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Marshall Space Flight Center Approach In Achieveing High Reliability of the Saturn Class Vehicles

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On the subject of reliability and approaches to its achievement, I guess thousands of papers have been written and thousands of speeches and presentations have been delivered in the past ten years. As a matter of fact, barely any issue in recent years has prompted as many heated debates which have been carried through with almost religious fanaticism as the reliability question. These debates have focused mainly on reliability philosophies and concepts, on definitions: what is reliability after all?, on the mere mathematical - or better, the analytical - approach vs. common engineering practices. In the discussions, both parties usually went to the extremes and the meetings finally ended without any tangible results. Both parties departed to their desks, drawing boards and shops with ill feelings. I have been in many of these meetings, siding with the practical engineer because we have a hardware job to do, always with a tough time schedule and very limited funds, with the hardware complex and at the boundary of known technology.

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Now, were these discussions really so fruitless as they seemed to be? On the way home after the meetings I could not get rid of some points the guy on the other side of the fence was making -- something sunk into me and my rigid concept started to become somewhat weakened. Of course, a hard-core man does not admit that to the outsiders - but I admitted it to myself and to my associates. The most difficult task was to convince our design and laboratory engineers and those of some of our contractors that, for instance, detail analysis of components and subsystems, the study of characteristic failure modes, the application of mathematical models, the use of logic diagrams, the establishment of relative reliability numbers or ranges of numbers, etc., are helpful and necessary tools for obtaining high probabilities of mission success. Now what could management do to introduce these tools?

We at Marshall set up a reliability group under the technical top management mainly for establishing guidelines, policies, and concepts. Simultaneously we established reliability groups under each Division Director in the various disciplines such as mechancial design, electrical design, guidance and control, quality assurance, etc. We insisted, however, that these groups consist of men who had a good background in hardware development. At the same time we hired a reliability contractor who had to work directly with our engineers in Huntsville. This integration into our operation of contractor personnel, who could demonstrate by day-to-day hard work to the hardware designer - and not merely by talking philosophy, helped greatly.

We, together with that contractor, analyzed already designed components, and especially subsystems, and we could show where, for instance, redundancy would increase reliability or where other methods of operation of a subsystem would decrease the possibility of malfunction. We set up logic diagrams for component and subsystem functions which, I believe, are excellent tools for analyzing a situation. To the electronic engineer this has been a common method but, surprisingly, the mechanical design engineer in the past made little use of it. We arranged design reviews on the component level, set up preferred parts lists, qualification programs, etc. This instigation and penetration program of reliability consciousness into our operation worked out better than I had dared to hope, so we felt that we could dissolve the group reporting directly to our top management and give the job to our Quality Assurance and Reliability Laboratory for the whole Center.

Of course, in accepting some of the mathematical and analytical methods we did not abolish good old engineering principles whatsoever. I do not believe that - at least in the earlier days of our fight for the common engineering approach - we made too much of an impact on the theoretical people on the other side of the fence with our arguments. Although we, together with the prime contractor, conducted a very successful reliability program based on sound engineering practice on the Pershing Guided Missile for the Army, this did not come into the limelight too much. It was the big Saturn I launch vehicle whose reliability - at that time before the first launching - was questioned by reliability theoreticians. The first task assigned to the reliability company which I mentioned before was to come up with a figure of inherent reliability on the first stage of the Saturn I launch vehicle design. Due to the engine-out capability designed into the 8-engine cluster, and due to the fact that the H-1 engine is a simplified version of the well-proven Atlas first stage engine, the Jupiter and the Thor engine, in combination with other factors, the mechanical part came out quite well - not so, the electrical part. The reliability company, based on lack of numbers for our design, had taken into its calculations figures at that time common to electronic components, especially as to connectors, relays, etc. We could show that the particular components selected for the Saturn I guidance, control, wiring, power supply, telemetry, etc., were well proven in other systems and had excellent records, or that new parts were designed on sound engineering principles. The final study yielded a fairly good reliability figure of somewhere close to .766 for the one-stage version of the Saturn I system prior to first flight. This was to the surprise of some of the more theoretically inclined reliability people who still believed that there might be a high probability that the vehicle would blow up at lift-off or during the early part of its flight. As you all know, it did not, although no mathematical reliability model was applied in its design, but mainly good engineering principles and sober engineering judgment. We applied a good qualification program and assessment of all components and subsystems and we had an excellent inspection, quality control and assurance program based on the principles which later became a salient part of the NASA NPC documents 200-1, -2, and -3.

This success proved our point to the extremists of the mathematical model community and made a noticeable impact on them, too, as we became impressed by some of their analytical approaches which we later applied extensively to the Saturn I 2-stager.

In telling you, maybe somewhat too elaborately, this story of the past, I just wanted you to know we went through the reliability struggle I feel you all had, more or less, in your own plants or program offices. We at Marshall Space Flight Center, together with our prime contractors in the Saturn launch vehicles for the Apollo program, have now arrived at a rather clear concept on how to achieve high reliability, or rather, on how to obtain high probability of mission success. 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 I have mentioned before, such as detailed analysis of each component and subsystem, logic diagrams, mathematical models, etc., and then most important, an exhaustive qualification test program, system tests program, and a quality assurance program according to NASA manuals NPC 200-1, -2, -3 and NPC 250-1 for reliability. Based on Marshall's general guidelines and the mentioned documents which are spelled out in the contract, each prime contractor establishes his own reliability program. We discuss these programs in detail with him but we do not, and should not, insist that each contractor plan and execute it exactly the same standard way.

We feel that the contractor should have room for his own initiative and imagination.

With this general approach we were able to demonstrate nine successful mission completions of the Saturn I launch vehicle out of nine launchings. Based on this record I am confident that the 10th launching, which happens to be tomorrow, will also be successful. This then concludes the Saturn I program with ten successes out of ten - I hope. Of course, this does not mean that the Saturn I launch vehicle now has a proven 100% mission reliability in the statistical meaning of the word. Due to constraints of time and funding, we were not able to run statistical reliability tests of all components with the proper quantity for establishing real meaningful reliability figures but we <u>can</u> make the statement that - considering all these program restraints - everything feasible was done to make the Saturn I as highly reliable as possible and we would have had utmost confidence that each manned space flight mission flown on this launch vehicle would have been successful.

During the execution of the Saturn I program we had - among minor difficulties - two salient occurrences which I think are worthwhile to recall briefly in context with this reliability conference - one on engine-out and the other on stress corrosion.

In order to test whether the engine-out scheme on the 8-engine cluster of the first stage would work, we, in one of the earlier flights, deliberately cut off one engine.

It worked well, but we hopefully thought that this scheme would never have to be enacted. However, due to a malfunctioning gear box of an older design version, we lost one engine during the sixth flight of Saturn I. If I remember correctly, it was after about 90 seconds or so of flight. We would have lost the whole mission had the sensors and the cut-off of this particular engine not worked properly and the guidance system not corrected out the deviation from the nominal trajectory caused by the loss of this engine. We really obtained the proper orbit. In this case the inherent reliability designed into the system had saved the mission although a weak component had been flown.

The other case: During a pressure test at Cape Kennedy a crack in the LOX dome on one engine of the first stage became apparent. An investigation revealed that there was a case of stress corrosion and we found beginnings of stress corrosion also in the LOX domes of some of the other engines. We pulled all the engines, and retrofitted them with new LOX domes from forgings of a more strrdd corrosion resistant material. This example shows that no reliability approach or concept could have helped us because when this engine was designed the best material of stress corrosion resistance known at that time was selected and the forging, machining and heat treatment process was well controlled. In the meantime, progress in the technological state-of-art as to stress corrosion was made.

In both cases we and the contractor knew the weaknesses of these components but, due to time pressure and long lead times involved, we decided to take the seemingly small risk to fly them in the unmanned version of the Saturn I because many of these types of gear boxes and many of these types of LOX domes had been tested and flown successfully before.

With the experience and knowledge gained by Marshall Space Flight Center and its contractor team, and with the application of many of the same or similar parts, components, subsystems and systems from the Saturn I program, we are going into the Saturn IB and Saturn V programs with greater confidence.

I don't think it is necessary to describe to you the technical features of these launch vehicles, how they function, and how they will be used. I presume this audience knows all about this. Let me point out, however, that the planning for these two launch vehicle classes of the Apollo program is markedly different from every other manned space flight program and from the Saturn I. The Redstone Missile and the Atlas Missile together had close to 200 flights before their use as boosters on the Mercury program. Also, the Titan II had a long record of successful test flights as a weapon system before the first manned Gemini mission was flown.

The time schedule for the manned lunar landing mission does not allow such a number of test flights for the development of the Saturn IB and Saturn V. In addition, the high cost per launching of the huge Saturn V is prohibitive. On the other hand, the reliability goals for these two vehicles serving the extremely complex manned lunar mission have to be as close to the figure "one" as possible. Moreover, we have to shoot for these goals early, starting with the very first flight.

The few unmanned launchings allowed prior to the manned ones each carry important spacecraft missions in addition to the launch vehicle development missions. In other words, every launching has to be successful in all aspects. We cannot permit ourselves the luxury of learning and gaining experience and knowledge by failure during lift-off and flight. It is even mandatory that preparations for flight and countdown proceed as flawlessly as possible. If you add to these requirements the complexity and size, especially of the Saturn V, you will realize the enormous challenge of this program with regard to the reliability problem.

Right from the outset it can be stated that a classical reliability test program resulting in a statistical reliability figure and the proof of numerical reliability goals by testing is not in the cards for all components and systems. We will, however, conduct such test programs wherever feasible, especially in the area of small components. Confidence in larger components and their proper function under prevailing environmental conditions will be established by a thorough qualification test program and by testing them within the system. Considering the constraints we have to live under in the program, I do not believe that we can ever prove an established numerical reliability goal.

In the following I will now briefly touch on the various hardware groups and systems and give some few examples of our approach to achieving high reliability:

1. Launch vehicle stages

For the development of each stage we have in principle established five full-size ground test stages in the program; namely, a stage for structural testing, a stage for dynamic testing, a stage for checkout of the launch facilities at Cape Kennedy as to its compatibility with the launch vehicle, a battleship stage for early hot testing of the main propulsion system, and an all-systems stage. This latter stage is for hot static testing of the configuration of the stages for the first flight and is then used for continuing development, engineering effort, and improvement of components and subsystems in the environment of the overall system. This stage is most important for establishing confidence in the hardware and its proper function. The test activity will continue throughout the program. In the S-II stage we saw a particular need of structural testing under cryogenic conditions. For this, an additional stage of full size diameter but shorter length was built.

2. Instrument Unit

This unit, which is a 3-foot high ring sitting on top of the stages, is the brain of the launch vehicle. It contains guidance and control equipment, electrical power supply and distribution, telemetry and tracking equipment, etc. Here we have a similar approach as in the stages; namely, the manufacturing of a number of full size ground test units, some of them fully equipped - some of them partially. Particular emphasis is given to structural testing, vibration testing, systems testing, compatibility testing with the S-IVB stage, and especially with the ground equipment for automatic checkout.

3.. Overall launch vehicle

For the dynamic behavior of the total configuration during the flight we mount the entire full-size space vehicle, including spacecraft dummies, in a dynamic test tower and expose it to vibration. The dynamic test stages and ground test instrument units are used in this test. It yields us natural frequencies, the bending modes, control system responses, etc.

The facility stages and a test instrument unit, assembled to make up a complete Saturn V, are primarily used for checkout of the launch facility, as I mentioned before. This is an essential step for establishing compatibility of launch vehicle and launching site. There shortcomings and weaknesses in design on vehicle connections and systems, as well as on mechanical and electrical ground support equipment, will be revealed. Planned operational procedures, for instance, for propellant loading, handling of the vehicle, will be exercised, reviewed, and changed. We call this facility vehicle the "Wet Test Bird."

4. Automatic checkout equipment

Within the time allotted to me for this presentation it is not possible to explain to you the scheme and concept of how the automatic checkout of stages and instrument unit works and what equipment is involved. However, since this checkout method, among other advantages, eliminates to a great extent the human error, I think it should be mentioned in this presentation. The prime contractors, in their plant checkout before captive acceptance testing and in their final checkout before shipping, are using this automatic equipment which is compatible with the checkout equipment at Cape Kennedy. In order to guarantee this, to develop the system, to make it compatible with the instrument unit, to test the hardware of the system, to work out overall checkout procedures, to train operators and for various other purposes, especially in the field of systems integration, a systems development facility for this automatic checkout equipment of the Saturn IB and V is at the present being built up at Huntsville.

In the mechanical field of ground equipment I want to mention one particular area which can cause trouble and lead to catastrophic failures. These are the mechanical connections between the umbilical tower at the launching site and the vehicle, the so-called swing arms. Again, it would go too far into detail to describe the functions of each swing arm and the environmental conditions under which it had to work. We have at Huntsville a swing arm test facility where all swing arms will be tested under various wind conditions and under cryogenic conditions as to their qualification, timing of their retraction, disengagement from the vehicle, etc.

It is hard to express in reliability numbers the influence of the testing on both facilities but we believe that it will increase the confidence in reliable function of these components remarkably.

5. <u>Components</u>

In the field of components we adhere strongly to NASA documents NPC 200-1, -2, and -3 and NPC 250-1. Marshall Space Flight Center, as I mentioned before, was instrumental in setting up these documents. The concepts spelled out in them are, in my opinion, some of the keystones for achieving high reliability. I would like to direct your attention to two salient points in those documents which I personally believe are, among others, very important. These are: in-process inspection and the application of preferred parts lists.

A 100% in-process inspection, if thoroughly conducted everywhere, expecially in the plants of our subvendors, is quite expensive. However, I feel it should be applied on all critical components.

When detail design begins, we require that the parts used in the design be selected from the Marshall Space Flight Center Preferred Parts List, PPD-600, or MIL-STA-143, in that order of preference. This serves two purposes: standardization across the total launch vehicle with the resulting reduction in qualification testing required and the assurance that only parts with known reliability histories are used. Of course, these lists have to be kept up-to-date.

In the area of mechanical components, our main trouble makers are still cryogenic valves, pressure switches, reducers, long cryogenic lines of large diameters, expansion joints, pipe connections - the ever-present leakage problem - and welding problems of high aluminum alloys involving large diameters and rather high precision. We try to overcome these difficulties by almost daily exchange of experience between us and the contractors and their subs. Marshall Space Flight Center devotes considerable in-house efforts on the design of these components, on qualification testing and backup solutions. As to the welding problem, for instance, we carry out in our shops, in cooperation with our material experts and contractors, developments of welding methods and conduct training of welders.

In this connection, we also develop non-destructive inspection and test methods. It may be of interest to you to know that we have a training program on non-destructive test methods going on for NASA as a whole, and executed by a contractor.

As to the electrical components, we have made extensive use of triple redundancy with voting circuits which gives us a very high inherent reliability for the guidance and control system. The only place where such a redundancy scheme is not feasible is the stabilized platform in the Instrument Unit of the launch vehicle. Therefore, we have introduced redundancy for the stabilized platform by using the IMU (Inertial Measuring Unit) in the Apollo spacecraft command module as a backup. In case the stabilized platform, for instance, of the Saturn V launch vehicle fails, the IMU can take over from ignition of the S-II stage on through the whole launch vehicle operation.

Before we give the go-ahead for the first flights of these big launch vehicles, and after a thorough design analysis of the components, we conduct a qualification test program for the critical components under all critical flight environments, which we try to simulate as closely as possible. We consider this test program most important and from it we expect to arrive at a proper confidence level for success. Since, however, the real function and quality of all components, subsystems, and systems can only be proven by exposing them to flight conditions, we equip the first flights with ample measuring devices. This is especially important since we have only a few unmanned development flights from which we have to obtain as much knowledge as possible about the behavior and function of the vehicle and the real environment during all flight phases.

In our flight measuring program on Saturn I we telemetered to the ground around 1000 measurements, of which we lost only 2 - 3%, totally or partially. In the first Saturn V flights we plan to equip the launch vehicle with over 2000 measurements, which ought to give us all necessary information to judge the quality of the vehicle and its components. If something goes wrong or some components function out of specified tolerances, we have to know this. Malfunctions have to be explained and then corrected. Otherwise we cannot dare to go into manned flights.

For the Saturn V we have allocated the following preliminary reliability predictions or goals:

First stage	S-IC	=	.95
Second stage	S-II	=	.95
Third stage	S-IVB	=	.95
Instrument Unit	IU	=	.992
GSE		=	.95

These tentative figures are based on test data from known components, on assessments of less known components, on extended test programs for engines, on calculated criticality numbers, and finally, on engineering judgment. They can be debated and, of course, criticized. For instance, the S-IVB stage has to be reignited in earth orbit and has to have proper ullage and attitude control over a longer period. It, therefore, appears that it ought to have theoretically a lower reliability than the other stages. On the other hand, it has only one main engine compared with five each for the other stages.

Sometime in the program there will be the crucial moment when management has to decide which vehicle will be assigned the first manned lunar landing mission. This will be done after a series of thorough and detailed reviews during which all previous results of ground testing, analyses, qualification surveys, quality assessments, single point failure analyses, etc., will be put on the table and scrutinized. Checkout procedures, results of countdowns of previous launches, and all other operational procedures will be reviewed. Most important, of course, are the flight results of previous unmanned vehicles. Finally, with all this material on hand and after thorough discussion with contractor and government personnel, top program management will have to make a judgment whether confidence of all leading participants high enough and whether everything humanly possible has been done to make the mission a success. Although reliability and criticality figures will be strongly considered in coming to a conclusion, I do not think that the rationale will be, and can possible be:

"Since a predicted reliability figure, of say .835 or .877 or similar for the whole launch vehicle system, has been reached, we are now ready to give the go-ahead," or conversely, "Since such a figure cannot be proven, we are not ready," In the final analysis it will be the engineering and management judgment of a few responsible top people. It is the task of the contractor-government engineering and program management team to have the proper material prepared, enabling top management to make this decision.

Let me, at the end of my presentation, express some few observations which I have made over long years on guided missiles and space launch vehicles, and which I think are worth being noticed in connection with the reliability effort:

1. The inherent reliability of a launch vehicle is only as good as its design and engineering. This is very often conducted by personnel in the lower ranks and younger, freshly hired people with little experience. The excellent and outstanding people have left the drawing board and laboratory long ago and have become managers or salesmen. Mostly, they do not involve themselves any more in technical details. I believe this is to the detriment of this kind of complex technical program and to the reliability problem as such. I believe the middle management - even up to the top level - should engage itself constantly, and not only in emergencies, in detail design reviews, detail test planning, detail supervision of results, etc. Excellent designers and engineers should get incentives to stay on the drawing board, in active testing and in laboratories. I am sure we would then come up with more reliable designs. I feel the good old designer with novel ideas who lives with his task and is proud of his accomplishment has become a figure of the past. He is replaced more and more by reliability philosophies, computers, management experts, salesmen, representatives, etc. We ought to educate hard core designers and engineers again.

2. The technical difficulties in all these programs are found, almost without exception, in subsystems and components. They are mainly procured from subvendors who often have difficulties keeping their small shops financially out of trouble. They need the job badly and therefore, bid low. These subcontractors should be more carefully selected, especially as to their technical capability. After award of contract and right from the outset they should be more closely monitored and more often visited by the leading design, test, and quality engineers of prime contractors and Government. Stronger day to day technical penetration of subvendors by Government and prime contractor personnel is a "must" because these subvendors in their struggle to meet schedules and costs, being under fixed price contract, resort frequently to shortcuts, sloppy work, fixes, neglect of proper cleaning and packaging for shipment, deletion of tests, and the like. This is to the detriment of reliability.

3. When funds have to be reduced, the last thing which should be done is to cut down on test facilities and equipment and on the planned volume of testing. Elimination of inspection and quality control procedures is equally dangerous. We at Marshall do not believe in so-called "minimum test programs" because it is always debatable what this minimum is. I hate to see money saved, for instance, from development testing in order to buy immature and unqualified long lead time hardware in great quantities.

4. Don't, on the other hand, over-inspect and over-test flight hardware. This is equally hostile to reliability and reduces liftime of components, for instance, too much static firing of flight stages or engines.

5. If, during testing or checkout of a component or a stage, there occurs an unexpected and irregular function which does not show up any more in a repeat test, don't let it pass. The cause should, by all means, be investigated and then corrected and documented, if necessary. I have seen it happen quite often that during a certain step of a checkout a red light would flash. The test was repeated. When red did not appear again, everybody was happy. The checkout proceeded and was finally declared successfully accomplished. This is against an integer checkout and test concept.

6. Although I feel we all, together with our contractor family, constitute a pretty good team in the Apollo program, I still believe - and I think this goes for other programs, too - that we can improve in communication as to:

Exchange and acceptance of experience.

Collecting and transfer of test data.

Frank submission of failure and unsatisfactory condition reports.

Closing the loop by reporting corrective action

Uninhibited admission and reporting of shortcomings and weaknesses in components and systems.

Data and experience exchange with other programs and agencies.

There are many more such items in the line of communication, where improvement ought to be achieved.

I honestly believe that this last point which I have been trying to make represents the most important factor in achieving high reliability in such a program as the Apollo.

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