PHILOSOPHY AND PRACTICES OF RELIABILITY AS APPLIED IN THE DESIGN OF THE SATURN INSTRUMENTATION SYSTEM

XI.08

by Dr. M. A. Griffin
Head, Industrial Engineering Department
University of Alabama
University, Alabama

Mr. J. E. Rorex
Chief, Telemetry Systems Branch
Astrionics Laboratory
George C. Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

The basic engineering approach used in the Saturn instrumentation system has evolved to provide a highly reliable design for short periods of operation. The airborne measuring and telemetry systems including preflight tests, inspection, documentation, and feedback between the users and designers are discussed.

The apparent differences between the practice and theory of reliability are rationalized.

Some consideration is given to new problems in designing systems that must operate in hostile environments for long periods. The potential contribution of redundancy as a design concept is discussed.

INTRODUCTION

The design philosophy applied to the development of the Saturn V instrumentation system has evolved from the Redstone, Jupiter, Saturn I, and Saturn IB boosters. Much of the hardware and system presently used on the Saturn IB and V was proven in 10 flights of the Saturn I. While the Saturn V instrumentation system does include some new designs and components, it is basically an expanded and upgraded Saturn I design.

Instrumentation systems for missiles have been essentially developed since the early 1950's. Instrumentation engineers responsible for the development of the Redstone were offered very few choices of telemetry components. At that time a small nucleus of engineers embarked on a program of evaluation and development to design an instrumentation and telemetry system suitable for use in the development of the Redstone ballistic missile. The laboratory equipment for test and evaluation was as meager and inadequate as the existing airborne instrumentation components. There were very few procedures and little documentation to build on. Considerable intuition and "best judgment" had to be used. With the exception of the few engineers that had gained experience on the V2 and Hermes rockets, the solution of every problem was a new experience. Procedures were improvised on the spot and precedents were set in every phase of development and test. However, in spite of the handicaps, the few experienced engineers managed to put together a team, a missile, and an instrumentation system that worked. The Redstone was used for the first reentry vehicle; it also placed the first American satellite in orbit and was used for the first manned suborbital flight. Several failures occurred in some of the early missiles as well as parts of the measurement and telemetry system; however, the engineers who worked on the Redstone instrumentation system were rewarded for their efforts since no essential data were lost.

The Redstone averaged two links of FM/FM telemetry with about 125 measurements per missile. In general, the data gathered from the flights were very satisfactory and proved to be extremely valuable in the development of the missile.

After the short range Redstone was deployed, the Army realized the need for an intermediate range missile and started the development of the Jupiter, which averaged three telemetry links with about 200 measurements. In principle, the instrumentation system was similar to the Redstone, but instrumentation technology had improved considerably in the few intervening years. Laboratory equipment and test facilities had improved and test equipment was added. Significantly, because of such programs as the Atlas, Navaho, Thor, Titan, and Bomarc, the commercial market had expanded and a wide variety of instruments and telemetry components was available to choose from. Instrumentation components were not only more accurate, more efficient, and smaller and lighter in weight; but most important they were also more reliable. Although we have not researched the records of the Jupiter program, it is estimated that more than 98 percent of the flight data was retrieved.

The Pershing, a medium range solid propellant rocket developed in the late 1950's, used practically the identical instrumentation system as that used in Jupiter.

This paper is concerned with the airborne measuring and telemetry systems; it does not attempt to treat the entire Saturn instrumentation system which consists of tracking devices including optical, radar, and doppler, plus television, film cameras, and a myriad of instruments connected with factory checkout, ground test, and launch.

At this time in history the Department of Defense assigned to the team, then named the Army Ballistic Missile Agency, the job of developing a booster rocket made up of clustered tanks and a cluster of eight Rocketdyne H-1 engines developing a total thrust of 6.7×10^6 N (1.5 million lbs). This booster rocket was named Saturn. The first Saturn, now referred to as Saturn I, brought on new and formidable problems to the instrumentation designer. The clustered engine concept increased the data requirements to over 500 measurements. With the increase in engines and engine measurements, the probability that an engine measurement failure could cause a vehicle failure was greatly increased.

The tremendous increase in the number of measurements required made it necessary to develop new instrumentation concepts to avoid reducing vehicle reliability. The transducers associated directly with engine operations that could effect reliability were ruggedized and made an integral part of the engine system. Other problems such as information transmission and data management were increased comparable to the magnitude of measurements. As a result, new and improved telemetry systems had to be developed.

Early in the development phase of the Saturn I, the program and the team were absorbed by the National Aeronautics and Space Administration. This change also introduced the concept of using the vehicle for manned flight which compounded the instrumentation problems immensely. Concepts such as the emergency detection system associated with astronaut safety and data management associated with vehicle checkout created new problems. The expanded magnitude of the data management problem made it necessary to develop a computer controlled checkout system. Consequently, a remote automatic calibration system and a digital data acquisition system were developed to calibrate the airborne electronics and to retrieve and format the onboard data for use by the computer.

It may be interesting to note that on all the programs prior to the Saturn IB and V, emphasis was on working hardware and craftsmanship with minimum documentation since the work was primarily research and development. The complexity of the Saturn program has compounded the communication problem and increased the need for more documentation and configuration management. On the early programs such as Redstone, the laboratory engineer was intimately familiar with his transducer or telemetry component from the "cradle to the grave." In this specialist concept, some art is involved; everything is not explainable in simple terms; consequently, it is more difficult to manage. However, it does give deeper technical penetration. The production approach leaves little room for "fine tuning;" it is either in tolerance or out. It is easy to document, explain, and manage but leaves little room for individualism and innovation. It does not lend itself as much to craftsmanship as the specialist approach.

SATURN LAUNCH VEHICLES

Saturn I

The Saturn I program consisted of a series of 10 vehicles and served as a test vehicle for most of the design concepts used in the Saturn IB and V, including the measurement and telemetry system. The last three of the series were used for placing Pegasus micrometeroid detection satellites in earth orbit.

The first four vehicles consisted of only the S-I stage with a boilerplate upper stage to simulate weight and aerodynamic characteristics of the Apollo spacecraft. The data system consisted of an average of about 560 measurements and eight telemetry links. The telemetry system on the first vehicle was PAM/FM/FM, which was similar to the system used on the Jupiter with the exception of a newly designed 216-channel solid-state multiplexer. The second flight carried a newly designed SS/FM telemetry system. This system occupied the same bandwidth as the FM/FM system but consisted of 15 single sideband AM subcarriers modulating an FM carrier. It was designed to carry 15 channels of vibration data (50 to 3000 Hz) and was several times as efficient as FM/FM for this purpose. The third and fourth flights carried an experimental PCM system and an experimental UHF transmitter. The PCM system converts the analog, digital, or event data into a series of ten-bit words, serializes them into a 72 kilobit non-return-to-zero (NRZ) wavetrain, and modulates an FM carrier.

On flight No. 6 the PCM system was modified for eventual use as the heart of the digital data acquisition system (DDAS). The multiplexer was also modified to receive up to 270 channels of data rather than the original 216 channels.

After the S-I stage was successfully tested in four flights, the S-IV stage and an Instrument Unit were included in flight No. 5 and later flights. The measuring program was expanded to an average of about 1170 measurements and 13 telemetry links per flight.

Flight No. 7 was the first flight test of the airborne DDAS. Flight Nos. 7 and 8 both carried an experimental inflight fire detection system on the S-I stage.

Saturn IB

The Saturn IB launch vehicle measuring and telemetry systems are shown in Figure 1. This vehicle is similar to Saturn I except the first stage, S-IB, is uprated and the second stage, S-IVB, is a new design. The S-IVB stage is also used as the third stage of the Saturn V. The Instrument Unit contains the guidance, control, and sequencing equipment and the associated instrumentation. This vehicle will be used as an operational vehicle to place the Apollo spacecraft in earth orbit for testing certain rendezvous, reentry, and recovery concepts prior to the lunar mission. It will also be used to launch a series of scientific and experimental payloads in the Apollo Application Program (AAP).

The first four vehicles of the series are instrumented for research and development (R&D) while No. 5 and subsequent vehicles are considered operational. Because of the small number of R&D vehicles, there is still some limited R&D instrumentation on the early operational vehicles. The measuring program will undoubtedly be further reduced as the program progresses.

The R&D vehicles averaged about 1400 measurements with 13 telemetry links while the operational vehicles will require about 670 measurements and six telemetry links per vehicle.

Saturn V

A simplified instrumentation outline for the Saturn V launch vehicle is shown in Figure 2. Saturn V, the monster of the Saturn family, consists of three stages and an Instrument Unit. The S-IC stage, built by The Boeing Company, has 904 measurements and six telemetry links on the R&D vehicle. The operational configuration is reduced to 317 measurements and two telemetry links. The second stage, S-II built by North American Aviation, has 975 measurements and six telemetry links for the R&D configuration while the operational stage is reduced to 510 measurements and three telemetry links. Douglas Aircraft builds the S-IVB stage used on both the Saturn IB and V. This stage carries 590 measurements and five telemetry links on the R&D vehicles. The operational stages have 250 measurements and one telemetry link. Provisions are included for the addition of one telemetry link on the operational vehicle if additional measurements are required.

The Instrument Unit, which is similar to the one on the Saturn IB, is built by IBM. The R&D Instrument Unit has 322 measurements and four telemetry links. The operational configuration will be reduced to 200 measurements and two telemetry links. Although the measuring program changes somewhat from one flight to another, the number of measurements shown represents averages.

Adding these figures, we see that one Saturn V R&D vehicle has 2791 measurements and 21 telemetry links; i.e., approximately 20 times as many measurements as required on the Redstone. Thus, all of the problems associated with the system design have been multiplied by at least a factor of 20.

In viewing the number of measurements and data links and considering the size and complexity of the total vehicle, its associated launch equipment, and the problems associated with checkout and launch readiness, it is easy to understand why it is necessary to have a common data management scheme. This was partially accomplished by designing the onboard telemetry system to act as the data gathering and formating portion of the DDAS system. To simplify factory checkout and vehicle interfacing, each stage has its independent measuring and telemetry system. Also all of the telemetry subsystems use a common design. To implement this system, each stage contractor was given the design for 27 different telemetry assembly configurations to choose from. Each of these assemblies may be programed to meet the unique measuring requirements of a particular stage. A central configuration management is maintained by MSFC and The Boeing Company for each piece of hardware. This approach not only simplifies the data management and vehicle checkout problem, but also enhances the system reliability. Because of the mass usage of equipment, design and reliability problems are isolated and corrected more quickly. Production techniques can be more readily applied, and parts obsolescence does not occur so soon. Both of these points incidentally contribute to reduced costs as well as increased reliability. Operational familiarity is also a positive contributing factor to reliability. In general, redundant data transmission has been avoided on the R&D vehicles. On these flights, more information is retrieved by using the hardware for transmitting different measurements and risking the loss of a little data rather than building in loss of half the data by redundant transmission. On the operational vehicles, certain operational flight control parameters are considered important enough that their loss might jeopardize the mission. These measurements are transmitted redundantly.

MEASURING AND TELEMETRY SYSTEM

A block diagram of the measuring and telemetry system is shown in Figure 3. Each of the 2800 measurements to be made on Saturn V will use a transducer-signal conditioning element consisting of about 100 electrical components. Hence, the measuring system consists of about 300,000 electrical components. Similarly, each link of the telemetry system consists of about 500 components. Altogether, the airborne instrumentation system for the Saturn V contains approximately 500,000 electrical components. Failure data on the 10 flights of Saturn I and the three flights of Saturn IB for the instrumentation shown in Figure 3 have been collected.

Figure 4 lists the measurements and telemetry links in the Saturn I program. Of the 9258 measurements, 117 were failures and 182 were partial failures. A failure is defined as a measurement where no useful data were obtained. The failure measurement was probably inoperative before lift-off and could not be detected because of the inability to add stimulus. The remote automatic calibration system was designed to stimulate and calibrate the electronics associated with signal conditioning, but most transducers require physical stimuli to check out; this cannot always be achieved because of inaccessibility. A partial failure is defined as a measurement which operated properly for part of the flight but did not give valid data for the total flight period. Fortunately, there were no telemetry system failures in the Saturn I program. Note that most of the measurement failures can be attributed to the transducers being necessarily located in an unpredictable and hostile environment.

An outline of the instrumentation history of the first three flights of Saturn IB is shown in Figure 5. Of the 3889 measurements, 44 were failures and 90 were partial failures. There were no failures in the 39 telemetry links. It may be observed that the number of partial measurement failures of flight 201 of the S-IVB stage is above normal. This can be explained by the fact that the flight environment in some areas of the vehicle exceeded the anticipated levels. The situation improved on the second flight (S-IVB 203). The instrumentation reliability in the Saturn IB program compares favorably with the Saturn I.

In summary, the analysis indicates that the reliability of the measuring and telemetry systems for the Saturn I was as follows.

Reliability based on measurement failures = 0.9873.
Reliability based on failures plus partial failures = 0.9675.
Reliability of the telemetry system - no failures observed.

For Saturn IB, similar calculations on the data in Figure 5 are as follows.

Reliability based on measurement failures = 0.9887.
Reliability based on failures plus partial failures = 0.9655.
Reliability of the telemetry system - no failures observed.

Although we have no flight history on the Saturn V, sufficient data have been gathered from ground test to predict that the reliability of the instrumentation system will be similar to that of the Saturn I and IB.

Note that the reliability based on actual inflight data of the total measurement and telemetry system is greater than the reliability based on theoretical expectations. The various attempts to compute total reliability from component failure rates have varied from about 0.46 through 0.86.

RELIABILITY

It is theoretically possible to test a sample of individual electrical and mechanical components and to construct failure frequency functions which may be used to estimate the reliability of a system as complex as the Saturn V. A brief description of such a procedure is as follows.

1. Determine the failure frequency function $f(t)$ from test results for each of the 500,000 electrical components, plus all of the related mechanical components.

2. Determine mission time T, the period of time the system must operate without failure.

3. Compute component reliability $R(t)$ where $R(t) = \int_T^\infty f(t)\,dt$ for each component.

4. Construct reliability logic diagrams from the schematic models of the subsystems.

5. Apply the addition and multiplication theorems of probability to compute subsystem reliability according to the rules governing series, parallel, and complex arrangements.

6. Treat subsystems as components and construct a reliability logic diagram for the total system.

7. Compute total system reliability as in step 5.

It is also theoretically possible to conjecture several alternative system designs, each of which is capable of accomplishing the mission, and to evaluate each alternative in terms of its performance, reliability, or other criteria.

In practice, it is not possible to afford the expense of complete alternate designs which are sufficiently explicit to make a thorough reliability evaluation. Also, in most cases where new untested designs are involved, it is impossible to determine a failure frequency function before the subsystem is designed, built, and tested under actual operating conditions.

Therefore, under normal conditions, design engineers must be relied upon to use their good judgment to create designs which are sufficiently reliable to meet the performance objectives. This does not mean that the theory of reliability should play no part in the designers creations. Certainly if a designer has a choice between two components which differ only in their MTBF, he will invariably choose the longer life component. Similarly, when completely new apparatus or new component designs are being investigated, he will design, produce, and run environmental tests to assure himself that the new product exhibits satisfactory performance.

The reliability design philosophy at MSFC incorporates and makes some use of mathematical reliability theory. For example, all airborne telemetry components have been subjected to a thermal stress analysis and a worse case analysis. Several recommendations for changes were implemented as a result of these analyses.

A few of the essential ingredients applied to the Saturn instrumentation design are as follows.

1. A well-equipped development and test laboratory manned with experienced engineers and technicians.

2. A development program to explore new ideas and

concepts for tomorrow while finding practical solutions to today's "real world" problems.

3. Realistic specifications and criteria that are generated and tested by specialized engineers.

4. Workmanship specifications that require craftsmanship, integrity, and pride.

5. An evaluation program to evaluate "off the shelf" hardware and vendors components to have a yardstick for performance. These "black boxes" are often used in system design when they meet requirements.

6. The use of screened, high reliability and process controlled parts so far as practical. The cliche' "a chain is no stronger than its weakest link" holds here.

7. A reproducible design that is thoroughly tested environmentally and electrically. It is tested both as a "black box" and in a system "breadboard" before inclusion in the vehicle design. When a single failure would cause a loss of a large proportion of the data such as a telemetry failure, the item is often flight tested prior to actual use for prime data.

8. Adequate and concise documentation and engineering drawings with good in-process manufacturing inspection and controls.

9. Clear and concise acceptance test and inspection procedures used by well-trained inspectors and quality control personnel.

10. Good communications, understanding, and feedback between the circuit designer, systems engineer, manufacturer, quality control engineer, test engineer, and data user.

11. Each part is treated as if the primary purpose of the flight is to gather data. This hypothesis is essentially correct for the R&D vehicles.

12. Rigid quality control procedures to preclude inferior and irresponsible workmanship in manufacturing instrumentation components and subsystems.

Although instrumentation designers should be held responsible for the performance of their designs, they should also be provided with competent assistance. For example, they must be supplied with accurate failure frequency functions on all components used in their designs. They must be able to easily determine the reliability of each component over a known mission time T. Ideally the reliability would be 1.0 for time T and 0.0 for time $T + \Delta t$ as was the case of the wonderful one-horse shay. Component life is of little or no value after the mission has been accomplished.

Similarly the designer needs competent and responsible help from quality control staffs. Although it is usually necessary to compare the measured quality characteristics of a particular component with its procurement specifications, it is also important to determine whether the component works.

CONCLUSIONS

The measuring and telemetry systems used on the Saturn vehicles have not performed perfectly, but the results are judged to be highly satisfactory. Although the application of reliability theory has made some contribution toward improving designs, the greatest contribution has been made by following the essential elements previously enumerated.

The Saturn I and IB flights have operated for periods of time ranging from 150 seconds to about 6 hours. These operating periods are very short when compared to the proposed operating periods for the Apollo Telescope Mount and the Voyager programs. We expect that greater use will be made of redundant systems for these programs which will demand trouble-free operations for a period of several months.

Possibly the application of reliability theory will help designers make a greater contribution to the design of more reliable systems for the longer operating periods. Hopefully the reliability and quality control staffs can help overcome a deep-seated conviction on the part of design and production engineers that their principal function is to so improve their designs and technical methods that no important quality variations remain and that, in any case, the laws of chance have no proper place in producing complex systems.

In our judgment the task of the individual designer to design complex man-machine systems involving chemical, electrical, and mechanical components is too great to be accomplished within the knowledge of any one area of specialization. The only solution is to collect the necessary skills and specialists whose combined knowledge is equal to the task. Each group must learn enough of the jargon and techniques of every other group to effect information transfer. Each group must be given sufficient status to do responsible work and with reasonable luck the whole will be greater than the sum of the parts.

Some of the present problems involved in designing systems with MTBF of 10,000 hours and longer with no chance for maintenance tax the best of our design and production capability. Some of these problems may be solved through research. We must continually investigate the causes of failure and learn to better predict chance life and wearout life of components, subsystems, and systems. We must also be more concerned about the transient effects which are frequently encountered in electromechanical instrumentation systems.

Meanwhile, continued support for reliability research should be encouraged. Research should not only be limited to esoteric theoretical investigations but should also include new investigations of how the theory can be put into practice. The social problems of implementation should also be a part of our research programs.

Similarly a combined effort of all groups interested in collecting and analyzing component data should be encouraged. The cost of studying some particular style or size of component should not be borne by every large user. Such combined efforts should be encouraged to extend the present types of reliability information beyond the individual component curves to typical systems reliability.

If the space industry is to continue to develop and produce manned-space flight systems of high reliability, it must devote more attention to the quality control function. Ways must be found to solve the problems causing inferior workmanship.

BIBLIOGRAPHY

Books

(1) Ackoff, Russell L., Scientific Method, New York and London; John Wiley & Sons, Inc., 1962.

(2) Hoel, Paul G., Introduction to Mathematical Statistics, New York, London, and Sydney; John Wiley & Sons, Inc., 1962

(3) Lewis, C. I., A Survey of Symbolic Logic, New York; Dover Publications, Inc., 1960.

(4) Lindgren, B. W., and McElrath, G. W., Introduction to Probability and Statistics, New York; The Macmillan Company, 1959.

(5) Lloyd, David K., and Lipow, Myron, Reliability: Management, Methods, and Mathematics, Englewood Cliffs, New Jersey; Prentice-Hall, Inc., 1962.

(6) Sokolnikoff, I. S., and Redheffer, R. M., Mathematics of Physics and Modern Engineering, New York, Toronto, and London; McGraw-Hill Book Company, Inc., 1958.

(7) Spiegel, Murray R., Theory and Problems of Statistics, New York; Schaum Publishing Company, 1961.

(8) Barlow, R. E., and Proschan, F., Mathematical Theory of Reliability, New York; John Wiley & Sons, Inc., 1965.

Articles

(1) English, J. Morley, Understanding the Engineering Design Process, Journal of Industrial Engineering, Vol. XV, No. 6, pp. 291-296, Nov.-Dec. 1964.

(2) Epstein, Benjamin, and Sobel, Milton, Life Testing, American Statistical Association Journal, pp. 486-502, Sept. 1953

(3) Powell, J. T., Jr., Saturn Flight Instrumentation Systems, ISA Journal, pp. 51-63, Nov. 1964.

(4) Rorex, James E., and Eichelberger, Robert P., Digital Data Acquisition System in Saturn V, Proceedings of Second Space Congress, Cocoa Beach, Fla. 1965.

(5) Frost, W. O., and Norvell, D. E., The Telemetry System Design for Saturn Vehicles, Proceedings of International Telemetering Conference, Vo. II, pp. 66-83, 1966.

(6) Talley, D. H., Special Instrumentation for Liquid Hydrogen Experiment AS-203, NASA Technical Memorandum X-53544, Nov. 1, 1966.

ILLUSTRATIONS

?