Reliability in the Apollo Program
A Balanced Approach Behind the Success

by Yasushi Sato

Reliability assurance is a central concern in the design and development of space systems. A minutest source of unreliability in a component or a subsystem can cause the loss of an expensive system. Reliability is all the more important in human spaceflight programs, where human lives are at stake. Thus the disastrous failures of Space Shuttles *Challenger* and *Columbia* have come under intensive scrutiny not only from technical but from organizational viewpoints.[1] On the other hand, reliability efforts in space programs that underwent no catastrophic failure have not attracted much scholarly attention. This does not mean that those successful programs achieved reliability with ease. Reliability assurance was an utmost issue in those programs also. Their reliability problems are relatively invisible retrospectively only because of the lack of conspicuous tragedies. [2]

Official histories of the Saturn launch vehicles and the Apollo spacecraft do note the importance of reliability. They also briefly review the techniques used, including the failure mode and effect analysis, the closed failure reporting and corrective action scheme, and the systematic implementation of design reviews. They also discuss conservative engineering practices of NASA and contractor engineers, such as the use of proven parts and techniques, the pursuit of simplicity, and the elaborate deployment of redundancies. These studies, however, see the question of reliability in the Apollo program in a largely static manner. They do not tell how the reliability approach at NASA evolved over time.[3]

This article describes NASA's effort to establish effective approaches to assure reliability of the Saturn launch vehicles and the Apollo spacecraft. In the beginning of the 1960s, NASA had no consistent philosophy on how to achieve high reliability of those systems. Engineers at NASA headquarters, the Marshall Space Flight Center (MSFC), and the Manned Spacecraft Center (MSC) had diverse assumptions on this question. Only after a long period of trial-and-errors and negotiations did they attain workable approaches.

Some explanation on the word "reliability" is in order. Sometimes "reliability assurance" and "quality assurance" are understood as mutually exclusive in meaning. For example, an engineer at MSC said: "In simple terms, reliability means the thing is designed so that it will work; quality means that it is built so that it will work."[4] In other cases, however, reliability is a more general term subsuming quality assurance. [5] This article adopts the latter usage and uses the word "reliability" to mean generally the ability of achieving expected performance.

This article does not intend to describe the whole reliability program in the Apollo program. Instead, it demonstrates the fact that divergent philosophies in the early 1960s interacted with one another until workable approaches emerged in the mid-1960s. Some advocated extensive use of statistical techniques based on test data, while others stressed the inherent soundness of design. Striking the proper balance between the two gave rise to the high reliability of the Apollo spacecraft and the Saturn launch vehicles, which in turn enabled the successful completion of the program.

RELIABILITY OF THE SATURN LAUNCH VEHICLES

The Need for a New Approach

The problem of reliability assurance predated the Saturn launch vehicles. Earlier missiles and rockets were also complex and expensive enough to call for acute awareness of the importance of reliability.6 The primary means for reliability assurance in those earlier programs was extensive testing, not only at the component and subsystem levels but also at the level of the whole vehicle. The test firing of many flight models directly demonstrated the rate of success. Only after the reliability of a vehicle was actually proven did it come into use for human spaceflight. Thirty-seven Redstones had been fired before the missile was declared operational and then was used for astronaut Alan Shepard's suborbital flight.[7] More than 100 Atlas missiles had been launched before the rocket carried astronaut John Glenn to an Earth orbit. [8]

In the beginning of the 1960s, Don R. Ostrander, director of the Office of Launch Vehicle Programs at NASA headquarters, still upheld this approach. Ostrander, an Air Force Major General temporarily on loan to NASA, had an overall responsibility for all of NASA's rocket programs. He argued that NASA must "create a fleet of standard vehicles with a minimum number of different designs and configurations." Then, he continued, NASA must "attain a high degree of reliability through repetitive use of these basic vehicles, much as the automotive industry has achieved reliable cars through the millions of miles of driving on each of their standardized vehicles." Here Ostrander was talking about launch vehicles in general but also had in mind those for human spaceflight programs. [9]

This approach of actually verifying the statistical probability of successful flights no longer worked for satellite and launch vehicle projects of the 1960s. They became so expensive that reasonable financial resources did not allow the building of

many flight models. Nor was there long enough time for testing all these models, especially in the urgent circumstances of the Cold War. Thus the development of the Saturn launch vehicles required NASA engineers to formulate a new scheme to estimate and improve their reliability.

From Divergent Philosophies to an Integrated Approach

In the early 1960s, officials in charge of reliability policy at NASA headquarters were engineers with background in statistics such as Nicholas E. Golovin and Landis S. Gephart.10 Even those statisticians were aware that it was impractical to directly verify the success rate of launch vehicles through large numbers of test flights under actual operating conditions. Instead, they argued for the indirect use of statistical techniques: first, components and subsystems are tested under simulated environments, such as vacuum, vibration, and extreme temperature; second, functional diagrams representing the relationships between these components and subsystems are translated into statistical terms. These procedures then make it possible to integrate the reliability numbers of components and subsystems and thus to calculate the reliability of the entire system.[11]

Von Braun and Marshall engineers, on the other hand, tended to belittle NASA Headquarters' statistical approach. Von Braun admitted that statistical reliability analysis was a powerful tool. Yet he believed that it was not an independent statisticians' group at NASA headquarters that would guarantee the reliability of launch vehicles. What was fundamental to reliability was, he argued, "an almost religious vigilance and attention to detail on the part of every member of a development team."[12] This approach emphasized carefulness in work throughout the entire developmental phases, constant and meticulous search for errors and defects in hardware through inspections and testing, and strict and thorough implementation of corrective actions.

Other Marshall engineers shared von Braun's view that reliability assurance was the inherent responsibility of individual engineers. One of his aides believed that reliability belonged "in the first class" to the engineer himself and asserted that "If the engineer designs one piece of hardware, he also has to look into the reliability."[13] From their viewpoint, engineers practicing hands-on work, not statisticians, knew best how reliable the hardware was. The center's intensive reliability effort extended to its contractors. Marshall engineers closely supervised their contractors' operation and meticulously pointed out sources of the unreliability. In 1962, von Braun once told D. Brainerd Holmes, Director of the Office of Manned Space Flight at NASA headquarters, that the penetration of contractors' operation by Marshall engineers did "more for reliability than all the statistical studies combined - in my humble opinion, at least."[14] His observation was justified when all ten Saturn I launch vehicles achieved successful flights from 1961 to 1965 despite pessimistic predictions by theoretically-oriented reliability experts.[15]

At the same time, however, Marshall engineers did not ignore analytical methods that engineers both within and without NASA were refining in those days. One of such methods was a technique called the failure mode and effect analysis. It was a method to identify the most likely patterns of failures of a particular system and estimate the effects of those failures on the sound functioning of the system. Then, those patterns of failures were eliminated one by one by either deploying redundancy or sacrificing the systems' specifications. A closely related method was the criticality analysis. Engineers assigned criticality numbers, which indicated the relative degree of criticality of components or subsystems for the success of the entire system, to all parts of the system. Then they determined the optimum apportionment of reliability requirements to those components and subsystems, taking their criticality into consideration.16 As Marshall engineers came to recognize the usefulness of those analytical methods, they sought to incorporate them in their scheme of reliability assurance.

Coordinating the reliability efforts of various elements of the center was crucial, because a change in the reliability of one component or subsystem affected that of others, and also because interfaces of components and subsystems were themselves typical sources of unreliability. The principal places for the integration effort were weekly and special meetings. In those meetings, engineers in charge of reliability analysis brought up potential failure patterns, alternative designs, and trade-off factors. They discussed such issues with engineers from laboratories and project offices, and sought consensus on the course of actions to be taken.[17]

As MSFC aimed for a balanced approach integrating statistical/analytical methods with engineers' unremitting efforts, NASA headquarters also came away from the purely statistical approach. Golovin, the strongest proponent of the statistical approach, left his position in the Office of Manned Space Flight in late 1961. A less adamant statistician, Gephart, came to call for the integration of the two extreme views of von Braun and Golovin.[18] He still considered it "essentially pointless" to discuss reliability without quantitative technique.[19] He did not emphasize statistical methods too much, however: "Reliability engineering can be viewed as a mating of sound engineering disciplines with analytical techniques." [20]

NASA headquarters' reliability philosophy changed even more when Joseph F. Shea, a senior systems engineer, joined NASA in the beginning of 1962 as Golovin's replacement. With his experience in military missile programs, he had a practical view on the problem of reliability. He considered the statistical demonstration of reliability impractical not only for the entire vehicles but also for subsystems due to limitations in cost and time. Cautioning against the tendency of engineers to be attracted to the superficial rigor and precision of numbers,[21] he argued that "The statistical confidence must be replaced with 'engineering confidence.'" [22] The key to attain engineering confidence, in his view, was "the rigorous identification of the cause for all failures encountered during all phases of developmental testing." Shea's boss, Mueller, also supported Shea's view, asserting that in the Apollo program they were attempting to replace "statistical confidence" with "inherent confidence."[23]

Meanwhile, Golovin, who left NASA in April 1962, still advocated statistical approaches. He admitted the importance of "engineering judgments," which involved "the weighting of many elements and only some of which can be usefully reduced to quantitative form." At the same time, however, Golovin saw such judgments as often "relatively subjective" and criticized the "escape to 'engineering confidence.'" Thus he continued to insist on the "increased emphasis on quantitative methods." He believed that "the route of greater reliance on qualitative approaches, such as those based on, so called, "engineering judgement [sic]," avoids rather than solves the problems which must be overcome."[24]

By contrast, von Braun's team at

MSFC habitually let their engineering judgment override statistical analysis. An example was their decision regarding the configuration of the first stage of Saturn I. They were contemplating whether to include the "engine-out capability," a redundancy mechanism that would enable the rocket to continue its mission even when one of the stage's eight engines malfunctioned. In making a decision in the affirmative, they weighed a wide range of factors--a sophisticated mathematical analysis on the net gain in reliability, the effect of the redundancy on requirements in the vehicle's guidance scheme and structural strength, the possibility that it might result in a more favorable abort condition for a crew, and the probability that a similar mechanism might be needed for a later booster.[25] Marshall engineers made use of statistical analysis, but their final resort was their overall engineering judgment.

Conservatism vs. the All-Up Concept

In practicing either quantitative or qualitative approaches to reliability, testing was the most fundamental activity. At MSFC, approximately 50 percent of the total man-hours for the development of the Saturn launch vehicles were spent for testing.26 Engineers at the center tested the hardware thoroughly and rigorously. Not content with conducting routine tests, they often deliberately let potential problems happen and made sure that they would not lead to catastrophic failures. One famous example was their testing of the F-1 engine, which was used for the first stage of Saturn V. In the course of developing the F-1, they struggled for years with the nagging problem of combustion instability. In testing combustion chambers, they intentionally caused instability by placing a small bomb inside and letting it explode. Then they saw if the instability would converge and the combustion would return to normal. [27]

Marshall engineers were conservative in designing and developing hardware. They used proven parts and components wherever possible, and set relatively high safety margins. According to an industrial executive, they required 35 percent safety margin in structural design where the Air Force required 25 percent.28 Their testing practices also reflected their conservatism. They actually let components and subsystems break down in ground tests by testing them in tougher environmental conditions and for longer periods of time than those in actual missions. By such a rigorous testing process, which they called "limit testing" or the "testing to failure" philosophy, they could tell how robust the hardware was.[29]

Their conservatism and "testing to failure" philosophy had a remote origin. Using testing as a primary means for identifying and solving problems was their tradition from the Peenemünde period. With scientific theories in relevant fields sparse and engineering experience still limited, failures in testing taught them more than anything else. Failures were often more instructive than successes; they were "successful failures" in historian Michael J. Neufeld's words.[30] Peenemünders made progress by knowing what not to do rather than what to do. They carried this testing practice into the 1960s.

It might seem paradoxical at first sight that such an entrepreneurial group of people who pioneered the field of rocketry harbored conservatism in engineering. But it was exactly because they had to build the body of knowledge in rocketry from scratch that they acquired this solid approach. Their fundamental method in pursuing the art of rocketry was to extend and clarify the boundary of their art and knowledge step by step through "successful failures" and "limit testing." When they actually built hardware, they depended on what was within the boundary at that time, and then added safety margins that they felt proper from their experience. This was how they built the high reliability of their hardware incrementally.

Marshall engineers' conservatism sometimes had to be compromised with the tight schedule of the Apollo program, however. In 1963, their cautious, step-by-step plans for the flight tests of Saturn V gave way to NASA headquarters' direction to adopt a crash approach. Marshall's original plan was to fly the first Saturn V in March 1966 with a live first stage and dummy second and third stages, then the second vehicle in July with live first and second stages and a dummy third stage, and finally a complete live vehicle if the preceding two were successful.[31] Von Braun's team had always taken this incremental approach in the past. It had an advantage of offering them opportunities to cope with technical difficulties, which they could not foresee but nonetheless expected to be there. With Saturn I, they had actually implemented this step-by-step approach. The first three flight models of the two-staged Saturn I had only the first stages live. The fourth Saturn I had both stages live for the first time.[32]

This cautious approach was abandoned soon after George E. Mueller joined NASA headquarters in September 1963 as Associate Administrator for Manned Space Flight. Mueller proposed the "all-up" concept for Saturn V, which meant launching a complete vehicle with its all three stages live for its first flight. Mueller knew that the Air Force had already adopted this approach, for he had previously been involved in Air Force missile programs for a few years as a contractor's executive. Mueller decided that NASA should apply this approach to the Apollo program because there was not enough time left for the step-by-step flight testing to reach JFK's goal of "the end of the decade."

Marshall engineers, who had taken their step-by-step testing philosophy for granted, reacted to Mueller's proposal with "shock and incredulity."[33] In light of their experience to that day, the all-up testing for an unprecedented launch vehicle like Saturn V appeared impossible. For them, Mueller's idea violated the conventional assumptions on how to assure the reliability of the complex system. Von Braun, however, promptly decided to follow Mueller's direction.[34] He valued loyalty and order, and had always followed directions of his boss ever since the Peenemünde period. At the same time, he was persuaded by Mueller's argument that the step-by-step approach actually did not increase the overall success rate of the Saturn V program.[35]

Mueller's bold all-up approach worked. It turned out that all thirteen Saturn Vs completed their missions successfully. Von Braun later reminisced that the all-up decision "sounded reckless, but George Mueller's reasoning was impeccable."[36] Others considered that it was Mueller's gamble. Nobody could prove at that time that it would work; but nobody could prove that it would not. The decision was proper because it worked; it would have been improper if it had not worked.[37] A little after the decision for the all-up testing, Mueller's staff sponsored a study on the reliability of the first all-up launch of Saturn V. The contractor who did the study reported the number of 0.497 or 0.682, depending on the availability of the engine-out capability.[38] These numbers might have given Mueller reasonable confidence. But Marshall engineers must have regarded them as invalid, still less with their three-digit significant figures.

Aside from the validity of such a mathematical analysis, what led Mueller to his judgment for the all-up approach was his logical reasoning that there was no specific problem expected with the vehicle. On the other hand, Marshall engineers believed from experience that such reasoning was usually not good enough to anticipate all problems in advance. They had by then gone through such a long period of constantly encountering failures that they assumed that they had to find out through step-by-step testing what those unanticipated problems were. Their disagreement can thus be seen as one between Mueller's confidence in his own reasoning and von Braun team's experiential judgment. In this instance, the advocate of reasoning had the decision-making authority, and the embodiment of experience was ready to comply. As it turned out, this interaction of reasoning and experience resulted in a fortunate turn of events.

Engineers at MSFC and NASA headquarters thus solved the problem of reliability inherent in the development of launch vehicles with the blend of statistical treatment and vigilant attention, cold reasoning and long experience. A speech by Eberhard Rees, the center's deputy director who had closely followed the reliability problem of the Saturn launch vehicles in the first half of the 1960s, summarizes well how they overcame the problem. Rees declared in 1965 that engineers at MSFC and its contractors had now arrived at a rather clear concept on how to achieve high reliability. . .It is, in one sentence, the application of sound and knowledgeable engineering and engineering judgment - let me repeat the word "engineering judgment" - based on long-range experience and supported by all the analytical tools ... such as detailed analysis of each component and subsystem, logic diagrams, mathematical models, etc., and then most important, an exhaustive test program, system tests program, and a quality assurance program[39]

RELIABILITY OF THE APOLLO SPACECRAFT

Combination of Quantitative and Qualitative Techniques

As Marshall engineers struggled to attain proper reliability of the Saturn launch vehicles, those at MSC faced the same problem with the Apollo spacecraft. The Mercury program had started before 1960, when the center was still called the Space Task Group. In the 1960s, they moved on to develop the Gemini spacecraft and the Apollo spacecraft. Although those programs overlapped in developmental period, later programs benefited from the experience of earlier ones. Reliability approaches at MSC evolved continuously through these programs.

From the beginning, engineers at the center knew that attaining perfect reliability was impossible. Although human lives were at stake, they did not believe that inexorable concern for crew safety should unduly preclude their developmental effort from moving forward. Walter C. Williams, who led the operations segment of the center in the early 1960s, once talked of "the trade-off between emphasis on crew survival as such, and the end accomplishment of the mission."[40] While he said he had much respect for the value of life, he considered it necessary to recognize that risks would remain. Joseph F. Shea, who joined MSC as manager of the Apollo Spacecraft Program Office in 1963, had a similar view:

> The program ... must maintain the proper balance between the safety of the crew and the success of the mission. Although we desire the probability of safe return of the crew to be approximately one-hundred times greater than the probability of mission success, the designs cannot be implemented only to provide safety. In the limit, the safest mission will be one in which the abort rules are set up so that the vehicle never leaves the pad - obviously reductio ad absurdum.[41]

The relative reliability requirements for mission success and crew safety would actually change over time.

FIGURE 1: Probabilistic Reliability Program [48]

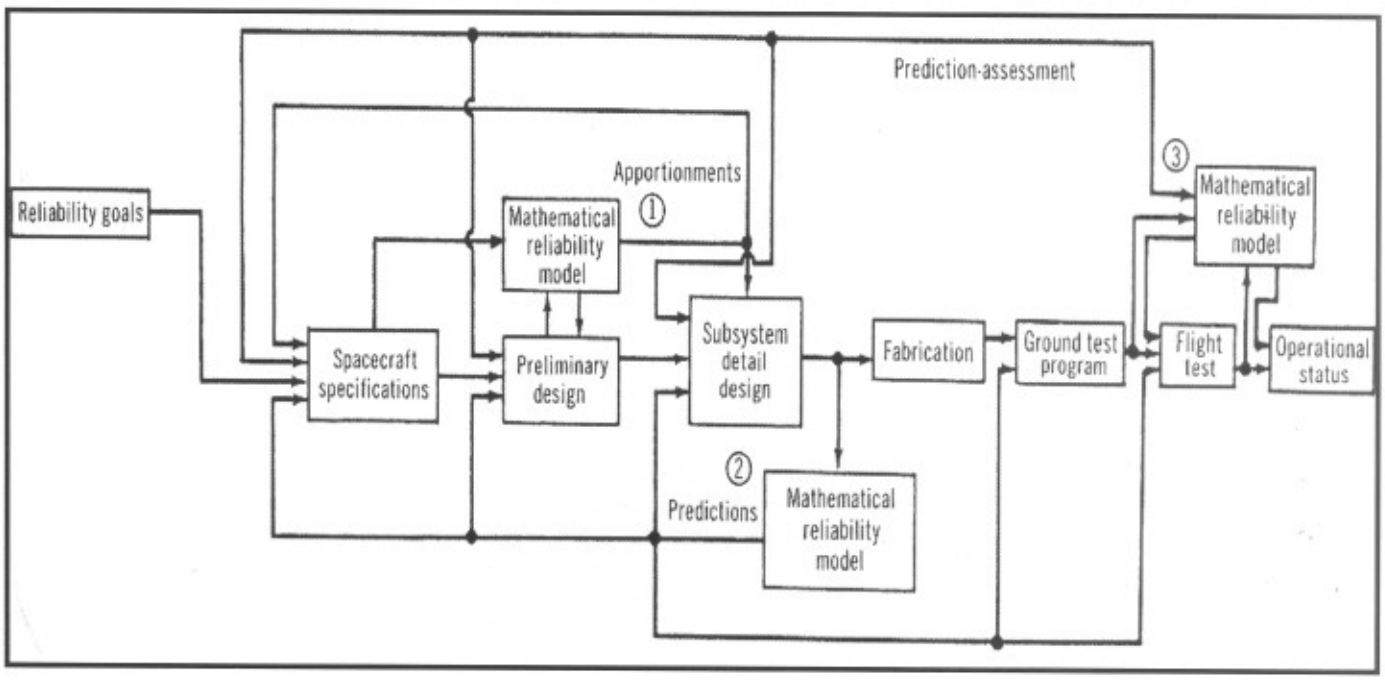
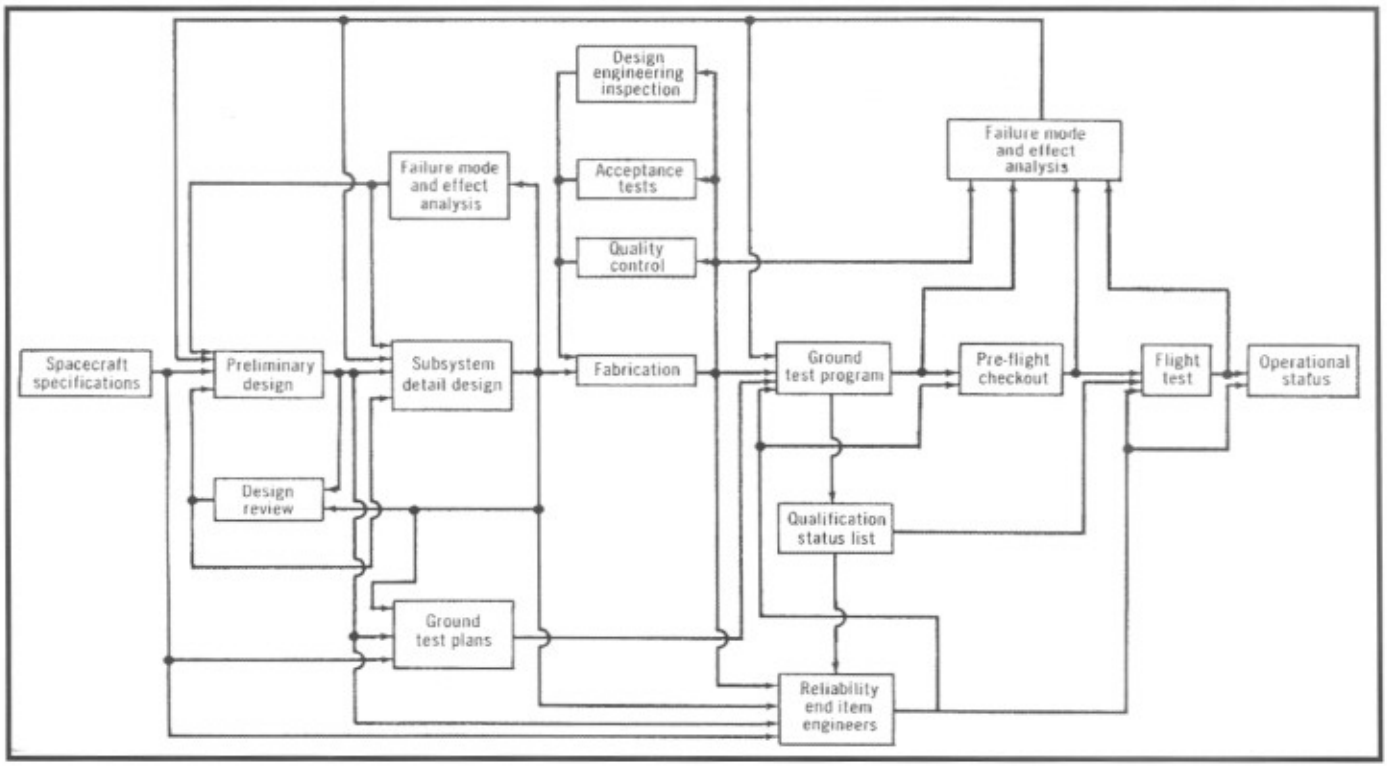


FIGURE 2: Qualitative Reliability Program [49]



Generally the probability of crew safety was set an order of magnitude higher than that of mission success.

In achieving a high level of reliability, the management of MSC believed that human-oriented approaches were fundamental. Robert R. Gilruth, the director of MSC, once wrote: "Accomplishing true reliability will require people who will never overlook or ignore, but rather who will recognize, the slightest sign of trouble - people who will freely give the last bit of extra effort that so often spells the difference between success and failure."[42]

The center's deputy director, George M. Low, echoed Gilruth's view. Low stated that what was needed to eliminate the minutest flaws and attain the near-perfect reliability was "a dedication to get the job done well, by all people, at all levels, on every element of Apollo."[43] For Gilruth and Low, it was high morale and uprightness of those involved that constituted the reliability of space systems. In order to add a personal motivation in men in the plants and shops, the management of MSC often had astronauts meet with them.[44]

While the management thus emphasized the human aspects of reliability effort, engineers at MSC did not ignore analytical/statistical techniques. Like their counterparts at MSFC, they defined the overall numerical reliability and safety requirements and apportioned them to each subsystem and component. They did so not to strictly enforce such numerical requirements; they knew that was impractical. Instead, their rational was to let those reliability numbers "act as a guide and goal for the individual designers."[45] Thanks to those numbers, designers of subsystems and components could make decisions on "the degree of redundancy, derating of parts, and other reliability improvement measures."[46] Here "derating" means reducing stress on parts to levels below their specified ratings or their proven capabilities and thereby enhancing their reliability.

As was the case with Marshall engineers, engineers at MSC took the position that a combination of quantitative and qualitative techniques would offer the best strategy in assuring reliability of the Apollo spacecraft. Owen G. Morris, chief of the Reliability and Quality Assurance Division in the Apollo Spacecraft Program Office at the center, stated: "Although reliability cannot be rigorously demonstrated [through quantitative methods], unreliability can."[47] In other words, proper use of statistical methods would make any unreliable components and subsystems evident and enable appropriate corrective actions. On the other hand, Morris of course appreciated the role of qualitative techniques as well. Particularly important among them were failure mode and effect analysis, closed-loop failure reporting and corrective action, and preflight checkout. (See Fig. 1 and Fig. 2.)

Engineers at MSC also shared conservatism with their counterparts at MSFC. They used proven components and simple designs even at the cost of some performance. For example, they restricted the use of integrated circuits, which still had relatively few years of history then and expected developmental problems. Only where the potential gain in reliability and weight was significant enough did they use integrated circuits.50 They also tested hardware in excess of the expected environmental conditions to identify failure modes. Through the numerous cycles of taking corrective actions and retesting, the system achieved reliability.

Testing in various phases of design and development was cardinal for reliability. Early in the design cycle, engineers conducted developmental tests to obtain data useful for design. When prototype models came up, they conducted qualification/certification tests, by which they verified the soundness of design and the

proper functioning of the hardware in all environments, such as vacuum, vibration, and extreme temperatures. Finally, in acceptance tests, engineers tested flight items to make sure that there was no manufacturing error. Those tests applied to all levels of systems, subsystems, and components. Low asserted: "The single most important factor leading to the high degree of reliability of the Apollo spacecraft was the tremendous depth and breadth of the test activity."[51]

Redundancy was employed wherever practical. All subsystems, except the structure, heat shield, and certain portions of the main propulsion systems, contained redundancies. There was a basic mission rule calling for the abort of a mission when one more failure in a critical component would cause loss of the crew. Therefore, engineers at MSC often used triple redundancies, which allowed one out of three elements to fail without requiring abort.[52] Along with conservative engineering practices in component selection and intensive testing, extensive and elaborate use of redundancies helped assure the reliability of the Apollo spacecraft.

The Question of Onboard Maintenance

A unique problem in the reliability assurance of crewed spacecraft was whether astronauts onboard should perform maintenance activities. In the early years of Project Mercury, the pilot was hardly expected to maneuver, let alone conduct maintenance on, the spacecraft. Systems were designed to function automatically, as the capabilities of humans under alien conditions of weightlessness and radiation, were unknown. One could expect that astronauts would have physiological or psychological breakdowns and lose capacity for maneuver.

However, once the experience of Mercury revealed that astronauts could function well in outer space, the role of astronauts was greatly augmented. Many engineers at MSC, who had previously worked on aircraft research at NACA, were eager to give astronauts large room for maneuver. Those NACA veterans respected pilots and had propensity to emphasize human role in assuring reliability. George M. Low, for example, asserted in 1961 that "the reliability of any system is greatly enhanced by the integration of man into the system." Low pointed out that many flights of the X-15 rocket airplane would have failed without a pilot correcting malfunctions of the system. "Only man can cope with the unexpected," Low said.[53]

Thus the role assigned to astronauts had become large by 1963, when Shea joined MSC. In addition to the normal tasks of maneuvering the spacecraft, monitoring the systems, and communicating with the ground, astronauts were now expected to carry out maintenance of the spacecraft during the flight. In this scheme, the astronauts would carry tools and spare components with them and replace the malfunctioning components of the spacecraft as necessary. Thus, as Shea observed, "the pendulum [had] swung very far" into the other direction on this basic problem in crewed spaceflight.[54]

By mid-1964, however, the concept of onboard maintenance died. Astronauts were relieved from the task of maintenance during flight. This reversal of trend resulted from both the operational and systems engineering viewpoints. First, it became apparent that onboard maintenance during lunar orbital maneuver was impossible. Christopher C. Kraft, who took charge of operational activities at the center from 1963 on, argued that astronauts simply would not have time to do maintenance during the busy maneuvering phase. Grumman, the contractor, agreed, maintaining that onboard maintenance would end up with degraded reliability.[55]

Following the decision to cancel onboard maintenance for the Lunar Module, the concept was dropped for the Command and Service Module also. After weighing such factors as the weight increase incurred by tools and spare components, the decrease in reliability of spare electronic components due to humidity of the cabin, and the time-criticality of the expected failures, Shea in April 1964 concluded that NASA no longer favored onboard maintenance. Instead, he took the approach of preparing redundant, black-boxed components built into the system so that astronauts could switch to them in case of the malfunction of main components.56 Thus NASA corrected the pendulum that had gone too far and established a balanced position.

MSC approach to reliability assurance emphasized the proper combination of human and analytical aspects of the problem. In this sense, engineers at the center shared the basic philosophy with MSFC engineers. They faced a problem unique to crewed spacecraft, however; they had to define the extent to which astronauts would be involved in assuring the reliability of spaceship. Their viewpoints moved back and forth between the extremes in the first years, but then stabilized toward the mid-1960s.

CONCLUSION

When the Apollo program started, NASA engineers had no clear prospect on the method and feasibility of lunar landing, still less with the reliability approach that they would employ. It was clear that the conventional approach of statistically demonstrating the rate of successful missions was impossible. Yet NASA engineers needed to attain a near-perfect reliability in the human spaceflight program. It took several years for NASA headquarters, MSFC, and MSC to establish workable approaches to assuring reliability of the Saturn launch vehicles and the Apollo spacecraft. Engineers at both MSFC and MSC consistently emphasized the importance of nonanalytical aspects of reliability assurance-religious vigilance and attention to detail, "engineering judgment" and "engineering confidence," and dedication for work by all those involved. As they came to recognize the usefulness of statistical techniques, they also incorporated them into their reliability efforts.

This article has focused mainly on the evolution of reliability philosophies and approaches in the Apollo program, while discussing the actual practices-testing, use of redundancy, failure reporting-only in a sketchy manner. More research in this area would lead to a fuller understanding of the reliability effort in the Apollo program. It is certain that studying past failures and troubles is vital in reflecting on the reliability of space systems. But it is also important to learn from the experience of engineers who overcame difficult reliability problems in successful programs.

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