Chapter 25

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

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Abstract

The highlight of Joseph Gavin, Jr.'s distinguished career as an aerospace engineer and leader was serving as Apollo Lunar Module (LM) Program Director from 1962–1972. Gavin believed the Apollo Program "would be the biggest engineering job of history … bigger than building the pyramids or inventing the airplane and would take every ounce of ingenuity … to pull off." In it, Gavin led as many as 7,500 employees in developing the LM and ultimately building twelve operational vehicles. All met mission requirements, and those that were used worked every time. "For the 1960s, that was the place to be, that was the program to be involved with," he later reflected. "As tough as it was, none of us would have chosen not to be there." Developing the state-of-the-art machine required multiple unprecedented innovations and maximization of reliability amid inherently imperfect testing conditions. When congratulated on the success of each LM landing, Gavin typically replied that he would not be happy until his

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spacecraft and its crew got off the Moon. This process required three procedures in unison (the firing of explosive bolts, the severing by guillotine of wires and other connections between the descent and ascent stages, and the firing of the ascent engine). All could be tested on Earth individually, but their simultaneous action could not. Gavin drew multiple lessons from his Grumman Corporation team and its subcontractors' experience that may be distilled into eight principles. There is some overlap among them and it is difficult to assign priorities, with one important exception: the safety of the astronauts was clearly the overarching priority:

1. create conditions for success,
2. reliability is attainable,
3. true innovation renders cost and schedule unpredictable,
4. don't complicate things unnecessarily,
5. remove hierarchical barriers,
6. empower individuals,
7. share information, and,
8. above all, return the crew safely to earth.

Serving in top management positions subsequently returned Gavin to the naval aircraft development that remained the core of Grumman's business. He applied LM best practices, particularly improving initial construction to reduce the need for tests (per principle number two). Drawing on Gavin's original calendars, notes, and presentations, as well as extensive interviews, this chapter explores his lessons and explains how he envisioned them and applied them in practice as an aerospace project engineer leading one of history's greatest aerospace engineering achievements.

I. Lunar Module Program, 1962–1972

Having launched his career at the inception of jet engines and carrier aircraft, Gavin took it to a whole new level with the advent of the Space Age. With the Soviet launch of the first artificial satellite on October 4, 1957, he "was a little surprised that they got there first." But he was not surprised at the possibilities for activities in space:

> "At the end of my tour in the Navy, we wrote a report at the request of Senator 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" [1].

I.1. Launching the LM Program

Four years later, on May 25, 1961, inspired by the bold initiative President John F. Kennedy announced, the Apollo Program brought Grumman, and Gavin, the opportunity of a lifetime. It was during a decade as Vice President and LM Program Director that Gavin faced his greatest challenges in the management of technological innovation, when 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. From Grumman's very first announcement through Apollo's conclusion, Gavin led the team:

> "Full authority for directing Grumman personnel assigned to the LEM [2] and for controlling the resources required to achieve LEM objectives will belong to LEM Program Director Joe Gavin, who, since his graduation from MIT, has piled up 20 years of experience in aircraft, space, and missile engineering" [3].

As the Grumman Vice President responsible for the LM contract, Gavin had LM engineering, procurement, manufacturing, and field operations reporting to him, and was deeply involved in all areas. He spent considerable time with major subcontractors, especially those producing the rocket engines and radio and electronic devices [4]: "I spent a lot of time on the road [and] in the air" [5]. Under Gavin's management, Tom Kelly, the LM Chief Design Engineer for the first seven years of the program [6] 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. At its peak, Gavin managed 7,500 employees (including nearly 4,000 engineers and 400 draftsmen) in several locations across the United States. Approximately 55 percent of what totaled $2,287,600,000 in LM program expenditures by the program's conclusion at the end of 1972 went to subcontractors that Grumman oversaw [7]. The buck stopped in Gavin's office: "we were responsible for putting it all together and making it work" [8].

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" [9].

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” [10]. Beginning in 1961, 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, [11] lunar-orbit rendezvous (LOR) [12]. “We were convinced that LOR was the way to do it,” Gavin explains [13].

On May 15, 1961, ten days before Kennedy’s announcement, Gavin’s group submitted their summary report to NASA [14]. Under his leadership, Grumman recruited subcontractors, starting with Honeywell and Space Technology Laboratories [15]. NASA requested Apollo spacecraft proposals in July. Gavin and his colleagues hoped to bid as a prime contractor, which Gavin believed to be 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 [16]. They were prevented by Grumman’s management from betting the firm on such an ambitious and risky endeavor, however [17]. Instead, Grumman bid as a contractor for GE, learning much but encountering differences in corporate culture [18]. On November 28, NASA selected North American Aviation as the Apollo spacecraft contractor, precluding such a path [19].

Seizing their final chance to join Apollo, in early December 1961 Gavin and his team made a pitch directly to Robert Gilruth, founding director of NASA’s Manned Spacecraft Center in Houston [20], and his colleagues. Their vision for a lunar lander coincided strikingly with NASA’s own internal estimates, including regarding the weight of such a vehicle [21].

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” [22]. They lost NASA’s January 1962 study competition to General Dynamics/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 select Wernher von Braun’s preferred approach of Earth-orbit rendezvous, or the “dark horse” approach of LOR [23]. LOR finally prevailed with von Braun’s endorsement, triggering a bidding competition that fall. Gavin’s team submitted their bid two hours before the deadline and dropped everything for a “fire drill” to answer follow-up questions from NASA’s Source Evaluation Board in less than forty-eight hours. Unusually, proposals had involved addressing a set of twenty questions, to be answered in 100 pages using standard margins and type [24]. “To answer the questions, we had to postulate a design,” Gavin later recalled [25]. But “NASA hadn’t really bought [our] design. They thought they’d bought an engineering service" [26]. "We had just passed the entrance examination, and we would have to work with [NASA's] Johnson Space Center to develop a design" [27]. Grumman won officially on November 7, 1962 [28].

In mid-November, Gavin's team began marathon negotiations with NASA. 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. On January 14, 1963, Gavin and Gilruth resolved remaining issues at Grumman headquarters (on Long Island, in Bethpage, New York), yielding a verbal go ahead from NASA. A formal $387.9 million contract followed in mid-March [29] for an initial production run of six LMs [30]. Gavin now faced the challenge of heading "the last major portion of the Apollo program to be defined and started" [31]. 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" [32]. He repeatedly credited Gavin's "steadying influence" with enabling focus amid extraordinary pressure and occasional withering criticism from NASA over any possible errors [33].

I.2. Unprecedented Engineering Challenges and Innovation

"You must remember how many things we didn't know at the very beginning," Gavin emphasized [34]. 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" [35]. Accordingly,

> "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" [36].

The LM was then the largest US spacecraft by internal volume and per-capita crew space yet developed [37]. During the mission, its gross weight would vary by a factor of ten [38]. It had to be completely reliable even though lunar conditions could not be duplicated on Earth for full testing. Moreover, there were conflicting information and assessments about the suitability of the Moon's surface for a landing. Worst-case scenarios included Cornell University Professor Thomas Gold's theory that the LM would sink into "ten meters of impalpable dust … electrostatically it'll probably just cover everything up" [39]. All this had to be overcome without today's modern electronics, computing, or employee databases. Over 50,000 engineering drawings supported the design [40] and integration of its one million parts [41].

This 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" [42]. Unlike their aviator counterparts, Gavin 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" [43]. 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 inside-out. Unlike aircraft, for which range can generally be traded somewhat for payload or speed, the LM's range was fixed [44].

Indeed, it took strong management backing to overcome opposition by a faction of "conservative aircraft traditionalists" [45] who believed that "these guys on the lunar module are nuts" [46] 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 had to recruit from the company at large … the core were a group that I had worked with for about 10–15 years" [47].

The "bug's" configuration and engineering evolved in a relentless effort to counter growth of the 32,000-pound vehicle while maximizing reliability under uncertain conditions in a remote environment with 500-degree temperature variation, radiation, and even micrometeoroid risks [48]. The heavy, weak, thermally wasteful, helicopter-style windshield that Gavin initially envisioned shrank to small triangular windows pressed against the faces of two standing crewmembers, their seats eliminated in recognition of the flight's short duration and one-sixth gravity environment [49]. This was only one of many design adjustments [50]. 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" [51]. To make the LM work, Grumman and its subcontractors developed multiple firsts:

- "First broadly throttleable rocket engine.
- First solid-state radar.
- First 'strap down' navigation unit.
- First fly-by-wire control system for a rocket-powered vertical takeoff and landing (VTOL) aircraft" [52].

Gavin and his team faced extreme pressure to improve schedule and weight, as well as cost to some extent—all while ensuring reliability. Minimizing inflammability following the *Apollo 1* tragedy necessitated neater configuration of its 40 miles of wiring [53] and additional weight in the form of fire retardant [54]. The NASA-mandated Super Weight Improvement Program yielded soda-can-thin aluminum alloy walls (0.12 inches) [55].

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. As Kelly relates, "responding to pressure from NASA, Joe Gavin became involved in the leak problem" [56]. 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 configuration was accurate" [57].

Oversights were usually harmful but occasionally helpful. Unexpected stretching of the LM's fuel tank membranes, proportionally thinner than egg-shells, accommodated twenty seconds' additional fuel—the margin that Neil Armstrong had left when he landed four miles downrange of the planned site [58]. 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 [59]. "We had very small margins," he explained. "We were all counting seconds as to how much fuel we thought remained" [60]. 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" [61].

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 [62]. 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. Apollo launched at Cape Kennedy following weeks of preparation by over 8,000 who remained nearby on Earth; 250,000 miles away, two astronauts had to launch the LM themselves [63]. 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 ex-

> plode. 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" [64].

Moreover, there was no way to include a backup engine. "Once you pressed the button, that was it," Gavin emphasized. "It was really quite tense" [65]. "For all the other parts of the mission, you could find a back-out mode," he explained. "But when you had to take off from the Moon, it either worked or it didn't work" [66].

To address these challenges, Gavin and his team developed and implemented a testing regimen whose rigor then far exceeded that for aircraft. "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" [67]. "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'" [68]. "We got into the business of trying to compute reliability," Gavin explained [69]. A decade of exhaustive LM ground testing yielded 14,247 test failures or anomalies [70], in a process Gavin termed "turning over every rock on the beach" [71]. Only twenty-two defied analysis; the parts involved were replaced [72]. A central example of this regimen was testing for 500–600 different landing conditions involving the equivalent of everything from dust to brittle chalk to hard ice, including ones in which the LM skidded laterally and caught its spindly legs in a crater or curb-like formation [73]. "We worried tremendously about tipping over," Gavin relates [74]. The need to finalize the landing gear well before the first Surveyor probes sampled the lunar surface in 1966 [75] led to a conservative design that Gavin believed in retrospect was twice as heavy as strictly necessary [76].

I.3. Safety Trumped Schedule and Cost

As Program Director, Gavin dealt intensively with NASA, subcontractors, and Grumman's own management. To him,

> "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" [77].

NASA imposed incentives on Grumman and other Apollo contractors with a complex formula trading off fulfillment of three major objectives: safety, schedule, and cost. "It took us about 90 days to figure out that there was no trade off," Gavin recalled [78]. The equation quickly became largely fixed. Mission success was non-negotiable; the LM "was always an engineering program" [79]. Schedule was important: having started a year behind the Command and Service Module, the LM faced continuous catch-up efforts to match up with the rest of the program. 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 3,600 contract changes, the LM's cost tripled [80]—but with only a 12–15 percent overrun of cost on an evolving contract [81]—ultimately amounting to approximately 10 percent of Apollo's expenditures [82]. The mounting costs required considerable forbearance from NASA and its Congressional funders; 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" [83].

By fall 1968, the LM had finally caught up with the rest of Apollo [84], just in time for a spate of missions that laid the groundwork for the *Apollo 11* landing in July 1969 and six subsequent missions through 1972. *Apollo 15–17* employed heavier extended duration LMs with additional fuel, oxygen, water, and batteries; as well as an improved descent engine and enhanced thermal protection [85]. Increases in the Saturn rocket's power also allowed more scientific equipment as well as a lunar rover stowed in the descent stage [86].

I.4. Difficult Judgment Calls

Gavin had to make some demanding decisions on the spot. 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 Administrator Maxime Faget] said, 'Fine,' and that was that" [87].

In a singular instance, meeting a scheduling target for NASA was so important that Gavin found a way to work around normal prelaunch test procedures. A motor in the LM environmental control unit needed to be replaced in a confined space that could only accommodate two people. Gavin set up a procedure in which 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 personal knowledge that Gavin accrued over the years of the people within his organization.

Gavin directly telephoned Nelson J. Vosburgh [88], 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 the Cape, 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."

In yet another judgment call, Gavin had to require 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 quite closely [89].

Another important decision by Gavin concerned not technology per se but rather supporting his colleagues in developing it. In fall 1961, when he took his team to negotiate details of the LM contract, Houston was still racially segregated. Hotel after hotel would not accommodate two of their lead engineers. Being regrettably familiar with such prejudice, they volunteered to find their own lodging. 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. He 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" [90].

I.5. *Apollo 13*'s Lifeboat

During the aborted *Apollo 13* mission of 1970, the LM became a capable lifeboat and tugboat. While not specifically designed to provide supplemental propulsion, electricity, and oxygen in the event of a Service Module fuel tank explosion—as happened then—it was designed with considerable reserves [91]. "One major result" of the Grumman-led Apollo Mission Planning Task Force, initiated in 1964, had been "the identification of the 'LM Lifeboat' mission," which triggered prescient increases in tank size for consumables [92], although it "had never been rehearsed by either the ground or flight crews or written into specific operational procedures" [93].

During that crisis, Gavin was at NASA's Mission Control Center in Houston helping to coordinate the urgent assessment 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 Cape Kennedy.
2. Second, "almost disassembling" the LM 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 the Cape from launch until the spacecraft was safely in orbit [94], before flying to Houston to support the mission—normally a busy but routine process [95].

On April 13, Gavin and several colleagues were concluding a long day in Houston at the Manned Spacecraft Center'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" [96].

"I think all of us had a sense of tension in those hours that we've not felt before or since," he recalled [97]. Moreover, 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 some time 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" [98].

Staring reality in the face, Gavin directed the Apollo Mission Support Center back at Grumman's headquarters to address the new priorities imposed by the emergency:

> "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" [99].

It was truly an all-hands-on-deck time for Grumman. Kelly and fellow LM engineer Howard Wright were recalled from year-long Boston-based industrial management courses by midnight phone calls and boarded a 2:00 a.m. chartered flight for Grumman's Airport in Bethpage [100]. As he rushed into Grumman's Apollo Mission Support Center at around 3:15 a.m., Kelly saw a "flood tide" of engineers entering the building, assembling of their own accord to serve as needed [101].

Remaining at his post atop Grumman's multiple layers of technical support [102], "the tensest episode in my career" [103], Gavin estimates that he only "got two hours of sleep in that whole [four-day] mission." His leadership was particularly important in deciding on 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 [104]. This way, "you could get an answer on almost everything in 1–2 minutes." Initial worries about not having enough 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" [105].

Upon the astronauts' successful splashdown, NASA Administrator George Low invited Gavin 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" [106]. "There was a sense of relief—you could feel it" [107]. Several weeks later, the astronauts visited Bethpage to offer mementos and thanks. Watching the movie *Apollo 13* in retirement, Gavin observed that it did not depict the small American flags that people were waving in celebration or the stench of 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 [108].

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 was a good feeling to get [the astronauts] back on the carrier" [109].

For his contribution, NASA awarded Gavin its Distinguished Public Service Medal in 1971. In 1974, in 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" [110]. In accepting recognition, Gavin always credited these technical triumphs to the spirited teamwork throughout Grumman, across the nation, and around the world.

Grumman was not successful in all of its efforts. Rising to management, Gavin observed the impact of politics and bureaucracy on procurement decisions: "Success does not mean you necessarily get the next job" [111]. Gavin believed that his team produced a "first-class" lunar rover design, and was disappointed when NASA selected Boeing abruptly when his company's prototype was still in testing. Grumman likewise lost the bidding competition for the Space Shuttle, despite submitting what Gavin believed to be a superior proposal. Indeed, "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" [112]. Grumman was instead selected to build the shuttle's wings as a subcontractor to North American Aviation [113].

II. Lessons from Bethpage and Beyond

Gavin drew larger lessons from his team's experience in developing the state-of-the-art LM and ultimately building twelve operational vehicles [114]. Some he applied to Grumman's subsequent aircraft business. All he distilled and shared with interested audiences, culminating with his delivery of a paper at the 2002 International Astronautical Congress in Houston, Texas: "The Apollo Lunar Module (LM): A Retrospective." Written in an engineer's impersonal bulletized shorthand, the four pages of text and figures represent the capstone of Gavin's public discussion of his career and the machine that made it. Here, the author draws on additional sources to offer a more comprehensive picture of the eight fundamental conclusions Gavin drew from his experience in leading the LM program.

II.1. Create Conditions for Success

Gavin emphasized the essential conditions powering Project Apollo and its LM. He cited three significant decisions: (1) President Dwight 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" [115], and (3) President Kennedy's bold commitment to land a man on the Moon by the end of the decade. "In hindsight," Gavin assessed, putting NASA rather than the US 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 Russian secrecy, and in the long run this worked out very much to the advantage of the American effort" [116].

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 [the] Saturn [, or Nova, rocket]" that Wernher von Braun had championed [117]. A product of the era that motivated its creation, the Apollo Program was energized by heightened Cold War competition on the ultimate stage and sustained by Kennedy's backing and legacy as well as President Lyndon Johnson's persistence. Regarding the *Apollo 1* fire, 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" [118]. Reflecting in 2001, Gavin concluded, the

> "LM was part of a unique, unambiguous goal. President Kennedy made a long-term commitment. We had real competition. The congress of the '60's had some safe seats so that some, like [Representative] Olin Teague [a Democrat serving Texas's sixth congressional district from 1946–1978], could vote [in] the national interest" [119].

II.2. 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" [120]. As explained previously, Grumman under Gavin adopted a rigorous testing regimen grounded in the principle that they must "take nothing for granted" because "there is no such thing as a random failure" [121]. He 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" [122].

> "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" [123].

To identify and eliminate sources of failure, they 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" [124]. To maximize program efficiency, they used the latest systems management practices adopted by NASA [125], including the Program for Evaluating and Reviewing Technique (PERT) devised by the Navy and the configuration control devised by the Air Force [126].

II.3. True Innovation Renders Cost and Schedule Unpredictable

Gavin subsequently encapsulated his experience in managing technological innovation, which he believed rendered schedule and cost impossible to forecast:

> "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" [127].

Accordingly, Gavin and his team prioritized performance and safety first, schedule second, and cost a distant third [128]. "Whenever you start a complex program," he explained, "it's impossible to foresee every little thing that has to be proved out" [129]. The biggest surprise for Gavin? It was "the time it takes to do anything really well—it's much longer than you think" [130]. Even after the design was frozen, it took an average of 2.5 years to build a LM (as many as three were under construction simultaneously) [131]. Another factor of particular importance to the LM was 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" [132].

II.4. 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.’ He described this as “the basic rule that if something works, be very careful if you try to change it, because maybe you’ll get into something you don’t foresee” [133]. 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, upgrading to a costlier, purer rust-inhibitor additive produced unexplained glycol crystals in electronic coolant fluid that no amount of exotic filtering could remove. In this case, 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” [134].

II.5. Remove Hierarchical Barriers

Gavin credits Grumman’s informal, responsive, relatively flat organizational structure with fostering innovation and quality control. “The Grumman Lunar Module program organization 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” [135]. Gavin and others regularly received reports from employees of all types who felt empowered to pick up the phone and 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” [136]. Gavin worked to enhance communications and morale by regularly traversing different departments after lunch when not on travel, and overlapped with the night shift for extended periods on multiple occasions [137]. Maintaining constructive relations between Grumman’s engineers and the skilled tradesmen staffing its manufacturing floor was a top priority, and the company ensured that they were located as close together as possible physically to maximize information flow and minimize dissonance between the disparate crafts [138].

II.6. Empower Individuals

This organizational culture empowered individuals 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 [139]. In one-third of the cases, sectioning samples revealed loose solder pellets that could mis-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 were 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.'" [140].

"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" [141].

II.7. Share Information

Constant information flow was likewise essential. Gavin emphasized the value of the daily stand-up meeting from 7:30–8:00 a.m. held with twenty to thirty principals in Bethpage, themselves linked by telephone conference to field sites at Cape Kennedy, Houston, and White Sands, New Mexico [142]. This ensured shared awareness of design changes and their potential consequences ("configuration control") [143].

II.8. Return Crew Safely to Earth

Most importantly by far, Gavin and his team knew that they were building the LM for real people whose lives literally depended on it [144]. "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 operate, not some faceless individuals unknown to us" [145]. "It was not just 'put it in a package and ship it'" [146]. While the astronauts' personalities varied greatly, they were clearly competent and "their 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" [147]. This encapsulated an ethos dating to the philosophy of the company's founder, Leroy Grumman, a former World War I-era naval aviator. Grumman, Gavin recalled, "had one basic direction to all of us … 'You bring the pilot back one way or another'" [148]. Gavin and the Grumman LM team always fulfilled this most critical of missions.

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" [149]. The responsibility 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" [150]. During *Apollo 13*, Haise's experience and expertise would prove invaluable; he took the LM to its performance limits in unforeseen circumstances despite being desperately ill.

III. Broader Applications and Legacy

Having already combined LM program management with service as Senior Vice President from 1970–1972, Gavin rose to the top of Grumman following Apollo's conclusion. Gavin was President of Grumman's aircraft subsidiary, Grumman Aerospace (1972–1976) and Chairman of its Board (1973–1976). In 1976, replacing Lew Evans who had tragically died of a heart attack, Gavin was elected President and Chief Operating Officer of the Grumman Corporation itself, then a Fortune 500 Company and Long Island's largest employer [151]. In 1985, upon reaching Grumman's mandatory retirement age [152], Gavin concluded his leadership responsibilities. That year, he became Chairman of the Executive Committee of the Board of Directors and Senior Management Consultant [153]. He served five years in the latter capacity before retiring fully in 1990. Even after formally retiring from Grumman, Gavin remained quite active professionally. He attended his last MIT Corporation board meeting on October 1, 2010, driving the two hours each way alone. This was just twenty-nine days before his death at age ninety, surrounded by family members at the Applewood Retirement Community in Amherst, Massachusetts. This concluding section explains how Gavin applied lessons from the LM as a corporate executive and reflects on his core identity and legacy as an aerospace project engineer.

III.1. Applying LM Management Techniques 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 took unusually good care of its employees [154] and granted supervisors marked autonomy in how best to manage their charges. As an executive, one of his ceremonial roles involved presiding over the distribution to every employee of a turkey at Thanksgiving and Christmas. He shook hands with hundreds of Grummanites, a particularly humbling process in the case of some workers from the manufacturing floor who possessed extraordinary grip strength. Employees were encouraged to literally have a stake in the company through generous stock options. "Grumman was a strange company," Gavin recalled, "in that employees regarded it as 'our company'" [155].

A central tenet of Grumman's philosophy was keeping a smaller workforce and having them work overtime rather than raising a larger workforce that would face layoff risks. As part of that equation, particularly during the peak tempo of the Apollo years, employees—and 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," Gavin recalled. "So the spirit was there. … There were cases when we had to send people home to rest up" [156]. Despite NASA concerns about overtime, he pushed back to allow "group leaders to take care of their people" [157]. Gavin himself spent considerable time away from home, both daily and with frequent travel: "We put in a lot of 80–90 hour weeks. It was tough on the families" [158]. 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" [159].

Serving in top management positions brought Gavin full circle, back into the naval aircraft development that remained the core of Grumman's business. He worked rapidly to reacquaint himself with the aircraft side: "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" [160]. 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: "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 [161].

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" [162].

III.2. Larger Legacy

Gavin had an extraordinary aerospace engineering career in an extraordinary age for American aerospace achievements. His employment coincided exactly with the Cold War era's lofty defense spending and ambitious megaprojects. 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 accrued some extraordinary personal experiences. Among his favorites: "I met Orville Wright before he died …

showed Charles Lindbergh the Lunar Module under construction; [and] survived the anxious hours of *Apollo 13*" [163]. Gavin also briefed von Braun on Grumman's original Apollo bid [164], escorted him on his visits to Grumman and hosted his inspections of the LM, and spoke with him on many other occasions. Gavin's own combination of diligence, personal modesty, and constant focus forward rather than recounting past glories probably inspired Neil Armstrong to write a glowing tribute. It described him 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" [165]. It reads as the heartfelt admiration and respect of one humble engineer's engineer for another.

Asked for career guidance, Gavin emphasized, "The most important thing to be doing [is] the thing that you would rather be doing than anything else. … I happened to get hung up on flying machines" [166]. Gavin elaborated, "When I was at Grumman I was doing something I would have preferred to do over anything else. When you're in that situation, the hours don't mean much. You do whatever is necessary" [167]. Addressing the tremendous commitment and sacrifices that Grummanites made to the LM Program, 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" [168].

Most fundamentally, Gavin was driven by the excitement of innovation in engineering: "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 talks to students, 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 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" [169].

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" [170]. Regarding the space program more broadly,

> "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" [171].

Asked to situate his own discipline, 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" [172].

An engineer at heart, who believed strongly in the potential for his profession to contribute to society, Gavin was concerned that after the Apollo years the American political process did not support sufficiently foresighted planning and investment concerning science and technology over a range of potential applications, from energy to space [173]. He was particularly interested in the potential of Japan and China to develop advanced aerospace technologies and programs. "I think the place that we're going to have to watch is the Japanese and the Chinese," he told the author in 1998 [174]. At the first opportunity, through the 1996 International Astronautical Congress, he visited China. In the process of touring space facilities in Beijing, Xi'an, and Shanghai, he was impressed by the caliber of the leading young aerospace specialists that he met. He assessed that if placed in top US programs (e.g., at MIT and Caltech) they would perform with distinction [175].

Gavin's lifetime of devotion to the pursuit of technological innovation at the frontier of cosmic discovery is encapsulated in 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?'" [176].

Gavin did far more than dream, however. By nature and interest, he was also a leader and a doer. Innovation, leadership, and execution ran throughout 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 during the heady 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 and never formally published—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?
- 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.

Appendix A
How the Aerospace Project Engineer Saw His Role

Joseph Gavin, Jr., started his aerospace project engineering career as a Design Engineer (1946–1948) on the Grumman Corporation's first jet fighter, the XF9F *Panther*, before becoming Engineer, Preliminary Design Group (1948–1950). He worked on various other aircraft projects, including Grumman's first and second jet fighters: Grumman's first swept-wing fighter, the F9F-6 *Cougar* (Project Engineer, 1950–1952), and supersonic F11F-1 *Tiger* (Co-Project Engineer, 1952–1956). During 1956–1957, Gavin served as Grumman's Chief Experimental Projects Engineer. From 1957–1962, as Grumman's Chief Space and Missile Engineer, Gavin planned and directed all spacecraft and missile technical activity for Grumman and led the corporation's unsuccessful 1958 bid on Project Mercury. In May 1962, Gavin was charged with centralizing space and missile efforts within the new Grumman Space & Missile Center. This heading of a new organizational entity as Space Programs Director capped his early leadership in Grumman's development of manifold aerospace products. Prominent among these was NASA's contracting Grumman in 1960 to produce its first space telescope, the Orbiting Astronomical Observatory (OAO). Then America's largest scientific satellite, of which four were launched and two operated successfully for five years each by NASA's Goddard Space Flight Center, OAO was a precursor to the Hubble Space Telescope and the James Webb Space Telescope. This followed soon after Grumman's first NASA contribution: building the launch adapter and canister for *Echo*, NASA's first communications satellite. 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 [177]

Rather than pursue the problem 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.

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 to 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. Effort 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.

References

[1] 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.

[2] 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 letter. Thomas J. Kelly, *Moon Lander: How We Developed the Apollo Lunar Module* (Washington, DC: Smithsonian Books, 2009), 267.

[3] "Company President Clint Towl Announces LEM Appointments," *Grumman Plane News* 21.21 (November 30, 1962), 8.

[4] Joseph Gavin, Jr., comments written in December 2001.

[5] Keegan, Interview of Joseph G. Gavin, Jr.

[6] "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." Joseph Gavin, Jr., comments written in December 2001. For Kelly's experiences in this position, which he held from 1961–1969 before Grumman sent him to MIT for a year and then tasked him with working on its Space Shuttle bid, 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 J.G. Gavin, Jr., 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), 179–181.

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[10] Gavin, "Introduction."

[11] "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.

[12] The initial US lunar landing concept, direct ascent, would have involved 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 would

continue to orbit with one astronaut while the Lunar Mode (LM) separated and delivered two other two astronauts to the lunar surface with its descent stage's rockets easing the landing. Upon completing activities there, they would blast off 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 after an explosion devastated the Service Module. 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.

[13] Keegan, Interview of Joseph G. Gavin, Jr. 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.

[14] Thomas J. Kelly, *Moon Lander: How We Developed the Apollo Lunar Module* (Washington, DC: Smithsonian Books, 2009), 14.

[15] Kelly, *Moon Lander*, 17.

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

[17] 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." Kelly, *Moon Lander*, 19.

[18] Kelly, *Moon Lander*, 20-21. On his personal copy of Kelly's book, Gavin noted, "I found dealing with GE painfully difficult—a clash of cultures."

[19] "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.

[20] 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.

[21] Kelly, *Moon Lander*, 22–23.

[22] Kelly, *Moon Lander*, 23.

[23] Richard D. Lyon, "Moon Landing Craft Unveiled by Astronauts: Moon Landing Craft Is Unveiled by Astronauts," *New York Times*, January 16, 1969, 1.

[24] Keegan, Interview of Joseph G. Gavin, Jr.

[25] "The Lunar Module Story."

[26] Rebecca Wright, Interview of Joseph G. Gavin, Jr., 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].

[27] "The Lunar Module Story."

[28] "The Lunar Module Story," 33–36; "NASA Selects Grumman Lunar Excursion Module Proposal: Negotiate for $350 Million Contract," *Grumman Plane News*, Special Bulletin, November 9, 1962, 1.

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

[30] Keegan, Interview of Joseph G. Gavin, Jr.

[31] Joseph G. Gavin, Jr., "LEM Design Evolution," *Astronautics & Aeronautics* (April 1965): 46.

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

[33] Kelly, *Moon Lander*, 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.

[34] "Part 4: The Lunar Module," Moon Machines, Science Channel HD documentary miniseries, June 2008, https://www.youtube.com/watch?v=f2Tc8z2xO74.

[35] Gavin, Jr., "LEM Design Evolution," 51.

[36] John Noble Wilford, *We Reach the Moon* (New York: Bantam Books, 1969), 149.

[37] Brooks, *Chariots for Apollo*, 147.

[38] Joseph G. Gavin, Jr., "The Apollo Lunar Module (LM): A Retrospective," IAC-02-IAA.2.3.08, paper presented at 53rd International Astronautical Congress, Houston, Texas, October 10-19, 2002 [Hereafter: IAC, 2002], 2.

[39] NASA Interview, 2003. Gavin recalled: "It was in 1965 that a prominent astrophysicist assured me that the lunar surface was covered by 10 meters of impalpable dust; fortunately, he was wrong!" IAC, 1990, 2.

[40] Kelly, *Moon Lander*, 96–97.

[41] Wilford, *We Reach the Moon*.

[42] NASA Interview, 2003.

[43] Richard D. Lyon, "LEM Holds Key to Apollo's Success," *New York Times*, May 18, 1969, 69.

[44] "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.

[45] IAC, 2002, 2.

[46] NASA Interview, 2003.

[47] Keegan, Interview of Joseph G. Gavin, Jr.

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

[49] NASA Interview, 2003. Additional window-related considerations included pilot mobility, restraint, and suit design; as well as vehicle attitude in the terminal descent phase. Gavin Jr., "LEM Design Evolution," 49.

[50] Other design choices involved the selection of widely-spaced four-legged extendible 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, throt-

tle-controlled descent rocket engine; and landing radar derived from that of the *Surveyor* probe. Gavin, Jr., "LEM Design Evolution," 46-51.

[51] Evert Clark, "Moon Landing Capsule Passes Final Design Test," *New York Times*, March 27, 1964.

[52] Joseph G. Gavin, Jr., "The Design of the Lunar Module," presentation to AIAA New England Section, The MITRE Corp., Bedford, Massachusetts, April 10, 2002.

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

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

[55] Kelly, *Moon Lander*, 122–123.

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

[57] Keegan, Interview of Joseph G. Gavin, Jr.

[58] 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.

[59] Author's discussion with Gavin over the years and review of his public statements and his annotated flight plans, especially for *Apollo 11.* 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?src=busl.

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

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

[62] Author's interview with Gavin, Amherst, Massachusetts, December 11, 1998.

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

[64] NASA Interview, 2003.

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

[66] "The Lunar Module Story."

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

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

[69] Keegan, Interview of Joseph G. Gavin, Jr.

[70] IAC, 1990, 2.

[71] Keegan, Interview of Joseph G. Gavin, Jr.

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

[73] Gavin, Jr., "LEM Design Evolution," 47–48.

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

[75] "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." Tom Buckley, "It Looks Like a Martian, It Will Land Our Men on the Moon," *New York Times,* February 23, 1969, 35.

[76] NASA Interview, 2003.

[77] NASA Interview, 2003.

[78] Gavin, "Introduction."

[79] Keegan, Interview of Joseph G. Gavin, Jr.

[80] IAC, 1990, 2.

[81] Keegan, Interview of Joseph G. Gavin, Jr.

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

[83] IAC, 2002, 3.

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

[85] Keegan, Interview of Joseph G. Gavin, Jr.

[86] Kelly, *Moon Lander*, 245. Many other LM variants applications were contemplated. "The Lunar Modules That Never Were," Chapter 6 in Stoff, *Building Moonships,* 111–120. The Air Force even considered using a modified LM to disable Soviet satellites mechanically. Stoff, *Building Moonships*, 116.

[87] NASA Interview, 2003.

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

[89] NASA Interview, 2003.

[90] Keegan, Interview of Joseph G. Gavin, Jr.

[91] In fact, five years previously, Gavin concluded 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, Jr., "LEM Design Evolution," 51.

[92] "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 to 15 percent 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.

[93] Kelly, *Moon Lander*, 226. A daunting challenge remained: "to go from a preliminary systems design study done six years earlier to real-time execution of a complex and unplanned sequence of space maneuvers by flight and ground crews untrained in specifics was quite a leap." Kelly, *Moon Lander*, 226–227.

[94] 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 the Cape 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, New York), June 14, 1998, A16.

[95] Keegan, Interview of Joseph G. Gavin, Jr.

[96] Richard Thruelsen, *The Grumman Story* (New York: Praeger, 1976), 13.

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

[98] Keegan, Interview of Joseph G. Gavin, Jr.

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

[100] Thruelsen, *The Grumman Story*, 13–14. Kelly was at MIT's Sloan School, Wright at Harvard Business School. Kelly, *Moon Lander*, 225.

[101] "The Age of Aquarius," *Grumman Plane News* 29.8, April 24, 1970, 5; Kelly, *Moon Lander*, 227.

[102] 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 made *Apollo 13* different was the lack of occasional down time to sleep.

[103] 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.

[104] Kelly, *Moon Lander*, 228–229.

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

[106] NASA Interview, 2003.

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

[108] In particular, Gavin regarded the cameo appearance of a Grumman representative to be an unfair portrayal. Author's experience watching *Apollo 13* with Gavin upon its release at a theater in South Hadley, Massachusetts, and discussing it with him subsequently. A humorous detail not included in the film occurred after *Apollo 13*'s crew was safely home. In jest, Grumman submitted $300,000 "towing" bill to North American Rockwell, builder of the Service Module that had caused the crisis by malfunctioning:

- "$4 for the first mile and $1 for each additional mile the LM towed the crippled spacecraft.
- Sleeping accommodations for two, no TV, air-conditioned with radio, modified American plan, with view … prepaid
- Additional guest in room. Check out no later than noon, Friday … $32
- Battery charge, road call--$.05 kwh, customer's jumper cables …
- Water from the LM's supplies was thrown in free. More than $88,000 was discounted as 20 per cent commercial discount plus 2 per cent cash discount."

Thruelsen, *The Grumman Story*, 16.

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

[110] Neil A. Armstrong, "Joseph G. Gavin, Jr., 1920–2010."

[111] Keegan, Interview of Joseph G. Gavin, Jr.

[112] Richard Witkin, "Grumman Is Seeking $1-Billion in Subcontracts in US Space-Shuttle Program," *New York Times*, July 29, 972, 54.

[113] Kelly, *Moon Lander*, 261.

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

[115] Keegan, Interview of Joseph G. Gavin, Jr.

[116] Author's interview with Gavin, Amherst, Massachusetts, December 11, 1998.

[117] Author's interview with Gavin, Amherst, Massachusetts, December 11, 1998.

[118] NASA Interview, 2003.

[119] Gavin's note, Kelly, *Moon Lander*, 266. "A great supporter of the [Apollo] program," Teague communicated with Gavin for 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 colourful character, Teague suffered for most of his life from wounds received heroically in the Italian campaign. "He wound up in Walter Reed 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 Joseph G. Gavin, Jr. See also "Teague, Olin Earl [Tiger] (1910–1981)," https://tshaonline.org/handbook/online/articles/fte32.

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

[121] Keegan, Interview of Joseph G. Gavin, Jr.

[122] Keegan, Interview of Joseph G. Gavin, Jr.

[123] "The Lunar Module Story."

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

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

[126] Kelly, *Moon Lander*, 101–103.

[127] "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.

[128] IAC, 2002, 4.

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

[130] Wilford, *We Reach the Moon,* 156.

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

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

[133] NASA Interview, 2003.

[134] NASA Interview, 2003; "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.

[135] IAC, 2002, 4.

[136] Keegan, Interview of Joseph G. Gavin, Jr.

[137] Regarding 1967–1968, Gavin recalled, “It was a very tough period. I spent two months on a 1 pm to 1 am schedule to be on hand for both day and night shifts!” Gavin’s notation; Kelly, *Moon Lander*, 188.

[138] 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.

[139] IAC, 2002, 4.

[140] NASA Interview, 2003.

[141] Keegan, Interview of Joseph G. Gavin, Jr.

[142] IAC, 2002, 4.

[143] NASA Interview, 2003.

[144] IAC, 2002, 3.

[145] Childs, “Joseph Gavin.”

[146] Keegan, Interview of Joseph G. Gavin, Jr.

[147] NASA Interview, 2003.

[148] NASA Interview, 2003.

[149] Gavin’s notation, Kelly, *Moon Lander*, 39.

[150] Keegan, Interview of Joseph G. Gavin, Jr.

[151] Frank Lynn, “Voices That Are Heard,” *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.

[152] 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.

[153] In that capacity, Gavin championed the continuation and coordination of American manned and unmanned space programs: “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.” Joseph 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.

[154] 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.

[155] Keegan, Interview of Joseph G. Gavin, Jr.

[156] Keegan, Interview of Joseph G. Gavin, Jr.

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

[158] Keegan, Interview of Joseph G. Gavin, Jr.

[159] 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.

[160] NASA Interview, 2003.

[161] NASA Interview, 2003.

[162] Gavin, "Introduction."

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

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

[165] Neil A. Armstrong, "Joseph G. Gavin, Jr. 1920–2010."

[166] Keegan, Interview of Joseph G. Gavin, Jr.

[167] 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.

[168] "The Lunar Module Story."

[169] NASA Interview, 2003.

[170] "The Lunar Module Story."

[171] "The Lunar Module Story."

[172] Keegan, Interview of Joseph G. Gavin, Jr.

[173] Seeking to preserve a US role in ITER to pursue fusion energy, Gavin declared, "A national asset is going to slip away from us if this panel doesn't stand up." Andrew Lawler, "Panel Would Close Princeton Reactor," *Science* 271 (February 2, 1996): 592. See also Colin Macilwain, "Panel Backs Closure of US Fusion Machine," *Nature* 379 (February 1, 1996), 387; Andrew Lawler, "Fusion Advocates Scramble for Scraps," *Science* 270 (December 15, 1995): 1755.

[174] Author's interview with Gavin, Amherst, Massachusetts, December 11, 1998.

[175] Author's discussion with former *Aviation Week & Space Technology* journalist Craig Covault, who accompanied Gavin on the trip.

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

[177] 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. The two design tradeoffs Gavin mentions were then in play. Stoff, *Building Moonships,* 20. During that time, the LM's legs were reduced from 5 to 4 as part of a weight-vs.-strength trade-off. In meetings during October and November, a cantilevered landing gear was selected. Brooks, *Chariots for Apollo*, 151–152.