Aerospace Needs, Microelectronics, and the Quest for Reliability: 1962–1975

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> This computer system is not intended for use in the operation of nuclear facilities, aircraft navigation or communications systems, or air traffic control machines, or for any other uses where the failure of the computer system could lead to death, personal injury, or severe environmental damage.
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> —Apple Computer, Inc., *Macbook Users Guide*, 2006, p. 109.

In the past few years several bestselling books appeared that chronicled key elements of the spread of computing technology into contemporary society. Many of them focus on the exponential increase of computing power, accompanied by a corresponding decrease in size, weight, and power consumption of the integrated circuits that make up most of modern electronic devices. The shorthand phrase that expresses this phenomenon is "Moore's Law," based on a brief note published in 1965 by Gordon Moore. There is another facet of the advances in computing and electronics implied by the term "Moore's Law" as events unfolded in the 1960s, shortly after the invention of the silicon integrated circuit. That facet is the issue of reliability.

This month's article emphasizes the role played by reliability in establishing the technology of, and market for, the silicon integrated circuit by citing key developments in the Apollo program.

From its origins in the work of Thomas Edison through the 1950s, electronic equipment was centered around a component that was fragile, unreliable, bulky, and power hungry: the vacuum tube. Unlike most other components in an electronic device, the tubes were mounted in sockets, so that they could be replaced when necessary—which was often. When the point-contact germanium transistor was invented in the late 1940s, it was heralded as eliminating all of the above drawbacks, especially the reliability problem. When first applied to complex circuits, however, the transistor came with its own set of problems. Because it had no filament, it did not burn out as vacuum tubes did, and it consumed less power. However, the transistors were difficult to produce. The early point-contact design required placement of leads at close tolerances. In many cases, one did not know how much gain a transistor could deliver until after it came off the assembly line and was tested. Reliability was poor: transistors made of germanium had a limited temperature range, and they often failed when subject to shock and vibration.

The earliest electronic digital computers, built in the late 1940s and early 1950s, used thousands of vacuum tubes as their main switching element. Computer designers took heroic steps to keep the machines running long enough to deliver useful results, but failures caused by the vacuum tubes were to be expected. Where the devices were intended for critical aerospace applications, for example, the U.S. Air Force SAGE air defense system, the computers were built as twins, with one taking over if the other failed [1], [2]. The SAGE computers worked well, although they never were tested against an actual attack by the Soviet Union.

As the transistor went into mass production, the notion of using solid-state computers onboard aircraft became practical. The Bell Laboratories TRADIC,

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the first transistorized airborne digital computer, flew in the late 1950s [3].[1]

The TRADIC was intended to compute bombing trajectories, and its operation was not critical to the safety of the aircraft or its crew. It did not have duplicate circuits.

At the same time, the notion of using digital computers in real-time applications, where reliability was an absolute requirement, became accepted. Several aerospace applications dovetailed with the emergence of the silicon integrated circuit as a means of producing reliable digital circuits, in an environment where both aerospace and microelectronics were progressing rapidly. The Apollo missions to the Moon were one of them and illustrative of the tradeoffs that designers of electronic equipment faced to meet requirements of cost, schedule, performance, and reliability.

The Apollo program carried a total of 12 astronauts safely to the Moon and back between 1969 and 1972. Other Apollo missions sent astronauts into lunar orbit without landing, ferried three crews to the Skylab space station, and finally in 1975, conducted a rendezvous in Earth orbit with a Soviet spacecraft. Digital electronics played a crucial role in the success of these missions. The rapid progress of human space exploration from simple suborbital flights in 1961 to landing on the Moon in 1969 dovetailed closely with advances in microelectronics, from the invention of the integrated circuit in 1958–1959 to the use of a 256-b memory chip in place of magnetic core for the ILLIAC-IV computer in 1970, to the introduction of the "Altair" personal computer in December 1974. Writing in *IEEE Spectrum* in 1983, Evan Herbert described the Apollo program's relationship to electronics as "the driver and the driven" [4]. Herbert's analysis is still relevant today: Apollo drew from advances in digital electronics as it progressed from one mission to the next; it also drove the electronics industry forward, leading to products and applications in many areas beside aerospace. Apollo's need for reliability was one among several arenas where that driving force was most significant.

I. MINUTEMAN

Before Apollo, the aerospace community worked on ways of adapting transistors and the newly invented integrated circuit. The notion then common in the electronics industry, of designing equipment to be serviced periodically, was scrapped. Electronic equipment was an increasing part of the expense of next-generation aircraft and missiles. But as U.S. Air Force Major General Bernard A. Schriever noted, "A number of American missile failures can be traced to faulty small 'nickel and dime' components…" For aerospace customers, reliability was first among equals, along with weight, power consumption, and volume [5], [6].

The Air Force's first ICBM, Atlas, was liquid fueled and took a long time to be readied for launch, rendering it of limited value against a possible Soviet attack. The Titan, a successor to Atlas, was marginally better, but the real breakthrough came at the end of the decade, when advances in solid fuel technology, warhead design, and inertial guidance led to the Minuteman—a rocket that was ready for launch on short notice [7].

In 1958, the Autonetics division of North American Aviation was selected as an associate prime contractor responsible for the Minuteman's guidance system and associated electronics. Minuteman production proceeded in the following years through 1977. In its selection of Autonetics, the Air Force stressed the need for reliability that was at least two orders of magnitude greater that existing military electronics systems. The missiles had to remain on constant alert, yet be ready to fire in less than 60 s after a command was given. The warheads had a much smaller yield than the Titans that it was to replace; the Minuteman compensated for that by having greater accuracy. Thus, the guidance system had to be not only more accurate, but also it had to maintain that accuracy with no degradation while in the missile's silo [8], [9]. To achieve the necessary reliability, Autonetics documented the history of every electronic component, who handled it, what was done to it and when, what tests were performed on it and when, and what "lot" or production batch a particular component belonged to. Certain types of components, such as potentiometers, were expressly forbidden. Those that were selected were "derated," or designed to operate at power levels lower than they were designed for. Assembly was to be done in strictly regulated clean rooms [9, ch. 1]. If a device failed a test, all devices from that lot were rejected.

For the Minuteman guidance system, Autonetics decided that the mesa-type silicon transistor (discussed later) was to be used wherever possible [9, pp. 7, 14], [10].[2]

Fairchild Semiconductor was among the suppliers that were hoping to sell transistors to Autonetics, and in preparing their offer they adopted the stringent reliability demands needed to qualify. The much larger firm Texas Instruments also met those requirements, and TI went on to become the main supplier of components to the Minuteman program.

Fairchild, at the time a small startup company, regarded the stringent requirements from Autonetics as crucial to their success as a supplier of transistors, and later integrated circuits [11], [12, ch. 12]. At its plant in Mountain View, CA, USA, Fairchild instituted a testing program that went far beyond what then was common. Transistors were mounted in a centrifuge and spun up to high G-forces. They were tested at extremes of temperature, hot and cold. Packaging was designed to protect the circuits once delivered. Borrowing from the aerospace field, the silicon devices were bonded to a nickel–cobalt alloy "Kovar," which had the property of

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[1] A TRADIC was installed in a C-131 B aircraft on loan to Bell Labs from the U.S. Air Force. No date for the first flight is given.

[2] Grumman engineer Tom Kelly recalled a visit he made to a manufacturer of batteries for the Apollo Lunar Module (LM). He observed a worker assembling a battery while smoking a cigarette, with the ash growing longer and longer, until it finally "broke off and fell into the assembly."

having the same coefficient of thermal expansion as borosilicate glass, thus preventing the circuits from cracking as they underwent temperature changes. In large rooms, women peered into binocular microscopes to check the connections and integrity of the devices.

These Minuteman "Hi-Rel" techniques, imposed by Autonetics, were initiated to improve reliability of discrete silicon transistors. The techniques carried over to the integrated circuit era, and to Apollo, with few modifications. One change was that after wafers were processed but before they were diced, women guided a set of tiny pins onto each chip, to test the circuitry. If it was defective, the worker dabbed on a spot of ink on it to mark its rejection. The percentage of good chips on a wafer, called the "yield," remains one of the most critical metrics in the industry. This approach to reliability played a crucial role in getting NASA to accept the use of chips in spacecraft. Once a chip passed these tests, the customer was confident that the device would not fail in use. With that confidence, one could eliminate the cumbersome "belt and suspenders" redundancy, or the need to carry diagnostic instruments, tools, and spare parts to make repairs in cislunar space.

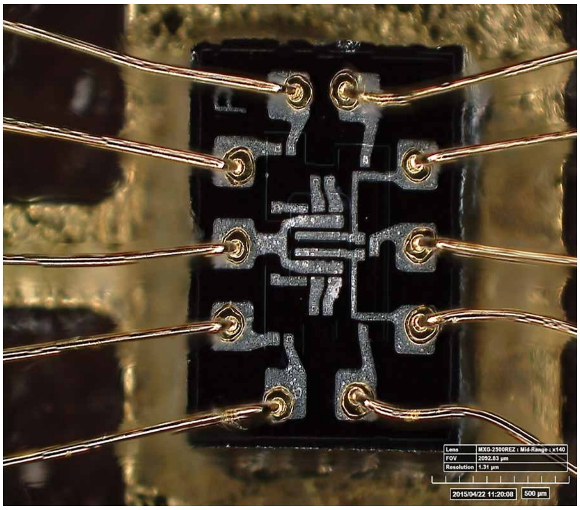

Fig. 1. **Dual, three-input NOR gate, used in the Block II Apollo Guidance Computers. Photo by Lisa Young, Smithsonian National Air and Space Museum (TMS A20170003000).**

II. THE INVENTION OF THE IC

Accounts of the growth of Silicon Valley cite the invention of the planar process as the key to the ever-increasing density of silicon chips. But it is also the key to the issue most pressing for NASA, namely the reliability of electronic circuits. It was invented by Jean Hoerni, a Swiss-born chemist who worked at the Shockley Semiconductor Laboratory [13]. In 1958, Fairchild's main product was high-speed silicon transistors, in which layers of materials were built up on a silicon base using photographic techniques that Fairchild had mastered. The layers of materials resembled the mesa rock formations of the American southwest. "Mesa" transistors worked well but were fragile. Hoerni's insight was to leave a layer of silicon oxide on the circuit and then remove select sections later on by photographic etching [14]–[16]. This made the transistor at once more rugged and resistant to damage; it also had the effect of electrically isolating the underlying layers of transistors. The planar process made possible the transition from a single transistor on a chip to an integrated circuit containing transistors, resistors, diodes, etc., on a chip, eventually by the hundreds of millions.

A. Texas Instruments

Around mid-1962, work began on an improved Minuteman. The second generation missile was to have greater accuracy, greater range, and was to be quickly retargeted if necessary. That placed demands on the guidance computer, which led in turn to the selection of integrated circuits in its design. The primary supplier was Texas Instruments. Together with Westinghouse, TI delivered 15 000 circuits to Autonetics per week by the summer of 1965.

The near-simultaneous invention of the integrated circuit by Jack Kilby at Texas Instruments and Robert Noyce at Fairchild has been extensively studied. Kilby applied for a patent in February 1959, Noyce in July. Ten years later, the inventors' companies agreed to share credit and cross-license each other's portfolio of patents relating to the IC [17], [18]. The dispute centered around Kilby's method of interconnection among the various components on the chip: his patent application showed fine wires, presumably attached by hand, to make the connections, while Noyce's drawing showed a flat surface that contained both the devices and their interconnections. The TI method was known as "flying wires," which Fairchild argued was inferior to its planar design. With the cross-licensing, Texas Instruments was able to use the planar process as well as its own [19]. By the mid-1960s, TI and other chip manufacturers abandoned the "flying wire" technique, but chip production at that time still involved rooms full of women carefully attaching gold wires to the leads of planar ICs.

For the Minuteman II, Texas Instruments developed a set of around two dozen different types of integrated circuits.[3]

[3] Different reports, including several notes by Kilby himself, give varying numbers, from 18 to 24. Letter, J. S. Kilby to Gwen Bell, June 26, 1984, Computer Museum (Boston) Archives. Copy in author's possession. The Smithsonian Institution's National Museum of American History has an extensive collection of early TI chips, information on which is available at http://smithsonianchips.si.edu/texas/t_421-14.htm. The Smithsonian site says there were 19 types of circuits.

The computer itself had about 2200 ICs, plus several hundred in other onboard circuits. Kilby recalled how in the early 1960s electrical engineers were skeptical about the value of this invention. Traditionally an engineer would design a circuit and choose the optimum values of discrete components to perform its function, balancing cost, reliability, power consumption, etc. With the IC, this design work was encapsulated inside the "black box" of the package, with design decisions made by the chip manufacturer in advance of any application. Kilby recalled making numerous presentations to military brass, in which he compared the performance of the Minuteman I computer with its successor, Minuteman II, which used ICs: "In the early 1960s these comparisons seemed very dramatic, and probably did more than anything else to establish the acceptability of integrated circuits to the military" (see footnote 3). The first contracts from Autonetics to TI for the Minuteman II were dated November, 1962, about a year after the MIT Instrumentation Lab was selected to provide guidance and navigation for Apollo.

B. Apollo

Between 1969 and 1972, twelve American astronauts walked on the Moon's surface and returned home safely, fulfilling a challenge set by President John F. Kennedy in 1961. Among the many technical advances that made the missions possible was the Apollo Guidance Computer: a device that combined the operations of navigation, guidance, and control of the Apollo space craft and the Lunar Lander by digital means. The Apollo Guidance Computer used integrated circuits, whose low power consumption, compact size, and switching speed make the decision obvious in retrospect. It was a bold decision, however, as the devices had just barely emerged from the laboratory at the time that decision was made.

The decision reveals a complex interplay between the need to meet the requirements for Apollo, the hard deadline for the landing, the budget, and systems integration with the other components of the spacecraft. At the top of that decision was the criterion for the computer to be reliable. The Apollo decision was not a trigger for the electronics revolution that followed. It would be more accurate to use Evan Herbert's phrase: Apollo was the "driver and the driven" in relation to microelectronics [20], [21].

Fig. 2. **Lunar Module Abort Electronics Assembly, in its handling fixture. Photo Credit: Smithsonian National Air and Space Museum (TMS A19731554000cp04).**

The role of the Apollo Guidance Computer has led to a distorted view of its history. When, on July 16, 1969, a Saturn V rocket launched astronauts Neil Armstrong, Edwin "Buzz" Aldrin, and Michael Collins on a path to the Moon, they were assisted by not one but four digital computers and one analog computer. Two of the four were the Apollo Guidance Computers, one each in the Command and Lunar Modules. The other two embodied a different philosophy of design and construction. NASA managed the reliability for those computers in different ways, even for the two identical Apollo Guidance Computers. Those four were assisted by a suite of IBM System 360/75 mainframe computers at NASA's Mission Control in Houston. On the final Apollo mission, an Earth-orbit rendezvous with a Soviet Soyuz capsule in 1975, the crew carried a fifth digital computer, again with a unique design and construction. The different designs reflect not only a vigorous debate among engineers as to the best way to build reliable, powerful, and compact digital devices on which human lives depended. They also give us a window into the pace of component innovation—a look at the broader process behind the phrase "Moore's Law."

C. The Launch Vehicle Digital Computer—The First of the Five Apollo Computers

The 1961 NASA contract with the MIT Instrumentation Laboratory for the Apollo guidance and navigation system was one of the first contracts signed at the onset of the program. Independently of that effort, engineers at the Marshall Spaceflight Center in Huntsville, AL, USA, worked on a succession of ever more powerful launch vehicles, culminating in the Saturn V. The engineers in Huntsville had established a strong relationship with IBM Corporation for the critical launch vehicle guidance components [22, pp. 19–31]. For the Saturn 1B and Saturn V rockets, IBM's Federal Systems Division supplied an Instrument Unit, mounted above the upper stage of each, on which the various guidance components were mounted. A Launch Vehicle Digital Computer (LVDC), built by IBM, performed critical guidance and navigation functions. For the Apollo Command and Lunar Modules, the Apollo Guidance Computers performed all functions digitally. In contrast, the control of the Saturn V rocket engines was handled by a separate analog computer, supplied by Electronic Communications, Inc. of St. Petersburg, FL, USA [22, p. 28]. That reflected the conservative approach to missile guidance at Huntsville, going back to the V-2 rocket of World War II.

Fig. 3. **HP-65 programmable calculator, configured by NASA for use in space. Photo Credit: Smithsonian National Air and Space Museum (TMS A20120307000cp07).**

The LVDC did not use integrated circuits. At the time of its design, IBM was aware of the invention of the planar process at Fairchild, and its engineers were facing a decision that would affect the very survival of IBM in the coming decade. IBM was one of the largest customers in the United States for transistors and other discrete computer components; it was also a major manufacturer of solid state devices. In August 1961, not long after Noyce patented the planar integrated circuit, an internal IBM report described the need for miniaturized components for its new line of computers, eventually announced in 1964 as the "System/360" family of mainframes [23, p. 105]. IBM developed its own method of miniaturization, which consisted of mounting transistors and other components on a ceramic substrate. IBM called the method "solid logic technology" (SLT). Shortly before the System/360 announcement, another internal report argued that "monolithics" (IBM's term for the integrated circuit) did not pose a competitive threat. IBM produced SLT devices in large quantities for the System/360 and other company products for the remainder of the decade. For the LVDC, IBM used a more compact version of that device, which the company called "unit logic device" [23, p. 108]. However, by 1970, IBM recognized that the integrated circuit was the superior technology, and built its follow-on mainframe, the System/370, using monolithics.

The designers of the LVDC addressed the reliability issue by having the computer's major circuits installed in threes, with a voting circuit to select the majority if one failed. IBM called it "triple modular redundancy" [24], necessary to ensure reliability for a computer that was subject to the high accelerations, temperature extremes, and vibration modes that the Saturn rockets experienced during launch. During all of the flights of the Saturn 1B and Saturn V, the computers worked without failure. That included the flight of Apollo 12, in November 1969, when the Saturn V was struck by lightning just after launch. Mission Control did not apparently monitor how often, if ever, the voting circuits were put to use during that or other launches.

D. The Apollo Contract

In August 1961, NASA awarded the MIT Instrumentation Laboratory a contract to supply the guidance system for Apollo. The close personal relationship between NASA Administrator James Webb and I-Lab Director Charles Stark Draper played a role [25], [26, pp. 270–300]. It was the first of what would turn out to be a myriad of contracts with laboratories and aerospace suppliers [12, p. 51]. Following this award, most of NASA's contracts for Apollo went to aerospace firms, not to academic laboratories. But the Instrumentation Lab was unique. Its expertise in inertial guidance was widely acknowledged as one of the best. In the early discussions about how to get to the Moon and back, it was navigation, not computing, that was of primary concern. At MIT, "Doc" Draper had established strong relationships with industrial firms, including Sperry Gyroscope Corporation of New York and the AC Spark Plug Division of General Motors. A few months after getting the Apollo contract, the Instrumentation Lab enlisted the support of the Raytheon Corporation, which built the computers in its suburban plant outside Boston [12, p. 51], [27].

It is not clear when the first ICs flew in space, but the Orbiting Solar Observatory, launched in March 1962, carried ICs supplied by Texas Instruments for evaluation, that is, a failure of the IC technology would not jeopardize the mission [28].[4]

Texas Instruments supplied these first chips in space, but Fairchild discrete transistors were also extensively used in spacecraft by that time as well. By 1962 Fairchild was marketing a family of six to nine ICs, which the company advertised would be suitable as building blocks for a general-purpose digital computer [29]. The elegance of Fairchild's planar technology, plus its emphasis on component reliabil-

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[4] Most historical accounts state that the first use of ICs in space was on the Interplanetary Monitoring Platform (IMP-A), launched in November 1963. In both spacecraft the chips were supplied by TI, and they functioned well.

ity, led MIT's Eldon Hall to consider their products. Noyce was an alumnus of MIT and may have been more comfortable with the academic culture of the Instrumentation Lab. In late 1962, on Hall's recommendation, NASA decided to use integrated circuits for the computer, and to use Fairchild's design [12, pp. 19, 184–187].

In 1962, when the Apollo Guidance Computer was first taking form, it was possible to place about six devices on a chip. In May 1963, in response to a further understanding of the computational needs for the Lunar landing, the early "Block I" design evolved into a "Block II" Apollo Guidance Computer, with more memory and faster execution. The Block II computer used a chip that contained two, three-input NOR gates but still relied on a single type of gate for all logic. Block II ICs were packaged in a flat housing with leads coming out the edges, instead of the bulkier TO-5 cans used in the Block I. The number of integrated circuits increased from 4100 to 5600 while volume and weight were reduced, from 1.2 to less than one cubic foot volume and from 87 to 70 lb of weight [12, ch. 10]. Thus, the Block I computer was obsolete before it ever had a chance to guide a human crew; only the unmanned Apollo 4 flew, in November 1967, with a Block I computer [30], [31].

The reliability issue was not settled by the decision to use ICs, nor by the progression to the higher density chip for the Block II computers. Recall that Texas Instruments developed a set of around 20 types of ICs for the Minuteman II. Fairchild was offering a set of six to nine ICs that performed the basic functions of computer logic, arithmetic, and processing—a smaller number, but sufficient to build a high-performance general purpose computer. The Apollo Guidance Computer, however, would use only one of them: a three-input NOR gate.

All of the functions of a computer processor can be built up from a single device of sufficient complexity, including a three-input NOR gate. In practice, that is seldom done. Why use several of these logic gates to form, say, an adding circuit when Fairchild was offering a single chip to do just that? The designers of the Apollo Guidance Computer decided to use a single reliable device, and to pay close attention to the circuit they chose to use. In Hall's words:

> Had a second type of logic microcircuit been employed in the computer, the number of logic elements could have been reduced by about 20 percent. But it is clear that to have done so would have been false economy from the point of view of reliability, for neither of the two circuits would have accumulated sufficient operating history to demonstrate the high mean time between failures with the confidence level of a single nor circuit [27, pp. 61–62].

Early in the Apollo program, NASA contracted with AT&T to provide technical and managerial assistance for select technical issues. AT&T in turn established Bellcomm, an entity that carried out these analyses. In late 1962, Bellcomm recommended that IBM, not MIT, supply the computers for the Apollo Command and Lunar Modules. The arguments were complex and contentious, and even reached members of the House of Representatives [32], [33]. In a letter to NASA Administrator James Webb, Representative Joseph E. Karth (D-Minnesota) listed a number of questions. Among them were these:

> 2. There has always been apprehension about the MIT guidance system achieving the required reliability to ensure a safe mission. Is there documented test-proven data to show that it will meet the needs of APOLLO/LEM?
> 3. In regard to the previous question, is there a backup guidance function of sufficient breadth and proven development that can allow the APOLLO/LEM mission to attain success… in the event of catastrophic failure of the MIT guidance? [32]…
> 7. Is a backup system still contemplated for either APOLLO or LEM?

The letter listed five other questions, but of all the questions raised, these stood out: was the Apollo Guidance Computer reliable?

The MIT Instrumentation Lab resisted the Bellcomm suggestion. Because the Command and Lunar Modules were carrying human crews, the environment inside them was not as harsh as the environment of the Saturn V Instrument unit. The LVDC had a specific and narrow task, while the Apollo Guidance Computers needed a more general capability. They had to be programmable by the human crew and accept inputs from telemetry and other on-board systems over the span of a long journey. The greater computational needs were enough to sway NASA away from the Bellcomm critique, after a vigorous defense by the Instrumentation Lab engineers.

In response to the seventh question from Representative Karth, NASA did specify a backup, but a different backup for each of the two. The LM carried the Abort Guidance System, discussed later [26, p. 284]. For the Command Module, the crew themselves would serve as a backup, executing commands sent up from Houston and derived from the System/360 mainframes. Thus, although Apollo carried two identical computers, each had a different backup in case of failure.

Otherwise, the Apollo Guidance Computer had none of the redundancy of the LVDC. The Apollo Guidance Computer embodied a philosophy of reliability quite different from that used on the Saturn V. The MIT engineers argued for a different approach: rather than design circuits that would detect and compensate for errors, design enough reliability to be confident that there would be no failures.[5]

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[5] Jayne P. Hanley, private communication, July 16, 2015. Hanley was a physicist who worked on failure mode analysis for the Apollo project.

The resulting computer would be simpler: no redundant logic modules, no voting circuits, and no "disagreement detectors" to record when a module failed.

E. Reliability and the Electronics Industry, ca. 1960

> "… systems designed for in-flight maintenance will justify that decision by inherently requiring more maintenance."
>
> —Joe Shea, Apollo Program Manager

The planar process allowed Fairchild Semiconductor to turn the whole reliability issue upside down. It justified the MIT decision to use ICs in the Apollo Guidance Computer, and to forego the redundancy techniques that IBM employed in its Saturn LVDC. It also eliminated the need, which had been suggested for earlier AGC designs, of having spare modules onboard, so that the astronauts could replace a defective module with a spare should the computer fail inflight [12, ch. 6–7]. During fall 1964, as the "Block II" Apollo Guidance Computer was taking form, the decision was made to forego inflight maintenance and repair. By the early 1960s the reliability of the electronic devices was becoming evident, while the disadvantages of inflight maintenance were creating further problems of weight, volume, and thermal control [34], [35]. A major turning point was the flight of Mercury-Atlas 9, piloted by Gordon Cooper in May 1963. Several critical electrical systems failed near the end of the mission, and Cooper had to reenter the atmosphere by manual control. It was later determined that acidic fluids, floating in the zero-gravity environment of the capsule, penetrated small openings in the electronic devices, and in the oxygen-rich environment the fluids corroded the electronics more readily than when the devices were tested on the ground [36]. The Apollo Guidance Computers circuits were "potted" to keep out contaminants, and they would be inaccessible to the crew during a flight.

F. The Abort Guidance System—The Fourth Computer

The detailed analysis of the Lunar Module's requirements in 1963-1964, however, did lead to a backup computer: the fourth of the five computers for Apollo. It began as a simple sequencer, whose primary mission was to get the crew safely off the Moon in an emergency. A redefinition of the program in 1964 led to the much more capable "Abort Guidance System" (AGS), a general-purpose computer with its own data entry and display assembly (DEDA) interface for the crew [37]. The computer was built by TRW of Redondo Beach, CA, USA. It had a smaller instruction set and a smaller memory, but a faster cycle time than the Apollo Guidance Computer [38]. TRW also supplied the software. This computer also used integrated circuits, supplied by Signetics, a Sunnyvale, CA, USA, company founded by employees who left Fairchild in 1961 [39]. Signetics was founded with the goal of producing nothing but silicon integrated circuits. It also specialized in a circuit design that had several advantages over the Fairchild products then available. The Fairchild chips used a form of logic that combined a set of resistors and transistors to carry out the NOR function. It was also known as "resistor transistor logic" (RTL). Signetics perfected a way of using not resistors but diodes in the circuit, which resulted in better performance: higher speeds, lower power consumption, and greater noise margins. The AGS used diode transistor logic (DTL). Thus, by getting a late start in the process, the AGS was in some ways a superior computer, even if it had a more modest design and fewer requirements.

The AGS was successfully tested during the Apollo 10 mission, and the Apollo 11 crew used it to assist in the rendezvous of the LM with the Command Module after the landing. It was never used as an emergency backup. In 1975, NASA conducted a brief analysis of the Apollo guidance and navigation systems. The study concluded that the redefinition and expansion of the capabilities of the AGS had its drawbacks. In particular, its display/keyboard, DEDA, was similar, but not the same, as the one used by the Apollo Guidance Computers ("DSKY"). That meant that the astronauts had to learn two separate sets of keystrokes that essentially carried out the same functions, thus increasing their workload. The report concluded that "Every consideration in future hardware definition should be given to placing redundancy in the primary system rather than incorporating a separate and different backup guidance system" [37, p. 64]. One may read that as an indictment of the MIT approach to reliability. This philosophy was carried out, to an extreme, in the Space Shuttle that followed Apollo.

By the time of the Apollo 8 mission in December 1968, around 400 devices could be "crammed," in Gordon Moore's term, onto a single IC. By that metric the functions of the Apollo Guidance Computer could have been carried out by around 100 ICs instead of the 5600 it used. Of course that was not practical, as the testing and validation process for Apollo or any aerospace application took time. Designers of aerospace computers cannot follow the practice of designers of modern consumer electronic products. Those who produce consumer products design the product not with the chips that are available today, but with chips that the engineers expect will be available on the day that production begins. The chip manufacturers have to deliver what they promise. They have been doing that for five decades now, and anyone who claims that Moore's Law is ending has to be willing to be embarrassed when it continues [40].

By 1968 neither Fairchild nor its spinoffs were interested in marketing or manufacturing chips with six transistors on them. By then Fairchild had mostly abandoned resistor–transistor logic, as did its competitors in the Valley. The chips used in the Apollo Guidance Computer were not made by Fairchild but by the Philco

Corporation, at a plant in the suburbs of Philadelphia, PA, USA. After the Apollo 8 mission in December 1968, the Fairchild employee newsletter reported how its products were of crucial importance in the Apollo telemetry system. The newsletter did not mention the Guidance Computer. Fairchild had moved on.

Philco's production line was crucial to the success of the Apollo missions. Yet the company is hardly discussed in the official histories. The company supplied thousands of integrated circuits, which had to pass rigorous quality control tests, and on which the lives of astronauts depended. Philco was paid for its work, although by 1965 the prices for the chips had dropped significantly. The contract did little to help Philco's position in the industry. In the late 1950s and early 1960s, Philco was a world leader in the production of fast transistors. The nascent minicomputer manufacturers located around Boston's Route 128 used them to great advantage as they competed with IBM and the other giants of the computer industry [41]. Beginning in 1953, Robert Noyce had worked for Philco before moving to California to work for Shockley [42]. For the Apollo chips, Philco had a cross-licensing agreement to use the Fairchild processes. It did not leverage the Apollo contract into a competitive position in the integrated circuit industry.

G. Apollo-Soyuz and the Fifth Computer

After the successful Apollo missions to the Moon, the United States struggled to come up with a sensible next step in human space exploration. Piloted missions to the Moon were cancelled after Apollo 17. Surplus Saturn-Apollo hardware was used successfully for the Skylab space station in 1973, to which three crews of astronauts visited. Finally, in 1975, an Apollo Command and Service Module was joined to a Soviet Soyuz capsule in low Earth orbit. The crews of the two craft met, shook hands, and exchanged ceremonial gifts, in hope of future collaboration in space. The Apollo-Soyuz mission was a one-off, however, and genuine cooperation between the United States and Russia did not occur until years later.

Once again the critical calculations for rendezvous and docking between the two spacecraft were carried out flawlessly by the onboard Apollo Guidance Computer. In case anything went wrong, the American crew carried a backup. In January 1974, the Hewlett-Packard Company of Palo Alto, CA, USA, introduced the HP-65 programmable pocket calculator, which stored instructions on magnetic cards the size of a stick of chewing gum. HP advertised the HP-65 as a "personal computer," although purists complained about that designation. Nonetheless, it did have the capability of performing complex trigonometric calculations, and it was programmable. The Apollo-Soyuz astronauts carried one into space, and NASA developed a set of programs for it to perform rendezvous and docking calculations, orient the high-gain S-Band antenna, and prepare the capsule for reentry, should the main computer fail [43], [44]. According to an HP advertisement in *Scientific American*, "… Using complex programs of nearly 1000 steps written by NASA scientists and pre-recorded on magnetic program cards, the astronauts made the calculations automatically, quickly, and within ten-digit accuracy." The HP-65's amazing capabilities came not only from its taking advantage of the progress in integrated circuits; it was also its use of an algorithm, called "CORDIC," that enabled it to compute trigonometric values quickly and economically [33], [45].[6]

One often hears the cliché about some consumer product having more power than the Apollo Guidance Computer that took astronauts to the Moon. In this case, we have an actual pocket-sized device working side by side with an Apollo Guidance Computer, carrying out similar calculations. The HP-65 used a special-purpose integrated circuit, provided by American Micro-Systems, Inc. of Santa Clara, CA, USA.

III. POST-APOLLO: THE SHUTTLE

In 1973, NASA was working on the design of the Space Shuttle's computers. Like the Apollo Lunar Module, the Shuttle had to land under computer control. The contract for the Space Shuttle General Purpose Computers went to IBM, not to Draper Labs. For the Shuttle, IBM used a variant of its 4Pi Model AP-101 avionics computer, two of which had been used on the Skylab space station, and which IBM had produced by the thousands for a variety of military aircraft and guided missile applications.

The 4Pi computers used transistor–transistor logic (TTL) integrated circuits. The chips had what was called medium scale integration [46]. They did not use a microprocessor. The computers also used magnetic core memory, with a capacity of about half a megabyte. By the mid-1970s, IBM was already shipping its mainframe computers with semiconductor memory in place of magnetic core—semiconductor memory was another advance pioneered by Fairchild [47]. Core was chosen for the Shuttle because it was a proven technology, and because it was "nonvolatile": it retained its data even if the device was unpowered. As with the Block I Apollo Guidance Computer, the Shuttle Computers were obsolete by the time of the first Shuttle flight in 1981. A later upgrade to the Shuttle avionics suite replaced the core with semiconductor memory, and the TTL logic with flight-qualified microprocessors.

The Shuttle used five general-purpose IBM computers. Although

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[6] Chuck House of Hewlett-Packard says that, as a company known for producing oscilloscopes that displayed data in the form of sine and cosine waves, it wanted its line of calculators to be of use to those customers who dealt with such data. Chuck House, private communication with the author.

designed a decade after Apollo, and in spite of Moore's Law, the weight and volume of the Shuttle computer system was no less than that of the computers used in Apollo. The fifth Shuttle computer was programmed by a different software team, to prevent a "common mode" software error that might infect all the computers with the same fatal bugs. NASA later concluded that software errors were less likely caused by poor coding practices than by errors in specifications, which in the case of the Shuttle would have affected the fifth computer as well.

IV. CONCLUSION

The above chronology shows an understanding of the need for redundancy to achieve the reliability necessary for aerospace applications. But at what level is the redundancy to be added? And how is that decision affected by the rapid evolution of microelectronics technology, an evolution that continues to the present day? The Apollo decision seems correct, although ground-based mainframes performed the primary navigation functions after Apollo 8. We see that the inclusion and use of the AGS in the Lunar Module was not as well coordinated with the primary computer as it could have been. We also see that the Shuttle orbiter could have performed its missions with fewer than the five general-purpose computers it carried, although its designers did not anticipate that the concept of "fail operational" would never be used.

The Apollo program was played out in the open. Launches were televised, the astronauts and their families were well known to the public, the technical details of the Saturn Rocket and Apollo Modules were explained in lay terms in great detail. The computer became a character in the drama of the first Apollo landing. The world learned that Neil Armstrong had to take over manual control of the LM, as the computer was directing him to land in a field of boulders. The story was later embellished: all the Apollo landings were done manually, by choice. It was not the fault of the computer that the planned landing site was not safe. The success of the Apollo missions was dramatic proof that the integrated circuit was real, that it could be used as the foundation for complex systems. Although far more Minuteman than Apollo computers were built, many aspects of the Minuteman guidance system were—and remain—classified. The missiles themselves were literally out of sight, buried in silos.

The early adoption of the IC allowed NASA to buy into the culture of innovation that was characterized by Fairchild Semiconductor. Had NASA chosen "molectronics," "cordwood," "micromodule," or any of the other competing ways of miniaturizing circuits, Americans might not have made it to the Moon by the end of the decade. That Fairchild moved on and ended up not manufacturing the Apollo chips did not seem to be a problem. The choice by MIT of using a single logic device, the three-input NOR gate, rather than the multiple devices that were used in Minuteman, worked, but it came at the cost of adding to the computer's weight. The Apollo computers were reliable. None ever failed during a space mission, although both MIT and IBM struggled with reliability problems in the early phases of the project. By choosing Fairchild and its dynamic management led by Robert Noyce, NASA tapped into the creative energies of what later became Silicon Valley. Yet that was not fully realized at the time, given the decision to use IBM hardware for the Shuttle. Calling the program the "trigger" of the microelectronics revolution is a stretch. However, the debates over reliability, which were so much a part of the race to the Moon, resonate well to the present day. ■

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