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LESSONS LEARNED
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DESIGN REVIEWS

There was never a valid CDR of the Solid Rocket Motor (SRM) or the Space Shuttle Main Engine (SSME). I was a Laboratory Director and several of my people normally participated in the element CDR's. I chaired the Structures part of the External Tank (ET) and Solid Rocket Booster (SRB) CDR's. ET and SRB reviews were conducted according to the Marshall Space Flight Center (MSFC) review standard, which used Review Item Deficiencies (RIDs) to surface potential problems. I never heard of an SRM CDR, so I assume that if there was one, it was unilaterally conducted by the SRM Project Office. The SSME CDR was conducted by the SSME Project Office and was done more perfunctorily than rigorously. RIDs were not used and independent reviewers were not involved.

The SSME survived the lack of a valid CDR without a safety threat because of the subsequent extensive testing and problem exposure at Stennis. The excess funding required, due to this approach, can only be speculated on.

My experience with valid CDR's is that there is an almost overwhelming number of RID's which must be dealt with. Many of the RID's were due to the lack of familiarity with the element. I can only remember one RID, from the ET CDR, that was a potential show stopper. It pointed out that separation pyrotechnics could physically be installed incorrectly. The design was changed to preclude this. To me, this RID was more than worth all the CDR effort.

Based on my participation and experience with Design Reviews, I feel certain that, had a valid CDR been performed for the Solid Rocket Motor (SRM), temperature limits of the segment o-ring seals would have been required. It is unheard of for any key spacecraft component not to have specified temperature limits.

The design review short-comings were prior to STS-1 and were associated with schedule pressure due to all Shuttle elements being behind schedule.

Subsequent to STS-1, the Administrator declared the Shuttle fully operational after STS-5 flight. Soon after STS-5, there was a late breaking launch concern due to Orbiter Auxiliary Power Unit (APU) hydrazine leaking into the APU lubricating oil and forming sludge. The JSC Center Director was dismissed (not transferred) for holding up the launch so as to understand the problem. This consequence was not lost on other Center Directors and Shuttle Managers.

To summarize, schedule pressure contributed to lack of a valid RSM CDR and to a faulty decision to launch on a cold day. This does not excuse poor management associated with the lack of a CDR, or of launch in spite of out-of-experience weather, and, against prime contractor advice, but it was a strong contributor to the causes for these mistakes.

The External Tank CDR was conducted according to the review standards and very well executed. The root cause of the foam debris effects on the Orbiter was the lack of systems engineering to identify foam debris impact as an Orbiter threat. The main purpose of the foam was to minimize pre-launch propellant boil off. The ogive section of the oxygen tank was the only place where foam was needed to maintain positive structural margins during ascent. A RID was submitted to develop a Nondestructive Evaluation (NDE) technique for verifying foam adhesion, but was never satisfied. Foam plug-pull coring was used instead.

All Shuttle elements were developed in parallel. The ET was designed as if it flew alone. CDR is not the place to define new requirements, such as foam impact threat to the Orbiter (although it's better than never). Systems Engineering systems trades and integration should start at program initiation and should be, in effect, complete before PDR.

SUB-TIER VENDOR OVERSIGHT

With rocket engine contractors, the percentage of parts procured from subcontractors has varied from roughly 100 to 50 percent. Theoretically, the prime contractor has acceptance criteria, and subcontractor parts which pass these criteria are considered flight worthy. The various prime contractors deviate in varying degrees of oversight on their subcontractors.

It is not sufficient to use part inspection as the only measure of subcontractor performance. Example: We had an engine test failure which was caused by a subcontractor part failure. Upon delving into the background data, it was found that the parts were produced in lots of 12 (twelve). Of the lot of interest, 9 (nine) of the 12 (twelve) parts were unacceptable. That gives two messages: (1) we were paying four times too much for each part and (2) the high scrap rate called into question the quality of the accepted parts.

Dealing with subcontractors is a delicate thing. You must demand quality but, considering the small number of parts you buy from each subcontractor, you have to be careful of your relationship with him, or he may decide to quit making the part.

It is preferable to have engineers who are accountable for the quality of the furnished product, rather than a special organization for supplier oversight. When using a supplier oversight organization you sacrifice engineering knowledge and accountability.

CERTIFICATION DEVIATIONS

- Design
- Manufacturing/fabrication
- Use conditions
- Inspections
- Processes

Changes are fair game in the PDR, and CDR time periods, but not after DCR. DCR confirms that components and systems have been demonstrated by tests, to meet requirements.

Exceptions are the discovery of safety or operational problems which dictate change. But these changes require certification, and instilling this concept into program culture is very difficult. All changes are thought to be improvements, but history indicates that every change has side effects. Only testing under use conditions can be considered proof.

As an example: A lead manufacturing engineer made a change to a major SSME component electrolysis plating process, to save time and reduce the cost of electrolyte. An unrecognized side effect of this change resulted in nine faulty major components. The cost impact was several million dollars. Even worse, though, was the inability to support the flight schedule safely. To support the flight schedule the component had to be removed from the Orbiter immediately upon landing and reinstalled in another engine. This caused out of sequence KSC work and risk of collateral damage in swapping components, which both added flight risks.

Consequently, much time, money, and effort were spent trying to identify the change which caused previously good hardware to be defective. No one but the manufacturing people who made the change were aware of it. Neither Engineering nor resident NASA people were aware.

Recommendation

- Every award fee plan should include a statement that all changes must be approved by NASA. This is over and above the Material Review (MR) process of evaluating out of specification parts. The change approval requirement should include processes, as well as design.
- A prime concern of the Residence Office at the contractor facility and S&MA should be to be aware of and report changes.

Certification consists of tests, where flight conditions are achieved. Where only some flight conditions can be simulated in testing, systems engineering must be used to determine the consequences of the flight conditions which cannot be simulated. At least one vehicle flight must verify certification. Certification is expensive and requires significant time and manpower.

<u>If a change is made, for any reason, the change must be fully certified before incorporation, even if the change is thought to be an improvement in design, process, or operation</u>. Process changes are as important as design changes.

During the operational phase of a space component or system, improvement type changes should not be made. Only make changes required by safety condiderations. All changes are thought to be improvements, but often cause unanticipated problems.

HANDS-ON EXPERIENCE AND OVERSIGHT

<u>Effective contractor oversight requires that the responsible government employee know as much, or preferably more, than the contractor</u>. The government objectives are <u>good hardware at a fair price</u>. The contractor objectives are <u>good hardware at a fair profit</u>. These objectives are almost identical but the <u>difference could cause a difference in risk acceptance</u>.

Since the government has cognizance over many and varied programs, it has a potential advantage in oversight capability. However at the main NASA propulsion center, MSFC, hands on work on manufacturing and engine testing no longer exists. The latter can be solved by a cooperative partnership with the Stennis Space Center. The former is difficult to remedy, and requires serious attention.

Traceability is expensive but economical, considering its value in failure investigation and determining the health of the systems. Workmanship, material manufacturing problems etc… sometimes vary with the time of manufacture and with component lot number. If a failure can be isolated to a specific lot, or specific worker, much money and schedule can be saved by eliminating need for a lengthy failure investigation. This is especially valuable in maintaining a flight schedule, which is put on hold while the failure cause and corrective action are determined.

MAINTENANCE AIDS

There have been failures and delays caused by maintenance personnel leaving foreign objects in engine and propellant systems. Use of tape and other improvised aids should be avoided in favor of permanent aids such as plastic caps. Also, closeouts should have a second set of eyes to prevent foreign object occurrence. Usually, a green run before flight will surface an engine foreign object problem, but serious engine damage usually occurs.

REDUNDANCY

Redundancy is a powerful safety feature for random failure, but ineffective for generic problems. Example: Skylab fluid system modulating valves stuck due to contaminates. There was no practical way of testing Skylab fluid systems in zero "g". Rigorous System Engineering would have recognized that stagnant regions during ground flushing could harbor particles which would enter the flow stream during zero "g".

Systems Engineering should be intense where testing with flight conditions is not possible.

TEST FIDELITY

It is not always possible to replicate all flight conditions in ground testing. Deviations between flight and ground tests should be treated as changes. That is, the deviation should be reviewed by Systems Engineering, and also be elevated within management. All test deviations have side effects which are sometime not recognized, and may incur risk.

Example: The Saturn V SII stage J-2 engines had cryogenic hydrogen and oxygen lines feeding the augmented spark igniter on each engine. Ground dynamics tests of the lines were performed without a vacuum enclosure, allowing formation of frost on the line. In flight, a hydrogen line rupture shut down an engine. The cause was fatigue failure of the line. The lack of damping by frost on the flight line changed the modal response of the line, relative to ground testing.

ENGINE INTERNAL FLOW DYNAMICS

COMBUSTION INSTABILITY:

The worst engine problem in the Apollo/Saturn program was combustion instability of the first stage F-1 engines. The engine propellants were kerosene (RP-1) and LOX, and the thrust was 1.5M lbs. The combustion process in the combustion chamber was unstable and could cause destruction of the engine.

On the Atlas program, there was a case where increasing the thrust of the center (sustainer) engine caused combustion instability to a formerly stable engine, without change to the combustion chamber.

Combustion instability of the F-1 Saturn First Stage engine threatened to seriously delay the lunar landing program. The unsteady pressure pulses in the combustion chamber would destroy an engine if allowed to persist. The first thought was that there was not good mixing of the RP-1 and oxygen at the injector face area. Design changes did not correct the instability. Several other ideas were tried without success. Finally, the large combustion chamber was divided into sectors by use of baffles. There was speculation about the cause of the instability. One theory was that the dynamics of combustion was coupling with the chamber structure dynamics. The fact is that the process is still not understood.

The Space Shuttle Main Engine (SSME) combustion chamber was designed using baffles, which were later determined to be not needed. Removal of the baffles (late in the program) reduced cost and weight, plus yielded a small increase in specific impulse.

The RS-68 engine combustion chamber design included baffles (which are probably not needed). The incorporation of baffles was traded off verses the program risk of a redesign, if baffles were later shown to be required by ground tests.

Speculation, based on limited experience suggests that use of hydrogen fuel decreases the possibility of combustion instability (probably due to hydrogen wide combustion limits), and very large combustion chambers may increase it, for some unknown reason.

ENGINE INTERNAL FLOW

The most serious problem in the SSME program was a flow induced vibration in the oxygen propellant flow system. There was strong 7200 hertz vibration which destroyed KelF seals in the Main Oxidizer Valve, causing test engine destruction. Several months were required by a combined MSFC/Rocketdyne effort to determine the cause. There was no practical way to effectively use instrumentation within the flow stream. The cause of the problem was finally determined by analyzing the internal engine flow surfaces for "triggers". The offending source was a flow discontinuity, which had the effect of a backward facing step. A simple "washer" type filler eliminated the flow disturbance and the 7200 hertz disturbance.

POGO

The POGO experienced on the Saturn vehicles was limited to the center engine of the five J-2 engines on the S-II stage. The center engine was mounted on a crossbeam which was not as stiff, structurally, as the attach structure of the other four engines, which transferred their thrust load into the main structural shell of the vehicle. POGO did not occur until fairly late in the S-II burn. We lived with the problem by shutting down the center engine just before the time for POGO to start. There were a couple of lunar flights which used this technique while the POGO accumulator system was being designed and built.

ENGINE RESTART in ZERO "g"

Gravity is an effective damping force. In zero "g", the damping depends on the energy loss due to impact of the slosh wave and the tank, and internal friction within the fluid. These effects are small, compared to gravity.

In Saturn, the S-IV B stage was shut down in Earth orbit, and then restarted for Trans-Lunar-Injection. Small "ullage engines" were designed to apply positive thrust to settle the propellants prior to restart.

Due to concern that the ullage engines would not be sufficient, a drop tower was designed and installed in the Saturn V dynamic test stand. At the time, the tallest drop tower was at LeRC and had 100 ft drop capability. The test fluid needed a finite time to change from a 1 g meniscus to the zero "g" configuration , and the allowable size of the test fluid container was a function of the zero "g" test time. A 100 ft drop would require an unacceptable small fluid container, about the size of a hospital type tube.

A 360 ft drop tower designed and built at MSFC gave a 4.3 seconds zero "g" time, which allowed a 4-inch diameter test specimen.

The drop capsule which contained lights, cameras, instrumentations, and small test thrusters, weighed 4000 lbs, was bomb shaped, and was the size of a full scale automobile. A unique catch tube with seals and orifices was designed to decelerate the capsule pneumatically at the bottom of the drop without causing rebound. The test capsule was in free-fall during the test and was settled on a floor just before entering the catch tube.

Testing which simulated the hydrogen tank, the hydrogen, and the ullage engines was preformed. The tests indicated that the slosh wave moving forward, when the S-IV B engine was shut down, would not be settled by the ullage engines for engine start.

A baffle in the form of a concentric ring was attached to the forward inner surface of the model. The purpose of the slosh baffle was to remove enough kinetic energy from the slosh wave such that the ullage engines would be capable of settling the hydrogen for engine start. Tests showed the baffle would solve the slosh problem.

After model testing, a fiberglass cloth baffle was installed in the hydrogen tank of an S-IV B for flight test. Cameras and lights in the area of the internal hydrogen tank forward zone were used to verify the effectiveness of the baffle. Flight cameras showed remarkable similarity between drop tower model tests and full scale fight.

SUPERVISING PERSONNEL

Good coaches don't win because all their players are all-stars. They win because they extract the maximum efforts that each player is capable of giving.

Experience in directing large organizations (<100) indicates that the following techniques are effective:

1. Know the face/name of every one of your employees. Some organizations are too large for 100 %, but do the best you can. People appreciate being treated as persons rather than warm bodies
2. For awards which include money, let the employees' direct supervisor give the award. The employee should understand that his main responsibility is to his direct supervisor. Everyone enjoys being Santa Claus so there is a temptation for the top supervisor to give the awards. This undermines the immediate supervisor's effectiveness.
3. For less important awards, such as years of service and other awards like this, meet one-on-one with the employee. Face time with the manager is a positive morale factor for the employee, and it helps the manager's name/face recognition for the future.
4. For low performing employees, find out the cause and try to improve the employees' performance. One effective way of detecting problems is to compare years of service with accrued sick leave. If his or her accrued sick leave is very small, compared to years of services, one of the following is probably true:

    a. The employee has had a medical problem. No further action is required.
    b. The employee is not interested in his job. Change his job.
    c. The employee thinks he was treated unfairly in the past. Talk with him and try to change his attitude.
    d. The employee has outside interests which take precedence over his job. Talk with him and if not successful take disciplinary action

*Employee number can be used to approximate years of service.

SYSTEMS ENGINEERING

Many propulsion problems are due to insufficient systems engineering.

It has a powerful influence on design. In preliminary design, systems engineering is the prime discriminator in performing design and integration analyses.

The places where systems' engineering is often inadequate are in (1) design and operational changes, and (2) testing which does not include all flight conditions.

Every change has side effects. Some can cause failure. Test conditions which are impossible to duplicate or where 100% duplication is thought to be unnecessary, can cause erroneous conclusions. These changes have historically caused significant reliability problems.

DESIGN FOR MANUFACTURING, INSPECTION, AND MAINTENANCE

Experience has shown that a lack of communication during the engine design phase causes failures and operational problems. Designers must make manufacturing, inspection, and maintenance personnel an integral part of the design process. Example: An engine was destroyed during testing due to inability to verify proper installation of a small part. Redesign was required. Example: Another part caused an on-pad abort due to a blind installation of a part which was difficult to install properly. Redesign was required. Example: A ground test failure occurred due to failure of a part which was unnecessarily difficult to manufacture, causing high scrap costs.

All groups should communicate and work together during the design phase or serious downstream problems will occur.

ACCIDENT INVESTIGATIONS

Timely and accurate accidents investigations are of great importance. The cause of the failure and corrective action, if any, must be determined before the next flight can occur.

There are standard actions which are always taken, such as impounding the accident site and the measured test or flight data. A team of experts in all applicable disciplines is formulated in advance, and is immediately activated for a serious accident or failure. Similar teams exist for both the contractor and government.

The teams convene at the accident site, and the recorded data is displayed, in time sequence, usually attached to the wall in the meeting room, so multiple people can examine and discuss the data at the same time.

Synchronizing the various sources of data is usually the first step in the investigation. There may be camera data, recorded data, and a test plan timeline. Since the sequence of events is critical, the various sources of data must be correctly synchronized at the beginning. Also, it is normal to review all hardware discrepancies, such as MRs (Material Review) for a clue.

Some accident causes are very hard to determine. Even when there is camera coverage, engine explosion smoke and steam often mask the initial point of structural failure. Normally, a failure tree is constructed to begin the investigation. Experience has shown that almost any accident can be explained if the investigation allows consideration of two separate failures which together caused the accident. Consideration of dual failures is likely to lead to erroneous conclusions. Dual failures are not impossible, but a single event should be found which explains all the data.

ACCOUNTABILITY

Lack of accountability is the most important cause of program cost, due to scrappage of expensive hardware and delayed development. It can also increase flight risk. Lack of accountability is a product of organizational culture, and organization. Example: In a pump development program, a part failed during testing. Part of the investigation was to critically examine all similar parts which had been previously tested. A part which had been tested over a year before had a crack in the same place where the failure occurred. This type thing happened three times during development. To Engineering, the problem was that Inspection had failed. To Inspection, the part had not been sufficiently cleaned for them to detect the crack. The cleaning people said that a dry lubricant used in assembly was almost impossible to clean off. There should have been one person who felt responsible for the total process. It would be up to him or her to assure good cleaning, thorough inspection and all other factors affecting the quality of the part. This is only one example. There are similar problems at many contractors. Most company organizational charts show individual blocks for manufacturing, inspection, design, etc. This tends to create territories and boundaries.

RATES

The SSME costs were too high. Part of this is because Boeing used the SSME as a cash cow. A rate change which affected NASA included SSME (Rocketdyne), Space Station (Boeing), and United Space Alliance (USA work on ISS).

Boeing was getting a lot of heat because of ISS overruns, and they wanted to bid for more work for USA. The rates were changed such that every rate affecting NASA was lowered except for SSME, which was substantially increased.

We called in GAO to audit Boeing's SSME rates. The GAO "audit" was superficial and didn't change anything. My take is that the GAO doesn't want the Government to be cheated, but doesn't care about the division of rates between programs. The GAO "audit" consisted of a short viewgraph presentation by Boeing.

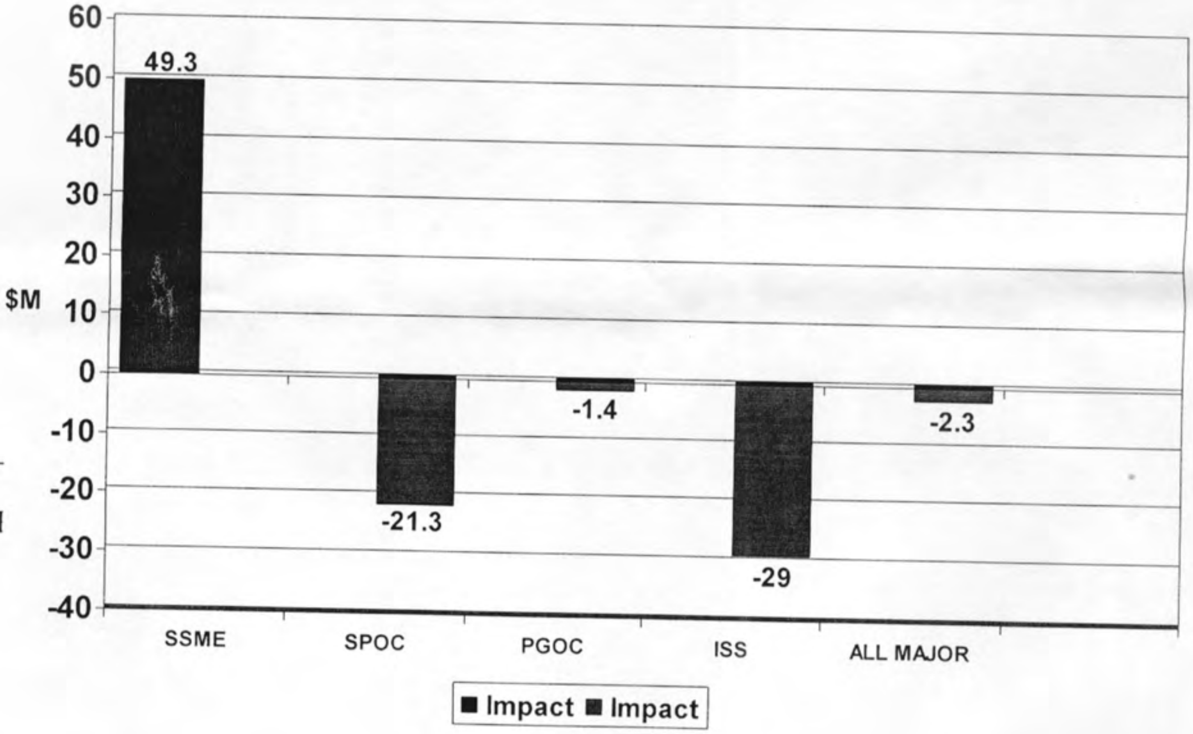
We had to have SSME's and had nowhere else to go. (It should be noted that Rocketdyne didn't like this Boeing rate manipulation any more than we did).

There is probably no solution for this sort of thing, and maybe the overall cost to NASA is not affected, but it does skew the cost within NASA. With a fixed budget, SSME work had to be reduced because of the rate increase, which added risks due to effects on SSME analysis and hardware. Boeing was in a better position to bid on new NASA work because of the rate changes. This may or may not be legal, but is not ethical.

A chart (FIGURE 1) is included which is admittedly out of context, because the data came from a several chart presentation. But, it is the bottom line.

Updated Impacts Through CY 2001 to Major NASA Programs

Dated July 2001



FIGUI

GOOF PROOF

Any bad thing that can happen will probably eventuality happen. This is not because people are stupid or careless. Sometimes its due to preoccupation with personal problems, repetitious job syndrome, etc.

Example: If there are two supply connectors for hoses used for supply of oxygen and nitrogen, don't use color coding to preclude inadvertent switching. Make the connectors different so that connecting the wrong hose is impossible. This was an actual event during my first year or two with NASA. I was embaressed by what sounded to me like an insult to the contractor's intelligence and competence. Now, I know that it was not an insult. It was based on experience, that things which sound foolish really happen.

How many times has a 28 volt power supply been connected to a 5 volt control circuit? How many times have propellant tanks been purged with nitrogen and sealed, causing tank buckling when the ambient temperature went down? How many structural failures have been due to using the wrong weld wire?

SOURCE EVALUATION BOARDS

NASA should critically review how Source Evaluation Boards are conducted.

They last too long. The SRB recompetion took one year. The Space Station Freedom, Work Package 1 SEB was planned to last one year, but the Request for Proposals were held up for six months for Congressional review. In order to have a contract before the end of the fiscal year, only six months were available for the SEB. Notwithstanding the time constraint, the SEB was conducted in an efficient manner, with no loss of fidelity.

The quality of SEB members is reduced because the best potential members cannot be spared from their organizations for one year.

Choose a Board Leader with program management and hardware experience. Choose competent Board members and Review Team members. Inexperienced people, and lack of technical penetration can doom a program before it starts.

Proposal cost data submitted by the bidders should be in a separate document and should be guarded, and available only to the Cost Evaluation team and the SEB Board Members. The delay between the initial proposal and Best and Final proposals provides an opportunity for leaks of cost information, which has a powerful influence on proposal success.

Experience shows that very little consideration is given to the winning contractor's Make or Buy plan. This plan can have enormous effects on cost and schedule. Contractors often have conflicts of interest. Sometimes it is a choice between downsizing their workforce v.s. taking on an in-house job which they are not qualified for. Other times it is to have the government finance their addition of a new business line.

Example: The Spacelab contractor elected to fabricate, in house, the flexible tunnel connecting the Spacelab with the Orbiter, for crew transfer. The construction was of a rubber like elastomer, laminated with fabric. similar to an automobile tire constuction. After several test failures, several months schedule slip, and several million dollars overrun, the contract was subcontracted to Goodyear.

Example: Orbital Maneuvering Vehicle:

An inexperienced leader and lack of technical penetration resulted in baseline of a cold gas propulsion system. Immediately after contract award the system was changed to hydrazine, at great cost increase.

The winning contractor, TRW, was one of two companies specializing in photovoltaic power systems. Their competitor had Air Force contracts for gallium arsenide systems which was a leap in technology, but very expensive. TRW baselined gallium arsenide, (its first use by this contractor). Silicon cells were adequate but the contractor fought going this route so as to improve his future competitive position. The NASA Program Manager took no action. The OMV program was cancelled due to out of control cost overruns. The cost reserve was depleted before the program was a year old. The solar cell selections appeared to be a case of the contractor putting his company interest ahead of the program's.

NUCLEAR PROPULSION

Fifty years ago there was great interest and large funding for nuclear propulsions systems (rockets using hydrogen, and air breathing engines). Also there was considerable work on nuclear powered electric propulsion.

Work on electric propulsion has continued, for applications to geosynchronous satellite station keeping, but funding for nuclear power and propulsion for space applications has been practically non-existant.

In the late fifties, General Dynamics designed a nuclear powered Shuttle-like, reusable single-stage-to-orbit vehicle using hydrogen as a propellant, with a reactor heat source. The specific impulse used was 800 seconds, about twice that of the SSME. The project was unsucessful, not due to the propulsion system, but due to the impracticality of the single-stage-to-orbit concept. This lesson was learned again on the X-33 program at great expense and NASA embarrassment. The X-33 single stage to orbit concept was originated by the NASA Administrator, with no input from NASA propulsion engineers.

The Air Force funded the Aircraft Nuclear Propulsion (ANP) program for several years with Lockheed and General Dynamics as vehicle designer/integrators, and General Electric and Pratt and Whitney as nuclear system propulsion designers. Because of weight, hazards, and other considerations, the program was finally terminated, but there was a huge amount of materials testing, including metals, elastomers, fluids, and electronics, in radiation environments. The test results are still valid.

Recommendations:

Make use of past nuclear studies and radiation testing. NASA should not expend resources on reactor design. Reactors have been designed for rockets, jet engines, electric propulsion, commercial power generation and ship, and submarine propulsion. Industry is capable of designing reactors. The problems with Space Propulsion and Power have to do with Systems problems, such as shutdown after-heat removal, protection of ground personnel during and after reactor test and shutdown, reactor disposal, etc.

SOME THOUGHTS ON COMBUSTION INSTABILITY AND POGO

Neither combustion instability nor POGO can be tolerated, but reliable analytical models which predict their occurrence do not exist. Consequently, fixes which may not be needed are commonly incorporated.

a) Combustion Instability (CI)

Combustion instability is an uneven combustion process which results in a pulsating engine chamber pressure, which can result in engine structural failure.

One of the first instances of CI was with the Saturn V first stage engine, the F-1. This problem was probably the most serious of all Apollo program schedule threats. Many solutions were tried without success. Finally, the F-1 combustion chamber was divided into pie shaped sections, by use of baffles, or short dividing walls. Much work has been done to develop analytical methods to predict the occurance of CI, so as to understand how to prevent it. To date, no useful analytical model has been developed.

The F-1 engine CI was eliminated by use of baffles. The main unusual characteristic of the F-1 was its large size and thrust (1.5M lbs). Its propellants were kerosene (RP-1) and LOX. The other Saturn V (J-2) engines were smaller (200k lbs thrust) and used LH_2 and LOX. There was no CI associated with these engines.

With very little understanding of the process, one might consider the engine size and/or the propellants used, to be the discriminating factors. But, the CI process is much more complicated than this simple hypothesis and has defied reliable analytical treatment.

The bright side of CI is that engine ground testing will verify its existance or lack of. The downside is that an engine design based on the premise of no CI may require a redesign if CI should occur later during engine ground testing. Consequently, engines, such as the SSME and RD-68 were designed using baffles. Ground testing showed the SSME baffles were not necessary. Late in the program, the baffles were removed, which reduced weight, and somewhat increased performance (specific impulse). But the program costs and early performance were impacted. The jury is out on the RD-68, but it may well mimic the SSME.

NASA Research on CI, might be more important than work on other in-space combustion processes.

b) POGO

POGO is an axial oscillaion of the vehicle structure caused by coupling of the dynamic structural modes with those of the engine propulsion systems.

POGO is a fairly common problem which must be dealt with, particularly on vehicles which have several in-line stages. The vehicle structure tends to act like a spring when excited by the propulsion system, which acts as a forcing function.

During manned flight, the Saturn exhibited pronounced POGO which occurred when the S-II stage LH_2 tank level decreased to below the half full fuel level. The POGO had probably been present during early unmanned flight but was not picked up by the instrumentation.

The major oscillation was associated with the center (of five) engines which was attached to a "cross beam". Fortunately, there was enough propulsive margin that the Saturn V mission could be accomplished in spite of shutting down the S-II center engine before onset of POGO. Early lunar missions used this technique before a POGO suppression system was available.

Like combustion instability, POGO analysis tools have not been available to reliably determine the existance of, and the prevention of POGO. The problem with reliable analytical methods is probably the almost prohibitive size and complexity of the vehicle structural models required.

Although the S-II POGO was associated with the relatively flexible cross beam, the fact that the LH_2 fuel level was important leads to the conclusion that the entire vehicle structure and propusion systems were involved.

Unlike CI, POGO cannot be tested on the ground. So once POGO preventional design is incorporated, it cannot be eliminated later.

POGO suppression/prevention systems use a liquid/gas shock absorber in the propellant system. SSME uses "POGO accumulators" integrated into the LOX propellant system. Each POGO accumulator weighs about 165 lbs (wet) and adds complexity and failure modes to the engine. Whether the ~500 lb payload penalty, the complexity, and the added failure modes are required is not known.

The use of POGO suppression on SSME's was probably appropriate given the lack of reliable POGO analytical methods, and since the first flight was manned. However good analysis techniques might have eliminated the requirement for the POGO system penalties.