Technological Problems of the Saturn Class Vehicle

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June 66

It is indeed a pleasure to be in Hawaii. This is the kind of temporary duty assignment we always hope to get--but seldom do receive. I am with you today to tell you of some of the problems we have encountered in the development of a lunar launch vehicle. My subject is "Technical Problems of the Saturn Class Vehicles."

As I have visted several areas in the States and talked to different groups, I have come to realize that we all share the same enthusiasm for exploration and that we all support the program adopted by our nation for methodical and steady advancement in our space capability.

With the announcement of the lunar goal by President Kennedy, we were able to focus our national research and development goals in the space field toward the capability of sending men to the moon and returning them safely to earth.

We in Huntsville, Alabama, at the George C. Marshall Space Flight Center have one important responsibility; that of creating the strong arm or the muscle to start the lunar expedition out of earth into the lunar transfer trajectory with the correct vector, that is, with the correct direction and velocity.

The long range goal of the Saturn development program is, as I said, to provide a series of space carrier vehicles with the capability of carrying men and equipment to the Moon and planets of our solar system. The NASA program for manned exploration of the Moon is called Apollo. A considerable segment of the scientific and technical capability, representing a heavy commitment of our national resources, is working on the Apollo program. In terms of dollars, manpower, facilities, and technical know-how, the Apollo program far exceeds that of any other single research and development program in history. Many thousand industrial firms--prime contractors, subcontractors, suppliers, and vendors--are participating. The major contractors and organizations involved in only the carrier vehicle or Saturn phase of the Apollo program are shown in SLIDE 1.

SLIDE 1

Development of the Saturn series is progressing steadily, successfully, and on schedule. We have just finished a year marked with the acccomplishments of its scheduled milestones. These milestones constitute critical development steps toward the total successof the Apollo program with its scheduled goal of carrying man to the surface of the moon before 1970. The Saturn I program,

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the first development step in the Saturn family, has been completed. It proved the concept of engine clustering and the application of hydrogen for upper stages. It also injected three meteoroid measuring satellites into near-earth orbit in support of the Apollo program. This satellite series known as "Pegasus" is producing data which form an important link in the chain of information about the hostile environment that Moon explorers must overcome. The first launch of the improved Saturn I

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medium-sized space booster took place February 26. We were well pleased with the success of that mission. The important role of this size booster is borne out by its multiple use for several missions which serve fully the developmental testing and proof testing of elements of the spacecraft, such as high-speed reentries, astronaut training flights, and a complete exercise of the Lunar Excursion Module (LEM). These flights are scheduled in a timetable which allows utilization of the information and experience gained for design confirmation, or for modification of the spacecraft used for lunar exploration. Other experiments are planned to confirm the results of the analysis of certain features of the launch vehicle which cannot be fully tested on earth.

One of these technologies is the behavior of liquid hydrogen (with its low density, low inter-molecular friction, and low surface tension) under the condition of weightlessness, subject to heat transfer through the container insulation, and subject to minute disturbances caused by attitude corrective motions. Not only the necessary NPSH (net positive suction head) has to be assured; but also a certain temperature of the liquid under the condition of maximum allowable design gas pressure of the container. This flight was successful last month.

Before I lose myself in many technological details of the program, let us first look at the Saturn V

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and its status. We have successfully captive fired the first two stages of this super rocket many times. The first stage

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develops a total thrust of 7,500,000 pounds.

The propellants are kerosene and liquid oxygen. The achieved specific impulse is well above 260 seconds.

The second stage

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has also been captively fired, but as a test stand version only. It was inadvertently destroyed by an operator's misjudgment after completion of a series of tests. The propellants in this case are liquid hydrogen and liquid oxygen. The specific impulse (I_{sp}) is well over 420 seconds.

The third stage

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has been test fired several times as a research version and also as flight version for early developmental flights on the improved Saturn I. This stage burns liquid hydrogen and liquid oxygen, as does the second stage.

The first three stages are solely propulsion stages. The fourth element of the Saturn V is the IU (instrument unit) as shown in

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which contains the intelligence for the propelled flight, coast, and the re-ignition of the S-IVB for injection into the lunar transfer trajectory. The IU consists of a structural shell and contains pressurized instrumentation boxes mounted on environmental conditioning plates. A water sublimator, pump system, etc., keeps the instruments to a close temperature tolerance for higher reliability and better accuracy.

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represents the functional schematic in a simplified form to show the hand and the influence of the system engineering effort. You recognize at the first glance a repetition of the basic control elements on the left. Furthermore, an entirely separate system is indicated as EDS (Emergency Detection System). This system has the threefold task of informing the astronaut of an imminent failure, giving him a status indication of the momentary flight worthiness of the vehicle, or acting as an automatic safety command system separating the spacecraft from the launch vehicle.

In the center of SLIDE 9 you can see an exact repetition of the powerplant command circuits. On the right is the communication arrangement. We achieve a much higher confidence level for high reliability by using not only the general arrangement but also hardware of the same origin.

The task of system engineering is to penetrate deeper into the elements or single components of the vehicle system. Thorough failure effects analyses are performed, and reliability requirements are assigned to the components. High reliability requirements impose on all system engineering thorough understanding of all elements which compose the overall system of space vehicles of such extreme complexity.

To define and describe the unique task which is performed in all developmental phases of a program of the magnitude, complexity, cost and timetable of the Saturn development, let us take a look at the propulsion stages in more detail. Generally speaking, these stages are built around the rocket engines, with some of the stage requirements passed on to the engine subsystems which are laid out to fulfill the performance and engine-related requirements. Basically, these subsystems are a fuel system, an oxydizer system, pressurization systems (one high pressure level and storage system, one for the oxidizer and one for the fuel), one system for control pressures if necessary, and a hydraulic system for vectoring requirements. Single engine stages will have an auxiliary system for roll control, eventually combined with attitude control.

The H-1 engine system, as shown schematically in

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is a typical propulsion system. Eight of these systems are used in the improved Saturn I first stage. Firing range considerations require a destruct system triggered by ground command for protection against erratic flights. After establishing functional sequences, determining sequence successions, event A triggers event B, etc., the single failure mode links are carefully analyzed and wherever possible backed up by redundant hardware for improved reliability.

It is evident that it is not possible to have redundant container or feed lines but looking at valves, regulators, pressure switches, etc., the approach in these areas is to use redundant equipment. Wherever redundancy is not practical, other steps have to be taken, usually to establish high confidence levels for high reliability of components and subsystems.

After thorough ground and reliability testing, obtained data are introduced into an established mathematical model depicting the functional subsystem and systems. With data on hand and the enormous speed of today's computers, launchings can be test run on the computer, feeding in a "Monte Carlo" distribution of failure modes based on the qualification and reliability test results.

Again, in the areas of mechanical hardware such as tankages, engines, large valves, etc., not enough test specimens can be made available to obtain meaningful statistical results. The approach in such cases is to acquire knowledge of the environmental strain (as accurately as possible), and second, to establish a relatively high safety factor with limited allowable margins to assure a gaussian distribution of strain points and strength points and to avoid an excessive overlap of both curves. In most cases, for manned space boosters, we prescribe a safety factor of 1.4 for structural elements exposed to combined static and dynamic loads.

High pressure-carrying components wherever possible have a safety factor against ultimate strength of the material up to 4.

In the large rocket field such safety factors for man-carrying vehicles are without any additional "fudge" factors to bolster your ignorance.

Disregarding aerodynamic, vibration, acoustical, temperature, and upper atmospheric wind distribution problems, the most annoying experience is the occurrence of dynamic coupling. These effects are more difficult to approach theoretically because of missing knowledge about structural damping, damping in fuel, oxidizer system, where even the dynamic characteristics of pumps, lines, pressure system, tec., are of utmost importance. Longitudinal excitation due to functionally required abrupt changes of loads is a possibility. For instance, the use of multiple engines requires the hold-down of a vehicle until it is evident that all engines have properly ignited. After automatic registration of the proper ignition of all engines, the vehicle is released. This rather sudden change causes a longitudinal excitation, which undampened could cause the destruction of several vehicular structural elements. These elements, due to their size and weight, can only be efficiently laid out with a safety factor of 1.4.

As a more specific example, we have found by analysis in the Saturn V that the LOX container lower bulkhead would be destroyed if the thrust buildup of all five engines followed an in-phase pattern in close succession. Therefore, the ignition staggering of the large F-1 engines was introduced. Even after this precaution, a certain possibility existed of reaching a longitudinal vibration wandering through the vehicle.

Incidentally, if we were to release the hold-down mechanism in phase with the thrust buildup of the engines, we could still experience an overshooting of the design loads. Therefore, a unique method of gradual release over the first 6 inches was introduced by a mandrel and sphere-type arrangement of an energy-consuming simple device. The repeatable energy amount consumed by this arrangement, as shown in

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is depicted in the diagram on the right.

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There is another interesting but destructive coupling which has to be avoided. We have spent a great deal of effort trying to establish or positively determine whether we are plagued by the so-called "POGO" effect. Hydraulic coupling and amplification from turbopump machinery of the engine with structural components might cause a low-frequency longitudinal sustained oscillation which could reach "g" levels which are unpleasant to the astronaut or destructive to the vehicle. After establishing the propellant pump properties such as damping, possible amplification values are fed into a mathematical model depicting the loop which might hydraulically change the suction head causing eventually an undesired coupling. All indications today point to the fact that we might not be prone to this undesirable destructive vibration.

Very interesting problems are those encountered with the launch vehicle and its environment during transportation to the launch pad and prior to launch. The ocean breeze which makes Florida a year-round paradise has sometimes unpleasant effects on a launch vehicle of this size. The vortex shedding of exposed slender cylindrical objects (like chimneys and launch vehicles) in a steady airstream cause excitation to a vibration perpendicular to the wind direction (von Karman effect). The right combination of wind velocity and structural response can easily lead to a structural failure. Damping devices were, therefore, introduced. The transportation of an assembled launch vehicle, 380 feet high, from the Vertical Assembly Building to the launch pad over 12 miles of hardened road on a huge caterpillar-type transport mechanism is a problem if the bending frequency of the total assembled vehicle is close to the minute change in acceleration caused by the cleats of the chains impacting on the road.

Precautionary measures, such as reducing the width of the cleats by one-half in order to decrease the magnitude of velocity change and increasing the frequency, thus bringing it out of the near resonance of the free cantilever bending frequency of the vehicle, have been undertaken.

I have discussed some of the plain structural and propulsion systems problems. Development requires as complete as possible flight data consisting of information covering the following areas: pressures of all pressure-carrying subsystems, temperatures of critical system areas, gases and liquids, all events such as acceleration, vibration, stresses, temperature caused by aerodynamic heating, by jet radiation, and flame recirculation in the tail areas. Therefore, the instrumentation engineer is faced with the mammoth task of surveying all measurements constantly to ascertain their flight readiness and calibrating all end organs or pickups to make sure that pressure switches work in a desired or prescribed tolerance band.

Flight delays are absolutely intolerable. This becomes crystal clear when you consider that cryogenic propellants are on board, the astronaut is encapsulated on top of the vehicle ready to go, the relative tightness of the launch window (considering the weather at the launch site), importance of the weather conditions at the recovery site for possible undesired abort, and the lunar data to be considered for a successful lunar landing.

An early experience with a fully automatic launch sequence on Saturn I for the last 60 to 180 seconds led to a full automation for the improved Saturn I and Saturn V. Again, as in the vehicle mechanical area, ground support components and parts are screened as to their reliability and as to their location in the critical path of the one single component failure sequence. Wherever possible, feasible, and compatible with cost and schedule, redundant electrical components were introduced. Even voting circuitries and triple redundancies were introduced to take two out of three indications as to the correct one to continue in any electronic step of the sequence ladder. Fully automated computer-equipped installations are now commonplace. The programs fed into the memory of the computer serve mainly two purposes:

a. To fully automate launchings with a manual override and repetition of portions of the program.

b. To fully automate data acquisition and calibration. At any time during the launch preparation, the computer can scan the status of instrumentation and indicate to the test conductor the readiness of the systems.

Thus, not only a manpower saving is realized, but all the delays caused by human slowness and shortcomings are categorically eliminated.

The main elements of the launch vehicle controls and intelligence are as shown in

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In the middle, a 3-gimbal ring-stabilized platform is indicated. Integrating gyros are included. The second important component is the digital computer with a memory bank for 16,000 items. Preprogrammed event sequences are capable on board of surveying and computing the control correction for every subsequent flight period out of the data received from the gyros and their previous status indication.

To the right you see the control computer indicated. This computer must translate the received commands into digestible forms for the control valves of the actuators and the auxiliary propulsion system (APS).

Other tasks and problems are faced by the systems engineers who must knit the threads and ropes to the neighboring systems. Basically, three major systems must be knitted together: the spacecraft, the launch vehicle, and the launch facility. This is indicated by

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At the right of the diagram is the space launch vehicle as it interfaces with other vital elements of the Apollo program. Obviously, this is a task for the next higher echelon, the Office of Manned Space Flight (MSF). By delegation of this responsibility to senior knowledgeable engineers of the Centers involved, and by establishing working panels, the so-called interface problems are solved and automatically acted upon. In cases of unresolved differences, the Panel Review Board (PRB) of MSF enters the picture.

It is worthwhile to mention that in the case of the interfaces of the different stages, a similar arrangement has been set up whereby working groups are solving the internal interface problems. The examples previously given show a cross section of the versatility of the system engineer in our time.

Man must organize and utilize all known advances in all technological areas. Today we cannot imagine life without computers. Sizes of computers and their elements have continuously shrunk so that today we are able to take a multipurpose computer on board and use it in orbit to help check out the flight readiness of the stage.

Instrumentation technology has also improved. Most of the off-course analog data have to be translated into bit information for the digestion of the computer and the telemetry links for easier transmittal.

It is difficult to state which technological breakthrough is the most important for our lunar flight program. Is it in the electronic, the mechanical, or the physical areas? Is it the "hydrogen technology" which includes the production of rather high quantities of this propellant? Is it the art of producing and handling large rocket engines, or could it be the manufacture of flight hardware of such large dimensions?

I will review several areas where technological breakthroughs have occurred and consider them specifically as to their impact on the large space vehicle development.

PROPELLANTS AND PROPULSION

The most important breakthrough in the field of propellants is our now increased familiarity with liquid hydrogen. Production of LH_2 is routine; handling, storage and usage are well-mastered trades. Additives to liquid oxygen for increased performance of the fuel: fluorine, berylium, or lithium are not yet considered useable in the Saturn family.

Storeable propellants are widely used and have found their way into the auxiliary propulsion system for attitude control. Expulsion of these propellants under zero "g" condition was mastered by using propellant compatible bags. Metal bellows are also under consideration and have been tested.

I will not elaborate upon the advancement of solid propellants because they play a secondary role in the Saturn development, despite the fact that Saturn carries more solid propellant engines than liquid ones. Solids are used as retrorockets for separation purposes, and in ullage rockets for settling propellants. Hybrid systems are being studied and have their advantages, but they do not belong to the mainstream of our efforts.

In the fields of engines we have a considerable selection with different levels of maturity. Four such engines, as shown in

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are:

a. THE RL-10, 15,000 pounds thrust, LH_2 and LO_2, used in the Saturn I and Centaur--has a fine reliability record.

b. THE H-I, 200,000 pounds thrust, LO_2 and kerosene, used on the first stage of Saturn I and the improved Saturn I (Saturn IB). These engines, or close relatives, have flown several hundred times.

c. THE J-2, 200,000 pounds thrust, LH_2 and LO_2, is in the process of being flight-rated or quality tested. For many years to come, this engine will be used on all space launch vehicles.

d. THE F-1, 1,500,000 pounds thrust, LO_2 and kerosene, the biggest single-barrel engine used in the Saturn V program, is in very good shape.

MATERIALS AND MANUFACTURING

A steady improvement of the launch vehicle efficiency has led to a drive for better materials. Our approach in the development of space vehicles is to use high-strength lightweight metals in a self-supporting structure. As shown in

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we have developed aluminum alloys with considerable strength values.

Berylium-aluminum, berylium-magnesium, berylium-lithium alloys are under advanced research development.

Steel and alloys play a less important role in the Saturn progress except as high-strength components.

The art of compound structures with lightweight core material has found wide application in these launch vehicles. Both upper stages of the Saturn V have a common bulkhead separating LH_2 and LO_2. This consists of two spherical or ellipsoidal face sheets of welded contoured gores of 2014 aluminum with a core of two to four inches of hexagonal core material of fiberglass reinforced plastics. This construction

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has been flown several times in the S-IV stage of the Saturn I vehicle.

The technique of sculpturing the necessary ringframe profiles, and longitudinal longerons out of solid plates up to two inches thick is commonplace in optimizing design and manufacturing.

In the areas of metal joining, we have mastered multipass welding of 2019 blocks 6" by 16" finally to form a ring which is the raw material for a huge machined ring frame 33 ft. in diameter, as shown in

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The achieved welding strength is shown in

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The art of inspecting weldments ranges from the old reliable x-ray to dye penetration and even ultrasonic investigation. Every one of the many weldments is carefully inspected to allow us to use the safety factor I mentioned earlier. The use of insulation ma terial has developed to a fine art. Low temperature, low weight insulation for cryogenic propellants ranges from inside application to outside application. Utilizing cryogenic pumping, vacuum, helium flushing to improve and maintain low-heat-transfer coefficient is commonplace.

High temperature insulation ranges from plastic coats (epoxies) to unfired, troweled-on ceramic mixtures which are actually cured in flight by the severe radiative and convective heat loads of the engines in the rear or by the reentry heating on structural elements.

Newly introduced manufacturing techniques such as explosive forming are widely used to produce true shapes without the high cost of dies for large presses; stretch forming is commonplace, also.

There is a limited application for the newly developed electromagnetic hammer which uses induced eddy currents in light metals to push the metal into the desired forms and location.

Tooling concept for self-supporting structures was developed utilizing the strength of the subassemblies. Simple externally applied locating tools do allow a perfect alignment of sheets prior to welding.

There are many more practical approaches and simplifications which allow us to decrease the cost and manufacturing time and at the same time to improve the quality to the desired level.

GUIDANCE AND CONTROL

In order to meet the overall flexibility requirements of the vehicle, the guidance concept must be broad enough to encompass all forseeable mission objectives and vehicle configurations, including different payloads. The mathematical structure of this concept is termed the "Adaptive Guidance Mode." It is sufficiently comprehensive to cope with all foreseeable specific guidance problems. Although maximum reliability is the primary goal, maximum flexibility is a strong secondary goal. The Adaptive Guidance Mode requires the inflight solution of guidance equations by an airborne digital computer which evaluates the current vehicle coordinates and flight status and selects an optimum flight path. This computer controls the direction of thrust applications in order that the vehicle will follow this optimum path during powered flight. The computer also provides the cutoff command for the uppermost launch vehicle stage. In order to cope with perturbations (such as thrust variations) occurring during flight, trajectory selection is repeated continuously and approximate new steering and cutoff commands are generated.

Since a discussion of all elements of the guidance and control system would take too much time, let me mention only as an example the digital computer to show you what progress has been made in this area. The digital computer utilizes a duplex memory and triple redundant logic. It determines desired vehicle heading, transforms this heading into the platform coordinate system, and compares vehicle attitude with platform gimb al angles and forwards the result of this comparison to the control computer. It computes engine cutoffs and S-IVB engine re-ignition and provides data for the emergency detection system. It performs the orbital checkout of the space vehicle, updates the guidance functions and performs attitude control functions during orbital operations. A few years back a computer for such a task would have filled a good sized room with electronic equipment. Through microminiaturization we are able to pack this equipment into one box the size of a small suitcase.

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Undoubtedly, meeting all the requirements of the NASA Space Program for manned exploration will, in time, call for space vehicles more powerful and more advanced than Saturn. However, Saturn offers the important advantage that it is based on a technology which we understand and which, for the most part, has been thoroughly tested.