer from Aerospace Unit," *New York Times*, February 15, 1985, http://www.nytimes.com/1985/02/15/business/business-people-grumman-picks-officer-from-aerospace-unit.html.

responsibilities.

"Joe Gavin has provided leadership for some of the greatest achievements of Grumman's post-war history," Chairman John Bierwirth concluded upon Gavin's retirement. "No other company in the world can claim for its legacy the first landing on the moon and the lifeboat mission that saved Fred Haise and his crewmates. Since 1976, Joe has been our president and chief operating officer through a time of change and challenge that has seen our sales and equity double, our earnings increase four times, and … in which Grumman has become recognized around the world as the premier producer of flying electronic systems."[280] On February 14, 1985, Gavin transitioned from President and COO to Chairman of the Executive Committee of the Board of Directors and Senior Management Consultant. He retired from the committee on September 30, 1985, remaining a consultant through 1990.[281]

Beyond Grumman, Gavin served as President, American Institute of Aeronautics and Astronautics (AIAA) (president 1982–83; honorary fellow beginning in 1988)[282]; Governor, Aerospace Industries of America; and on the Board of Directors, American Association for the Advancement of Science (AAAS) (1988–91; fellow beginning in 1991).[283] Other professional memberships included: the National Academy of Engineering (NAE); International Academy of Astronautics (IAA); and British Interplanetary Society (BIS) (fellow beginning in 2007).

Gavin remained quite active professionally until his death in 2010. This concluding section explains how Gavin applied lessons from the LM as a corporate executive and considers his core identity and legacy as an aerospace project engineer.

3.1. Applying LM management and technical lessons

Gavin took the helm of Grumman as a company man and a true believer. He viewed Grumman as a special enterprise that granted supervisors marked managerial autonomy and took unusually good care of its personnel.[284] As an executive, his ceremonial roles included presiding over the distribution of a turkey to every employee at Thanksgiving and Christmas. He shook hands with hundreds of Grummanites, a particularly humbling exchange with manufacturing shopworkers possessing extraordinary grip strength. A government survey rated Grumman "the most generous major pensioner."[285] Its plan was "fully-funded … best in industry …. "[286] Employees were encouraged to literally have a stake in the company through generous stock options. Innovators received generous prizes.[287] Grumman stressed worker protection, and provided the best possible training and equipment.[288] Gavin presided over the receipt of an industry award for LM program safety.[289] Internal publications reveal a strong sense of community.[290] Local media claimed that "Persons not connected with the firm … say that no Grummanite has ever been heard to knock the company."[291] "Grumman was a strange company," Gavin recalled, "in that employees regarded it as 'our company'."[292]

Grumman's unusual corporate ethos was questioned by multiple outsiders. Congressional overseers speculated about the percentage of

[280] John C. Bierwirth, Chairman, Report of Annual Meeting, Grumman Corporation, Bethpage, NY, April 18, 1985.

[281] In that capacity, Gavin championed the continuation and coordination of American manned and unmanned space efforts: "NASA programs, both manned and unmanned, have been remarkably successful and have clearly established this country as a technological leader—a position of considerable advantage. NASA's future programs should integrate both manned and unmanned efforts in a mutually supportive manner. When viewed in this light, the space station becomes a significant step in a longer-term program rather than an end in itself." Gavin, "Space Station Is a Step into The Beyond," *New York Times*, January 19, 1986, http://www.nytimes.com/1986/01/19/opinion/l-space-station-is-a-step-into-the-beyond-561487.html.

[282] Duane Hyland, "AIAA Mourns the Death of Joseph Gavin Jr.," Washington, DC, November 5, 2010.

[283] "Joseph G. Gavin, Jr., Joins Board of Directors," *Science* 241.4861 (July 1988): 101, https://science.sciencemag.org/content/241/4861/101.3; Joseph G. Gavin, Jr., personal curriculum vitae.

[284] Grumman underwrote access to the Mayo Clinic for any of its employees. It "paid for hospitals, Little League teams, hunt clubs, and sponsored drives to raise money to help the sick and injured." James Bernstein, "Grumman's Reign on LI: Humble Start, Lunar High Point," *McClatchy-Tribune Business News*, July 12, 2009, https://www.newsday.com/long-island/li-life/grumman-s-reign-on-li-humble-start-lunar-high-point-1.1277995.

[285] "Labor: Penchant for Pensions," *Time*, September 18, 1964, 99.

[286] "Clint Towl on Pensions," *Grumman Plane News* 32.18 (October 15, 1973), 2, 10.

[287] "Hicks, Hackett Named Top Idea Men of Year," *Grumman Plane News* 33.14 (July 29, 1974), 1–2; "McKeon is Top Winner," *Grumman Plane News* 33.19 (October 25, 1974), 1.

[288] "No Trick to Eye Safety … And Wise Owls Are Proving It," *Grumman Plane News* 34.11 (June 13, 1975), 8.

[289] "Grumman Aerospace Corporation has received the 'Award of Honor' from Travelers Insurance Corporation reflecting the Company's safety performance in the Apollo Lunar Module Program. Grumman received this honor for its outstanding achievement in the prevention of employee accidents … a total of 8,333,000 man hours without a disabling injury." "Eight Million Safe Man Hours," Grumman Press Release LM 71-1, January 15, 1971.

[290] *Grumman Plane News*; *Grumman at the Kennedy Space Center, 1963–1970* (Grumman, 1970). The Gavins played weekly as a team in Grumman's bowling league. Author's interview of Dorothy Gavin, August 2, 2020.

[291] William Butler, "L.I. Economy Helps Cushion Blows at Grumman," *Daily News*, August 13, 1972, 3B. Even a new employee laid off following the Shuttle contract loss supported Grumman: "'It's a damn good company to work for, the best I ever worked for,' said John Billington of Huntington, who got the ax three days after moving into a newly purchased home. Asked if he felt management had let him down, he replied: 'For heaven's sake, they've done their best to keep people on. When they've had to cut back, they have cut back as fairly as possible. I don't think management could have done any more than they really did.'" William Butler, "Grumman & L.I.: At the Crossroads," *Daily News*, September 18, 1972, 56.

[292] Keegan, Interview of Gavin.

the price tag for each Grumman aircraft that covered employee healthcare and other benefits. One of Gavin's greatest tests as a leader concerned the company's very name and future. Beginning on September 23, 1981, LTV Corporation attempted a hostile takeover of Grumman.[293] In the end, the leadership of Gavin and has colleagues, and their employees' loyalty, enabled Grumman to survive as an independent firm with unusually strong investment in long-term research and human capital.[294] To Gavin, this vindicated Grumman's founding philosophy—grounded in technological innovation, product fundamentals, employee welfare, and fiscal prudence as opposed to exotic financial maneuvering—which he embraced sincerely in leading it.[295]

A central Grumman tenet was keeping a smaller workforce and having them work overtime rather than allowing a larger workforce to risk layoffs. As part of that equation, particularly during the peak tempo of the Apollo years, employees—especially managers—worked extraordinarily long hours. "We had a problem with people on the day shift staying extra hours off the time clock to make sure that the night shift knew what they were doing. So the spirit was there … There were cases when we had to send people home to rest up."[296] Despite NASA concerns about overtime, Gavin pushed back to allow "group leaders to take care of their people."[297] Gavin himself spent considerable time away from home, both daily and with frequent travel. "We put in a lot of 80–90 h weeks. It was tough on the families."[298] On August 2, 1966, he concluded in his dayplanner, "This day was a blur!" With understatement characteristic of his era, Gavin told a NASA interviewer, "We did work a lot of overtime … I don't think we had any deaths directly attributed to it."[299]

Serving in top management positions returned Gavin to Grumman's core naval aircraft development business: "I was faced with catching up on what had been happening for ten years in naval aviation and for getting the F-14 into production, and that was a learning experience."[300] In making this transition, Gavin applied best practices from Grumman's spacecraft development. "Because of becoming president," he recounted, "I got back into worrying about aircraft. We adopted a lot of the practices learned on the LM back into the aircraft business and managed to cut down the number of tests before delivery." The key to saving time, effort, and money: "you build a better vehicle with discipline, and then you don't have to flight-test it so many times to work out the bugs …."[301]—"we did more work on the ground and didn't try to fly at the earliest possible date."[302] Additionally, "we built a new culture in dealing with, particularly, the electronics in Grumman, and it paid off in later times in our aircraft business. We made a major improvement in the mean-time-to-failure [reliability] of the tactical systems that we represented in the aircraft."[303] Systems engineering lessons came full circle:

> We took what we had learned in the aircraft business and used it in the LM … [then we] sharpen[ed] up the aircraft business … after we space cadets took it over. We instituted formal pre-flight reviews. Now, there always had been some sort of review prior to flying a new airplane, but nothing like what NASA had taught us to do. So we

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[293] Among other motives, LTV's leadership sensed an acquisition opportunity to bail out its underfunded pension plan with Grumman's overfunded one. Robert J. Cole, "LTV Seeks Control of Grumman," *New York Times*, September 24, 1981, A1; "Grumman Corp. v. LTV Corp., 527 F. Supp. 86 (E.D.N.Y. 1981)," US District Court for the Eastern District of New York - 527 F. Supp. 86 (E.D.N.Y. 1981), October 14, 1981, https://law.justia.com/cases/federal/district-courts/FSupp/527/86/2368771/. The timing was difficult: Grumman's Chairman of the Board, John ("Jack") Bierworth, was cruising the Mississippi River with his wife aboard the *Delta Queen*. "John C. Bierwirth, Leader of Grumman in Time of Uneasy Transition, Dies at 89," *New York Times*, May 28, 2013, https://mobile.nytimes.com/2013/05/29/business/john-c-bierwirth-leader-of-grumman-in-time-of-uneasy-transition-dies-at-89.html. In that pre-cellphone era, it took time to recall him to Bethpage. Gavin quickly assembled a team and met with lawyers late into the night for several days straight. Together with Bierworth, other executives, and even the company's 86-year-old founder Leroy Grumman who emerged temporarily from medical retirement, he rallied his employees, who owned a great percentage of Grumman stock, and persuaded them to reject LTV's offer. In advertisements aired on fifteen Long Island radio stations, Gavin urged, "Grumman shareholders, don't sell out." "Grumman Ads Attack Offer," *New York Times*, September 29, 1981, D6. As part of a massive legal battle, Gavin also testified in U.S. District Court. James Barron, "Rival Suitors for Grumman on the Horizon in Takeover Bid: Grumman Takeover Battle," *New York Times*, October 11, 1981, 1, 18. Support arrived from such influencers as former Chief of Naval Operations Admiral Elmo Zumwalt. James Barron, "Zumwalt Criticizes LTV Grumman Bid: Antitrust Violations Charged Bank Memorandum on LTV," *New York Times*, October 7, 1981, D4.

[294] Financial prudence had also prevailed. In 1986, in what was then "the largest bankruptcy filing in United States history," LTV would file for Chapter 11 protection against more than $4 billion in debts to more than 20,000 creditors. Thomas C. Hayes, "LTV Corp. Files for Bankruptcy; Debt Is $4 Billion," *New York Times*, July 18, 1986, http://www.nytimes.com/1986/07/18/business/ltv-corp-files-for-bankruptcy-debt-is-4-billion.html. There it remained into 1993 in "one of the longest, and most complicated, bankruptcy cases in American history." "The LTV Corporation History," http://www.fundinguniverse.com/company-histories/the-ltv-corporation-history/. In 2000, LTV filed for Chapter 11 a second time. David Barboza, "LTV Seeks Bankruptcy, Citing Slower Economy and Steel Imports," *New York Times*, December 30, 2000, http://www.nytimes.com/2000/12/30/business/ltv-seeks-bankruptcy-citing-slower-economy-and-steel-imports.html.

[295] Gavin later stated that he was relieved to have retired before the company that he so loved was acquired by Northrop for $2.17 billion in 1994, forming today's Northrop Grumman Corporation. NASA Interview, 2003. See also "Northrop Grumman Corporation History," http://www.fundinguniverse.com/company-histories/northrop-grumman-corporation-history/.

[296] NASA Interview, 2003.

[297] Gavin, "Apollo: Reflections and Lessons," *MIT World Series: Giant Leaps*, June 2009 (published March 15, 2013), http://videolectures.net/mitworld_debate_apollo/.

[298] Keegan, Interview of Gavin.

[299] NASA Interview, 2003. Several individuals died during the program from what today might be interpreted as working-related complications; although at least in some cases smoking might well have been a contributing factor. Kelly relates, "I believe that Larry Moran's dedication to the LM program ultimately cost him his life." Kelly, *Moon Lander*, 152. Some employees' marriages succumbed to program pressures.

[300] NASA Interview, 2003.

[301] Ibid.

[302] Gavin, Gardner Lecture.

[303] Gavin, "Introduction," Apollo Guidance Computer History Project.

introduced that … That and the simulation are the two big things … at the time, we were involved in some aircraft that … had a lot of electronics in them, and where things like crosstalk and mutual interference had really been worked on very, very hard … we … also introduce[ed] the matter of certifying the people who could open a connection. With all those prongs in a plug, it takes real skill to avoid damaging it. And that helped … some of the aircraft we were building at the time were … [even] more complicated than the Lunar Module … the EA-6B had something like 80 antennas on it.[304]

Beyond Grumman, Gavin saw equally clear "Applicability to future: define the mission; long-term commitment; a dedicated, motivated team."[305] His optimistic conclusion, delivered in Tokyo in 1977: "Men have always showed imagination and a venturesome spirit. Walking on the moon represents a high point in adventure and science. As long as we do not lose this spirit, man will progress through challenges and hazards to new accomplishments."[306]

3.2. Profession, inspiration, contributions

This concluding section reflects on Gavin's core identity, motivation, and legacy as an aerospace project engineer. Gavin enjoyed an extraordinary engineering-executive career in an extraordinary age for American achievements in air and space. His employment coincided exactly with the Cold War era's lofty defense spending and ambitious megaprojects. Like an unusually talented and fortunate surfer, Gavin caught an unprecedented wave at just the right time and rode it nearly perfectly. Yet this would not be indicative of conditions before or since in what President Kennedy termed the "new ocean" of space.[307]

Gavin's wide-ranging responsibilities, contacts, and experiences afforded him unusual insights into the military-technological frontier of his era and the people that propelled it. Along the way, Gavin enjoyed fascinating personal experiences.[308] He met President Johnson at the White House, attended the "Dinner of the Century" President Nixon hosted honoring the Apollo 11 astronauts, briefed Senators and Congressmen, and knew successive Secretaries of the Navy.[309] Among his favorites: "I met Orville Wright before he died … showed Charles Lindbergh the Lunar Module under construction[310] [and] survived the anxious hours of Apollo 13."[311] Clearly inspired by history's first successful heavier-than-air powered aircraft, Gavin kept artist's drawings of the Wright Flyer, as well as a copy of its original patent, in his personal collection. He also briefed von Braun on Grumman's original Apollo bid,[312] escorted him on his visits to Grumman and hosted his inspections of the LM,[313] and spoke with him on many other occasions.[314]

Gavin's own combination of diligence, personal modesty, and constant focus forward rather than on recounting the glories of past accomplishments is reflected in a glowing memorial tribute by Armstrong. He described Gavin as "a highly regarded aerospace engineer" as well as "an engineer and engineering manager in the highest tradition of the National Academy of Engineering [who] will be well remembered."[315] It reads as the heartfelt admiration and respect of one humble engineer's engineer for another.

Asked for career guidance, Gavin advised, "Find a way to do something you love. You'll never do anything better."[316] He emphasized, "The most important thing to be doing [is] the thing that you would rather be doing … I happened to get hung up on flying machines."[317] "When I was at Grumman I was doing something I would have preferred to do over anything else," he illustrated. "When you're in that situation, the hours don't mean much. You do whatever is necessary."[318] Explaining the tremendous commitment and sacrifices that Grummanites made for the LM, Gavin emphasized, "There wasn't any question in anybody's mind that we were going to make it work, that we were not going to leave any astronauts on the moon, and that we were going to get them back safely."[319]

Most fundamentally, the excitement of innovation in engineering inspired and drove Gavin: "There's a certain exuberance that comes from being out on the edge of technology, where things are not certain, where there is some risk, and where you make something work." He was forced to elaborate on this core philosophy when, during one of his many classroom talks, a schoolgirl asked him, "Mr. Gavin, why would anybody want a job like the one you had?" He replied: "Well, you must understand that there's a certain satisfaction in living and working at the

[304] Gavin, Gardner Lecture.

[305] Gavin, notes for talk, "L.I. Apollo Anniversary."

[306] Gavin, "A Review of Two Past Space Programs."

[307] "Text of President John Kennedy's Rice Stadium Moon Speech," September 12, 1962, https://er.jsc.nasa.gov/seh/ricetalk.htm.

[308] On October 29, 1970, Gavin recorded in his dayplanner, he met Singaporean leader Lee Kuan Yew, then visiting regarding NASA's High Energy Astronomy Observatory Program.

[309] Letter from The White House to Mr. and Mrs. J. Gavin, Jr., Grumman Aircraft Engineering Corporation, Bethpage, NY, postmarked August 2, 1969. Invitation to President's Dinner Honoring Apollo 11 Astronauts, Century Plaza Hotel, Los Angeles, CA, August 13, 1969.

[310] On November 18, 1968, Gavin noted in his dayplanner, lunched with Lindbergh, gave him a tour of the LM, and presented him a "booklet and pictures."

[311] "Gavin, Joseph G. Jr.," *50th Reunion Yearbook* (Cambridge, MA: MIT Class of 1941, June 3–8, 1991).

[312] Bob Rosenthal, *From Passaic to the Moon: An Insider's True Adventures* (Funkstown, MD: Star-L Press, 2001), 128.

[313] "Visiting Space Officials Study LEM Mockup," *Grumman Plane News* (October 23, 1964), 8–9.

[314] Gavin's dayplanner reflects: communications with von Braun, January 8, 1964, June 2, 1969, and September 5, 1969; LM inspection visits, October 6, 1964 (mockup), May 11, 1967, October 17, 1968, and December 20, 1968; other Grumman visits, November 17, 1965 and November 23, 1970; meeting in Huntsville, AL, August 26, 1969; meeting on November 5, 1970; and meeting in Washington, DC, May 17, 1971. Von Braun was "extremely charismatic." In a typical example, when Gavin "took him on a tour of the Grumman shop," he asked a machinist about his work. The machinist's jaw dropped in awe, and he repeated afterwards, "What a wonderful guy. What a wonderful guy." Gavin saw firsthand how von Braun was supported by the quiet diligence of his longtime deputy Eberhard Rees, the Huntsville-based counterpart with whom Grumman dealt most. Gavin described him as "one of the unsung heroes of the Apollo program. A wonderful engineer." Gavin dined with von Braun and his younger brother Magnus and discovered that they telephoned their father in Germany each morning. Keegan, Interview of Gavin; Gavin's many discussions with author over many years.

[315] Armstrong, "Joseph G. Gavin, JR. 1920–2010."

[316] Author's discussion with Gavin, 2002.

[317] Keegan, Interview of Gavin.

[318] David L. Chandler, "Aerospace Engineer Joseph Gavin '41, SM '42 Dies at 90: Former President of Grumman Aircraft Led Lunar Module Development for NASA, Aided in the Rescue of Apollo 13," MIT News Office, November 5, 2010, http://news.mit.edu/2010/obit-gavin.

[319] "The Lunar Module Story."

cutting edge of new technology. And while this isn't for everybody, for those of us who are true enthusiasts, it is the place to be."[320] As for the LM specifically, "This wasn't just another flying machine, this was unusual. It had not been done before. And I think there's something that many engineers respond to in the sense that it is at the forefront of knowledge and there are risks being taken."[321] Regarding the space program writ large, "In the decade of the sixties, there was no question that there was a sense of competition with the Soviets, and that the Apollo Program was considered a regaining of our leadership in technology. It had impacts in the educational system, it inspired a whole generation of young people to be interested in high technology."[322]

Asked to define his profession, Gavin opined, "I think aerospace engineering is a little bit different. The margins are less, and you're defying gravity every day. The results, if you fail, are quite notable. If you look at the margins of safety in a bridge or an airplane, it's really a different game. Being an aeronautical engineer myself, [I can attest that] we live more dangerously. And so we're more careful."[323]

Gavin's lifetime of devotion to the pursuit of technological innovation at the frontier of cosmic discovery is encapsulated by the quote by George Bernard Shaw that was flown to the moon on his behalf: "You see things, and you say: 'Why?' But I dream things that never were, and I say 'Why not?'"[324]

Gavin did far more than dream, however. By nature and interest, he was also a leader and a doer. Management, innovation, and execution defined his life's work. Indeed, no matter how far he rose in status and accomplishment, he remained an aerospace project engineer at heart. It was in that role, most prominently in the climactic Apollo decade, that Gavin made the contributions for which history will most remember him. It is only fitting, then, that perhaps his most personally-revealing, professionally-autobiographical writing—produced when he was LM Program Director—describes this role "from a very personal point of view." It is reproduced in full as Appendix A (below). As part of a far-ranging, "immense responsibility," Gavin held, an aerospace project engineer must answer "a few very basic questions … in almost every instance;

"If I permit the project to progress in this direction

- Would I go as a pilot?
- Would I ask my best friend to go as a pilot?[325]
- Would I invest my own money?
- Does this action really count?"

Gavin never failed to give satisfactory answers to these questions. The results live on in the first and only piloted vehicles to reach another celestial body; in new technologies and renewed educational institutions to sustain them; and in the many individuals whose lives he touched, including the families of three astronauts who never would have returned home without a conservatively-engineered lifeboat: the Grumman Lunar Module.

Declaration of Interest Statement

The views expressed in this article are those of the author alone. They do not represent those of the U.S. Navy or any other organization of the U.S. Government. The author is Gavin's eldest grandson and interacted with him intensively for three decades. He fully acknowledges the potential influences of such a deep personal connection, welcomes suggestions for improvement via <www.andrewerickson.com/contact>, and hopes that others in a position to be more objective will conduct their own studies of Gavin and his career. He thanks Hugh Blair-Smith, former MIT Instrumentation Laboratory software engineer; Craig Covault, former Space Editor, *Aviation Week & Space Technology*; Gary Johnson, former NASA Sequential Events Control Subsystem Manager; Jack Knight, former LM Flight Controller, Mission Evaluation Room; William T. G. Litant, former MIT Aeronautics and Astronautics (Aero-Astro) Department communications director; and Bill Reeves, former NASA Flight Controller supporting the LM Electrical Power System for professional insights. He appreciates substantive suggestions from Christopher Carlson, Kerrie Dougherty, Jason Dunklee, Dorothy Gavin, Joseph Gavin, III, Amalaye Oyake, and two anonymous reviewers.

Appendix A. How the Aerospace Project Engineer Saw His Role

Even as Gavin subsequently assumed higher management responsibilities culminating in leadership of Grumman itself, he remained an aerospace project engineer at heart. In a rare instance of personal expression on the subject, he elaborates on these points in the presentation below.

Problems Facing the Aerospace Project Engineer—Industry Viewpoint.

Joseph G. Gavin, Jr.

Vice President, Director LEM Program, Grumman Aircraft Engineering Corporation[326]

Rather than pursue the problems of the aerospace project engineer at a distant philosophical level, I would like to examine them from a very personal point of view. To begin with, let's establish a definition. The Project Engineer referred to here is the senior technical person holding line authority in a major program. Sometimes this person is called the Engineering Manager of a program. This distinction is necessary because occasionally the term 'project engineer' is applied to levels of engineering supervision more traditionally known as group leaders. This Project Engineer, of whom I speak, carries an immense responsibility, and must at various times display talents worthy of Albert Einstein and John Foster Dulles.

[320] NASA Interview, 2003.

[321] "The Lunar Module Story."

[322] Ibid.

[323] Keegan, Interview of Gavin. Gavin elaborated: "if you don't do a superior job [of systems engineering], the results are catastrophic, and wind up on page one. And you really can't afford to have that happen." Gavin, Gardner Lecture.

[324] Back to Methuselah, Part I, Act I, 1921.

[325] Gavin: "You don't send it off unless … you're … willing to bet your best friend's life on it, and not your own life because you've become awfully enthusiastic …. " Author's interview of Gavin, Amherst, MA, December 11, 1998.

[326] Transcribed by author from Gavin's original typed copy. Gavin apparently presented this paper at the AIAA Meeting, Heterogeneous Combustion Conference, Palm Beach, FL, December 11–13, 1963, https://arc.aiaa.org/doi/10.2514/6.1963-1448. Gavin probably spoke on the last day, as part of a frank set of government and industry leaders' viewpoints following many specialized technical presentations: https://arc.aiaa.org/doi/book/10.2514/MHCC63. Other capstone perspectives came from Dr. Edward Welch, Executive Secretary of the National Aeronautics and Space Council, who promoted the Kennedy Administration's consensus themes on meeting Moscow's challenge in "Space Policy and Space Management," https://arc.aiaa.org/doi/10.2514/6.1963-1449; Robert Piland, then Acting Manager, NASA ASPO, who summarized the "Apollo Program Evolution and Background," https://arc.aiaa.org/doi/10.2514/6.1963-1451; James Davis, Deputy Assistant Secretary of Defense (Installations & Logistics), whose "Government Viewpoint of the Management of Aerospace Programs" outlined sixteen acquisition challenges, https://arc.aiaa.org/doi/10.2514/6.1963-1447; and moonshot stalwart Teague, who shared a heartfelt "Congressional Viewpoint on Space Programs," https://arc.aiaa.org/doi/10.2514/6.1963-1450.

Let's first examine his technical problems. While he cannot be expected to be expert in all disciplines, he must be reasonably at ease in considerations ranging from heat transfer to digital data handling. His comprehension level must be sufficient to earn the respect of the various specialists within his organization. Modern complex systems require difficult trade-off and integration compromises. With the support of his group leaders, the project engineer must define the proper compromises without inordinately lengthy studies. He must require from his crew adequate, useful, and convincing information; he has to resist the sometimes-easier course of asking for further investigation—beyond the level of real significance. For example, in the LEM program, we are now examining a very interesting compromise—should weight be invested in a stronger landing gear to permit rougher landings or more propellant to permit better landings? We could continue to embroider this study for months; but we won't, we must avoid this temptation.

Another technical hurdle for the project engineer is the undefined or "floating" requirement. Designing to provide margin for such requirements requires conservative boldness—or is it bold conservatism—and strong convictions. Pursuing the example of the LEM, we are currently wrestling with the problem of what constitutes reasonably safe assumptions with regard to the lunar surface. How high a coefficient of friction might an assumed dust layer provide? A course of action will have to be taken long before all the answers are available; our solution must provide a reasonable degree of flexibility to cover the range of possibilities.

A further technical demand on our project engineer is a clear understanding of those areas within the project which press the state-of-the-art. The problem usually occurs in two steps; first to recognize these areas, and second to limit them. Our Orbiting Astronomical Observatory is an example of a program made rather difficult by the necessity of pressing the state-of-the-art in a number of areas simultaneously in order to achieve the desired results. In this case, astronomical precision has placed unusual demands on such things as star tracker gimbal angle accuracy, control of heat flux to minimize structural distortion, and data handling and storage capacity—all at unprecedented reliability levels. Again, without proper evaluation and approach, we could not have progressed from analysis to hardware.

In reviewing the project engineer's role, it is sometimes surprising to see how much of his efforts are devoted to administrative problems. He must maintain a delicate balance of emphasis between project and discipline—his specialists must be clearly project oriented, yet they must benefit from their ties with colleagues on other projects. The project engineer must resist the tendency for the myriad of insignificant, and therefore easier, administrative demands to dilute his attention to the significant and frequently thorny technical questions. At the same time, he must exercise judgment with respect to the delegation of both technical and administrative responsibilities—he must resist the temptation to carry out each study himself; he cannot funnel every detail through his office. By these last comments, I do not mean to imply that his administrative role is less important than his technical role. He must take a leading part in cost and schedule estimates—otherwise neither he nor his subordinates will live up to these seriously. He must demonstrate administrative as well as technical control to limit overelaboration, to resolve group interfaces, and to ensure coordinated milestone accomplishment.

While engineering education seldom stresses this point, a surprising proportion of the project engineer's trials and tribulations are in reality people problems. He must be able to approach each subordinate in a manner which will result in optimum performance. He must be able to apply the appropriate "filter" to each subordinate's comments so that the information is "normalized." He must exhibit leadership, must be able to inspire others to lead, and must be able to evaluate performance objectively. He must be able to communicate effectively within his engineering project, within the program organization, with representatives of the procuring agency, and with sub-contractors. One of his toughest tasks is to recognize and acknowledge those occasions when he is wrong.

In the case of manned vehicles, he is also confronted with the necessity of working with, understanding, and communicating with pilots or astronauts, as the case may be. Success for the project depends on the development of mutual respect.

Having progressed from technical problems to a discussion of human relations, I may as well go all the way and reduce the project engineer's considerations to a few very basic questions which he must answer in almost every instance;

"If I permit the project to progress in this direction

- Would I go as a pilot?
- Would I ask my best friend to go as a pilot?
- Would I invest my own money?
- Does this action really count?"

The project engineer can make use of the most refined methods—systems studies, multi-variable mathematical analysis, elaborate simulations and tests—but, in the end, he has to satisfy these questions.

In principle, everything I have said was just as true 10–15 years ago as it is today. What then are the differences which make the job of today's project engineer more difficult? Here are a few:

(a) Today's major program is larger, represents a greater technical step ahead, and is one among a smaller number of national programs. This makes every decision more significant in terms of either money or effort. Each decision requires greater justification and more careful analysis of its implications.
(b) The quest for performance—of all kinds—inspired by mission requirements and industrial competitiveness has increased the level of effort as well as the caliber of talent required to do all but the simplest engineering tasks.
(c) Flight testing has always been expensive and potentially dangerous. With the advent of manned space flight the magnitude of these conditions has increased drastically. More patience and ingenuity must be exercised in testing on the ground. The probability of mission success and mission safety must be explored with far greater care and understanding.
(d) And finally, I am convinced that, under the pressure of these more demanding programs, a better professional engineering job is being accomplished today—not easier but better.

More detailed technical study supporting the decision-making process, more detailed test programs with additional emphasis on extracting the maximum amount of information from every level of testing. Efforts such as these, and the multitude of others covering every technical—and human—aspect of the program, are the responsibility—and the salvation—of the project engineer of today's space programs.