Acta Astronautica 181 (2021) 167–189

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Joseph G. Gavin, Jr. and MIT's contribution to aerospace in the Apollo era and beyond

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ARTICLE INFO

Keywords:
Aerospace
Aeronautics
Air Force
Apollo Program
Astronautics
Charles Stark Draper
Computer
Draper Laboratory
F-14
Grumman Corporation
Instrumentation Laboratory
Joseph G. Gavin, Jr.
Lunar
Lunar Module
MIT
Moon
Moonlanding
Massachusetts Institute of Technology
Northrop Grumman
Navy
Space

ABSTRACT

Five decades after the Apollo 11 moonlanding, it is time to consider the individuals and institutions that made it possible. Examining the remarkable aerospace engineering career of Joseph G. Gavin, Jr. at the Grumman Corporation, together with the Massachusetts Institute of Technology (MIT)'s indispensable institutional role, reveals factors that helped generate a golden American age in air and space. Gavin's education and contributions offer an enlightening yet under-considered window into aerospace history. Coinciding exactly with the Cold War era's lofty defense spending and ambitious megaprojects, his employment intersected with dynamic developments unmatched before or since. Throughout, Gavin and his efforts connected symbiotically with "Tech"—a microcosm, meeting place, and mainstay of American aeronautics and astronautics. It was an intellectual home to which he constantly returned, offering lifelong association, inspiration, and support. A comprehensive federal-corporate-academic partnership brought strengths to Project Apollo that its Soviet counterpart lacked, and MIT was at the heart of it. At Gavin's graduation from MIT (S.B./S.M.) in 1942, President Karl Compton spoke presciently of path-breaking opportunities on new technological frontiers for the engineering graduates. Recruited by classmate Thomas Connolly—who would later help oversee development of Grumman's F-14 fighter, improved and sold under Gavin's corporate leadership—Gavin entered the Navy, itself a key sponsor of MIT and aviation. He spent four years at its Bureau of Aeronautics before joining Grumman in 1946. Gavin's career there is best known for his decade as Lunar Module Program Director (1962–72). Technological frontiers kept Gavin returning to MIT, including in LM leadership to coordinate challenges regarding MIT's Apollo Guidance Computer. Gavin remained closely involved with the development of his *alma mater* and its Department of Aeronautics and Astronautics, attending his last MIT Corporation meeting a month before his death at age 90 in 2010. Drawing on MIT documents and Gavin's own collection, as well as extensive interviews with him, this article explores his personal and organizational relations with his home institution as they played pioneering roles in aerospace engineering.

1. Formative fascination with flying machines—for MIT and Gavin

"With Joe Gavin's passing, the aerospace community has lost one of its great leaders,"[1] American Institute of Aeronautics and Astronautics (AIAA) President Mark Lewis declared in 2010. "Joe contributed to everything from early jet engines, to city buses, to the space shuttle, but he will be forever known as the leader of the team that produced the

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[1] 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; "Joseph Gavin '41, SM '42: Grumman Head Worked to Save Apollo 13," *MIT News*, https://www.technologyreview.com/2009/02/24/267519/joseph-gavin-41-sm-42/; Phil Davison, "Engineer Who Took Control When Houston Had a Problem," *Financial Times*, November 26, 2010, https://www.ft.com/content/ec0178d0-f998-11df-9e29-00144feab49a; James Bernstein, "Space Pioneer Dies—Joseph Gavin Had Key Roles in U.S. Moon Mission, Headed Grumman When It Was Largest LI Company," *Newsday* (Long Island, NY), November 2, 2010, A8; "Joseph Gavin Jr.," *Brattleboro Reformer*, December 8, 2010, http://www.legacy.com/obituaries/brattleboro/obituary.aspx?pid=147002803; "Apollo: Reflections and Lessons," *MIT Tech TV*, June 11, 2009, http://techtv.mit.edu/videos/16591-apollo-reflections-and-lessons; "Joseph Gavin, Jr.," Wikipedia, https://en.wikipedia.org/wiki/Joseph_G._Gavin_Jr; "Joseph Gleason Gavin, Jr.," *Who's Who in America*, 1988–1999, 45th Edition; "Joseph Gleason Gavin, Jr.," *American Men and Women of Science*, 1992, 16th Edition; "Background Section," *Apollo Spacecraft: Lunar Module News Reference* (Bethpage, NY: Grumman Aircraft Engineering Corporation (GAEC), Public Affairs, Space, 1968), B-2; Joe Gavin, transcript of interview by HBO Productions, June 26, 1996.

https://doi.org/10.1016/j.actaastro.2020.06.032
Received 1 February 2020; Received in revised form 7 May 2020; Accepted 18 June 2020
Available online 28 August 2020
0094-5765/Published by Elsevier Ltd on behalf of IAA.

Apollo Lunar Module, one of the greatest engineering accomplishments in human history."[2] Gavin helped develop Grumman's most noteworthy systems throughout its heyday as an innovator primarily serving the U.S. government,[3] particularly the military.[4] Within Grumman, his career likewise tracked the most dynamic elements. In the first phase, he was directly involved in the development of naval aircraft, a core Grumman product. He would return to this focus in his third and final phase as a senior manager. At the beginning of the middle phase, as Grumman built a space business, he headed the development of several key aerospace products, including the Orbiting Astronomical Observatory (a precursor to the Hubble Space Telescope) as Grumman's chief missile and space engineer.

It was the Apollo program that most captivated Gavin, and consumed the middle phase of his career. He believed it "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."[5] From 1962–72, Gavin oversaw as many as 7,500 employees as director of the Lunar Module (LM) program. NASA awarded him the Distinguished Public Service Medal for his role in saving the Apollo 13 mission; and in 1974 he became the latest of the many MIT affiliates elected to the National Academy of Engineering. "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."[6]

Gavin's wide range of responsibilities, contacts, and experiences—combined with a penchant for travel that included attendance at virtually every International Astronautical Congress (IAC) from 1980 to 2005—afforded him unusual insights into the geopolitics, military-technological frontier, and policies of his era. Aside from several characteristically succinct presentations, however, Gavin's humility and persistent focus on the future dissuaded him from writing a memoir or otherwise publicizing his experiences.[7] "Those who knew Joe knew he never sought to be in the limelight, though, as head of our space program, he should have been," Northrop Grumman vice president Patricia McMahon stated upon Gavin's death in 2010. "He was one of the great pioneers in the aerospace industry."[8]

As a world-leading institution of technology research and education, Gavin's *alma mater* MIT is naturally far better known than he. Yet their efforts were intertwined and integrated throughout the first aerospace age, and MIT's unique role merits further recognition and understanding. Well represented on the frontiers of science and technology, the MIT community includes 50 Nobel laureates, 33 MacArthur fellows, and 160 members of the National Academy of Sciences. MIT has produced more astronauts than any other school. Globally, alumni have founded nearly 26,000 companies, wherein 3.3 million employees have generated two trillion dollars' annual revenue—equivalent to the world's eleventh-largest economy.[9] To date, MIT's Department of Aeronautics and Astronautics (AeroAstro) records, "Five MIT faculty have served as chief scientist for the Air Force. More than 25 percent of professors in the nation's leading aerospace programs are MIT alumni. The aerospace program heads at a number of other world-class U.S. institutions are AeroAstro alumni."[10] These achievements unfolded over the course of Gavin's career. "With a bigger faculty, more graduate students, closer ties to industry, and better representation on government advisory panels than any other institution, MIT set the pattern for postwar aeronautics," historian Stuart Leslie elaborates. "Its graduates went on to become executives and chief engineers at leading aerospace contractors from Long Island to Los Angeles, highly placed officers in the Army, Navy, and Air Force (including two Secretaries of the Air Force),[11] and top academics at MIT and other universities."[12] On the threshold of that golden era, Jerome Clarke Hunsaker, who pioneered both American aviation and MIT's dominance within it, remarked that "MIT graduates include the chief engineers or engineering directors of Curtiss-Wright, Glenn L. Martin, Pratt & Whitney, Vought, Hamilton Standard, Lockheed, Stearman, and Douglas, as well as the engineer officers of the Naval Aircraft Factory and of Wright Field."[13] Accordingly, National Air and Space Museum senior curator Tom Crouch assessed nearly a century later, "AeroAstro at MIT has had a more extraordinary influence on our technology than almost any other institution."[14]

To draw larger lessons from this unique confluence of capabilities, this article traces the interaction of Gavin and his Grumman team with MIT and NASA to find reliable solutions for successful missions. It explores the whole-of-nation development of technology from start to spaceflight and how the participants made adjustments based on information from experience. It thereby offers deeper understanding of the intimate connections between American industrial aerospace and academia that emerged during the second half of the 20th century, with particular insights into a major participant's personal interface within a public-private partnership involving a government agency providing

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

[3] Grumman's 1962 report: "Business with the U.S. Government constituted over 90% of our sales, and was made up of some 14 major projects in the aircraft, space, and marine fields." GAEC, Thirty-Third Annual Report, 1962, 6.

[4] As late as 1972, "defense account[ed] for 95% of total business." Philip Shabecoff, "Defense Industry Adapting to Peace: War's End Likely to Be Boon to Some Concerns," *New York Times*, December 3, 1972, F1, https://www.nytimes.com/1972/12/03/archives/defense-industry-adapting-to-peace-wars-end-likely-to-be-boon-to.html.

[5] Thomas J. Kelly, *Moon Lander: How We Developed the Apollo Lunar Module* (Washington, DC: Smithsonian Books, 2009), 18.

[6] Brian Keegan, Interview of Gavin, Infinite History Project, MIT, July 17, 2007, https://infinite.mit.edu/video/joseph-g-gavin-jr-41-sm-42. [Hereafter: MIT Interview, 2007.]

[7] Gavin's death generated dozens of letters and reminiscences; some new to Gavin's family, as he had been too modest to recount them himself.

[8] "Joseph Gavin Dies at 90; Former Head of Aerospace Company Grumman," *Los Angeles Times*, November 3, 2010, http://articles.latimes.com/2010/nov/03/local/la-me-joseph-gavin-20101103.

[9] David Kaiser, "Introduction," in Kaiser, ed., *Becoming MIT: Moments of Decision* (Cambridge, MA: MIT Press, 2012), 4. Four-part series elaborates: "A Sesquicentennial," *High Tech History*, March 10, 2011, https://hightechhistory.wordpress.com/2011/03/10/a-sesquicentennial-becoming-mit-moments-of-decision-part-1/.

[10] "History," MIT AeroAstro, https://aeroastro.mit.edu/about/history. Further details: Lauren Clark and Eric Feron, "A Century of Aerospace Education at MIT," in Barnes McCormick, Eric Jumper, and Conrad Newberry, eds., *Aerospace Engineering Education during the First Century of Flight* (Reston, VA: AIAA, 2004), 41.

[11] The two MIT alumni who have been appointed to the service's leading civilian position are Robert Seamans, Jr., discussed later regarding his role in MIT's Instrumentation Laboratory (IL) and Apollo; and Sheila Widnall (S.B. 1960, S.M. 1961, Sc.D. 1964; AeroAstro), the first female Secretary of the Air Force and the first woman to lead an entire branch of the U.S. military in the Department of Defense. Widnall recently retired after totaling 64 years at MIT. Christine Negroni, Department of Aeronautics and Astronautics, "Sheila Widnall: A Lifetime Exploring the Unknown," *MIT News*, October 9, 2020, https://news.mit.edu/2020/sheila-widnall-lifetime-exploring-unknown-1009; "Dr. Sheila E. Widnall, Institute Professor, MIT, 2009 Arthur M. Bueche Award," National Academy of Engineering, https://www.nae.edu/55353/Dr-Sheila-E-Widnall.

[12] Stuart W. Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1994), 77–78.

[13] Valerie Silva, "Boston, A City in Ascent and an Aeronautics Innovation Hub," APEX: The Airline Passenger Experience Association, August 23, 2018, https://apex.aero/articles/boston-city-ascent-aeronautics-innovation-hub/.

[14] Jennifer Chu, "AeroAstro Turns 100: Nine Astronaut Alumni and Elon Musk Join in Celebrating Department's Centennial," MIT News Office, October 25, 2014, https://news.mit.edu/2014/aeroastro-centennial-symposium-1025.

effective management, a private company furnishing reliable products, and an academic institution serving as a vital educator and enabler.[15]

1.1. Gavin—Getting launched in life

At the personal level, this is the story of an engineer's extraordinary life and career in an extraordinary age of American aerospace activity. It begins with Gavin's birth in Somerville, Massachusetts on September 18, 1920. He grew up nearby in Brighton. His father, Joseph Sr., had to drop out of high school to help support his family after an industrial accident killed his own father. He ultimately became partner in a national syndicate of newspaper advertising brokers.[16] He served thrice in the U.S. Army: in 1916 on the Mexican border; in World War I as a lieutenant with the 26th Division Field Artillery, receiving the Purple Heart and Silver Star;[17] and in World War II in Germany with an Allied Military Government unit and ultimately as the military governor of Rheingau-Kreise, retiring as Lieutenant-Colonel. Gavin's mother, Elizabeth Tay, was a commercial artist who produced major displays for Boston storefronts. Gavin came into the world in the right place at the right time. His home state of Massachusetts, MIT Museum Director of Collections and Curator of Science and Technology Deborah Douglas explains, "was a really dynamic technical community that, for the first half of the century, nurtured people who would be pioneers and leaders in the aeronautics field."[18] A confluence of local culture, policies, institutions, and investment paid tremendous dividends in technology and industry, thereby contributing much to the public good and to Gavin's own life possibilities.

Gavin's lifelong interest in aircraft and space travel began early and was encouraged in three framing phases: youthful stimulus from fiction and experience, engineering education at MIT, and Navy work in Washington, DC. He drew early inspiration from Buck Rogers and Charles Lindbergh, traveling hours as a seven-year-old to see "Lucky Lindy" land on a small Vermont airfield following his transatlantic flight in 1927. "We got within 15 feet of Lindbergh, and about the same distance from his airplane," Gavin recalled, "From that point on, flying machines were my interest—doesn't matter if it's airborne or in orbit."[19] Thus, from early on, "I was pretty sure I wanted to be an engineer … and do something with flying machines."[20] Four decades later, in 1968, Gavin would receive Lindbergh at Grumman Headquarters in Bethpage, New York, and show him the product of the Apollo program he then led: the LM.[21]

After attending other public schools through sixth grade, Gavin pursued his secondary education at the Boston Latin School (BLS). There he received the Classical, Modern, and Fidelity prizes, lettered as manager of the baseball team,[22] and supported the football team as a 180-pound tackle[23] until he broke his nose.[24] He was also a rifle club marksman. Latin School was "a big leg up, very demanding. By the time I left, I knew how to study. Several teachers conveyed the idea that if you're going to do something, do it well." Senior year, Gavin enjoyed assembling experiments for the Physics Department.[25] In 1964, BLS would name the 1937 graduate "Man of the Year."[26]

2. Education at MIT

In part to support America's emergence as a leading industrial power, MIT leaders had spent the previous quarter-century transforming the former undergraduate engineering school into one of just two American comprehensive technological research universities and strengthening its connections to industry. This was perfect timing for Gavin, who like some of his most determined peers had been studying German in preparation to pursue graduate education in Germany, where some of the most advanced courses were then offered. The California Institute of Technology (Caltech) was MIT's only peer; they joined the elite Association of American Universities in 1934.[27] Amid this ascent, MIT led American aeronautical engineering from its humble beginnings. In 1896, seven years before the Wright brothers' historic flight, mechanical engineering student Albert J. Wells based his thesis on a 30-square-inch wind tunnel he developed in a duct from the engineering building's forced ventilation system.[28] In 1908, Columbia University professor and Department of Mechanics head Richard Maclaurin eagerly advised the country's first aeronautics major, Grover Cleveland Loening, even as colleagues remained skeptical of the undergraduate's ambitions. The next year, MIT students who had helped Orville Wright with his 1909 Flyer founded the Tech Aero Club, constructed a glider, and began participating in aerial expositions.[29] Maclaurin became the Institute's sixth president and "established at MIT the leading aeronautical engineering course in America" as part of his transformative leadership until his death in 1920.[30] Maclaurin believed in particular that the Institute should "lead in the study of aerial navigation in the United States."[31] As MIT's ninth president (1930–48), Karl Compton pursued similarly far-reaching initiatives.[32]

One of 35 selected among 75 applicants[33] for an aeronautics course that until recently had accomodated only 28–30 students,[34] Gavin arrived at "Tech" in fall 1937. After Latin School, "entering MIT was pretty straightforward." Gavin wanted to major in aeronautical engineering, which required successful performance in freshman year, followed by an interview. The department was highly selective because, before World War II, obtaining related employment was difficult. Hence his otherwise supportive father's advice: "Don't go into that business."[35] But, like many of his future MIT and Apollo peers, Gavin was a first-generation college student who charted his own course to follow his

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[15] The author thanks an anonymous reviewer for this conceptual perspective.

[16] Arthur A. Riley, "Ex-Hub Man Heads Moon Tour Phase," *Boston Sunday Globe*, May 17, 1964, 8A.

[17] Riley, "Ex-Hub Man Heads Moon Tour Phase," 8A.

[18] Denise Brehm, "Museum is State's Official Flight Commemoration Site," MIT News Office, December 17, 2003, https://news.mit.edu/2003/museum-states-official-flight-commemoration-site.

[19] "We Asked Great Leaps Participants: What Inspires You?" in Ian A. Waitz and William T.G. Litant, eds., *AeroAstro* 6 (Cambridge, MA: MIT, September 2009): 29, http://web.mit.edu/aeroastro/news/magazine/aeroastro6/aeroastro6.pdf.

[20] MIT Interview, 2007.

[21] Gavin, dayplanner, November 18, 1968.

[22] "Boston Latin School 'Man of the Year' 1964," in Wilfred L. O'Leary, Annual Report of the New Headmaster, November 25, 1964, 3.

[23] Will Cloney, "Latin Success Dependent on Omelet Eleven," *Boston Herald*, September 30, 1936, 1.

[24] "Boston Latin Awards Made," *Daily Boston Globe*, June 11, 1936, 4.

[25] MIT Interview, 2007.

[26] "Boston Latin School 'Man of the Year' 1964."

[27] Christophe Lécuyer, "Patrons and a Plan," in Kaiser, ed., *Becoming* MIT, 59–62, 75.

[28] "History," MIT AeroAstro.

[29] "Deborah Douglas, "The Most Remarkable Banquet in the World," *AeroAstro Magazine 2013–14*, 45.

[30] Grover Loening, *Our Wings Grow Faster* (New York, NY: Doubleday, Doran & Co., Inc., 1935), 14. See also "Richard Cockburn Maclaurin, 1870–1920," MIT History, https://libraries.mit.edu/mithistory/institute/offices/office-of-the-mit-president/richard-cockburn-maclaurin-1870-1920/.

[31] William Litant, "A Centennial Album: Images from 100 Years of MIT Aeronautics and Astronautics," *AeroAstro Magazine 2013–14*, 37, https://issuu.com/mitaeroastro/docs/aeroastro-magazine-2013-14.

[32] "Karl Taylor Compton, 1887–1954," MIT History, https://libraries.mit.edu/mithistory/institute/offices/office-of-the-mit-president/karl-taylor-compton-1887-1954/.

[33] Hunsaker, "Aeronautical Engineering—School of Engineering," *President's Report* 73.1 (Cambridge, MA: MIT, October 1937), 86–87.

[34] MIT Interview, 2007.

[35] Ibid.

passion, unaware that opportunities would soon unfold so dramatically.[36]

In 1938, freshman aeronautics intake remained capped at 35: "A larger number would lead, under present conditions, not only to placement difficulties but also to serious crowding of drafting and laboratory rooms."[37] Not until 1939 did Gavin's specialty become a full-fledged department under the landmark leadership of Hunsaker, who led it until Charles Stark Draper succeeded him in 1951. Hunsaker had devoted his career to aeronautics after graduating first in his class at Annapolis in 1908 and four years later receiving an S.M. from MIT in naval architecture, a department established in partnership with the Navy in 1893.[38] While meeting Naval Construction requirements, Hunsaker found his true love in the aeronautics literature he read extensively under Naval Architecture Department head C.H. Peabody and translated two leading French works into English.[39] Detailed to Boston Navy Yard as Assistant Naval Constructor during 1912–13, Hunsaker witnessed French pioneer Louis Blériot's flight around Boston Harbor during an aviation meet. He quickly became a protégé of Maclaurin, who succeeded in having the Navy reassign Hunsaker to MIT to fulfill one of his top priorities: establishing an aeronautics curriculum and world-class aerodynamics facilities. Later in 1913, Maclaurin sent Hunsaker to survey the aeronautical state of the art across Europe.[40]

Back in Cambridge, assisted by future aviation executive Donald Douglas (S.B. 1914) within the Department of Naval Architecture, Hunsaker offered America's first aeronautical engineering course, "13.72, Aeronautics for Naval Constructors." They established the first structure on MIT's new Cambridge campus, inaugurating a succession of increasingly advanced wind tunnels. Also in 1914, MIT approved an aeronautics master's degree program proposed by Instructor Hunsaker and Professors Peabody and E.B. Wilson. Hunsaker worked to transform his discipline from invention by trial and error to engineering and manufacture by science. In 1915 Hou-Kun Chow, the first to complete Hunsaker's course, received America's first master of science degree in aeronautical engineering. Chow, a polymath later acclaimed as "the father of the Chinese typewriter," was part of a cohort of Chinese students who distinguished themselves via MIT, particularly in naval architecture and aeronautics.[41]

Several factors generated this early ripple of what would become waves of Chinese contributions through MIT. MIT's naval architecture program attracted talented Chinese barred from its military counterpart at Annapolis.[42] Chinese students flocked to MIT's aeronautics program because they recognized the discipline's potential and were unmoved by skepticism then pervading their American peers. Moreover, typically selected through rigorous examination for Boxer Indemnity sponsorship, they were equal to unprecedented academic challenges.[43] Many of the first students to enroll in, and receive degrees from, the first American course in aeronautical engineering—Hunsaker's—were thus Chinese.[44] So pronounced was this pattern that MIT's 1917 yearbook devoted a page to what editors lacking historical foresight lampooned as a quixotic quest: "Why does [Hunsaker] teach the Chinese aviation? Oh, because they are the only ones who are foolish enough to believe he knows enough about it, and ... the only ones nervy enough to take the course."[45] In fact, as one study reflects a century later: "Pioneers in the history of flight, these MIT graduates went on to play central roles in developing Chinese aviation, which would prove crucial in the war against Japan."[46] Likewise recognizing MIT's pathbreaking promise, the National Advisory Committee on Aeronautics (NACA) based its first annual report on Hunsaker's research and appointed Maclaurin one of its first twelve members.[47]

In 1916, Hunsaker received the first aeronautical engineering doctorate from an American university: an Sc.D. for wind tunnel research on aerodynamic stability.[48] Degree in hand, Hunsaker left MIT to shepherd American aviation in the government and private sector for the next seventeen years. He "organiz[ed] the U.S. Navy's aviation design and procurement program, then work[ed] on aerial navigation systems for Bell Labs and commerical airships for Goodyear-Zeppelin." He led naval aircraft development; surveyed foreign technology as assistant naval attaché in London, Paris, Berlin, Rome, and The Hague; and spearheaded carrier aviation at the Bureau of Aeronautics.[49] While Hunsaker supported the war effort within Navy bureaucracy, his MIT wind tunnel helped bring America into World War I's military airpower age, and afterward received Army contracts.

During Hunsaker's nearly two decades' absence, MIT Aeronautics shifted repeatedly in organization and leadership. Alexander Klemin (S. M. 1916) took over Hunsaker's courses for 1916–17, but was sent to head research at McCook Field (Dayton, Ohio) after America entered the war against Germany in April 1917. Succeeding Klemin in leading graduate instruction, Hunsaker protégé Edward Warner (S.B. 1917, S.M. 1918) helped provide advanced nondegree Aeronautical Engineering instruction to Navy and Army officers amid MIT's broader wartime aeronautical education and training. Assisting staff included Edwin

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[36] The rapidity with which aviation advances made such passions practical is dramatized in the following novel by an early pioneer-participant: Grover Loening, *The Conquering Wing* (New York: Chilton Book Company, 1970).

[37] Hunsaker, "Aeronautical Engineering—School of Engineering," *President's Report* 74.1 (Cambridge, MA: MIT, October 1938), 78.

[38] Tom D. Crouch, *Rocketeers and Gentlemen Engineers: A History of the American Institute of Aeronautics and Astronautics ... and What Came Before* (Reston, VA: AIAA, 2006). Among his MIT publications: Jerome C. Hunsaker, "Technical Progress in Aviation," *The Technology Review* 43.4 (February 1941): 152–54, 178–80.

[39] These included the classic treatise by Gustave Eiffel, translated by Hunsaker, *The Resistance of the Air and Aviation* (London/Boston: Constable/Houghton, 1913). Impressed with Hunsaker's discovery of errors in his work as revealed in their subsequent correspondence, Eiffel—an engineer and aerodynamicist renowned for the tower bearing his name—invited Hunsaker to view aircraft construction at his laboratories near Paris. Jack L. Kerrebrock, "Jerome Clarke Hunsaker: August 26, 1886–September 10, 1984," *Biographical Memoirs: Volume 78* (Washington, DC: National Academies Press, 2000), 94–107, https://www.nap.edu/read/9977/chapter/7.

[40] Deborah Douglas, "The Most Remarkable Banquet in the World," *AeroAstro Magazine 2013–14*, 45–46.

[41] "Hou-Kun Chow 周厚坤 'Father of the Chinese Typewriter'," http://chinacomestomit.org/chou-houkun; "H. K. Chow (周厚坤)," Boxer Indemnity Scholars, https://boxerindemnityscholars.wordpress.com/2016/01/15/h-k-chow-周厚坤/; "Chow Hou-kun – Inventor," https://earlychinesemit.mit.edu/overview/chow-hou-kun.

[42] "Training China's Admirals and Shipbuilders," China Comes to MIT: MIT's First Chinese Students/早期中国留学生: 1877–1931, http://chinacomestomit.org/#/navy-students/.

[43] "The First Graduates," http://chinacomestomit.org/#/first-graduates/, and "The Boxer Indemnity Scholarship Program," http://chinacomestomit.org/#/new-page-2/; China Comes to MIT.

[44] In addition to Chow, Chinese recipients of some of MIT's earliest degrees in aeronautical engineering included Charles Hsi Chiang, Wai Po Loo, Tsao Yu [Ba Yu Cao], and Shao Fung Wong (S.M. 1917); as well as Wong Zen Tze and Zhou Heng Huang (S.M. 1918).

[45] *Technique 1917*, 450, http://web.mit.edu/technique/www/scans/1917_Technique.pdf.

[46] "Bringing 'Tech' to China," China Comes to MIT, http://chinacomestomit.org/#/bringing-tech-to-china/.

[47] Clark and Feron, "A Century of Aerospace Education at MIT," 33.

[48] Hunsaker et al., *Dynamical Stability of Aeroplanes (with three plates)* (MIT doctoral thesis, 1916), https://dspace.mit.edu/handle/1721.1/101759. Hunsaker was recommended for Doctor of Engineering by vote of the Corporation on June 9, 1916 (MIT Archives AC278, s. 3, b.1, reel 2). He is listed among successful candidates for graduation in the "Course Catalogue of the Massachusetts Institute of Technology 1916 – 1917" (https://dome.mit.edu/handle/1721.3/82757), with a description of his doctoral studies appearing on p. 430.

[49] Clark and Feron, "A Century of Aerospace Education at MIT,"Clark and Feron, "A Century of Aerospace Education at MIT," 34.

Aldrin, Sr. (S.B. 1918, Sc.D. 1928), future father of Apollo 11 astronaut Edwin "Buzz" Aldrin, Jr.; students in the 1918 groups included Gavin's future employer Leroy Grumman. Warner was next assigned to MIT's wind tunnel under Army lease and staffing (1917–18). Early in 1919, Warner was called to lead NACA's flight research, and first wind tunnel development, at Langley Field as Chief Physicist. In Warner's absence, Aeronautics reached a nadir. Peabody, who had supported Aero Engineering graduate courses in his department, retired in June 1920. Longtime supporter E.B. Wilson, having assumed leadership of Physics, absorbed all aeronautics courses into his department. In one of his last acts before his death, Maclaurin worked with Wilson to arrange Warner's return as an Associate Professor of Aeronautical Engineering. From 1920–26, Warner played a leading role in Aeronautics, enthusiastically expanding the nascent discipline's graduate program and wind tunnels. He was promoted to full professor in 1924. In 1926, Warner became inaugural Assistant Secretary of the Navy for Aeronautics; he would hold national and international aviation leadership positions for the rest of his career.[50] Wright Aeronautical Corporation chief engineer C. Fayette Taylor joined the faculty that year. Under his Aeronautics leadership, in 1926 MIT established a four-year undergraduate program in aeronautical engineering, known to this day as "Course XVI," within the Department of Mechanical Engineering. In 1928, MIT opened the Daniel Guggenheim Aeronautical Laboratory, one of many beneficiaries of the industrialist and his son Harry's support for the burgeoning field nationwide. Having met Hunsaker in Europe in 1913, Harry Guggenheim would repeatedly consult him in actively implementing his father's philanthropic vision.[51] Taylor served as full professor and head of aeronautical engineering from 1929–33.

Hunsaker's 1932 selection as inaugural president of America's Institute of Aeronautical Sciences confirmed his status as "a one-man clearinghouse for American aeronautical engineering,"[52] as did his receipt of the Guggenheim Medal the following year—heralding many future accolades.[53] In 1933, Compton recruited Hunsaker to head MIT's Mechanical Engineering Department. Linking his acceptance to sole authority over aeronautics instruction therein, Hunsaker replaced Taylor. Taylor became director of the Sloan Laboratory of Aircraft and Automobile Engines, and would lead aeroengine research until his retirement in 1960.[54] Taylor's lab was established from a 1928 gift by General Motors CEO Alfred Sloan, Jr., among his many bequests to his *alma mater*.[55] Hunsaker rapidly enhanced the curriculum and faculty publication channels. Presaging aeronautics' fusion with space to form a combined aerospace discipline, both in general and at MIT in departmental organization, Hunsaker would serve as NACA's chairman from 1941–56, shortly before it became NASA in 1958. Hunsaker retired from the MIT faculty in 1952, but maintained an office and formidable presence through the Apollo years.[56]

Other professors' and students' achievements reflect MIT's status as a wellspring of global aerospace talent, although they never worked directly with Gavin. Key graduates of the aforementioned Chinese MIT student cohort returned to establish a national aviation industry, including a fledgling air force serving China in World War II. Among the most famous, Tsoo Wong (Wang Zhu; S.B. 1916, S.M. 1917) was recommended by Hunsaker to Boeing. Employed there, using MIT wind tunnel data, Wong designed Boeing's *Model C*—its first military plane, first mail plane, and first financial success upon Navy adoption in World War I.[57] Throughout his subsequent career establishing Chinese aviation, Wong maintained strong MIT connections. Teaching at the engineering college of Tsinghua University ("China's MIT"), he encouraged promising students to go to "Tech," including Qian Xuesen.[58] Qian served as a full professor in MIT's Department of Aeronautics and Astronautics from 1947–49 before decamping to Caltech, and suffering deportation in 1955 to China, where he established its space program. Other departing professors made foundational contributions in Europe and Latin America.[59]

Among the department's handful of early faculty members was Draper,[60] who would play a similarly fundamental role after receiving his S.M. from MIT in 1928, beginning to teach courses, and joining MIT

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[50] Clark and Feron, "A Century of Aerospace Education at MIT," 34. From 1929–1945, Warner as served as a presidential appointee on the National Advisory Committee for Aeronautics; serving successively as Chairman of its Aerodynamics and Operating Problems committees. In 1934, President Roosevelt appointed Warner as a member of the Federal Air Commission; he was subsequently elected Vice-Chairman. In 1938, Warner joined the Civil Aeronautics Authority staff as an economic and technical consultant. For the next six-plus years, he was a member of the Authority and its successor Civil Aeronautics Board; serving as Vice-Chairman in 1941 and 1943–45. Warner left his greatest legacy as a civil servant establishing a global air transport system, known today as the as the International Civil Aviation Organization (ICAO). He was an American Delegate to the 1944 Chicago Conference for ICAO. Founding President of the Council of ICAO during its provisional status from 1945–47, Warner continued as President until his retirement in 1957. "Edward Pearson Warner (United States), First President of The PICAO and ICAO Council, Term Of Office: 1947–1957," https://www.icao.int/about-icao/Pages/biography-president-warner.aspx.

[51] Robert G. Loewy, "The Two Men Behind the Seven Guggenheim Schools of Aeronautics and Their Further Contributions to Aerospace Engineering," in McCormick et al., eds., *Aerospace Engineering Education During the First Century of Flight*, 73–84, especially 76.

[52] Thomas Wildenberg, *Hotspot of Invention: Charles Stark Draper, MIT, and the Development of Inertial Guidance and Navigation* (Annapolis, MD: Naval Institute Press, 2019), 26.

[53] Kerrebrock, "Jerome Clarke Hunsaker: August 26, 1886–September 10, 1984."

[54] Ibid.; "C.F. Taylor Sr., Retired MIT Professor Who Pioneered Development of Aircraft Engines, Dies at 101," *MIT News*, June 27, 1996, https://news.mit.edu/1996/taylor; "Professor C. Fayette Taylor," Resolution read before the MIT Faculty at their meeting on September 21, 1994, http://web.mit.edu/html/www/taylor.pdf.

[55] Leslie, *The Cold War and American Science*, 79.

[56] Kerrebrock, "Jerome Clarke Hunsaker: August 26, 1886–September 10, 1984."

[57] With fellow graduates Ba Yu Cao and Wong Shao Fung—all now Chinese Navy lieutenants—Wong returned home in 1917 to establish China's first airplane manufacturing facility (Mawei, Fuzhou). They built China's first floatplanes and designed the world's first floating seaplane hangar. In 1929, Wong helped found China Airways (later China National Aviation Corporation) as chief engineer. As hostilities erupted, Wong directed naval aircraft engineering, then oversaw China's first naval aircraft fleet construction at the Curtiss-affiliated Central Aircraft Manufacturing Company (CAMCO). Facing wartime rationing, Wong contructed bamboo gliders for troop transport, likely drawing on Chow's studies regarding the abundant material. In 1940, Wong directed China's Bureau of Aeronautical Research, and in 1945 he assumed leadership of the Aviation Research Academy.

[58] "Tsoo Wong 王助: Aviation Pioneer," China Comes to MIT, http://chinacomestomit.org/wong-tsoo.

[59] Shatswell Ober, *The Story of Aeronautics at M.I.T., 1895–1960* (MIT: Department of Aeronautics and Astronautics, April 28, 1965).

[60] John Noble Wilford, "Charles S. Draper, Engineer; Guided Astronauts to Moon," *New York Times*, July 27, 1987, A16, https://www.nytimes.com/1987/07/27/obituaries/charles-s-draper-engineer-guided-astronauts-to-moon.html; Robert A. Duffy, "Dr. Charles S. Draper, Senior Scientist, The Charles Stark Draper Laboratory, Inc.," *Memorial Tributes: Volume 4*, National Academy of Engineering (Washington, DC: The National Academies Press, 1991), 57–62, https://www.nae.edu/MembersSection/MemberDirectory/29469.aspx; "History of Charles Stark 'Doc' Draper and the Draper Prize," National Academy of Engineering, https://www.nae.edu/8876/DocDraper.

Aeronautics in 1929 as a research assistant in Taylor's aeronautical laboratory.[61] In 1934, Hunsaker reported, "The Aeronautical Instrument Laboratory, under the immediate direction of Mr. Draper, has made notable contributions in this field during the last two years and is attracting wide attention."[62] With Hunsaker's support, in 1935 Draper became assistant professor and his Instrumentation Laboratory (IL) was offically established. In 1938 the Department of Physics finally awarded Draper an Sc.D. despite his dissertation's applied nature. By then, Draper had taken well over 95 MIT courses—as many as 170, his son later estimated. A potent force had been fully unleashed that would drive MIT aerospace contributions for the next three decades.[63] In 1965, President Johnson would award Draper the President's National Medal of Science "for [his] innumerable imaginative engineering achievements which met urgent National needs of instrumentation, control, and guidance in aeronautics and astronautics," in part through establishing and leading the world's foremost academic center in this field.[64] Under Draper's leadership, IL would make seminal contributions to aerospace research, teaching, and curriculum development.[65] Gavin thus entered aeronautical engineering at the dawn of an era birthing new fields and institutions led by bold, larger-than-life personalities—a pattern that would soon be echoed in the postwar defense buildup and space age.

In a then-common MIT arrangement, Gavin continued to live in his parents' apartment as a commuter student. The varsity (heavyweight) crew team,[66] of which he ultimately became captain and rowed in the leading stroke position,[67] allowed him to meet classmates from other departments across the then-decentralized university. This kindled lifelong friendships.[68]

Academically, Gavin progressed "fairly easily," having learned the importance of "doing your homework on time." Emphasis on basic requirements left few curricular choices. Gavin described himself as part of "the last class that even worried about biplanes."[69] He was among the last aircraft engineers to take stoichiometry, which he regarded as "the chemistry of the furnace."[70] The faculty was fascinating. Otto Koppen, who taught Gavin and his classmates to design aircraft as part of a larger technological system, was "designing a little airplane at his home on the side." A Swiss engineer stranded in America by war found surprisingly effective ways to teach structural engineering using examples from his nation's railways.[71] Decades later, Gavin remembered "very clearly Professor Joe Newell, who taught structures, and who was a very conservative man. And when he went to Washington, he took the train. And that made a great impression."[72]

War clouds overhung society: "Everybody had a feeling that there was a blow going to fall."[73] MIT was on a war footing.[74] This urgency, combined with America's rapid rise as a technological superpower, continually afforded unprecedented opportunities that Gavin was well-placed to seize. Even amid this overall buildup, Gavin's department faced particular demand for its wind tunnel research—which assumed double shifts—and its graduates.[75] In 1940, it initiated an Aeronautical Engineering Honors Course offering "students selected for superior ability"[76] a need-blind accelerated advanced degree.[77] On track to obtain an S.B. with honors in 1941, Gavin was still underage to transition from the Reserve Officer Training Corps (ROTC) to military assignment.[78] This fact, combined with his demonstrated talent, prompted MIT to invite him and classmate Rudolf Hensel to spend a fifth year as MIT's only two students, on full-tuition scholarships, completing a combined bachelor's and master's degree in aeronautical engineering.[79] Like future selectees, they were nominally under the supervision of Draper, who in reality was too busy "building lead-computing gunsights in the basement for the Navy" to meet with them more than once, but who would interact extensively with Gavin during and after Apollo. Working largely on their own as part of Draper's new hybrid model of students learning through hands-on research, Gavin and Hensel analyzed wave effects in the department's pride and joy: the closed return Wright Brothers Wind Tunnel, then the world's most advanced

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[61] Leslie, *The Cold War and American Science*, 80.

[62] Hunsaker, "School of Engineering—Aeronautical Engineering," *in President's Report* 70.1 (Cambridge, MA: MIT, October 1934), 69, https://libraries.mit.edu/archives/mithistory/presidents-reports/1934.pdf.

[63] Wildenberg, *Hot Spot of Invention*, 27, 29.

[64] "The President's National Medal of Science: Recipient Details—Charles S. Draper," Presented by President Johnson at a White House Ceremony in the East Room on February 8, 1965, National Science Foundation, https://www.nsf.gov/od/nms/recip_details.jsp?recip_id=109.

[65] Some of Draper's efforts were distilled in a classic textbook: Charles Stark Draper, Walter McKay, and Sidney Lees, *Instrument Engineering, Volume I: Methods for Describing the Situations of Instrument Engineering* (New York: McGraw-Hill, 1952); *Volume II: Methods for Associating Mathematical Solutions with Common Forms (1953)*; *Volume III: Applications of the Instrument Engineering Method (1955)*.

[66] "Regatta on Charles Is Swept by MIT: Tech Freshmen Make the Best Showing," *New York Times*, April 24, 1938, 71.

[67] Lincoln A. Werden, "Harvard Varsity Crew First in Race, With MIT Second and Princeton Third," *New York Times*, May 5, 1940, 89; Robert F. Kelley, "MIT Developing Fast Eight," *New York Times*, April 15, 1939, 13.

[68] Gavin lunched and socialized between classes with other commuting students at their "5:15 Club," which "served a great purpose." MIT Interview, 2007. His other activities included serving as secretary-treasurer of the sophomore class, and membership in the National Rifle Association and the leadership-advising Osiris Society. "MIT Officers Chosen," *New York Times*, May 1, 1939, 23.

[69] 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.

[70] Gavin kept a quotation from the February 1937 *Scientific American* in his files: "Days of laborious computation by trained mathematicians are no longer necessary at MIT. A new one ton machine with many complicated levers and gears will, in a single action, solve nine simultaneous equations with nine unknowns."

[71] In a rare elective, a Princeton professor explained the Revolutionary War "and how we nearly lost it." MIT Interview, 2007.

[72] Gavin, "The Lunar Module Design and the Apollo Program," annual Lester D. Gardner Lecture, Aeronautics and Astronautics 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.

[73] MIT Interview, 2007.

[74] "Report of the President to Members of the Corporation," *President's Report* 78.1 (Cambridge, MA: MIT, October 1942), 5–29.

[75] Deborah Douglas, "MIT and War," in Kaiser, ed., *Becoming MIT*, 87.

[76] Hunsaker, "Aeronautical Engineering—School of Engineering," *President's Report* 75.1 (Cambridge, MA: MIT, October 1939), 87.

[77] Further context: Harry M. Goodwin, "The Graduate School at M.I.T.," *The Technology Review* 42.5 (March 1940): 197–98.

[78] "Area Man Plays Key Role in Apollo Moon Landings," *News-Review* (Exeter, NH), May 6, 1970, 14.

[79] The competitive selection process mandated "honor" grades throughout fourth year and "at least two months' industrial employment satisfactory to the department." Letter from Richard H. Smith, Daniel Guggenheim Aeronautical Laboratory, MIT, to Mr. J.G. Gavin, Jr., 1992 Commonwealth Avenue, Brighton, MA, June 26, 1940. Gavin made the grades, and did summer work at Pratt & Whitney.

setup of its kind with a 10-by-7.5 foot test section,[80] which had just commenced full-time operations in January 1940.[81] Here Gavin enjoyed constant access to MIT's first large-scale advanced aerodynamics research facility, a national center operating around-the-clock to schedule wartime design testing for Grumman and other aircraft manufacturers.[82] Gavin and Hensel presented and published their findings professionally.[83]

In addition to many other responsibilities during his transformative career, and while continuing to oversee his laboratory, Gavin's advisor Draper would later head the Department of Aeronautics and Astronautics (later informally abbreviated "AeroAstro") (1951–68).[84] It was so-renamed, at Draper's behest, in January 1959:[85] "In recent years, as the potentialities of rockets and other spacecraft have become plainer, the department has become increasingly concerned with space," Draper explained. "The airplane is here to stay for a long time, and we will continue to regard aeronautics as fundamental. But the sky, or speaking more precisely, the air, is no longer the limit … MIT must educate men who are prepared not only to design and build the craft that we conceive of today but to engineer new types of flight vehicles which at this time we can only imagine."[86]

On December 7, 1941, Gavin and Hensel were working in Gavin's parents' apartment. Mid-afternoon, his father interrupted: "You'd better come listen to the radio—Pearl Harbor has been attacked."[87] Despite earlier thoughts about applying to the Naval Academy, Gavin had taken the Army ROTC path to MIT. He would likely have been assigned to the Army engineers. However, his fifth year at MIT proved to be a turning point. He met naval officer classmates, back for advanced education after a decade in the fleet, among the 600 Navy and Army officers MIT then trained in aviation engineering (primarily structures and engines).[88] Some of them, led by fellow aeronautics major Thomas Connolly, recruited Gavin for the Navy and made sure that he received the proper application papers.[89] This launched another lifelong friendship: Connolly, who would ultimately help oversee development of Grumman's F-14 fighter and retire as a three-star admiral and Deputy Chief of Naval Operations, also kept in touch to pursue his conviction that the Navy should have a role in space.[90]

After completing a thesis on "Aerodynamic Damping of an Aerofoil Oscillating in Pitch," Gavin earned a combined S.B./S.M. with honors in 1942[91] as one of the first pair of students to do so.[92] He graduated in Walker Memorial Hall with blackout curtains drawn—German submarines then threatened America's East Coast.[93] At commencement, Compton declared, "our success in this war may very possibly depend in a large degree on the wisdom and efficiency with which the professional manpower of this country is handled and trained," particularly specialists in "'strategic' technological professions." He foresaw "an unprecedented era of opportunity in the post-war period for men trained as you have in the technological professions."[94] Gavin's early career reflected that very reality.

In parallel, MIT had emerged from World War II as America's largest nonindustrial defense contractor. It would maintain this position throughout the Cold War, often by a three-fold margin.[95] In the fifteen years following Sputnik's 1957 launch, MIT's faculty would triple.[96] Cold War federal funding for programs supporting Apollo and other MIT aerospace- and defense-related research and development would skyrocket. In addition to Draper's IL, the Department of Aeronautical Engineering would soon boast three other world-class facilities: the Gas Turbine Laboratory, the Aeroelastic and Structures Laboratory, and the Naval Supersonic Laboratory.

For much of the interwar, World War II, and Cold War eras, MIT affiliates would shape U.S. policy at the highest levels concerning aerospace and other technical areas. President Franklin Roosevelt put Compton in charge of his Federal Science Advisory Board. Compton's deputy, Vannevar Bush, architected World War II-era science-government partnership, advised Roosevelt on science, and envisioned a postwar path in *Science: The Endless Frontier*.

Lee Alvin DuBridge, founding director of MIT Radiation Laboratory (1940–46)—center of wartime radar development and a precursor to MIT's Lincoln Laboratory—subsequently served as Science Advisor to Truman (1952–53), Eisenhower (1953–55), and Nixon (1969–70). Among DuBridge's "Rad Lab" recruits was Isidor Isaac Rabi, who in 1952 became a member of the Office of Defense Mobilization's Science Advisory Committee (SAC) that Truman established the previous year, then its chairman (1956–57). Eleven days after Sputnik's October 4, 1957 launch, Eisenhower met with SAC. Rabi recommended that Eisenhower designate a trusted science advisor to provide more formal, timely technical advice; James Killian, Jr. that the advisor be supported by a committee.

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[80] George Dawson, "Tech Makes Tornado in 'Tin Can'—Local Scientists Build Huge Wind Tunnel to Test Airplanes Under Violent Storm Conditions," *Boston Sunday Post*, August 28, 1938; "400-Mile Winds in Tech's New Tunnel," *Boston Sunday Globe*, June 12, 1938; "The Wright Brothers Wind Tunnel," Dedicated as a Memorial to the Methods of Controlled Experiment Consistently Applied by the Wright Brothers in Their Historic Conquest of the Air," MIT, Cambridge, MA, September 12, 1938; Remarks by President Karl T. Compton at the Dedication of the Wright Brothers Wind Tunnel, September 12, 1938; Hunsaker, J.R. Markham, and H. Peters, MIT, "The Wright Brothers Wind Tunnel," draft of paper for Institute of the Aeronautical Sciences, January Meeting, 1939; John R. Markham, "The M.I.T.-Wright Brothers Wind Tunnel and its Operating Equipment," *SAE Journal* 49.3 (September 1941): 380–81; Ober, "The Wright Brothers Memorial Wind Tunnel: A Fragment of History of Aeronautical Engineering at MIT," March 15, 1963.

[81] Hunsaker, "Aeronautical Engineering—School of Engineering," *President's Report* 77.1 (Cambridge, MA: MIT, October 1941), 80. It was recently dismantled to make room for a new wind tunnel of the same name, which "will be the largest, most advanced academic wind tunnel in the country." "Building 17/Wright Brothers Wind Tunnel Renovation," MIT AeroAstro, https://aeroastro.mit.edu/about/building-17wright-brothers-wind-tunnel-renovation.

[82] Leslie, *The Cold War and American Science*, 82–83.

[83] Gavin and R.W. Hensel, "Elliptic Tunnel-Wall Corrections on Drag and Stall," *Journal of the Aeronautical Sciences* 9.14 (December 1942): 533–37. Paper presented at the Aerodynamics Session, Tenth Annual Meeting, Institute of the Aeronautical Sciences, New York, NY, January 30, 1942.

[84] From the News Service, MIT, For Release in Morning Papers of April 4, 1951; Clark and Feron, "A Century of Aerospace Education at MIT," 39; "A Brief History of MIT Aeronautics and Astronautics," MIT AeroAstro, http://aeroastro.mit.edu/about-aeroastro/brief-history. Gavin later said with admiration, "Some of the work on gyros was considered impossible … until he did it." MIT Interview, 2007. Draper continued to lead IL simultaneously.

[85] Ober, *The Story of Aeronautics at M.I.T.*, 22–23.

[86] From the Office of Public Relations, MIT, For Release to Morning Papers of January 5, 1959.

[87] MIT Interview, 2007.

[88] Clark and Feron, "A Century of Aerospace Education at MIT," 36. Ober, *The Story of Aeronautics at M.I.T.*, 46–48 details these and other wartime special programs.

[89] Connolly earned a B.S. in Gavin's class with a co-authored thesis on "Influence of Cylinder Injection on the Tendency to Detonate." MIT, "Graduation Exercises, Class of 1942: Doctor's and Master's Degrees," 26.

[90] MIT Interview, 2007.

[91] MIT, "Graduation Exercises, Class of 1942: Doctor's and Master's Degrees," 18. Gavin was a member of the Tau Beta Pi and Sigma Xi honor societies.

[92] Hunsaker, "Aeronautical Engineering—School of Engineering," *President's Report* 78.1 (Cambridge, MA: MIT, October 1942), 85.

[93] MIT Interview, 2007.

[94] "Nation's Fate Seen Resting on Specialists: Dr. Compton Speaks at Exercises of Tech Graduate Students," *Boston Herald*, May 29, 1942.

[95] Leslie, *The Cold War and American Science*, 14.

[96] David Warsh, "The Odd Couple: Harvard and MIT's Curious Relationship," *Boston Globe Magazine* (December 1, 1991): 19.

Accordingly, on November 21, 1957, Eisenhower upgraded SAC to the President's Science Advisory Committee (PSAC) and appointed Killian to lead it as Special Assistant for Science and Technology (1957–59). The first Presidential Science Advisor, Killian also remains unsurpassed in his association with, and service to, MIT.[97] From 1948–59, Killian succeeded Compton as MIT's 10th president; on leave for the last two years focused on advising Eisenhower. He oversaw PSAC's creation, then presided over its successful promotion of two major responses to Sputnik: national curricular reforms in science and technology and NASA's establishment. Killian also served as inaugural chair of the President's Foreign Intelligence Advisory Board (1956–63). After advising three presidents, he would spend the rest of his career in Cambridge.[98] Such MIT leadership, combined with America's rise and technology's evolution, created the perfect conditions for Gavin to launch a government-focused aerospace engineering career.

3. Aerospace achievements and their MIT roots

Following degrees from MIT and four years as a jet fighter project officer in the Navy's Bureau of Aeronautics, Gavin spent his entire career with Grumman. His 44 years in its employ included 39 in positions of rapidly increasing management responsibility. Gavin started in the lower engineering ranks as a design engineer in 1946 and concluded with nine years as Grumman's President and Chief Operating Officer (COO), retiring from management in 1985 and consulting through 1990. Many of Gavin's most important efforts at Grumman directly involved his organizational and personal associations with MIT. A number of Gavin's Grumman colleagues had their own MIT connections,[99] starting with founder Leroy Grumman, who had studied aeronautical engineering there after receiving an engineering degree from Cornell in 1916.[100] As Gavin helped plot a spaceward path for Grumman, "Tech" was developing its own core competencies to support such leading aerospace programs as Apollo, and educating many of the field's foremost future figures, from astronauts to administrators.

The bold moonlanding mission President Kennedy announced on May 25, 1961 brought Grumman, Gavin, and MIT the opportunity of a lifetime. It was during a decade as Project Apollo's 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

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[97] Killian began with a bachelor's degree (1926) and concluded as chairman of the MIT Corporation (1959–71). He spent much of the 1930s editing MIT's alumni magazine (*Technology Review*) and helping to establish MIT's press. In 1939, he became Compton's executive assistant and codirector of MIT's wartime operations, including nationally-critical military research and development.

[98] MIT affiliates' scientific service was often prescient and prevailing, but not unfailingly so. Kennedy's initially-selected Science Advisor, Jerome Weisner (1961–64), shared Killian's long, top-level MIT association but not his persuasive approach. Weisner worked at MIT's Rad Lab (1942–45), then as a faculty member at MIT's Research Laboratory of Electronics (1946–61). Weisner opposed many military developments, questioned the value of manned spaceflight, and vehemently opposed Lunar Orbit Rendezvous—and with it, the very raison d'être of Grumman's Lunar Module. Years later, Weisner acknowledged that he quietly ceased his opposition because it was delaying Apollo, Kennedy's signature initiative. Shortly before his assassination, Kennedy decided to replace Weisner with Princeton's Donald Hornig; Johnson implemented the change. Weisner returned to MIT as Dean of the School of Science, becoming MIT's Provost in 1966, and president from 1971–80. After a second tour of service by DuBridge, Edward E. David, Jr. (S.M. 1947, Sc.D. 1950) served as science advisor to Nixon and Director of the White House Office of Science and Technology Policy (OSTP) (1970–73) but resigned disappointed that Nixon opposed his advice and disbanded OSTP. He had advocated for a supersonic transport plane and criticized NASA for excessive reliance on the Space Shuttle, Nixon's signature space effort. David was elected to the MIT Corporation in 1974 and became a Life Member. Another major figure, Frank Press, MIT Earth and Planetary Sciences Department head (1965–76), served on PSAC under Kennedy and Johnson, and on the National Science Board under Nixon. From 1977–81, he was Carter's Science Advisor and Director of a restored OSTP. President Ford had successfully solicited advice (of a committee led by Killian) and legislation (The National Science and Technology Policy Organization and Priorities Act of 1976) that resurrected OSTP. Under George H.W. Bush, the office was transformed into the President's Council of Advisors on Science and Technology (PCAST). MIT affiliates continue to play key roles, with President Emeritus Charles Vest serving as president of the National Academy of Engineering (2007–13), with its 154 MIT-connected members. James R. Killian, Jr., *The Education of a College President: A Memoir* (Cambridge, MA: MIT Press, 1985); Killian, *Sputnik, Scientists, and Eisenhower: A Memoir of the First Special Assistant to the President for Science and Technology* (Cambridge, MA: MIT Press, 1977), 16–99, 242–64; Zuoyue Wang, *In Sputnik's Shadow: The President's Science Advisory Committee and Cold War America* (New Brunswick, NJ: Rutgers University Press, 2009); David Z. Beckler, "The Precarious Life of Science in the White House," *Daedalus* 103.3 (Sumer 1974): 118; David Kaiser, ed., *Becoming MIT: Moments of Decision*, 1–10; William F. Causey, *John Houbolt: The Unsung Hero of the Apollo Moon Landings* (West Lafayette, IN: Purdue University Press, 2020), 239–75; Sam Roberts, "Edward E. David Jr., Who Elevated Science Under Nixon, Dies at 92," *New York Times*, February 28, 2017, https://www.nytimes.com/2017/02/28/science/edward-david-dead-science-adviser-to-nixon.html; Michaela Jarvis, "Frank Press, MIT Geophysicist and U.S. Science Adviser, Dies at 95," *MIT News*, February 7, 2020, https://news.mit.edu/2020/frank-press-geophysicist-science-adviser-dies-0207; James J. Duderstadt and Paul E. Gray, "Dr. Charles M. Vest, President Emeritus, National Academy of Engineering," *Memorial Tributes: National Academy of Engineering*, Volume 18 (Washington, DC: National Academies Press, 2014), 334–39, https://www.nae.edu/File.aspx?id=190308.

[99] Michael Ciminera, *The Aircraft Designers: A Grumman Historical Perspective* (Reston, VA: AIAA, 2013), 1, 31, 67, 116, 167, 212, 215. In 1939, following an introduction from her mentor Amelia Earhart, Grumman hired Isabel Ebel (S.B. 1932), the first woman to receive an aeronautical engineering degree. She worked on several aircraft, primarily the XF5F-1 fighter interceptor. One of just two women studying aeronautical engineering among MIT's 3,000 male and 30 female students, she had been unable to find full-time employment in the field. Ebel's initial struggle echoed that of early African-American aero engineers such as Oswald Williams, Jr., who was likewise ultimately welcomed by Grumman. "80th Anniversary of First MIT Woman Aero SB," *AeroAstro eNews* June 2012, http://web.mit.edu/aeroastro/news/enews/june12/index.html#ebel; Deborah G. Douglas, with the assistance of Amy E. Foster, Alan D. Meyer, and Lucy B. Young, *American Women and Flight since 1940* (Lexington, KY: University Press of Kentucky, 2004), 38–39.

[100] Yet another historic intersection turbocharged Grumman's ascent. After receiving America's first aeronautics degree, an M.A. from Columbia, in 1910, Loening had worked for Orville Wright and other industry and government employers before starting his own Navy-focused aviation company in 1919. The Naval Aircraft Factory in Philadelphia began license-producing Loening monoplanes under the newly-employed Grumman. In 1920, Loening hired the precocious engineer as his production manager. Amid financial challenges and widespread industry consolidation, in 1928 Loening accepted a buyout from Wright Aircraft's chairman of the board and merger with his Keystone Aircraft Corporation of Bristol, PA. Retiring to his beloved research, an exhausted Loening proudly watched Grumman and several top associates establish their own company in Baldwin, NY on January 2, 1930. "Leroy R. Grumman (1895–1982), Founder of Grumman Aircraft Company," *Newsday* (Long Island), https://huntingtonny.gov/filestorage/13747/99540/16499/Leroy_R._Grumman.pdf; Loening, *Our Wings Grow Faster*, 104–05, 172; Ken Speiser and Larry Feliu, *"Ready When Needed"—From Floats to Jets: Grumman's First 25 Years* (Bethpage, NY: Grumman History Center, 2013).

Aldrin to the moon's surface on July 20, 1969;[101] and ten of their successors in five of six successful landings through 1972. From Grumman's initial efforts in 1961 through Apollo's conclusion in 1972, Gavin led the team: "Full authority for directing Grumman personnel assigned to the LEM [later renamed 'LM'][102] 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."[103]

3.1. *Preparing for Apollo in Bethpage*

Upon graduation in 1942, Gavin entered the Naval Reserve as an engineering officer with the rank of Lieutenant. He spent four years in Washington, DC, posted at the Fighter Design Branch of the Naval Bureau of Aeronautics,[104] then in wooden buildings on the National Mall roughly where the Vietnam Veterans Memorial stands today.[105] In the Bureau, Gavin "met several very competent mentors." Branch head Commander Jack Pearson made him the unit's expert in a nascent field: jet engines. Gavin "met very interesting people": Orville Wright, aircraft engine experts from Westinghouse and Pratt & Whitney, and British jet engine pioneers including British Royal Air Force engineer Air Commodore Sir Frank Whittle.[106]

Thanks to his recent MIT studies, Gavin enjoyed insights unthinkable to the "old salts" surrounding him. Most importantly, even though he had not heard so much as a "whisper" about jet engines at MIT, he viewed them as a revolutionary technology that would unlock tremendous potential by increasing aircraft flight speeds by hundreds of miles per hour. Some of the more senior naval aviation specialists dismissed the new development's promise, affording Gavin unusual opportunity and responsibility for his age:[107] "Things were moving very fast in those days, and it was very stimulating to be part of it."[108]

Involved in the early work on jet aircraft designs and propulsion, Gavin served as the project officer on the Navy's first jet airplane, the McDonnell FH-1 *Phantom*. When severe weather trapped his boss in Washington, Lt. Senior Grade Gavin—almost the most junior officer present—ran a mockup board on McDonnell's second jet fighter for the Navy, the F2H *Banshee*.[109] He later received a commendation for his contributions to the Navy's jet fighter program.

The Navy offered Gavin a chance to stay and undergo flight training, but he "decided I wanted to build something." Piloting flying machines was a path not taken for Gavin. "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.' While I had the urge [to get and maintain a pilot's license and fly], by Apollo 11 I was accustomed to saying [to astronauts], 'It's OK to go fly it.' That's something you don't say without thinking about it."[110]

In 1946, having selected from among offers from leading aircraft manufacturers such as Boeing and McDonnell, Gavin left the Navy to join what was then the Grumman Aircraft Engineering Corporation in Bethpage, New York.[111] Yet again, he met "wonderful mentors." He learned how to draft aircraft designs immediately. As "the only one in the company who'd really had any experience with jet engines," Gavin joined Preliminary Design, headed by Dick Hutton—"an extraordinary natural engineer." He worked with various departments on the Engineering Floor, and developed new connections, some of whom "became lifelong friends." Conditions were primitive by today's standards, with electric adding machines replacing slide rules a significant transition. But Gavin was fascinated: "You could work on three projects in ten years, which you don't do anymore."[112]

In this capacity, Gavin was deeply involved in the development of naval aircraft, a core Grumman product. Twenty-six-year-old Gavin started as a design engineer (1946–48) on Grumman's first jet fighter, the XF9F *Panther*, before becoming an engineer with the Preliminary Design Group (1948–50). He worked on various other aircraft projects, including Grumman's second and third jet fighters: Grumman's first swept-wing fighter, the F9F-6 *Cougar* (Project Engineer, 1950–52), and supersonic F11F-1 *Tiger* (Co-Project Engineer, 1952–56). During 1956–57, Gavin served as Grumman's Chief Experimental Project Engineer.[113] "The project engineer in those days did what today is called program management," Gavin explained. "He worried about everything, including the budget."[114]

From 1957–62, as Grumman's Chief Space and Missile Engineer, Gavin "planned and directed all spacecraft and missile technical activity for Grumman …. "[115] In this capacity, Gavin led Grumman's 1958 bid on Project Mercury, in which it tied with McDonnell given their "substantially equal technical and managerial excellence," but was rendered runner up over concerns—in the words of NASA's Administrator—that it

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[101] The first two moonwalkers could have been fellow alumni; Armstrong was accepted at MIT, but elected to attend Purdue on a naval aviation scholarship. James R. Hansen, *First Man: The Life of Neil A. Armstrong* (New York, NY: Simon & Schuster, 2012), 29. Eugene Cernan saw MIT as *"the premier engineering school," but took Armstrong's path for financial reasons. Eugene Cernan and Don Davis, The Last Man on the Moon: Astronaut Eugene Cernan and America's Race in Space* (New York, NY: St. Martin's Griffin, 1999), 22–24.

[102] Grumman's spacecraft was termed the Lunar Excursion Module (LEM) until 1967. At Office of Manned Space Flight head George Mueller's direction, to eliminate any "frivolous connotation" of gallivanting, NASA's Public Affairs Office dropped the middle word and initial. Thomas J. Kelly, *Moon Lander: How We Developed the Apollo Lunar Module* (Washington, DC: Smithsonian Books, 2001), 267; Chris Kraft, *Flight: My Life in Mission Control* (New York, NY: Penguin, 2002), 276.

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

[104] "Grumman Will Build New Space & Missile Engineering Center," *Grumman Plane News* 21.10 (May 25, 1962), 3.

[105] Kraft, *Flight*, 49, 52.

[106] MIT Interview, 2007.

[107] Author's many discussions with Gavin over many years.

[108] MIT Interview, 2007.

[109] Ibid.

[110] Ibid. For the LM, Gavin recalls, "We did a lot of simulator work. I crashed it myself a number of times." "Automatic vs. Manual," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/automatic-manual.htm.

[111] "'41: Joseph G. Gavin, Jr.," *The Technology Review* (April 1965): 72.

[112] MIT Interview, 2007. Gavin elaborates: "I had been involved with about four different programs before I got to Apollo … that breadth of experience doesn't exist in the same age group today." "Management Issues," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/management.htm.

[113] Neil A. Armstrong, "Joseph G. Gavin, Jr., 1920–2010, Elected in 1974," *Memorial Tributes, National Academy of Engineering of the United States of America*, Volume 15 (Washington, DC: National Academies Press, 2011), 111–14, https://www.nap.edu/read/13160/chapter/21.

[114] MIT Interview, 2007.

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

"was heavily loaded with Navy projects in the conceptual stage."[116] Gavin served simultaneously as President of the American Rocket Society's New York Section.[117]

In May 1962, Gavin was "assigned the responsibility of centralizing space and missile efforts in the new [$5 million Grumman Space & Missile Center] building."[118] This heading of a new organizational entity as Space Programs Director[119] capped his early leadership in Grumman's development of multifarious aerospace products. Prominent among them: NASA's contracting Grumman in October 1960 to produce its first space telescope, the Orbiting Astronomical Observatory (OAO).[120] OAO was then America's largest scientific satellite. Four were launched and two operated successfully for five years each by NASA's Goddard Space Flight Center, yielding major discoveries.[121] This followed soon after Grumman's first NASA contribution: building the launch adapter and canister for *Echo*, NASA's first communications satellite.[122]

Gavin's early career traced Grumman's preparation to compete for an opportunity unprecedented in both its own history and in the annals of engineering: serving as the prime contractor for the LM. Experience in developing the OAO, together with the canister for the *Echo* balloon, gave the aircraft-centric company the experience to compete credibly, if unsuccessfully, to participate in the Mercury program. Meanwhile, in developing the new S-2E *Tracker* anti-submarine warfare aircraft, Grumman developed systems engineering capability. "We won that competition, and that airplane was one that had a lot of my fingerprints on it," Gavin later recalled. Collectively, these Grumman achievements "provided a reasonable chance to bid on some of the space programs."[123] Specifically, they "qualified us to do something about Apollo."[124]

3.2. Researching and educating for Apollo in Cambridge

As Gavin learned on the job managing aerospace projects, and Grumman assembled an exceptional array of talent under him, MIT had been educating many key NASA astronauts and administrators who would soon become directly involved in developing and employing his firm's equipment. They benefitted from the efforts of Draper and his AeroAstro colleagues to chart a modern aerospace curriculum and distill a coherent four-year course of study.[125]

Forty-one astronauts, crewing more than one-third of piloted American space flights logging more than 10,000 hours in space to date, have been "Tech" students—the most of any single institution, including each of the U.S. military academies.[126] Among them, five Apollo astronauts studied in the land-, sea-, and space-grant university's Aero-Astro Department, including four of the twelve who walked on the moon: Buzz Aldrin (Sc.D. '63),[127] Charles Duke (S.M. '64), Edward Mitchell (Sc.D. '64), and David Scott (S.M. and E.A.A. '62). While he never reached the lunar surface, Rusty Schweickart (S.B. '56 and S.M. '63) was LM Pilot on the preparatory Apollo 9 mission giving the vehicle its first crewed flight test in Earth orbit.[128]

AeroAstro also educated several NASA administrators. Having been mentored by Draper and Robert Seamans, Robert Chilton (S.B./S.M. '49) proceeded to play an important role in Apollo, ultimately becoming Chief of the Houston, Texas-based Manned Spacecraft Center (MSC)'s Guidance and Control Division (1970–73).[129] If there is a single individual who embodies the MIT-NASA-Apollo triad, however, it is

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[116] Loyd S. Swenson, Jr., James. M. Grimwood, and Charles C. Alexander, *This New Ocean: A History of Project Mercury* (Washington, DC: NASA, 1966), 137; Kraft, *Flight*, 72–73. Grumman operations research nevertheless contributed to understanding of Mercury recovery requirements. Ibid., 159; "Company President Clint Towl Announces LEM Appointments," *Grumman Plane News* 21.21 (November 30, 1962), 8.

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

[118] "Grumman Will Build New Space & Missile Engineering Center," *Grumman Plane News* 21.10 (May 25, 1962), 3.

[119] "Space Center on Schedule," *Grumman Plane News* 21.17 (September 28, 1962), 1.

[120] "Eye on the Universe," Grumman Press Release OA72-1, August 10, 1972 and accompanying "Program History"; "Orbiting Astronomical Observatory," NASA Presentation (Bethpage, NY: GAEC, May 3, 1968); Walter H. Scott, Jr., OAO Program Manager, GAEC, "The Engineering Design of the Orbiting Astronomical Observatory," *The Observatory Generation of Satellites*, NASA SP-30, Session II of a Special Astronautics Symposium Held at the Franklin Institute, Philadelphia, PA, December 27, 1962, during the 129th Meeting of the American Association for the Advancement of Science, Prepared by Goddard Space Flight Center, Greenbelt, MD (Washington, DC: NASA Office of Scientific and Technical Information, March 1963), 53–62.

[121] Gavin, "A Review of Two Past Space Programs: The OAO (Orbiting Astronomical Observatory) and Apollo Lunar Module with Emphasis on Technical Successes and Problems," Tokyo, November 1977; Gavin, "The Orbiting Astronomical Observatory," *TRW Space Log* (Winter 1969–70): 2–9.

[122] Joshua Stoff, *Building Moonships: The Grumman Lunar Module* (San Francisco, CA: Arcadia Publishing, 2004), 16.

[123] Rebecca Wright, interview of Gavin, 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.]

[124] MIT Interview, 2007.

[125] Clark and Feron, "A Century of Aerospace Education at MIT," 41. During 1963–65, MIT added laboratories for Space Propulsion, Manned Vehicles, and Flight Transportation; as well as a Center for Space Research. Litant, "A Centennial Album," 39.

[126] The late MIT alumnus and NASA Orion safety manager Stacey Nakamura compiled a running list of all MIT alumni astronauts through the most recent U. S. astronaut class, 2017. The resulting 41 names are published in "Rocket Roll Call: All the MIT Alumni Astronauts," *Slice of MIT*, 23 June 2017, https://alum.mit.edu/slice/rocket-roll-call-all-mit-alumni-astronauts.

[127] Aldrin Sr. had received a similar Sc.D. in 1928. Ober, *The Story of Aeronautics at M.I.T.,* 44.

[128] Ian Waitz, "Perspective is Everything," in Waitz and Litant, *AeroAstro* 6, iii.

[129] "Coming from middle Tennessee," Chilton recalled, "I never heard of MIT … but I heard about it from [all] of these Yankee boys I got thrown in with in the service, and they were talking about this is the best school and all that sort of stuff." Summer Chick Bergen, interview of Robert G. Chilton, NASA Oral History Transcript, Houston, TX, April 5, 1999, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/ChiltonRG/RGC_4-5-99.pdf.

Seamans himself.[130] He received a degree in aeronautical engineering from MIT the same year as Gavin (S.B. '42).[131] During his doctoral studies, he helped Draper "develop tracking systems that enabled Navy ships to target enemy planes."[132] From 1941–55, he began his career in both academics and aviation/missile project management. In AeroAstro, he rose from Instructor (1941–45), to Assistant Professor (1945–50), to Associate Professor (1950–55). He simultaneously served as a Project Engineer in IL; a Chief Engineer of *Project Meteor*; and a Director of MIT's Flight Control Laboratory. Draper groomed Seamans to succeed him, but Seamans had broader ambitions.[133] From 1955–60, Seamans managed airborne systems and missile development at Radio Corporation of America (RCA)—which Gavin would later supervise as a LM subcontractor. Meanwhile (1948–58), Seamans served on NACA technical committees. In 1960, he joined NASA full-time as an Associate Administrator. In 1965, Seamans became NASA Deputy, and later Acting, Administrator. He was widely credited with leading Apollo's technical development while Administrator James Webb focused on managing relations with Congress and other Washington stakeholders. Having provided critical leadership for Apollo's first five years, in January 1968 Seamans returned to MIT as a visiting professor, while remaining a consultant to NASA's Administrator. In July 1968, MIT's AeroAstro Department named him the Jerome Clarke Hunsaker Professor, through the Hunsaker Professor Chair established in 1954.[134] Subsequently, Seamans served as Secretary of the Air Force (1969–73), building on previous advising for the service; president of the National Academy of Engineering (1973–74); and founding administrator of the Energy Research and Development Administration. Seamans returned to MIT in 1977, becoming dean of its School of Engineering the following year (1978–81) before retiring from MIT in 1984. Meanwhile (1977–84), he was the Henry Luce Professor of Environment and Public Policy at MIT, and an AeroAstro senior lecturer.[135] Like Gavin, he also served as a director of the MIT IL's post-July 1, 1973 successor, Charles Stark Draper Laboratory, Inc.[136]

In just two of many examples, Gavin's project management and Seaman's interdisciplinary leadership brought strengths to Project Apollo that its Soviet counterpart never enjoyed; MIT was at the heart of it all. Programmatic pressures generated some tensions, but NASA resolved them without the bureaucratic warfare that hamstrung Soviet efforts.[137]

3.3. Guiding Apollo with MIT

From 1961–75, with substantial contributions from AeroAstro's Instrumentation, Guidance, and Control Division,[138] MIT's Instrumentation Laboratory developed and supported Apollo's computerized onboard guidance, navigation, control (GN&C) system.[139] This would be "the first time human lives were intrinsically interlocked with the proper operation of a digital computer's hardware and software …. "[140] The resulting Apollo Guidance Computer (AGC) was the IL's "first fully programmable digital computer."[141] This critical role yielded the world's first all-digital fly-by-wire control system and unprecedented

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[130] Louis Padulo, "Celebrating the Life of Robert C. Seamans, Jr.," in Waitz and Litant, *AeroAstro* 6, 19–28; "Robert C. Seamans, Jr., NASA Deputy Administrator, December 21, 1965–January 5, 1968," NASA, https://history.nasa.gov/Biographies/seamans.html; Walter D. Sohier, Addison M. Rothrock, and Eugene M. Emme, "Robert C. Seamans, Jr, Oral History Interview—JFK #1, 03/27/1964," Washington, DC, March 27, 1964; https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/SeamansRC/seamansrc.htm; "Robert C. Seamans Jr., 89—Former dean of the School of Engineering; Worked on Apollo Program at NASA," *MIT News*, June 30, 2008, http://news.mit.edu/2008/obit-seamans-0630.

[131] Thesis: "Design and Test of Vibration Pickup with Improved Performance by Hydrodynamic Effects." MIT, "Graduation Exercises, Class of 1942: Doctor's and Master's Degrees," 27.

[132] Dennis Hevesi, "R. C. Seamans Jr., NASA Figure, Dies at 89," *New York Times*, July 3, 2008, https://www.nytimes.com/2008/07/03/science/space/03seamans.html.

[133] Wildenberg, *Hot Spot of Invention*, 115, 226–27.

[134] Office of Public Relations, MIT, For Immediate Release, "Dr. Seamans—Minta Martin Lecture," March 6, 1969; Ober, *The Story of Aeronautics at M.I.T.*, 24.

[135] Sheila E. Widnall, "Dr. Robert C. Seamans, Jr., 1918–2008, Professor Emeritus in Aeronautics and Astronautics, Massachusetts Institute of Technology," *Memorial Tributes: National Academy of Engineering, Volume 13* (Washington, DC: National Academies Press, 2010), 258–63, https://www.nae.edu/28583/Dr-Robert-C-Seamans-Jr.

[136] For background, see Christopher Morgan, with Joseph O'Connor and David Hoag, *Draper at 25: Innovation for the 21*st *Century* (Cambridge, MA: The Charles Stark Draper Laboratory, Inc., 1998), https://wehackthemoon.com/sites/default/files/2019-03/25thAnniversaryBook.pdf. [<Wehackthemoon.com> is an official Draper document compilation website, developed with considerable time and resources over several years.] Draper's laboratory has designed and developed the boost guidance system for every U.S. submarine-launched ballistic missile ever deployed. It parlayed its AGC expertise into helping NASA develop the first digital fly-by-wire control systems for aircraft. From Apollo onward, it has provided guidance and control capabilities for all American crewed space programs. Kathleen Granchelli, "80 Years of Draper Lab Innovation Began with MIT's Instrumentation Lab," *AeroAstro Magazine 2013–14*, 52.

[137] Andrew S. Erickson, "Revisiting the U.S.-Soviet Space Race: Comparing Two Systems in Their Competition to Land a Man on the Moon," *Acta Astronautica* 148 (July 2018): 376–84.

[138] W.E. VanderVelde, "A Major Contribution: Department of Aeronautics and Astronautics," MIT, October 23, 1975.

[139] Much GN&C gear (e.g., the Inertial Measurement Unit and sextant) was not computers. Ian Waitz, "MIT, Draper Lab, and Apollo," ii; and John Tylko, "MIT and Navigating the Path to the Moon," 1–6; in Waitz and Litant, eds., *AeroAstro* 6; Hoag, *The History of Apollo On-Board Guidance, Navigation, and Control* P-357 (Cambridge, MA: Charles Stark Draper Laboratory, Inc., October 1977); "Background on the Guidance & Navigation System for the Apollo Spacecraft" (MIT Instrumentation Laboratory), https://wehackthemoon.com/sites/default/files/2019-03/Moon%20Show%20%281%29.pdf; Robert Lee Hotz, "Apollo 11 Had a Hidden Hero: Software," *Wall Street Journal*, July 14, 2019, https://www.wsj.com/articles/apollo-11-had-a-hidden-hero-software-11563153001.

[140] Eldon C. Hall, "From the Farm to Pioneering with Digital Control Computers: An Autobiography," *IEEE Annals of the History of Computing* (2000): 30.

[141] Bryan Hayes, "Moonshot Computing," *American Scientist*, https://www.americanscientist.org/article/moonshot-computing. Code and other details: "Virtual AGC — AGS — LVDC — Gemini," https://www.ibiblio.org/apollo/index.html.

use of a digital autopilot, which involved Gavin and his team through their incorporation and use in the LM.[142]

Exploiting the 1960s' advent of integrated circuits, the IL's creation represented a major advancement over 1950s behemoths like the MIT-designed *Whirlwind* computer, even as it preceded the 1970s microprocessors that would subsequently enable desktop computers far more powerful than anything used in, or for, Apollo spacecraft.[143] Hunsaker and MIT aeronautical engineering professors such as Koppen and Joseph Bickwell played a critical role in conceptualizing the *Whirlwind* computer. Originally a Navy project, it shifted to MIT management under Air Force sponsorship. Eventually based at Lincoln Laboratory, *Whirlwind* supported that MIT institution's first project following its 1951 establishment: the Semi-Automatic Ground Environment (SAGE) air-defense system, the first major real-time computing system. Two of the most important early real-time computing systems thus started at MIT.[144] A key connection between them was Margaret Hamilton, the first programmer and first woman IL hired for Apollo. Having worked on SAGE from 1961–63, she brought insights from her pathbreaking experiences there. In 1965, Hamilton became director of IL's Software Engineering Division, lead programmer, and ultimately one of three colleagues to coin and conceptualize "software engineering." She balanced these responsibilities with caring for her daughter Lauren, often taking her to work on evenings and weekends. In 1968, Lauren's keyboard play revealed that selecting the prelaunch program while in mid-course would blank all AGC displays and require a manual restart. Subsequently, Hamilton succeeded in making anomalous software status events generate a coded display. The "1202" alarm code thus generated by temporary computer overload during the Apollo 11 LM's final moonward descent provided sufficient information to prevent a last-minute abort of the historic landing.[145]

In his foreword to the multi-thousand-page report *MIT's Role in Project Apollo*, Draper encapsulated: "Man's rush into spaceflight during the 1960s demanded fertile imagination, bold pragmatism, and creative extensions of existing technologies in a myriad of fields. The achievements in guidance and control for space navigation … are second to none for their critical importance in the success of this nation's manned lunar-landing program … The great achievement of this Laboratory was to supply the design for the primary hardware and software necessary to solve the Apollo guidance, navigation and control problem. It is to the credit of the entire team that this hardware and software have performed so dependably throughout the Apollo program."[146] Three major subcontractors built IL hardware: Raytheon's Sudbury Division (the AGC itself), GM's AC Spark Plug Divison (inertial instruments), and Kollsman Instrument Company (optics).[147] As with key elements of the LM, while highly reliable designs would typically require redundancy—an approach that Grumman advocated for the AGC guidance system and its landing capability—the mass and volume for redundancy was simply not available. This left exhaustive testing for unfailing reliability the only solution.[148]

Shouldering immense personal and group responsibility but unbound by contemporary bureaucratic constraints, aerospace pathfinders like Draper, Gavin, and their teams advanced at a scope and speed unmatchable today.[149] Then AeroAstro head, Draper recalled: "I had contacts with NASA because of relationships started during past projects of various kinds. It was at a meeting granted to us by Administrator James E. Webb, [Deputy] Administrators Robert C. Seamans and Dr. Hugh L. Dryden, that I told of the laboratory's ability to take on design for conception, theory, design, overseeing of construction and consultation during realization of navigation, for guidance and control of

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[142] Donald C. Fraser, Founding Editor-in-Chief, *Journal of Guidance and Control*, "My Memory of Dick Battin," *Journal of Guidance Control and Dynamics*, special issue dedicated to the memory of Dr. Richard H. Battin, https://wehackthemoon.com/sites/default/files/2019-04/Battin%20Editorial.pdf; Hall, *Journey to the Moon: The History of the Apollo Guidance Computer* (Reston, VA: AIAA, 1996), 274. By contrast, the *Polaris* missile system, with its pre-integrated circuit "cordwood" construction and Digital-Differential-Analyzer (DDA) architecture, was far from fully programmable. Related discussion: "Human-Machine Interface," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/interface.htm.

[143] Hall, *Journey to the Moon*, xix.

[144] Killian, *The Education of a College President*, 36–41.

[145] Warning that an astronaut might select "prelaunch" inadvertently, Hamilton advocated encoding an alert, but was stymied by an institutional culture professing pilot immunity to such operator error. Soon afterward, on Apollo 8's earthward return, James Lovell fumbled some keystrokes exactly as Hamilton had warned, requiring several hours' intense tech support from Hamilton and her colleagues to resolve. Alice George, "Margaret Hamilton Led the NASA Software Team That Landed Astronauts on the Moon," *Smithsonian Magazine*, March 14, 2019, https://www.smithsonianmag.com/smithsonian-institution/margaret-hamilton-led-nasa-software-team-landed-astronauts-moon-180971575/; "Margaret Hamilton: Computer Scientist & Software Engineer," https://wehackthemoon.com/bios/margaret-hamilton; "Margaret Hamilton's introduction," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/hamilton-intro.htm; Margaret H. Hamilton, "The Apollo On-Board Flight Software," March 2019, https://wehackthemoon.com/sites/default/files/2019-03/mhh.software.final-2_0.pdf. For a firsthand account of how Hamilton and her colleagues Dan Lickly and Fred Martin handled the December 25, 1968 problem in real time, see Martin, "Fred Martin's introduction," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/martin-intro.htm.

[146] James A. Hand, ed., *MIT's Role in Project Apollo*, *Volume I: Project Management, Systems Development, Abstracts and Bibliography* (Cambridge, MA: MIT Charles Stark Draper Laboratory, October 1971), iii, https://web.mit.edu/digitalapollo/Documents/Chapter5/mitroleapollovi.pdf. See also: *Volume II: Optical, Radar, and Candidate Subsystems*, March 1972, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19750020038.pdf; Hall, *Volume III: Computer Subsystem*, August 1972, https://www.yumpu.com/en/document/read/17738451/mits-role-in-project-apollo-vol-iii-ibiblio; Madeline S. Johnson with David R. Giller, *Volume V: The Software Effort*, March 1971, https://www.ibiblio.org/apollo/hrst/archive/1137.pdf.

[147] Nancy Atkinson, *Eight Years to the Moon: The History of the Apollo Missions* (Salem, MA: Page Street Publishing, 2019), 51.

[148] Joseph F. Shea to GAEC, "Abort Guidance System," Letter PO-3-64-45, February 11, 1964, JSC History Office LOC 064-22; Hall, *Journey to the Moon*, 113–15.

[149] Former NASA Apollo Primary GN&C System Project Manager Cline Fraiser: "I don't remember dealing with … a lawyer … in my 9 or 10 years on the project. And the management from the people that worked for me, all the way up… to Webb were either reasonably good, or very good technical people. And the same thing was true with the people we dealt with at, of course, at the Instrumentation Lab; they were all technical. At General Motors, the program manager … reported to another guy who reported to the head of the entire division. Both of those two were MIT engineering graduates; one a Ph.D. So you had people who you could actually talk to about what was going on, and they knew enough so that they had confidence in their decision making." "Management Issues," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/management.htm.

vehicles associated with the Apollo manned flight to the moon …. "[150] Draper promised to run the program, and vowed it would succeed. "After some discussion," Draper recalled, "the Laboratory received a contract that was to last for more than ten years."[151] Awarded on August 9, 1961 for a first year of $4 million[152] and subsequent installments toward an originally projected $50 million total,[153] among Apollo's prime contracts it was the first, the only no-bid, and the only one with a university.[154] Seamans, Draper's former student, fully appreciated the latter's superb qualifications for the job even as he quashed one proposal that would never fly:[155] on November 21 Draper wrote "to formally volunteer for service as a crew member on the Apollo mission to the moon … if I am willing to hang my life on our equipment, the whole project will surely have the strongest possible motivation."[156] So significant was the AGC contract for IL that it "dramatically shifted the Laboratory's balance of military and civilian commitments, from virtually all military in 1961 to about half and half by 1965, but without reducing the size or influence of the military programs."[157]

Well before NASA's awarding of the contract, several lab employees had envisioned and proposed to the Air Force and NASA a Sputnik-inspired photographic flyby of Mars with a notional probe that pioneered many of the GN&C techniques that Apollo required:[158] a space sextant, corrected-trajectory guidance, and "core rope" memory.[159] Together with its ongoing development of GN&C for the Navy's increasingly-capable submarine-launched ballistic missile systems, beginning with *Polaris*, this both helped position IL as uniquely capable of furnishing the computing needed for Apollo and directly informed its subsequent efforts. "Much of that [Mars probe] computer design was quickly and gladly repurposed into Apollo," IL hardware/software engineer Hugh Blair-Smith recalls. "That was, I believe, a factor in Webb's thinking."[160] A related advantage: U.S. officials initially worried that the USSR might compromise any radio signals guiding Apollo; i.e., from the reconnaissance ship that loitered off Cape Canaveral during launches.[161] This made Draper's championing of jam-proof inertial guidance irresistible.[162]

NASA soon approved Draper's management of a trailblazing program that no other organization in the world could then produce. The Mars probe breadboard model (Mod 1B) then under construction and testing became a basic baseline.[163] MIT's computer was the first to use integrated circuits; tens of thousands were used to guide Apollo.[164] During 1962–67, more than a million semiconductor chips were purchased to support the Apollo spacecraft and LM. In late 1967, NASA allocated IL an additional $31 million for operations from January 1,

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[150] Charles Stark Draper, "Aircraft and Spacecraft Navigation," presented as the 17th Lester D. Gardner Lecture, Department of Aeronautics and Astronautics, MIT, October 25, 1978, 47–48. For discussion of the exact date of the meeting, see Don Eyles, *Sunburst and Luminary: An Apollo Memoir* (Boston, MA: Fort Point Press, 2018), 329–30.

[151] Draper, "Aircraft and Spacecraft Navigation," 47–48. Draper's pitch reportedly occurred in the living room of Webb's Georgetown mansion over after-dinner drinks before a radiant fire. Draper had known Webb since wartime, when the latter had worked at Sperry Gyroscope. Eyles, *Sunburst and Luminary*, 34.

[152] NASA Headquarters, Immediate Release, "The National Aeronautics and Space Administration today selected the Massachusetts Institute of Technology to develop the guidance-navigation system for the Project Apollo spacecraft," August 9, 1961.

[153] Hoag, "Apollo Guidance and Navigation Program at MIT Instrumentation Lab: Material in Support of a $31 Million 30 Month Proposal to NASA to Continue Work from 1 Jan. '68 to 30 June '70," Memo dated October 4, 1967, 1.

[154] David A. Mindell, *Digital Apollo: Human and Machine in Spaceflight* (Cambridge, MA: MIT Press, 2011), 107.

[155] Robert C. Seamans, Jr., *Aiming at Targets: The Autobiography of Robert C. Seamans, Jr.* (Washington, DC: NASA, 1996), 81–82, https://history.nasa.gov/SP-4106.pdf.

[156] Draper, letter to Dr. Robert C. Seamans, Jr., NASA Headquarters, November 21, 1961, https://wehackthemoon.com/sites/default/files/2019-06/CSD-0319_DrDraper_AstronautLetter.pdf.

[157] Leslie, *The Cold War and American Science*, 94.

[158] 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; Eyles, *Sunburst and Luminary*, 123–24.

[159] Hoag, "The History of Apollo Onboard Guidance, Navigation, and Control," *Journal of Guidance, Control, and Dynamics* 6.1 (January–February 1983): 5; MIT Instrumentation Laboratory, in collaboration with AVCO Corporation, MIT Lincoln Laboratory, and Reaction Motors Division, Thiokol Chemical Corporation, *A Recoverable Interplanetary Space Probe* (Cambridge, MA: July 1959), volumes 1–4.

[160] Correspondence with author, April 30, 2020; Hugh Blair-Smith, *Left Brains for the Right Stuff: Computers, Space, and History* (East Bridgewater, MA: SDP Publishing, 2015), 93–112.

[161] Kraft, *Flight*, 133–35, 318.

[162] George T. Schmidt, AESS V.P. Technical Operations, "Inside Apollo: Heroes, Rules and Lessons Learned in the Guidance, Navigation and Control (GNC) System Development," 7, https://wehackthemoon.com/sites/default/files/2019-08/Inside%20Apollo%202019%20Title%20Location%20Fixed_0_0.pdf.

[163] Hall, Journey to the Moon, 47. For the final design of the Mars probe computer that was repurposed for Apollo, see R.L. Alonso, Blair-Smith, and A.L. Hopkins, "Some Aspects of the Logical Design of a Control Computer: A Case Study," IEEE Transactions on Electronic Computers (December 1963): 687–97.

[164] In 1963, Draper's lab "consumed 60% of the integrated circuit production in the United States." Unless otherwise specified, quotes and data for this paragraph are from John Tylko, "MIT and Navigating the Path to the Moon," in Waitz and Litant, eds., *AeroAstro* 6, 1–6. Organizational charts—May 1962: https://wehackthemoon.com/sites/default/files/2019-06/MIT%20Apollo%201962%20Org%20Chart.pdf; February 1, 1969: https://wehackthemoon.com/sites/default/files/2019-06/Apollo%20Org%20Charts%201969%20%28with%20Index%29_0.pdf; February 1, 1972: https://wehackthemoon.com/sites/default/files/2019-06/Apollo%20Project%20Org%20Charts%201972.pdf.

1968 through June 30, 1970.[165] Hardware activity peaked at 600 MIT staff-years in 1965, towards an eventual total of 2,000; software at 350 in 1968, towards a total of 1,400 through Apollo 11 (1969).[166]

At its zenith in 1969, IL's $54 million budget equalled those of MIT's other laboratories (save Lincoln's) combined.[167] Draper's lab supported 790 employees, 196 industrial residents, and 398 student affiliates, including 25 AeroAstro graduate students (half the department's enrollment). Twenty-five of AeroAstro's 80 courses concerned IL specialties, many were taught by IL staff. Thirty-six S.M. and Sc.D. dissertations were based on IL research.[168] IL had hundreds of resident corporate engineers on the payroll. Among IL's hundreds of alumni, dozens managed nearby contractors' laboratories.[169]

Like Grumman, Draper's Lab was a relatively flat, flexible organization that only issued a formal flowchart at NASA's insistence.[170] Draper maintained overall leadership throughout, but was often busy traveling and communicating with other organizations, leaving Ralph Ragan primarily responsible for daily operations. Three outstanding technical talents loosely led three subdisciplines: brilliant Richard Battin stood at the pinnacle of developing needed "processing-efficient GN&C algorithms."[171] Intellectually formidable Halcombe Laning was the genius of computer science specialties: the priority-driven multitasking operating system whose flexibility would save the Apollo 11 landing, and the development of an "interpretive" language to provide a form of assembly-level source coding much friendlier to Battin's GN&C engineers.[172] Farmboy-turned-*Polaris* computer designer Eldon Hall led electronics design and integration in his Digital Development Group.[173] Norman Sears likewise played a major role as Director of Systems Development.[174]

The MIT Apollo Program's rapid progress was greatly facilitated by Battin, who became its Director of Mission Development.[175] Like Draper, Battin exemplifies the cutting-edge talent, commitment to both research and teaching, innovative organization, and national networks centered on MIT; which together placed the institution at the core of America's Apollo-era aerospace achievements.[176] Battin regarded "The Apollo voyage to the moon" as "a new and exciting plateau in the ancient art of navigation."[177] A legendary AeroAstro professor, he taught three future Apollo moonwalkers. Aldrin, who received an Sc.D. from MIT in 1963, took Battin's first astrodynamics class in 1961. "His course in astronautical guidance was a real eye-opener to all of us in the Air Force who were undergoing an advanced program at MIT," Aldrin recalled.[178] "Dr. Rendezvous" Aldrin "became one of Battin's star students" and "a fixture at the Lab, working with [Battin's] Space Guidance Analysis Group members of the rendezous team."[179] The next year, students included future Apollo 15 Commander David Scott. In 1963, future Apollo 14 LM Pilot Edward Mitchell was a pupil. Apollo 16 LM Pilot Charles Duke achieved his S.M. in 1964 under the advisorship of Battin's colleague Laurence Young, Apollo Program Professor of Aeronautics and Astronautics.[180] They and their fellow astronauts regularly visited MIT, by then a well-established Apollo forum.[181]

Draper's Lab, which he ran as an "Athenian democracy where talent ruled," attracted intellectually-diverse creative thinkers and empowered them to solve problems as they thought best.[182] "Informal interdisciplinary exchanges" occurred constantly among staff, many of whom

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[165] Hoag, "Apollo Guidance and Navigation Program at MIT Instrumentation Lab: Material in Support of a $31 Million 30 Month Proposal to NASA to Continue Work from 1 Jan. '68 to 30 June '70," Memo dated October 4, 1967, 3.

[166] Hoag, "The History of Apollo Onboard Guidance, Navigation, and Control," *Journal of Guidance, Control, and Dynamics* 6.1 (January–February 1983): 10.

[167] Leslie, *The Cold War and American Science*, 77.

[168] Leslie, "'Time of Troubles' for the Special Laboratories," in Kaiser, ed., *Becoming MIT*, 134–35; Wildenberg, *Hot Spot of Invention*, 227.

[169] By 1965, IL "had spun off 27 companies, with 900 employees and total sales of $14 million." Leslie, *The Cold War and American Science*, 99.

[170] Eyles, *Sunburst and Luminary*, 75–76. For a chart effective February 1, 1969, see https://doneyles.com/LM/ORG/index.html.

[171] Philip D. Hattis, "How Doc Draper Became the Father of Inertial Guidance," Preprint AAS 18–121, 14, https://wehackthemoon.com/sites/default/files/2019-03/AAS%202018%20Doc%20Draper%20History%20Paper%20by%20Hattis.pdf.

[172] Blair-Smith, *Left Brains for the Right Stuff*, 100, 154, 160–62; Donald C. Fraser, "Dr. J. Halcombe Laning," *Memorial Tributes: Volume 22*, National Academy of Engineering (Washington, DC: The National Academies Press, 2019), https://www.nae.edu/29034/Dr-J-Halcombe-Laning.

[173] Philip D. Hattis, "How Doc Draper Became the Father of Inertial Guidance," Preprint AAS 18–121, 14; "Eldon Hall's introduction," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/hall-intro.htm.

[174] "Apollo: The Way it Was," Special Apollo Edition, *Draper Notes*, January 1973, 2.

[175] Fraser, "Richard H. Battin, 1925–2014, Elected in 1974," *Memorial Tributes: Volume 20*, National Academy of Engineering (Washington, DC: The National Academies Press, 2016), 30–39, https://www.nap.edu/read/23394/chapter/7#31.

[176] Richard Battin, "A Funny Thing Happened on the Way to the Moon," AeroAstro Department Lecture, January 22, 2009, https://www.youtube.com/watch?v=ieiEoTo8-XY.

[177] Battin, manuscript, untitled document, Draper Apollo folder, MIT Museum archives.

[178] J.M. Lawrence, "Richard H. Battin, 88; Worked on Apollo Missions," *Boston Globe*, February 23, 2014, https://www.bostonglobe.com/metro/2014/02/23/richard-battin-developed-and-led-design-guidance-navigation-and-control-systems-for-apollo-flights/vxP9iIEfKuKpR7eCfes4fO/story.html.

[179] Blair-Smith, *Left Brains for the Right Stuff*, 182.

[180] David L. Chandler, "To the Moon, By Way of MIT," *MIT News*, June 3, 2009, http://news.mit.edu/2009/apollo-tt0603.

[181] "Astronauts Briefed at MIT," *Christian Science Monitor*, December 3, 1962; "Noisy Welcome for Astronauts," *Christian Science Monitor*, December 4, 1962; "15 Astronauts Land at M.I.T. for Briefing," *Evening Globe* (Boston), October 24, 1963; "14 Astronauts at MIT Lab," *Record-American* (Boston), October 25, 1963.

[182] Eyles, *Sunburst and Luminary*, 34. Further background: http://sunburstandluminary.com/SLhome.html. Similar wording: Hall, *Journey to the Moon*, xxii; Wildenberg, *Hot Spot of Invention*, 141.

held MIT degrees, or were taking courses concurrently.[183] In one example of dynamic cross-pollination, a student-staffer derived and applied algorithms from Battin's course and *Astronautical Guidance* textbook.[184] Improvisation reigned: during Apollo 13 Hall and Jerry Gilmore used their car trunks through a cold Boston night as thermal test chambers for the AGC and Inertial Measurement Unit (IMU), respectively, to verify that the sensitive equipment could survive four days in the unheated Command Module (CM) prior to its being powered back up.[185] The principles were similar to those in Grumman's hardware shop, where even the lowest-ranking worker's opinion was heard; in MIT's pioneering software culture, they played out still more fluidly, sometimes at the intersection of science and art. The most dramatic and famous example is Don Eyles, whom IL LM descent software engineer Allan Klumpp (S.B. 1955, S.M. 1959)[186] selected as a 22-year-old to write code for the final LM landing sequence and program the LM computer. As one moonlanding history puts it, "From never having written a line of code in July 1966, by July 1969 he had written arguably the most important stretch of code in the most important computer in the world."[187] Eyles not only prepared for this critical role at a time when no manuals or training were available, but also several times under uncertain conditions and severe time pressure furnished judgments and inputs that saved landings from being aborted.

One potentially mission-compromising challenge emerged from "an instability in the control of the descent engine [which] … could cause severe vibrations in the lander."[188] "The problem was first noticed by Clint Tillman in LM simulations at Grumman after Apollo 12," Eyles recalls. "Tillman then reviewed flight data from Apollo 11 and 12 and saw that it also had occurred in flight. The problem was an apparent instability in the control of the engine throttle ... the throttle was not controlled smoothly but made wild excursions up and down, which when plotted had the shape of 'castellations'," patterns resembling the evenly-notched structures of castle turrets.[189] "The problem was caused by TRW [a LM subcontractor, formerly Thompson Ramo Wooldridge, Inc.] making a big improvement in the responsiveness of the descent engine, which would have called for a compensation of ~0.1 s, but nobody told MIT about it," Blair-Smith explains.[190] The shock of seeing "castellations" was a strange case of a problem being correctly detected and understood long after a partial but sufficient solution had been implemented for only slightly related reasons. Well before Apollo 11, at a time when nobody had ever heard of "castellations," Eyles was working to address a "ringing" phenomenon. He "found by changing one number related to the time delay between an engine throttle command and the ensuing response, he could dampen out this vibration. He never got official clearance to change that number but he went ahead anyway."[191] This despite the fact that Klumpp, his mathematically precise superior, in the leadup to the mission had questioned why Eyles picked 0.2 s of delay compensation instead of matching the 0.3 s engine response time modelled in the simulator. "It's just like medicine," Eyles reasoned, "don't give it more compensation than it needs." Klumpp, to his credit, "felt it was important to nurture self-reliance, to let co-workers' decisions on small matters prevail …. " Accordingly, he "let Don's decision stand, at least until he might reconsider it independently." Both Apollo 11 and 12 used Eyles' 0.2 s compensation. Subsequent analysis in 1970 by Klumpp and his Grumman counterpart Tillman revealed that "had [Klumpp] insisted on Don coding the optimum 0.3 s compensation, Neil Armstrong and Buzz Aldrin, about a minute before touchdown, would have been propelled like a yoyo by a throttle oscillating between full thrust and idle. They would probably have aborted the first lunar landing."[192] Eyles's sensible approach to a falsely modeled system thus fortuitously saved Apollo from the true

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[183] Blair-Smith, *Left Brains for the Right Stuff*, 213.

[184] Kurth Krause, *My 36 Years in Space: An Astronautical Engineer's Journey through the Triumphs and Tragedies of America's Space Programs* (2nd ed., 2019), 27–46.

[185] Blair-Smith, *Left Brains for the Right Stuff*, 324., 324.

[186] "Rocket Man: How Allan Klumpp '53 Helped the Nation Take One Giant Leap into Space," *Claremont McKenna College News*, October 3, 2013, https://www.cmc.edu/news/rocket-man-how-allan-klumpp-53-helped-the-nation-take-one-giant-leap-into-space; "Allan Klumpp, Luminary Software Designer," https://wehackthemoon.com/bios/allan-klumpp; Sandra Johnson, interview of Allan R. Klumpp, NASA Headquarters Oral History Project, Philadelphia, PA, May 9-10, 2018, https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NASA_HQ/Administrators/KlumppAR/KlumppAR_5-9-18.htm and https://historycollection.jsc.nasa.gov/JSCHistoryPortal/history/oral_histories/NASA_HQ/Administrators/KlumppAR/KlumppAR_5-10-18.htm.

[187] Charles Fishman, *One Giant Leap: The Impossible Mission That Flew Us to the Moon* (New York: Simon and Schuster, 2019), 177.

[188] Tom Fitzgibbon, "The Apollo Project," 15, https://wehackthemoon.com/sites/default/files/2019-03/Tom%20Fitzgibbon%20Apollo%20Story_0.pdf.

[189] Correspondence with author, May 7, 2020. See also "Figure 12: Throttle Excursions During Apollo 12 P66," Don Eyles, "Tales from the Lunar Module Guidance Computer," amended version of paper AAS 04–064, presented at the 27th annual Guidance and Control Conference of the American Astronautical Society (AAS), Breckenridge, CO, February 6, 2004, https://doneyles.com/LM/Tales.html.

[190] Correspondence with author, April 30, 2020.

[191] Fitzgibbon, "The Apollo Project," 15.

[192] Allan R. Klumpp, "LM Descent Engine Throttle Incident," in "Apollo Vignettes," 1985. See also Eyles, "Tales from the Lunar Module Guidance Computer."

problem, which nobody understood until three missions had been run with it.[193]

During Apollo 14, by contrast, then-27-year-old Eyles was formally charged with saving the mission from being terminated in response to a spurious signal from a contaminated abort button. A second failure after Apollo 13 might well have doomed future missions. Having written the signal-monitoring code, Eyles had less than 2 h to compose an alternative procedure to fix the problem. He crafted a 61-keystroke workaround to make his code ignore the faulty button, which the astronauts implemented successfully with minutes to spare.[194] In yet another example of Draper's "Athenian democracy," Eyles was permitted to decline a congratulatory meeting with President Nixon on anti-war principles; to speak his mind in a dramatic interview with *Rolling Stone* as a countercultural icon; and to become the Lab's most prominent member, with the exception of Draper himself.[195] Gavin's team boasted nobody as colorful, outspoken, or famous as Eyles, but similarly empowered youthful innovators within the more conservative hardware engineering and production culture. In emerging fields where no veterans yet existed and few established credentials mattered, both organizations proved adept at spotting and hiring the most intelligent, energetic, determined innovators and giving them considerable latitude to work as they thought best. In numerous instances, youth and inexperience yielded creative solutions that more formal training and direction might have inhibited.

Just as he thanked Grumman after Apollo 13 in 1970, in 1973 Nixon extended to Draper's Lab "my congratulations and the thanks of the American people for a job well done." He declared, "The knowledge gained through the Institute's contributions to the Apollo program will benefit humanity for centuries to come."[196]

3.4. Guidance implementation: challenges and resolution

Apollo management imperatives soon pushed IL into excruciatingly close collaboration with North American's team for the CM and Gavin's Grumman team for the LM. Gavin explains challenges facing his team, the product of Apollo's last major contract: "it took us about two years to firm up the final design, because at the time we were in the competition we did not know, for example, the details of the MIT-designed guidance system. And then, of course, there were requirements like a backup guidance system and so on."[197]

Each company's vehicle had a GN&C system controlling it. Per previous military contracts, North American and Grumman expected to define and design their own unique GN&C systems for MIT to build separately. Gavin recalled the determination that distinguished Grumman: "[W]e were going to design and build a LM that had our name on [it], and we would argue every inch of the way … we quickly became known as difficult."[198] Like Draper, Battin, and many other colleagues, IL's Apollo Technical Director David Hoag had MIT degrees, and from the same department as Gavin (S.B. '46, S.M. '50).[199] He accorded Gavin's group grudging respect: "it seemed to me I could walk all over [North American]. I had to tell them the questions they should be asking

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[193] Understanding how IL culture achieved success under such demanding conditions requires differentiating among the technical specifications of hardware (e.g., the descent propulsion system/DPS), physical facts (e.g., TRW's engine response time), and the functionality of the software controlling the hardware. Nobody had ever built a throttleable rocket engine before; who was to say that the compensation delay built into the controlling software should be equal to the specified response time? Unencumbered by existing rules of thumb, Eyles was free to research the interaction from first principles. Knowing how long the software took to get to the point where the delay should be applied, Eyles understood how to determine empirically the amount of the delay. He saw that for this engine with its 0.3 s response time, compensation delay of 0.2 s was optimal. Eyles's taking the initiative to tune the compensation to simplify its response to the mathematical model of the DPS engine, his resulting debate with Klumpp, and Klumpp's letting him do things his way and accept any consequences—which all occurred years before anybody was aware of "castellations" in DPS throttling—exemplified Draper's "Athenian democracy" in action. In correspondence with the author on October 11, 2020, Blair-Smith reconstructed the process chronologically: 1967—At a time when MIT is necessarily depending on a math model of a DPS which had a response time of 0.3 seconds, Klumpp and Eyles work out how to program control of throttle changes in the DPS. As Eyles writes on p. 238 of his book, he tries making no compensation and finds that the throttle setting is overshooting and then getting bounced up and down before converging on its intended setting. Then he tries a compensation of 0.1 seconds and finds that this "ringing" is better but still present. A compensation of 0.2 seconds makes the "ringing" disappear—*in the math model of an engine with 0.3 seconds response*. I'll guess that one reason Klumpp let that go is that he probably couldn't be sure that the amount of compensation time should be equal to the engine's stated response time, and that Eyles's empirical finding was at least equally valid. 1967 or 1968(?)—TRW makes a major improvement in the DPS engine, lowering its response time from 0.3 to 0.075 seconds, *but they don't document that change in any place where MIT can see it.* 1967 or 1968(?)—TRW delivers the improved DPS engine to NASA and Grumman, but all the software testing, at MIT and at NASA's lab in Houston, is still using the old 0.3-second math model: no castellations, not even a ripple. Kennedy Space Center and Grumman are the only places on Earth where system testing encounters the true DPS engine behavior, so the castellation must be happening then, but there's so much new stuff to be tested that nobody looks for it. The DPS throttle operates a little bumpily there but, because Eyles's 0.2-second compensation happens to mitigate it, it doesn't cause a real problem. 1969—Apollo 11 and 12 perform successful moonlanding missions, and whatever bumpiness in DPS throttling may have been observed by the crew is probably attributed to the roughness you expect with early trials of any vehicle. The castellation is happening, still mitigated by Eyles's 0.2 compensation, and it could be seen in the down telemetry, but there's much more to see there, so nobody scrutinizes the DPS throttling. 1970—Apollo 13's crew uses the DPS to power their return to Earth. There probably wasn't much variable throttling going on, so the castellation (still mitigated by Eyles's number) must have been infrequent and so escaped notice. 1970—In the intensified scrutiny of all spacecraft systems subsequent to Apollo 13, Clint Tillman spots the castellation at Grumman, tries to pin it on simulation faults, but then finds it recorded in the telemetry from Apollo 12. *That's when the action item gets written.* Also, Klumpp learns about the severity of an "IMU bob" phenomenon, which had been gradually growing with newer LMs that had been made more flexible to save weight; he sees that it makes the castellation worse. I believe Norm Sears recalls that IMU bob was extremely difficult to model, and to figure how to compensate for it. 1970—Reinspection of telemetry from Apollo 12 (I believe) finally reveals the unreported improvement of the DPS engine. Eyles's tuning of the compensation, performed three years earlier in response to an obsolete math model, is finally seen to have mitigated the castellation well enough, even with the IMU bob complicating things.

[194] Eyles, *Sunburst and Luminary*, 255–61; Alan Shepard and Deke Slayton with Jay Barbree, *Moon Shot: The Inside Story of America's Apollo Moon Landings* (New York: Open Road Integrated Media, 2011), 304–13.

[195] Eyles, *Sunburst and Luminary*, 261–67; Timothy Crouse, "Don Eyles: Extra! Weird-Looking Freak Saves Apollo 14!" *Rolling Stone*, March 18, 1971, https://www.rollingstone.com/politics/politics-news/don-eyles-extra-weird-looking-freak-saves-apollo-14-40737/.

[196] President Richard Nixon, The White House, letter to Dr. Jerome B. Wiesner, President, MIT, January 9, 1973.

[197] Gavin, Gardner Lecture.

[198] Mindell, *Digital Apollo*, 113.

[199] Norman Sears, "David G. Hoag, 1925–2015—Elected in 1979," Memorial Tributes: Volume 21 (Washington, DC: National Academies Press, 2017), 157–61, https://www.nae.edu/File.aspx?id=192032; "Dave Hoag's introduction," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/hoag-intro.htm.

me, and what did they really need to know so they could design their side to the guidance side." Grumman, by contrast, "had a sharp team. I met my mettle there … I enjoyed that part of the stuff, but it was a struggle."[200] In January 1963, NASA resolved the impasse, stipulating that the CM and LM would each contain virtually identical hardware versions of a common MIT-designed guidance computer with functionally-tailored software.[201]

In fall 1963, North American invited Grumman and MIT into a joint task force.[202] Dubbed "Project Christmas Present" for the timing of its plan submission, the effort ensured badly-needed comprehensive schedule integration. As part of this effort, Grumman hosted and led mission planning, including an MIT contingent onsite.[203] One outgrowth was the Apollo Mission Planning Task Force in January 1964, which anticipated and addressed numerous contingencies—including the "LM lifeboat" mission that would save Apollo 13.[204] Driven in part by specific prompting from NASA's Chief of Apollo Data Priority Coordination, Howard "Bill" Tindall, Jr.,[205] who was charged with riding herd over Apollo software,[206] IL presciently developed and loaded software that would enable the LM autopilot "to push the heavy Command and Service Modules through the limber docking joint."[207]

Christopher Witt coordinated Grumman's GN&C activity with Apollo Spacecraft Program Manager Joseph Shea at NASA's MSC, Wernher von Braun's NASA Marshall Space Flight Center team in Huntsville, Alabama, and Draper's team at MIT. "At Grumman we did great analysis and developed detailed performance requirements," Witt recalled. "These were integrated with MIT's Instrumentation Lab for the Primary G&C System and our Abort Guidance Contractor TRW. John Miller of MIT and I developed the interface requirements and specifications between the Primary and Abort Guidance and Control Systems. While the physical equipment was being developed, I created the LM Flight Control Lab at Grumman. This allowed us to integrate, operate and validate performance of the two Guidance and Control Systems prior to installation and use on the LM to the Moon and return."[208]

In January 1964, a disagreement culminated between Grumman and IL concerning the reliability of the latter's GN&C reliability estimates. This was a fraught issue grounded in overlapping Apollo program roles: IL was responsible for developing Apollo GN&C systems, including those used in the LM; while Grumman felt responsible for ensuring the reliability of everything employed in its vehicle, including those vital systems. "I envied the MIT people that they could use integrated circuits. We spent thousands of hours penalized because of having to use discrete devices and communications gear … NASA insisted that we not use integrated circuits in so many other places, and we had so much trouble as a result of that." Gavin recalled "how the system was hooked up on a complete Lunar Module system test in Bethpage … the Draper people wanted dearly to run the test [at MIT]. And we … being responsible for the overall module, said … Our name is on that vehicle and we're going to run that test, and we did."[209]

Regarding overall reliability, using different data and calculations, the parties reached divergent conclusions: IL believed its systems met

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[200] Mindell, *Digital Apollo*, 113–14., 113–14.

[201] "LEM to Use Apollo Components, Subsystems," *Aviation Week & Space Technology*, January 14, 1963; Mindell, *Digital Apollo*, 114; "1963 October 18—Selection of Five Organizations for Apollo LEM Guidance and Navigation Equipment," www.astronautix.com/a/apollolm.html.

[202] They had already met in an organizational meeting at the MSC. "1963 February 27—Apollo Mission Planning Panel," www.astronautix.com/a/apollolm.html; Hall, *Journey to the Moon*, 78.

[203] Kelly, *Moon Lander*, 73–77.

[204] Ibid., 73–77.

[205] Most importantly: Memorandum to PA/Manager, Apollo Spacecraft Program, from EA/Director of Engineering and Development, "LM Propulsion of the LM/CSM Configuration as an SPS Backup Technique," EG-23-88-68-486, May 1, 1968, http://www.collectspace.com/resources/tindallgrams/1968_tindallgrams.pdf. This item references a dozen related memos. Handwritten annotations suggest significant circulation and follow-up. The following extensive-but-incomplete set of widely-acclaimed "Tindallgrams" memoranda documenting key technical decisions made for all unmanned and manned flights through Apollo 13 (1966–early 1970) contains many references to MIT's AGC efforts: https://wehackthemoon.com/sites/default/files/2019-03/tindallgrams02.pdf. Background: Atkinson, *Eight Years to the Moon*, 37-39; "Bill Tindall: Chief of Apollo Data Priority Coordination," https://wehackthemoon.com/bios/bill-tindall; "Meetings with Bill Tindall," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/tindall.htm.

[206] Apollo Spacecraft Program Office Manager George Low put Director of Flight Operations Christopher Columbus Kraft, Jr. in charge; Kraft assigned Tindall. Kraft, *Flight*, 276–77. See also Fishman, *One Giant Leap*, 135–59; Atkinson, *Eight Years to the Moon*, 109–10.

[207] Hoag, "The History of Apollo Onboard Guidance, Navigation, and Control," *Journal of Guidance, Control, and Dynamics* 6.1 (January–February 1983): 5. "No one had ever tested the docking collar between the LM and CM/SM on being able to survive the LM pushing the much heavier CM/SM combination. Someone, thankfully, had asked 'What if we had to do that' and software and been written and installed in the AGC." Schmidt, "Inside Apollo," 7. William Widnall (S.B. 1959, S.M. 1962, Electrical Engineering; Sc.D. 1967, AeroAstro) joined IL's Apollo Digital Simulation Group, which tested and debugged AGC software, then became Apollo Control and Flight Dynamics Division director supervising final design and software testing of the CM and LM guidance computers' digital autopilot programs (DAP). Widnall "became concerned that there was no backup capability if the Apollo spacecraft Service Module single main engine were to fail before establishing the return-to-earth trajectory. Could the Lunar Module be used to push the combined docked configuration? He explored adding a 'lifeboat mode' to the Lunar Module DAP software, to give it the ability to do attitude control of the docked configuration using thrust vector angle control of the LM descent propulsion engine. Using some of the new developments in optimal control theory he was able to develop the nonlinear optimal control law that made accurate control of this configuration feasible." Widnall subsequently served AeroAstro as Lecturer (1972–75) and Associate Professor (1978–85). In one of the most prominent examples of an MIT aerospace power couple to date, he is married to Sheila Widnall. "In Their Own Words: Bill Widnall on Digital Autopilot," https://wehackthemoon.com/people/bill-widnall-computer-science; "William Widnall, Director of the Apollo Control and Flight Dynamics Division," https://wehackthemoon.com/bios/william-widnall; "Widnall, William Soule," MIT Museum, https://webmuseum.mit.edu/detail.php?module.

[208] Christopher J. Witt, Guidance, Navigation & Control Development, in Ross Fleisig and Lois Lovisolo, eds., "Lunar Module Remembrances," AIAA 25th Anniversary of the First Manned Lunar Landing, Regional Conference, June 18, 1994, 40–41.

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

reasonable requirements; Grumman raised concerns. In keeping with NASA's merciless advance, Shea (who was wearing his MIT ring, having studied there; and would ultimately adjunct-teach AeroAstro courses, sharing an office with Seamans)[210] sat the parties down "to force a black-and-white conclusion as a result of this meeting." Lengthy presentations revealed that IL possessed data that Grumman lacked, making its estimates more accurate: the computer was not quite as accurate as IL insisted, but significantly more so than Grumman feared. Gavin gave full acknowledgement on behalf of his team.[211] Subsequently, Gavin recalled, to manage such integration challenges, NASA manager George Low "set up a series of meetings ... he would take his leadership and bring them to Grumman for a meeting. We would go over all proposed changes. The next day, that group would be out at North American, and somebody from Grumman would go with them. In two days, all of the pending changes throughout the spacecraft system would be settled right then. It was a very successful system."[212]

"We were right most of the time," Gavin reflected at MIT in 2001. "When we weren't right … it was very obvious and very humbling. We had many cases … of having to eat crow. Amazingly enough, I think we all stayed more or less friends over the years. I'm sorry that a couple of the key people aren't [still alive] to talk about these things: Joe Shea and George Low, for example."[213]

Likened to the Wright Flyer in revolutionary architecture, by Apollo's conclusion with the Apollo-Soyuz Test Project in 1975 the AGC was maxed out; mission accomplishment removed justification for upgrades.[214] AGC thus pioneered many technologies, but could not incorporate their consequent advances. As Apollo 15 Commmander and AeroAstro alumnus David Scott reflected separately, "Now, it seems unbelievable that we were able to do all we did with that old stuff."[215] Time healed any wounds. The unprecedented complications imposed by needing to use computers so extensively for GN&C gave the organizations common cause; MIT proved the only source for AGC success. To integrate efforts, IL held biweekly meetings "with Grumman on the Lunar Module guidance and navigation … between September 1964 and April 1966."[216]

Grumman and MIT subsequently collaborated with great effectiveness in supporting Apollo flight operations.[217] With a division of labor finally clarified, their commitment to similarly high standards made saving Apollo 13 a shared finest hour. Whereas Grumman had added additional consumables to power the LM as a lifeboat and tugboat of last resort, Draper's Lab had coded and uploaded software to make sure the pushing interface remained intact.[218] Ultimately, Gavin's positive professional associations clearly transcended temporary tension between Grumman and MIT in the crucible of Apollo. After Apollo 11, Gavin and Draper each received a NASA Public Service Award "For his outstanding contributions as a key leader of the government-industry team which made possible the exceptional success of the Apollo Program."[219] Following his onetime professor, for whom it was named, Gavin would became a member of the Draper Laboratory corporation in 1981, and served on its board of directors from 1982 through 1989. He also served on the Draper Prize Committee, designed to remedy the lack of a Nobel Prize in engineering.[220]

3.5. *Naval aircraft: LM lessons, MIT connections*

Rising to President and COO in 1976, Gavin resumed focus on Grumman's core business: naval aircraft. Of the roughly 130 aircraft on an American carrier then, 80% were Grumman aircraft.[221] Here again, MIT and AeroAstro linkages permeated his work. Gavin applied LM experience to build higher-quality prototypes that required less-expensive testing. One highlight was inking and implementing a major F-14 contract with Iran.[222] Initiated in 1968 and first flown in December 1970, the aptly-named F-14 "Tomcat" benefitted from the critical support of Gavin's old classmate—now Vice Admiral—Tom Connolly, who sacrificed his chance for a fourth star to ensure the program's inception and later managed it from the Pentagon side.[223] In 1972, the year Gavin became president of Grumman's aerospace subsidiary, the Shah of Iran wrote to the F-14 Program Coordinator in the office of the Chief of Naval Operations, stating that he wished to consider purchasing F-14s for the Imperial Iranian Air Force (IIAF) to replace aged F-4 *Phantoms*.[224] An experienced pilot himself, the Shah sought to counter high-altitude

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[210] Seamans, *Aiming at Targets*, 140; George E. Mueller, "Joseph F. Shea, 1926–1999—Elected in 1971," *Memorial Tributes: Volume 10* (Washington, DC: National Academies Press, 2002), https://www.nae.edu/188102/JOSEPH-FSHEA-19261999.

[211] Kelly, *Moon Lander*, 77–79.

[212] "Integration Issues," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/integration.htm. "Everything had to be frozen at some point. It was very difficult," Gavin explains. At Grumman, "we had a meeting every morning at 7:30, spent half an hour, and the leaders of all of the systems stood by and took the oath that they hadn't changed anything. And if they were going to change anything, they had to get the approval of everybody else, because it wasn't instantaneous. In that way, we finally beat it into a stable configuration." "Software Issues," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/software.htm.

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

[214] O'Brien, *The Apollo Guidance Computer*, 365–66.

[215] Hall, *Journey to the Moon*, 36.

[216] Hoag, "The History of Apollo On-Board Guidance, Navigation, and Control," September 1976, presented at the International Space Hall of Fame Dedication Conference, October 1976, 16.

[217] Kelly, *Moon Lander*, 79.

[218] Schmidt, "Inside Apollo," 7.

[219] Honor Awards Ceremony, NASA, October 2, 1969.

[220] Following anti-war protests, the process of separating Draper Laboratory from MIT began in 1969. Killian, *The Education of a College President*, 276–77.

[221] Bill Gunston, Grumman: *Sixty Years of Excellence* (New York, NY: Orion Books, 1988), 152.

[222] In Gavin's view, Grumman was the underdog in the competition because of U.S. politics regarding the congressional districts in which competing aircraft were built. Grumman impressed the Shah of Iran, himself a pilot, by having its test pilot perform extra maneuvers in front of the reviewing stand at the Farnborough Airshow and presenting him with a Grumman flight suit. Author's many discussions with Gavin over many years.

[223] Robert Mcg. Thomas, Jr., "Thomas Connolly, 86, Top-Gun Admiral, Dies," *New York Times*, June 9, 1996, http://www.nytimes.com/1996/06/09/us/thomas-connolly-86-top-gun-admiral-dies.html.

[224] Rear Admiral Paul T. Gilcrist, USN (Ret.), *Tomcat! The Grumman F-14 Story* (Atglen, PA: Schiffer Military/Aviation History, 1994), 46.

Soviet overflights then violating Iranian airspace. In July 1973, in an F-14 demonstration for the Shah at Andrews Air Force Base against the rival F-15, Grumman's team stole the show with dramatic maneuvers. The Shah appeared to have made up his mind.[225] That December, Iran ordered thirty F-14s; complete with the AIM-54 *Phoenix* missile, of which the F-15 lacked an equivalent.[226] The Navy delivered the first F-14 on January 24, 1977.[227] A total of 79 were delivered out of an ultimate order of eighty.

Gavin personally oversaw the preparation and dispatch of 2,000 Grumman employees and their families to a facility near IIAF Base Khatami, fifteen miles north of Isfahan. At Khatami, a Grumman/Navy team trained approximately eighty pilots and 40–50 radar intercept officers.[228] Iran's revolution of 1979 terminated the effort just as Gavin was arranging a site visit.[229] Gavin continued to believe in the qualities of the F-14, which had many champions: "It was the best. First squadron went to sea in 1975. In 2002, F-14E was still the best in service and was used in Afghanistan!"[230] It was finally retired from active service on September 22, 2006, thirty-two years after its first deployment.

Gavin led Grumman for nine years in his capstone position, from which he retired in 1985, then served as a consultant through 1990. Concluding highlights include Grumman's development of the experimental X-29 aircraft, which explored control laws and systems to degrees never previously assessed. This led directly to the F-16 and F-117's exploitation of relaxed static stability for significantly improved tactical aircraft performance.[231] At the close of his career, Gavin led 33,000 employees in ten operational divisions.[232] A study of Gavin and well over five hundred other Grummanites "involved in the evolution of some 74 aircraft, aircraft derivatives, demonstrators, and selected future designs" credited Gavin with embodying the majority of Grumman's distinctive traits: "versatility; leadership; creativity, curiosity, innovation" and "customer focus."[233]

In 1994, amid major post-Cold War defense industry consolidation, Grumman was acquired and merged with Northrop under the leadership of Kent Kresa. Kresa brought his own MIT associations to aerospace work through his retirement in 2003.[234] The new Northrop Grumman chairman and CEO had received S.B., S.M., and E.A.A. degrees from AeroAstro before working at Lincoln Laboratory from 1961–68.[235]

For much of the ensuing period, Northrop Grumman was led by another MIT alumnus, Wesley Bush, who received his S.B. and S.M. in electrical engineering. In 2011, he was named Chairman, President, and CEO.[236]

Kathy Warden became President and COO in January 2018. Bush continued as CEO and Chairman of the Board (COB) for a while longer. Warden remained President. He resigned as CEO in January 2019 when Warden was named CEO.[237] Bush maintained the role of chairman until his retirement from the company in July 2019 when Warden was named Chairman.[238]

As Gavin did decades before, Bush served on the executive committee of the Aerospace Industries Association's Board of Governors; including chairman in 2013.[239] Currently, Warden serves as Vice Chair, Aerospace Industries Association.[240]

Today Northrop Grumman is the 96th-ranked Fortune 500 company

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[225] Ibid., 48–51. From minute 14:40, the following YouTube clip shows the Shah arriving at the event, observing, and afterward sitting in and examining the F-14's cockpit: https://www.youtube.com/watch?v=G-mrFcsw-Ew. Background: https://theaviationgeekclub.com/watch-the-f-14-demo-which-beat-that-of-the-f-15-and-sold-the-mighty-tomcat-to-shah-of-iran/ and https://theaviationgeekclub.com/former-iiaf-tomcat-pilots-tell-the-true-story-of-why-iran-picked-the-f-14-over-the-f-15/.

[226] Gilcrist, *Tomcat!*, 195.

[227] Ibid., 54.

[228] Ibid., 55. As part of this process, Gavin would obtain a unique window into some of the personalities and professional happenings of Iran's governing and technological elite of the time. Iran's ambassador to the Washington had the unenviable task of awakening in the early hours of each morning to give the Shah a daily telephone briefing concerning what was then Tehran's most important bilateral relationship.

[229] Fortunately, Gavin's employees were protected by local Iranians until they could exit the country safely via aircraft that Grumman had arranged at Tehran Airport. Amazingly, months after their return to the United States, the personal belongings that they had abandoned in their haste arrived by shipping container in Long Island without valuables missing. Gavin credited this humane treatment and the subsequent Iranian shipping of employees' personal effects to the Persian language and cultural sensitivity program that he had required all employees and their accompanying family members to take for six months before traveling to Iran. This "trans-cultural" training program began on January 20, 1975. Pranay Gupte, "Has Grumman Pulled Out of Its Tailspin? Grumman Saga," *New York Times*, January 19, 1975, 3A. For years afterward, Gavin followed the progress of Iranian government and industry leaders with whom he had become familiar professionally; many settled in Houston and Los Angeles and applied considerable talents to making a new life in their adopted home. Gavin's many discussions with author over many years.

[230] Gavin, notes written in 2001.

[231] W. David Gibson, "Poised for Takeoff: R&D Enhances Grumman's Prospects," *Barron's National Business and Financial Weekly* 64.11 (March 12, 1984), 14. The X-29 flight program was a Defense Advanced Research Projects Agency (DARPA)-sponsored R&D initiative to sponsor and rigorously evaluate leading-edge technologies, not to develop aircraft for serial production.

[232] Gunston, *Grumman*, 152.

[233] Ciminera, *The Aircraft Designers*, 203, 226, 231.

[234] Kresa was named President of the Northrop Corporation in 1987, adding the roles of COO in January 1990 and COB in September 1990. Likewise, he staggered his retirement with Ron Sugar, with Sugar becoming President and COO on September 20, 2001, dropping COO and adding CEO on April 1, 2003 upon Kresa's retirement, and finally adding COB on October 1, 2003.

[235] "Our Heritage," Northrop Grumman, https://www.northropgrumman.com/who-we-are/northrop-grumman-heritage/.

[236] Bush was Northrop Grumman's COO from 2003–06 and Chief Financial Officer from 2005–07. Bush was named president in 2006. In 2010, he was named President and CEO.

[237] "Northrop Grumman Announces CEO Transition," July 12, 2018, https://news.northropgrumman.com/news/releases/northrop-grumman-announces-ceo-transition.

[238] "Photo Release—Northrop Grumman Elects Wesley G. Bush President and Chief Financial Officer," May 18, 2006, https://news.northropgrumman.com/news/releases/photo-release-northrop-grumman-elects-wesley-g-bush-president-and-chief-financial-officer.

[239] "Historical Chairs of the Board," Aerospace Industries Association, https://www.aia-aerospace.org/about-aia/leadership-and-governance/past-chairs-of-the-board/.

[240] "Kathy Warden, Vice Chair, Aerospace Industries Association," https://www.aia-aerospace.org/personnel/kathy-warden/.

and one of the world's largest aerospace and defense technology firms, with over $33 billion in annual revenue.[241] It supplies continually-improved variants of the Grumman-originated E-2 *Hawkeye*[242] airborne early-warning and battle management aircraft and E-8 *Joint STARS*[243] airborne Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR) platform.

Major programs include the *F-35 Lightning II* multirole fighter,[244] the B-2 stealth bomber's successor, the B-21 *Raider*,[245] and the newly awarded Ground-Based Strategic Deterrent (GBSD).[246]

In a fitting follow-on to Gavin's oversight of the OAO[247] and a tribute to Apollo-era leadership,[248] his successor firm is the primary contractor for NASA's James Webb Space Telescope[249] and its Transiting Exoplanet Survey Satellite (TESS).[250] Northrop Grumman is part of a global team supporting Artemis[251]—NASA's program for returning to the Moon by 2024 with the first female astronaut to set foot there.[252]

3.6. Advising MIT & Public Policy

Towards the end of his career, and throughout his retirement, Gavin remained quite active professionally. He increasingly sought to apply his programmatic and engineering insights to public policy. He continued to conduct research and advise the U.S. government on space, technology, and energy resource issues. Gavin also engaged extensively in charitable activities, with core contributions concerning education, healthcare, and equal opportunity.[253] Across the board, he frequently worked with, and through, MIT. He constantly communicated, and exchanged research and policy ideas, with its faculty.[254]

An engineer at heart, who believed strongly in his profession's potential to contribute to society in the spirit of MIT's official motto "Mens et Manus" ("Mind and Hand"), Gavin worried that America's political process no longer supported sufficiently foresighted planning and investment concerning science and technology over a range of promising applications, from space to energy.[255] Rather, he lamented, short-term political expedience had replaced the technically-informed long-term leadership commitments prevalent from 1955–80 that underwrote such aerospace successes as Apollo.[256]

Space continued to be a major area of interest for Gavin. Despite great efforts, Grumman under Gavin had failed in its repeated endeavors to participate in space station development, including the ultimately-cancelled Manned Orbiting Laboratory and the McDonnell Douglas-contracted *Skylab*. Gavin thus seized an opportunity to support MIT's president in advising U.S. policy regarding *Space Station Freedom*.[257] He also chaired a major National Research Council committee on Advanced

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[241] "Fortune 500, Northrop Grumman—Rank 96, https://fortune.com/company/northrop-grumman/fortune500/.

[242] "E-2D Advanced Hawkeye (AHE)," Naval Air Systems Command, https://www.navair.navy.mil/product/E-2D.

[243] "E-8C Joint Stars," U.S. Air Force Fact Sheet, September 23, 2015, https://www.af.mil/About-Us/Fact-Sheets/Display/Article/104507/e-8c-joint-stars/.

[244] "Northrop Grumman Delivers 500th Center Fuselage for the F-35 Lightning II," February 25, 2019, https://news.northropgrumman.com/news/releases/northrop-grumman-delivers-500th-center-fuselage-for-the-f-35-lightning-ii.

[245] "B-21" News, U.S. Air Force, https://www.af.mil/News/Tag/62756/b-21/.

[246] "Northrop Grumman Will Lead a Nationwide Team to Deliver the Ground Based Strategic Deterrent Program," September 8, 2020, https://news.northropgrumman.com/news/releases/northrop-grumman-awarded-contract-to-replace-aging-icbm-system.

[247] "NASA's First Stellar Observatory, OAO 2, Turns 50," NASA, December 11, 2018, https://www.nasa.gov/feature/goddard/2018/nasa-s-first-stellar-observatory-oao-2-turns-50.

[248] "The Apollo Missions," NASA, https://www.nasa.gov/mission_pages/apollo/missions/index.html.

[249] James Webb Space Telescope, Goddard Space Flight Center, NASA, https://www.jwst.nasa.gov/.

[250] "TESS Satellite Discovered its 1st World Orbiting 2 Stars," Goddard Space Flight Center, NASA, January 6, 2020, https://www.youtube.com/watch?v=8FrlhrtVEW8.

[251] "NASA Awards Northrop Grumman Artemis Contract for Gateway Crew Cabin," NASA Release 20-06, June 25, 2020, https://www.nasa.gov/press-release/nasa-awards-northrop-grumman-artemis-contract-for-gateway-crew-cabin.

[252] "Artemis," NASA, https://www.nasa.gov/specials/artemis/.

[253] Beyond his professional responsibilities, Gavin was committed to public service in his community and beyond. He held many leadership positions, including member of the board of directors, European American Bankcorp and its subsidiaries, European American Bank and Trust Company and European American Banking Corporation; as well as five years as Chairman of the Huntington Hospital Board of Directors and additional service as a trustee. "Who's Who in the EBIC Banks," European Banks International Corporation, March 1983, 19. EAB was acquired by Citigroup in 2001. "Citigroup, Form 10-Q, Quarterly Report, Filing Date Aug 13, 2001," http://edgar.secdatabase.com/1031/91205701528176/filing-main.htm. He was a longtime participant in Long Island's United Way annual fund drive and the AFS international youth exchange program. "Gavin, Joseph G. Jr.," *50th Reunion Yearbook* (Cambridge, MA: MIT Class of 1941, June 3–8, 1991).

[254] See, e.g., "Next Steps," from Gavin to Professor Richard K. Lester, MIT, November 1990.

[255] Seeking to preserve a U.S. role in the International Thermonuclear Experimental Reactor (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 U.S. Fusion Machine," *Nature* 379 (February 1, 1996), 387; Andrew Lawler, "Fusion Advocates Scramble for Scraps," *Science* 270 (December 15, 1995): 1755.

[256] Gavin, remarks at MIT New Haven Meeting, New Haven, CT, November 20, 1986.

[257] Gavin, review of numerous reports, presentations, and other documents; Gavin, correspondence with Grumman Space Station Integration Division, Reston, VA, 1993; Gavin, extensive notes on draft reports and related correspondence with MIT President Charles M. Vest, 1993; Vest, Chair, President's Advisory Committee on the Redesign of the Space Station, *Final Report to the President*, June 10, 1993.

Space-Based High-Power Technologies.[258]

4. Giving back to MIT

To the very end of his life, Gavin remained focused on pursuing new technological horizons and helping the organizations he valued look to the future. Rather than basking in Apollo's glory, he sought to apply its lessons to pressing societal problems. In 1995, at Gavin's induction as a life member emeritus of the MIT Corporation, fellow classmate and crew team member Carl Mueller would attest that "his generosity and abiding concern have strengthened this institution immeasurably," describing him as "a modest gentle man whose powerful intellect and effective leadership have literally put men on the moon and returned them safely to Earth."[259]

A strong supporter of and fundraiser for the schools he had attended, Gavin was an active "Tech" alumnus. His lifelong association with and support for MIT included service as a member of its governing Corporation, which he joined in 1973. A founding life member (Sustaining Fellow), he served on the Corporation's highly-influential executive committee from 1984–91, as well as on its Corporate Development Committee. Gavin's personal correspondence from the 1980s and 1990s reveals repeatedly how he gracefully transitioned from some previous service responsibilities, and politely declined numerous new invitations, in order to participate in MIT activities as much as possible. Gavin attended his final board meeting on October 1, 2010, driving the 2 h each way alone. This was just twenty-nine days before his death at age 90, surrounded by family at Applewood Retirement Community in Amherst, Massachusetts.

Gavin also chaired and otherwise supported many MIT Corporation visiting committees. In at least three instances, he chaired the committee and authored its report. Most notably, Gavin served as a visiting committee member for his old home department beginning in 1983, and chairman beginning in 1987. As committee chair, he conducted a major reevaluation of AeroAstro in 1992, which had evolved considerably over fifty-three years.[260] In addition to universal university challenges,[261] Gavin and his colleagues wrestled with difficult discipline-specific curricular issues: "increasing commonality in aeronautics and astronautics," theory vs. practice, real vs. virtual worlds, and students' ever-increasing and diversifying use of computers and simulation software and how best to integrate this into classroom activities.[262] Regarding MIT's interdisciplinary Ocean Engineering Department, Gavin was likewise directly familiar with much subject matter. He chaired a visiting committee in 1984–86, and a major reevaluation in 1993.[263]

Gavin also supported MIT engineering education directly by participating in events,[264] recruitment, and classroom instruction. The MIT Alumni Association awarded Gavin its 1972 Presidential Citation for his two-decades' service[265] as a member of the Long Island Educational Council for "years of active contact with secondary schools, effective relationships with local students, and dedication to the institute," which "have resulted in an exceptional pool of talented young people who annually are admitted to MIT from Long Island."[266] Mirroring Apollo's fast-paced meritocracy, Gavin interviewed MIT applicants the same way he interviewed prospective engineers and managers throughout his Grumman career. He sought the top 5–10% of engineering talent, which he measured in raw aptitude and enthusiasm (as opposed to polish and established social-organizational credentials).[267] Gavin viewed the periodic replenishment of engineering talent in a national and international context: to him, it was essential for the United States to keep recruiting the top 5–10% of talent, which formed the critical superstructure for accomplishing important programs. In the final decades of his life, he used his numerous lectures and advisory positions to underscore what he considered a key problem: any downtrends in total new American engineering degrees mattered less than the fact that many potential engineering stars were going into other, often more lucrative, fields. This was a worrisome comedown from the 1950s and '60s, when aerospace projects drew some of America's very-most-capable engineers to MIT, Grumman, and other key centers of

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[258] To help inform this study, Gavin and his colleagues revisited NASA-Apollo organizational history. Gavin, speaking during "Sandy Brown's introduction," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/brown-intro.htm. Building on an interest on alternative energy that he had pursued at Grumman's helm, Gavin's passion for nuclear fusion, solar, and wind energy was the subject of many public presentations. Through Grumman's involvement in the Princeton Tokomak fusion energy project, he had developed a strong concern for energy policy issues. Gavin chaired the Committee on International Cooperation in Magnetic Fusion, National Research Council (1983–84); and the Technical Panel on Magnetic Fusion, Energy Research Advisory Board, Department of Energy. Gavin also served as a member of the Department of Defense's Policy Committee on Trade.

[259] 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.

[260] AeroAstro's 2020 Strategic Plan reflects the latest trends: https://aeroastro.mit.edu/about/strategic-plan. AeroAstro has roughly 35 faculty and 20 administrative staff supporting 170 undergraduate and 250 graduate students. Research volume in FY20 was $33 million (30% industry, 70% federal). The annual HQ budget is approximately $15 million.

[261] These included optimizing faculty compensation, promotion, and retention; teaching, research, and tenure processes; engaging students and recruiting them to major in the department; and explicit vs. implicit requirements.

[262] *Report of the Corporation Visiting Committee*, Department of Aeronautics and Astronautics, MIT, November 4–5, 1992.

[263] *Report of the Corporation Visiting Committee*, Department of Ocean Engineering, MIT, April 13–14, 1993. Gavin also chaired a committee on Music and Theater Arts at MIT. *Report of the Corporation Visiting Committee*, Music and Theater Arts Section, MIT, December 1–2, 1992. Having readily acknowledged that he couldn't carry a tune, he was reassured by MIT leadership: "You know how to run a meeting." Author's discussions with Gavin over the years.

[264] Gavin, welcoming remarks, "Technology and Society: Challenge and Conflict," MIT Eastern Conference, Garden City, NY, March 15, 1969; "It's Technical," *Newsday*, March 17, 1969, 27.

[265] Letter from MIT President J.R. Killian, Jr., welcoming Gavin to membership in The Educational Council, May 11, 1953.

[266] Distinguished service document signed by F.G. Lehmann, Secretary, MIT Alumni Association, November 1, 1972.

[267] Author's discussions with Joseph Gavin, III, January 2020.

excellence.

Gavin often lectured in the seminars of such MIT professors as Battin.[268] "He was really good with the freshmen," Battin recalled. "I didn't even have to ask" him to participate in the seminar. "He would call me up to ask to take part."[269] Gavin likewise participated in numerous conferences, workshops, and panel discussions.[270]

Through these efforts, Gavin became particularly interested in the potential of Japan and China to develop advanced aerospace and other technological programs. Over the course of his career, including support for the International Thermonuclear Experimental Reactor (ITER), he visited Japan several times beginning in the 1970s and was impressed with its government's ability to pursue far-reaching programs and invest with foresight. "I think the place that we're going to have to watch is the Japanese and the Chinese," he told the author in 1998.[271] At the first opportunity, via the 1996 IAC, he visited China. Touring space facilities in Beijing, Xi'an, and Shanghai, he was impressed by the caliber of the leading young aerospace specialists he met. If placed in top U.S. programs (e.g., at MIT and Caltech), he assessed, they would perform admirably.[272]

Gavin was also a member of the MIT Education Council and MIT's Alumni/ae Association (Vice President, Board of Directors, 1981–83; Vice-President, 1981–83; President, 1986–87).[273] He enjoyed interacting with MIT alumni associations across the United States and Europe, and considered the Paris chapter a "model."[274] Gavin proved a successful fundraiser by using a consistent approach: approaching financially advantaged classmates, describing a specific need (e.g., a new program), saying he was going to make a specific contribution, asking if they would join him, and following up as necessary. In an interview following his retirement from management, Gavin explained, "I'm committed to a great deal of fund-raising work for MIT, which is only fair. MIT was very good to me. I spent five years there as a scholarship student, and it changed my whole life.[275] To the very end, he strove to invest in the next generation of aerospace development.

Coming full circle with Massachusetts roots, MIT connections, and Grumman aerospace achievements, in Boston on June 11, 2010, less than six months before his death, Gavin shared the Godfrey L. Cabot Award for his lifetime contributions. Recipients—like Hunsaker, Koppen, Draper, Seamans, and Whittle previously—are "individuals or teams who have made unique, significant, and unparalleled contributions to advance and foster aviation or space flight."[276] It was presented by the Aero Club of New England, America's first aeronautical club, and longtime gathering place for visionary, influential "Tech" graduates.[277] Gavin discussed discoveries that ensured LM reliability, recounted the extreme sleep deprivation he had endured in helping to save Apollo 13, and expressed gratitude that he would never have to repeat the experience. In a fitting follow-up, Apollo 13 Commander James Lovell would receive the same award in 2018.[278]

5. Bringing it all together: Gavin, MIT, aerospace achievements

Revisiting Gavin's career-long intersection with MIT elucidates factors powering an era of American aerospace achievement whose dynamism and dominance may never be surpassed. A microcosm, meeting place, and mainstay of American aeronautics and astronautics development, "Tech" and its AeroAstro Department gave Gavin lifelong association, inspiration, and support as his intellectual home. Their efforts interacted intensively over decades, part of a potent phenomenon. Both connected closely with, and enjoyed strong support from, the Navy, itself a pioneering patron of American aerospace.[279] In managing his Grumman team, Gavin became a leading participant just as unprecedented dynamics were converging synergistically.

"We hear that technology is incremental, that it progresses in an ever upward arc of physical parameters," director of MIT's program in science, technology, and society David Mindell reflects. "Apollo showed how a perfect storm of politics, management, engineering, and

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[268] Neil A. Armstrong, "Joseph G. Gavin, Jr., 1920–2010, Elected in 1974."

[269] Chandler, "Aerospace Engineer Joseph Gavin '41, SM '42 Dies at 90."

[270] David E. Hastings, Associate Professor of Aeronautics and Astronautics, October 7, 1992 letter to Gavin thanking him for agreeing to participate in panel discussion entitled, "What is the Value of an Aerospace Education in These Uncertain Times?" to be held at MIT on November 5, 1992.

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

[272] Author's correspondence with Craig Covault, who accompanied Gavin on the trip, May 6, 2020.

[273] Gavin was also a trustee of the Polytechnic Institute of New York, whose Long Island Technology Leadership Award he received in 1979.

[274] Gavin, letter to Mme. Suzanne Weinberg-Bursaux, March 23, 1987.

[275] See, e.g., Gavin, letter to Dr. Buzz Aldrin, December 17, 1987. Quotation from "Gavin on Grumman," *Grumman World*, November 22, 1985, 5, https://www.grummanretireeclub.org/wp-content/themes/grumman-child/archive-newsletters/grumman-world-1985-11-22-Volume-4-Number-13.pdf.

[276] "2010 Eugene 'Gene' F. Kranz & Joseph G. 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. 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.

[277] Porter Adams, "Aviation in Boston," *Fifty Years of Boston: A Memorial Volume Issued in Commemoration of the Tercentenary of 1930* (Boston, MA: Subcommittee on Memorial History of the Boston Tercentenary Committee: 1932), 295–300.

[278] "The 2018 Godfrey L. Cabot Award Will Be Presented to James A. Lovell," *Aero-News Network*, May 13, 2018, http://aero-news.net/index.cfm?do=main.textpost&id=d2cbc935-22bc-45aa-b5df-f531657b4737.

[279] In one of many examples, the Navy funded the following diagnostic efforts involving IL and the AGC: Edwin D. Smally, *Computer-Controlled Software: Diagnosis of An Airborne Computer* (Cambridge, MA: Charles Stark Draper Laboratory, 1972); Smally, *Integration of Multiple Guidance-System Tests into One Software Program* (Cambridge, MA: Charles Stark Draper Laboratory, 1981).

operations can leap ahead of those ordinary rules." [280] Intertwined throughout, Gavin and MIT collaborated critically, contributing to and benefitting from that exceptional vitality. Former IL Command and Service Module Software Project Manager Fred Martin recalls a colleague lamenting "'Why can't I find another Apollo?' Because a lot of people searched for another program like that later."[281] Together with the potent federal-corporate interface involving NASA's managing capable private contractors like Grumman, MIT's nurturing and support of innovative leader-experts like Gavin afforded U.S. space programs unparalleled depth, vitality, and collegial connection. This proved simply unattainable by their Soviet counterparts, who succumbed to bureaucratic infighting, inadequate testing and quality control, catastrophic booster and spacecraft failures, and excessive dependence on Chief Designer Sergei Korolev, who died of old Gulag injuries and subsequent stressors at a critical time in 1966.[282]

Gavin's educational focus may hint at what he might have pursued had aerospace project management and executive leadership not consumed his career. He particularly enjoyed presenting to diverse young audiences; with a special emphasis on communicating with students, from schoolchildren to doctoral candidates.[283] In part for his longtime dedication to such outreach, the Aerospace Education Council named him its 1968 "Man of the Year." Interviewed then, "Mrs. Gavin thinks her husband would have made an excellent teacher if he ever decided to leave the world of space exploration. 'When you can explain to your wife why an airplane flies,' she said, 'that means you're a good teacher.'"[284] Gavin's wife, a family historian and educator in her own right, was his vital partner in everything.[285] In his 50th Reunion yearbook he concluded, "Couldn't have done it all without Dorothy's interest and support"[286] in what would total nearly seven decades of fruitful, fulfilling marriage.[287] Likewise vital, professionally, was Gavin's seven-decade partnership with MIT. Their interwoven efforts are now part of a glorious early chapter in aerospace history.

Declaration of competing interest

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 Anthony Zolnik, Manager of Infrastructure, MIT AeroAstro Department, for guidance; Deborah G. Douglas, Director of Collections, and Rachael Robinson, Curatorial Associate, MIT Museum for facilitating access to archives and related materials; Barbara Williams, MIT AeroAstro and Physics Librarian, for vital research suggestions and references; William T. G. Litant, former MIT AeroAstro communications director, David Mindell, MIT AeroAstro professor and Dibner Professor of the History of Engineering and Manufacturing, AeroAstro alumnus Col. Pete Young, USAF (Ret.), Gayle Gallagher, Senior Director of Institute Events, MIT, and Brían O'Conaill, MIT AeroAstro Administrative Officer, for invaluable inputs; Ingrid Drew Crete, Operations Manager, Charles Stark Draper Laboratory, Inc., Pamela Eve Griffin-Hansen, Project Manager and Archivist, Northrop Grumman History Center, and Dianne Baumert-Moyik, Senior Manager, Public Relations, Northrop Grumman Aeronautics Systems for furnishing unique sources and insights; Hugh Blair-Smith, Don Eyles, and Norman Sears for firsthand observations from their Apollo work in MIT's Instrumentation Laboratory, as well as Sue Laning Serino's generous contributions of sources and insights concerning her father J. Halcombe Laning's work there; and NASA engineer Michael Ciancone, former Grumman Public Affairs Director for Space Dick Dunne, Grumman History and Aeronautical Research Center archivist/historian John Eagan, Cradle of Aviation Development Director Carol Nelson, U.S. Space Force historian Rick Sturdevant, space historians Stephen Johnston and Asif Siddiqi, as well as David Grumman, Valerie Parsegian, Admiral Gary Roughead, USN (Ret.), Marc Szepan, and three anonymous reviewers for constructive suggestions.

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[280] David Mindell, "Apollo Was a Sheer Creative Expression," in Waitz and Litant, eds., *AeroAstro* 6, 15.

[281] "Fred Martin's introduction," Apollo Guidance Computer History Project, https://authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/apollo/public/conference1/martin-intro.htm.

[282] Blair-Smith, *Left Brains for the Right Stuff*, 249, 299, 308, 335, 392; Naomi Oreskes and John Krige, eds., *Science and Technology in the Global Cold War* (Cambridge, MA: MIT Press, 2014).

[283] Long active in local education, Gavin served as Chairman of the Greenlawn-Centerport School Board. In 2004, as the retiring president of the Harborfields School District Board of Education, of which he was also a member for eight years, he became the first board member to be recognized by a teachers' association in New York state history. *Long-Islander*, May 28, 2004.

[284] "Reacher for the Moon: Joseph Gleason Gavin Jr.," *New York Times*, January 23, 1968, 10. The latter quotation was the newspaper's quote of the day (p. 41). Gavin's parents were very proud when advertising colleagues sent it to his father, who responded that he had married a smart wife.

[285] In 1943, Gavin married Dorothy Grace Dunklee of Brattleboro, VT. He had met her at 4-H camp, where he had been her rifle instructor. Her brother Robert told her that Gavin was okay. It proved to be a love match for 67 years until Gavin's death at 90.

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

[287] A committed family man, Gavin devised numerous pastimes for his children and grandchildren and played with them extensively. He encouraged their interest in science, technology, and the world around them by introducing them to everything from toolboxes to fiber optics. He took his wife and children on numerous "family expeditions." "Gavin, Joseph G. Jr.," *50th Reunion Yearbook* (Cambridge, MA: MIT Class of 1941, June 3–8, 1991). He and his wife visited five continents—in part by attending virtually every annual IAC from 1980 to 2005, during which they interacted with numerous experts in the field and toured local space facilities. He designed the family home on Long Island and a vacation cabin in Vermont. He did so with an aerospace engineer's relentless efficiency, requiring his wife to request additional space in key areas. (Author's many discussions with Dorothy Gavin continuing to the present.) Gavin was an avid downhill skier until completing his last run at age 86, a regular tennis player, and a photographer captivated by the latest high-tech gadgets; all of which he enjoyed with his wife and family. A voracious reader of history, he also read Latin and read, wrote, and spoke German, corresponding with a family his father had befriended decades before and even keeping current with an intensive in-residence class at Dartmouth College in his mid-eighties.