NASA Experience with Pogo in Human Spaceflight Vehicles

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ABSTRACT

An overview of more than 45 years of NASA human spaceflight experience is presented with respect to the thrust axis vibration response of liquid fueled rockets known as pogo. A coupled structure and propulsion system instability, pogo can result in the impairment of the astronaut crew, an unplanned engine shutdown, loss of mission, or structural failure. The NASA history begins with the Gemini Program and adaptation of the USAF Titan II ballistic missile as a spacecraft launch vehicle. It continues with the pogo experienced on several Apollo-Saturn flights in both the first and second stages of flight. The defining moment for NASA's subsequent treatment of pogo occurred with the near failure of the second stage on the ascent of the Apollo 13 mission. Since that time NASA has had a strict "no pogo" philosophy that was applied to the development of the Space Shuttle. The "no pogo" philosophy lead to the first vehicle designed to be pogo-free from the beginning and the first development of an engine with an integral pogo suppression system. Now, more than 30 years later, NASA is developing two new launch vehicles, the Ares I crew launch vehicle propelling the Orion crew excursion vehicle, and the Ares V cargo launch vehicle. A new generation of engineers must again exercise NASA's system engineering method for pogo mitigation during design, development and verification.

GEMINI – TITAN II EXPERIENCE

NASA first identified pogo as a threat to spaceflight vehicles and their crews in the early 1960's during the Gemini-Titan II program. The Gemini spacecraft was to be a two-person vehicle with significant improvements in spacecraft design over that of the Mercury spacecraft, principally for simplified systems check-out and operations, and increased crew piloting functions. In particular, the Gemini project manager considered the event sequencing for the Mercury escape system as "…one of the major problem areas in Mercury in all its aspects - its mechanical aspects in the first part of the program, and the electronic aspects later." Thus the new design of the Gemini spacecraft eliminated the escape rocket tower used in Mercury and put the crew in ejection seats.[1]

The change from escape rocket to ejections seats was thought to exclude use of the Atlas booster (used for Mercury orbital flights) because its liquid oxygen and RP-1 propellant combination were considered too highly explosive for an ejection seat to respond quickly enough to save the crew. However, the USAF was developing a new missile, the Titan II, which would use storable hypergolic propellants: a blend of hydrazine and unsymmetrical dimethyl hydrazine (UDMH) as fuel with nitrogen tetroxide as oxidizer. These propellants were thought to react much less violently in the case of an abort then the cryogenic propellants of Atlas, so ejection seats were considered compatible with the Titan II. The increased thrust of the Titan II almost two and one-half times that of the Atlas, also made other Gemini spacecraft improvements more feasible. Thus Gemini and Titan seemed to be a perfect match.[1]

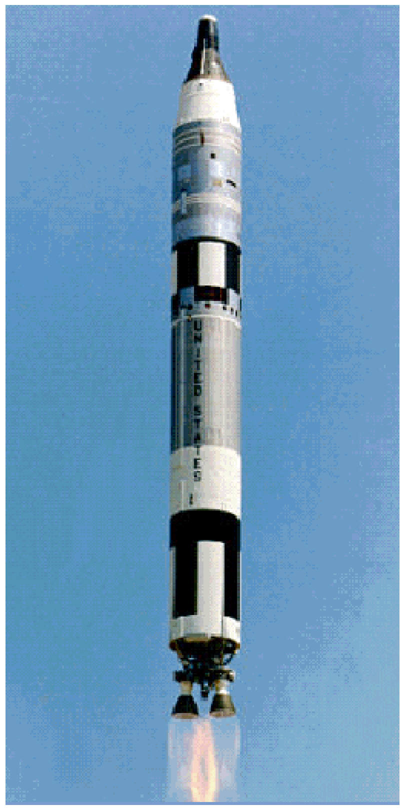

Figure 1. Gemini-Titan

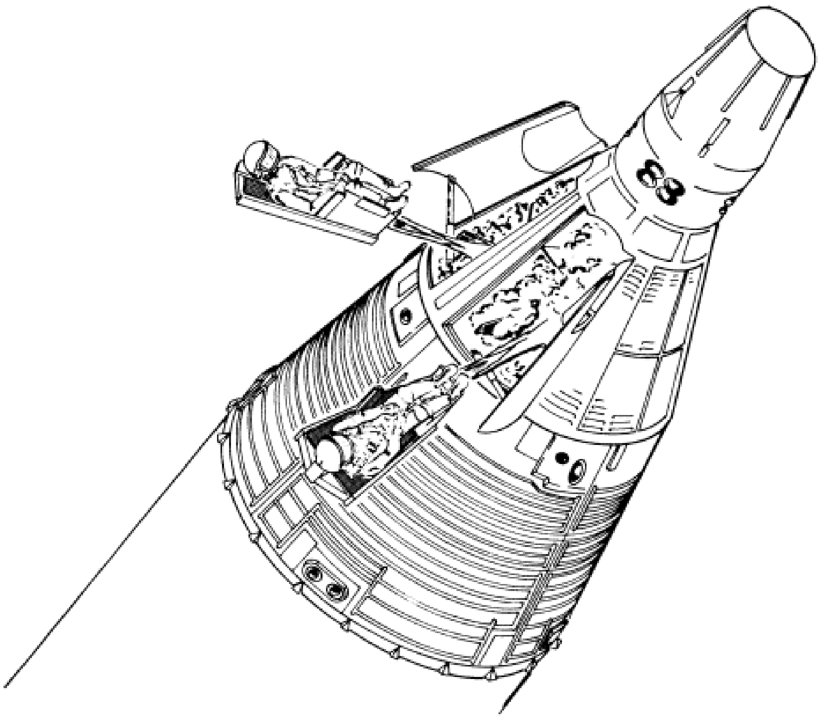

Figure 2. Gemini Spacecraft and Ejection Seats[1]

Artist's sketch of ejection seats propelling the astronauts to escape distance from a launch failure. They would be used in emergencies before launch (pad-abort) and in flight to about 18,000 meters altitude.

The USAF began test flights with the Titan II ballistic missile on March 16, 1962. Ninety seconds into the first-stage flight the missile began a longitudinal vibration going from 10-13 Hertz for roughly 30 seconds, reaching a maximum amplitude of +/- 2.5 g's at about 11 Hertz.[2,3,4] Even for a military payload this design environment was excessive (the USAF considered 1.0 g as a tolerable design load for the structure of the Titan II and it's payload).[2,4] But for a spacecraft's crew, vibration at 11 Hertz and +/- 2.5 g's could be painful and would greatly impair their ability to perform any piloting functions or respond to an emergency. NASA required that the vibrations be kept below +/- 0.25 g's.[1,2,3,4]

The longitudinal oscillations were soon given the nickname "pogo", because of the analogy to the ride on the children's pogo stick jumping toy. Pogo was a regular discussion item in Houston at the NASA Manned Spacecraft Center (MSC) and the USAF formed a special Committee for Investigation of Missile Oscillations. The fourth Titan II test flight in July 1962 provided engineers with a clue to the problem as the implementation of a higher operating pressure in the first-stage fuel tank seemed to have cut the pogo amplitude in half, to 1.25 g's.[1]

The Titan II contractor, The Martin Company, suggested that pogo might be caused by oscillating pressures in the propellant feedlines. Using what was thought to be an accurate mathematical model, Martin proposed to install a vertical surge-suppression standpipe charged with gaseous nitrogen in each of the oxidizer lines on a later Titan II test flight. NASA endorsed the plan, and the USAF agreed, launching the eighth Titan II development flight (N-11) on December 6, 1962 with the standpipes installed.[1,2,3]

But instead of damping the pogo effect, the vibrations at the payload actually increased to +/-5 g's, forcing an early first stage engine shut down and mission loss. The NASA MSC Director remarked to his Manned Space Flight Management Council that he saw one hope: "the fact that the addition of the surge chamber affected the oscillation problem may indicate that the work is being done in the right place." [1]

The Air Force then asked the Aerospace Corporation to join the team working a Titan II improvement plan. Led by Sheldon Rubin, the team reviewed pressure recordings from static engine firings conducted a year earlier and identified the key missing element in the pogo model as pump inlet cavitation at both the oxidizer and fuel pumps. Just as the gas in an accumulator, cavitation bubbles were found to lower the vibration frequency of the fluids in the feed lines. The previous analyses had shown the fuel frequency to be well above the structural frequency while the oxidizer frequency appeared to be closer to the structural frequency, prompting installation of the oxidizer accumulators. In fact, the cavitation bubbles also caused the fuel frequency to fall close to the structural frequency. The improved Aerospace model showed that without the oxidizer accumulators, the oxidizer feedback partially canceled the fuel feedback through phasing of their thrust contributions. Further, the model showed that when the oxidizer feedback was weakened by the addition of the missile N-11 accumulators, the net effect was a greater instability. The addition of accumulators in each engine's fuel line was shown to be essential to eliminate pogo on the Titan II.[2,3]

The next Titan II flew on December 19, 1962 with no standpipes, but increased fuel-tank pressure and aluminum oxidizer feedlines instead of steel. Surprisingly, the pogo amplitude was lessened but no reason for the effect was readily apparent. Pogo on the tenth flight on January 10, 1963, was recorded at a new low of ±0.6 g at the spacecraft interface. But the NASA requirement for the Titan II remained as ±0.25 g at most due to the larger role astronauts were to play in piloting Gemini compared to Mercury.

On January 29, 1963, the USAF Titan Program Office froze the missile design with respect to devices for cutting vibration levels because the pogo vibration had be reduced below the specifications for the missile air frame and systems, and in early March the USAF decided that it could no longer accept the costs and risks of efforts to reduce the oscillations any further.[1]

But the vibration was still too high for Gemini and the USAF decision was soon reversed due to visits by the NASA Associate Administrator and the Secretary of Defense to the MSC in Houston. NASA blamed multiple Titan II problems for a drastic change in the Gemini schedule: two unmanned flights were now necessary rather than one, the number of manned missions was cut to ten, and the first manned launch was delayed by five months until August 1964. The Secretary assured NASA that Titan II would be fixed.[1]

In a subsequent review with the commanding USAF general, the Titan II contractors argued pogo could be solved by increased fuel-tank pressure, and a combination of standpipes in the oxidizer lines and mechanical accumulators in the fuel lines. The USAF and NASA agreed to a joint development and test program expressly designed to bring Titan II up to Gemini standards. The Secretary of Defense and the NASA Administrator endorsed the plan and directed the Secretary of the Air Force both to fund the development and to flight-test the improvements in the missile program

The 17th test flight on May 13, 1963, reached a new low amplitude record for Titan II pogo of ±0.35g. However, the 19th Titan II flight on May 29, 1963, was another failure. Flying with pogo suppression devices for the first time on both oxidizer and fuel systems to test their combined effect, the missile leaked fuel in its engine compartment and burst into flame as it lifted off. With controls damaged by the fire, it pitched over and broke up 52 seconds later, too soon to provide any pogo data.

Yet another flight failure followed on June 20, on the 20th Titan II flight. Launched on a military-only mission without the fuel line suppressors, pogo levels were low enough (±.62g) to meet Air Force standards, but a second stage engine problem with the oxidizer injector of the gas generator caused thrust to fall off shortly after staging to about half the required value. The same thing had happened in two earlier tests, and had the missile been carrying a spacecraft, its crew would have been forced to abort the mission. The back-to-back failures resulted in the USAF suspension of Titan II flight testing. Only 13 flights were left in the test program and any further attempts to lower pogo levels seemed too great a risk to proving the Titan II was ready to join the American strategic deterrent forces. [1]

The potential hazard of pogo to pilot safety had prompted a survey of available data on human tolerance of such vibration, leading NASA to conclude that pogo should be completely eliminated, or at least not allowed to exceed ±0.25g. Test programs at NASA's Ames Research Center and the MSC in the summer of 1953 indicated that higher levels might be tolerable, but overall they provided strong support that the 0.25g was still a prudent upper limit. An experimental program to eliminate pogo at its source was preferred, but NASA would settle for the 0.25g as a bearable limit if it was proved on Titan II flights before the launcher flew the Gemini spacecraft. However, some at NASA were skeptical of ever solving the problem on Titan II and NASA's Marshall Space Flight Center began to study the substitution of the Saturn I launch vehicle for both Titan II and Atlas.

Titan II launched again on September 23, 1963, and suffered a guidance malfunction unrelated to the Gemini booster configuration. Pogo on this launch was reached plus or minus 0.75g.

An October meeting of the USAF management considered whether to follow through with plans to fly Missile N-25 with oxidizer standpipes and fuel-side piston accumulators. Engine tests begun in August had confirmed the fuel line resonance as the cause of the Missile N-11 failure and demonstrated that fuel accumulators would solve the problem. The extensive testing was used to generate test-verified equations describing the dynamics of structure, the propellant feed systems and the engines. Pump tests showed that as inlet pressures were reduced toward cavitation, the pump started acting as an amplifier and large oscillations resulted in the thrust chamber pressure. Aerospace and Space Technology Laboratories argued strongly for the planned flight and won the crucial decision to fly as planned. [1,3]

With both fuel and oxidizer suppressors installed, flight N-25 launched on November 1, 1963, recording the lowest vibration levels ever on Titan II of only 0.11 g's, well below the ±0.25g required by NASA as the upper limit for pilot safety.[1,2,3]

With the success of the standpipe and accumulator on Missile N-25, the NASA Gemini Program Office inferred that the pogo theory and analysis had been confirmed, and moved on November 6 to procure several sets of the suppression devices for the Gemini launch vehicles. After subsequent Titan II launches on December 12, 1963, and January 15, 1964, both carried the suppressors and both met NASA standards, the Titan II was declared suitable for human flight.[1,2]

The first unmanned Gemini launch occurred one second after 11 o'clock on Wednesday morning, April 8, 1964. The Gemini I mission post flight report showed pogo of low amplitude and slight build-up just prior to staging, but it was not considered significant. The second Gemini mission, on 19 January 1965, almost matched the first, in the quality of performance, proving Gemini's spacecraft and launch [1]

The first Gemini crew of Virgil Grissom and John Young launched at 9:24 am on March 23, 1965. The GT-3 vehicle lifted off so smoothly that neither Grissom nor Young felt anything, and they remarked later that there was less noise than they had heard on the moving-base simulator in Dallas. The Gemini flights continued with little pogo noted until GT-5, also designated as Gemini V.[1]

The Gemini V crew of Gordon Cooper and Pete Conrad reported experiencing objectionable pogo during launch at 126 seconds, although the booster systems engineer saw no evidence on telemetry. Unable to read the panel gauges to the desired degree of accuracy and finding speech difficult, the pilot estimated the magnitude at +/-0.5 g. [5]

Post-flight data analysis showed pogo onset at T+92 sec, lasting for 46 seconds, with maximum amplitude of +/- 0.38g at the spacecraft-launch vehicle interface. The vibration was further noted as sustained oscillation duration of about 13 seconds as compared to intermittent response on previous flights.[5]

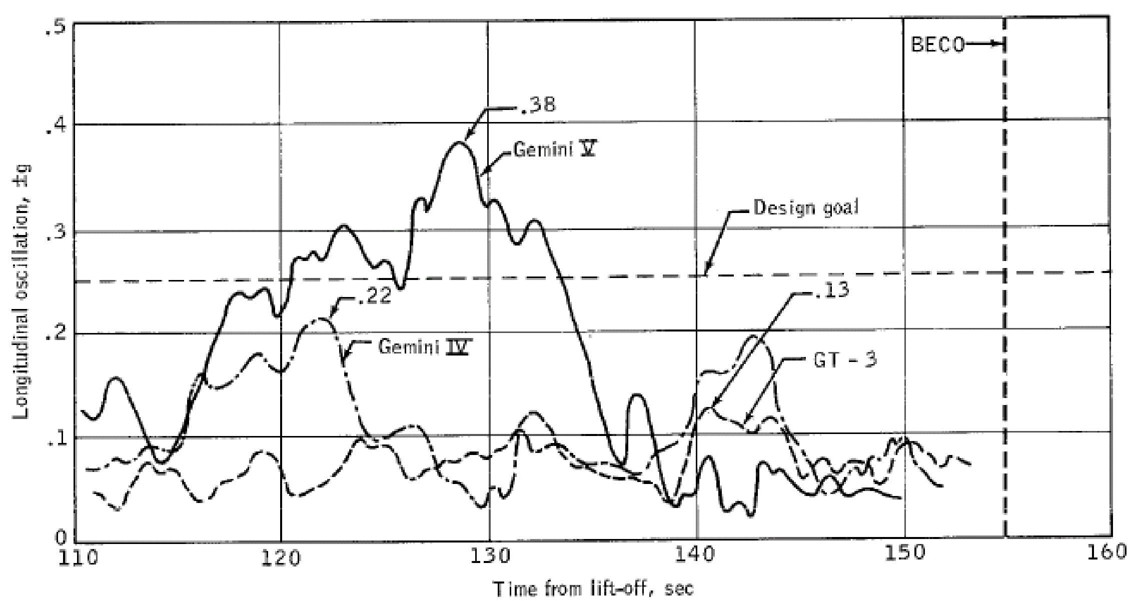

Figure 3. Comparison of Gemini-Titan Pogo Levels[5]

Further data analysis showed that the oscillations occurred only on the oxidizer side and not the fuel side. This was attributed to improper operation of the oxidizer standpipe as post-flight analysis and tests showed only about 10 percent of the normal gas bubble in the standpipe after charging was completed.[5] The standpipe was normally charged with nitrogen shortly before lift-off, but on this flight there was a hold on the countdown after the gas was inserted. It is significant to note that the nitrogen gas is readily dissolved in the nitrogen tetroxide oxidizer. [3]

No significant pogo was reported on any subsequent Gemini-Titan flights, although the vibration was still notable to the astronauts, as mentioned for example by Michael Collins in his book “Carrying the Fire”, reflecting on his Gemini VIII mission with John Young.[6] The postflight reports for Gemini X and XII noted intermittent suppressed longitudinal oscillation at T+123 seconds, at 10.9 Hz and +/-0.10 g; and at T+126.1 seconds at 11.2 Hz and +/-0.14 g, respectively.[7, 8]

In retrospect to the Gemini-Titan experience, it was recognized that the longitudinal oscillations experienced on previous Mercury flights on the Redstone and Atlas launch vehicles were also pogo, but not to such a severe level, the astronauts withstanding about +/-0.45 g.[4] The Redstone vehicle had exhibited pogo vibration in ground tests[3], and the Atlas vehicle experienced pogo at about 12 Hertz for a few seconds just prior to booster engine cutoff, as well as a vibration at 5-6 Hertz for the first 20 seconds after liftoff referred to as gas-pogo, ullage-coupled pogo, or bloating, which was unique to the Atlas’ pressure stabilized stainless steel construction.[1,3,4]

THE APOLLO SATURN V EXPERIENCE

In parallel to the Gemini Program, NASA was developing the Saturn rockets to take the Apollo spacecraft to the moon. The Saturn I vehicles all flew with no occurrence of pogo. The first Saturn V (AS-501) launched on Nov. 9, 1967, carrying the unmanned Apollo 4 spacecraft, and was thought to have performed nearly flawlessly.

Figure 4. Saturn V First Stage S-IC

The second unmanned Saturn V, designated as AS-502 or Apollo 6, launched on April 4, 1968, but unexpectedly experienced pogo at 5 Hz between 105-140 seconds during first stage (S-IC) boost with 0.60 g maximum acceleration at the command module and 0.33 g at the aft of the vehicle.[3] The second and third stages of flight also experienced problems with failures of the J-2 engines unrelated to the first stage pogo.[9] 9The acceleration response recorded at the lunar module simulator during the first stage pogo event is illustrated in Figure 5.[10]

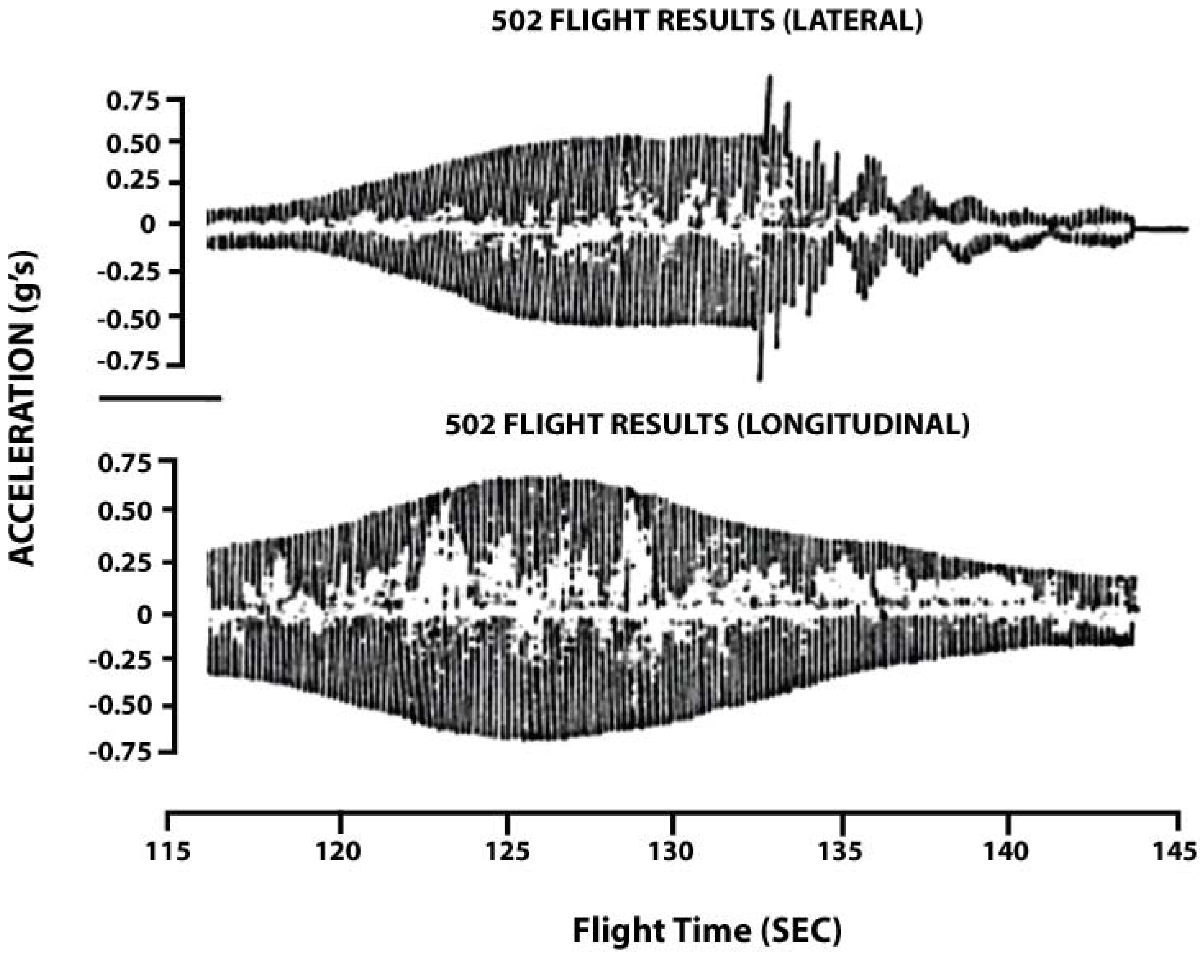

Figure 5. Pogo oscillation as measured at the LM simulator[10]

Following Apollo 6, re-inspection of the Apollo 4 data revealed a similar but smaller transient that had been previously overlooked.[3] This pogo vibration was not severe enough to impair structural integrity of the launch vehicle or spacecraft, but was greater in amplitude than that tolerated for Mercury or allowed for Gemini for crew exposure. Susceptibility of the Saturn V to pogo was thought to have been thoroughly investigated by the Saturn stage contractors, who had certified that their respective designs would be pogo-free. It turned out that these mathematical analyses had been conducted on an inadequate data base.[11] It had been determined from the mathematical models that low structural damping and wide tolerances were indicators of potential instability during flight. Narrowing the component tolerances by appropriate testing was thought to be a solution. Thus, pulsing tests had been run on the pumps for the F-1 (first-stage engine) and the J-2 (second- and third-stage engines) to estimate the fluid modulus due to cavitation. However, the complexity of pump cavitation had not yet been fully appreciated, and major interest was focused on the effect of the inlet pressure on the inlet line frequency, while the effect of amplification by the pump was neglected. It was thought that if a pogo problem was subsequently found it could be corrected by adding helium bubbling into the top of the appropriate propellant feed line which would further reduce the line frequency.[3] But incorporating pogo suppressors into the Saturn V vehicles was considered a difficult retrofit as the vehicles were already delivered to NASA.[4]

NASA decided not to risk stronger vibrations and a special pogo task force was assembled from NASA, industry and academia for an intensive investigation. At one time during the pogo studies, the Saturn V manager is reported to have said that 1,000 engineers from government and industry were working on the problem.[12]

It was known that the Saturn first stage F-1 engines exhibited combustion chamber vibration at about 5-1/2 Hz. As vehicle mass reduced during flight the frequency of structural vibrations coincided with the engine frequency, causing closed-loop coupling of the oxidizer feed system and the vehicle first longitudinal mode, resulting in pogo. An elegant solution was implemented by using helium gas from the tank pressurization system to fill cavities in the engines' liquid oxygen prevalves, converting them to accumulators that detuned the system.[11] The Aerospace Corporation preformed an independent analysis for NASA, and concurred with the proposal to use trapped gas in the oxidizer prevalve to serve as an accumulator.[2] The alternative oxidizer line helium trickle was rejected because NASA ground testing on a centrifuge showed such a strong effect that the frequency variation could not be controlled under flight acceleration and tank pressures.[3] The prevalve accumulator conversion was verified in ground testing in time to clear the Saturn V vehicle for crewed flight on Apollo 8.

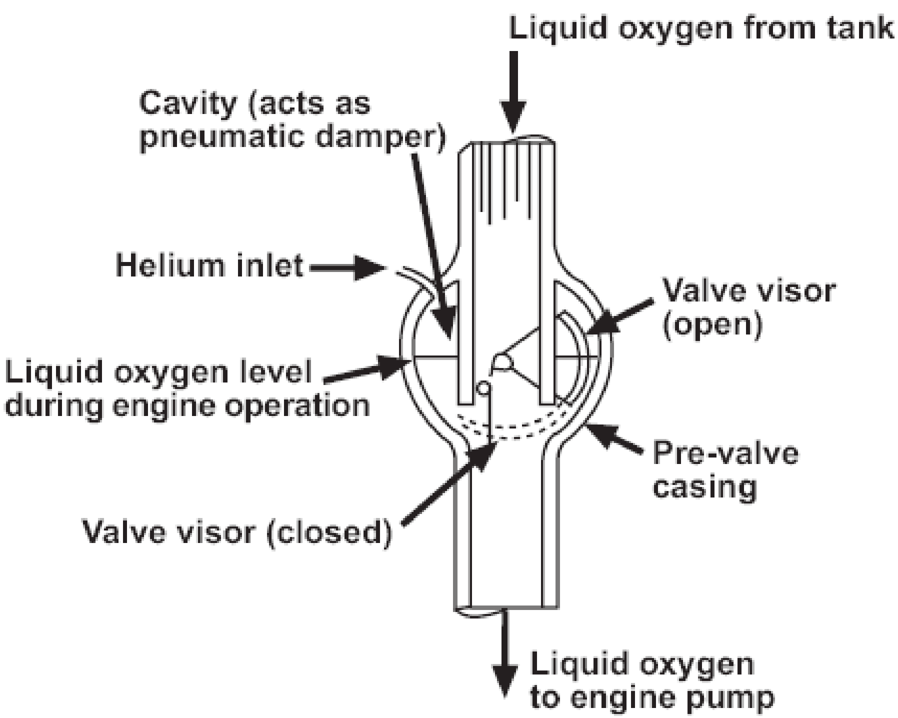

Figure 6. Saturn I-C Pogo Mitigation[11]

More subsequent analysis of the AS-501 and AS-502 flights demonstrated a previously unappreciated sensitivity of pogo to what may have been thought to be inconsequential changes to the Apollo spacecraft. The Apollo 4 (AS-501) flight had a low fidelity mass simulator of the lunar module, while Apollo 6 (AS-502) had a much more realistic model of the expected LM spacecraft. Mass changes from Apollo 4 also occurred in the escape system, command module and service module of the Apollo 6 spacecraft, but the total net weight difference was only 100 pounds.[12] As shown in Figure 7, these slight changes accounted for a small shift in the time at which the first oxidizer line mode crossed an AS-502 structural mode as compared to the same AS-501 mode, but the closed loop system gain from the change was increased by over 50 percent.[10]

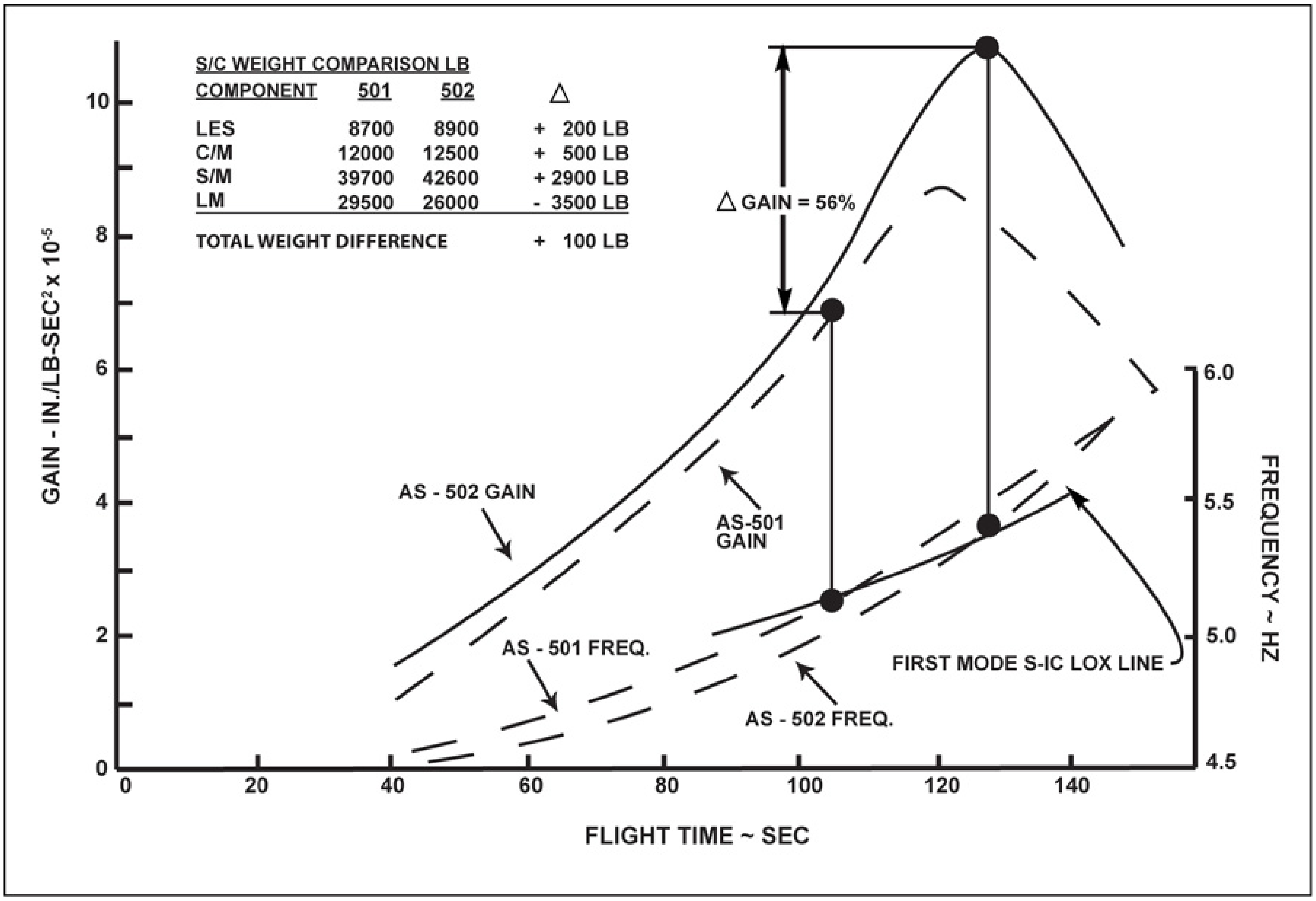

Figure 7. Illustration of Sensitivity to Small Changes: Comparison of AS-501 and AS-502 [10]

Apollo 8 (AS-503), the third Saturn V and first manned flight (Apollo 7 flew on a Saturn IB), successfully demonstrated the effectiveness of this pogo mitigation for the S-IC first stage. However, perhaps even more unexpectedly than the first stage pogo, on this mission the S-II second stage experienced pogo as reported by the command pilot at about 50 seconds before engine cut-off. Data analysis revealed an 18 Hz vibration of the center engine of the five engine J-2 cluster. Mounted on a crossbeam structure, the center engine was vibrating with the liquid oxygen (LOX) tank bottom. The magnitude at the crew cabin was actually quite small and no threat, but the local amplitude at the engine mount posed a threat the supporting cross beam structure.[3,10]

Figure 8. Saturn V Second Stage S-II Close up, J-2 Engine Cluster[15]

Because this pogo was localized and did not present the same concern for crew impairment as did the S-IC pogo, NASA treated this vibration as a “loads problem”, with some actually referred to this problem as “mini-pogo”[10]. A first mitigation was attempted on Apollo 9 (AS-504) by increasing the LOX tank pressure, and thus the oxidizer line frequency, in an effort to detune the system. However, Apollo 9 behaved opposite to the model predictions. A 17 Hz oscillation occurred between 500 and 540 seconds in flight, with peak amplitude of +/- 12 g’s at the local thrust frame. See Figure 9.

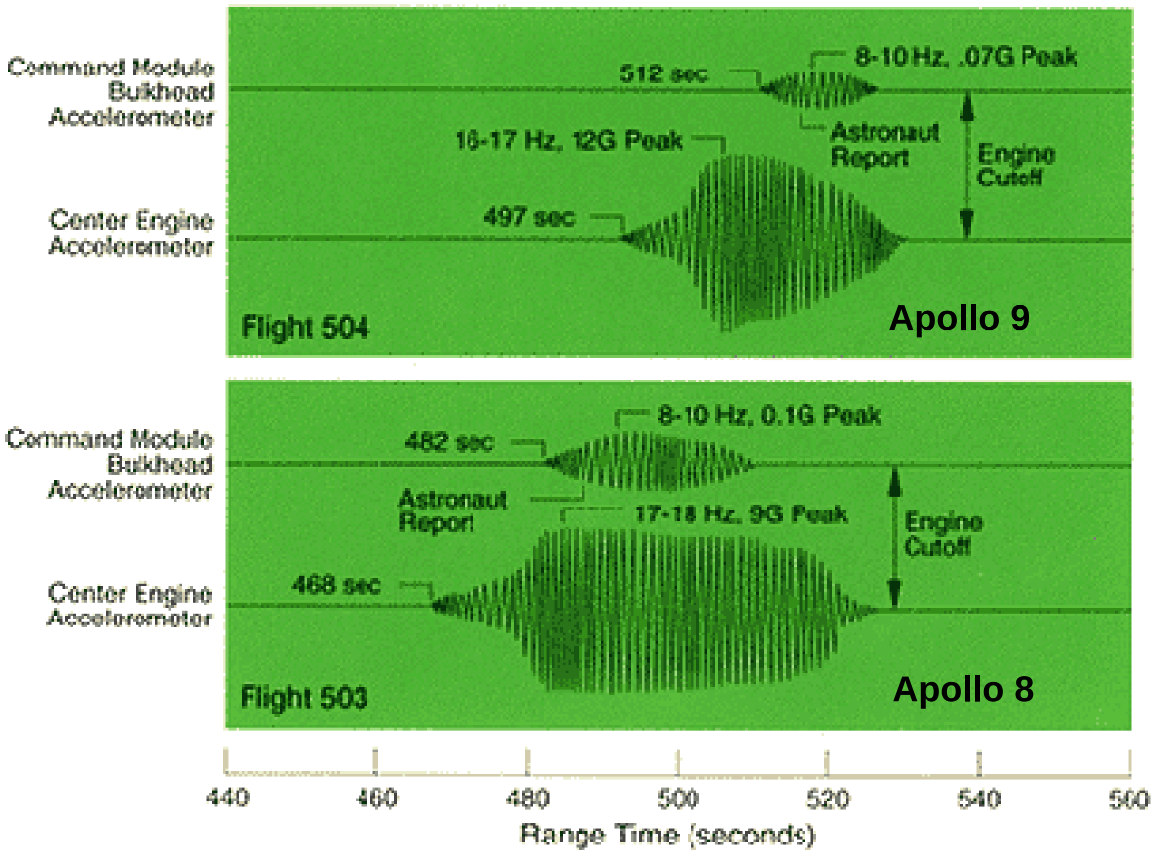

Figure 9: Apollo 8 and 9 Pogo[3]

Subsequent, more detailed post-flight analysis indicated that the ullage pressure increase would bring nonlinearities into effect which would actually increase the gain and instability.[10] The vibration amplitude experienced on Apollo 9 was judged to be too near the 15 g structural limit determined for the support structure for flights to continue without some mitigation.[2] So to keep the Apollo missions flying, an operational solution was implemented on the following missions to simply shut down the center J-2 engine some 60 to 75 seconds early to avoid the worst of the pogo, and leave the remaining 4 outer engines to just burn a little longer.[3,10] Under this operating condition, the flight of Apollo 10 was nominal.

Interestingly, on Apollo 10 (AS-505) the S-IVB third stage actually exhibited a pogo oscillation of 20 Hz from 50-100 seconds into that burn, but this was not thought to be a generic pogo problem based on all the previous flight history and it never occurred again although engineers remained watchful on all subsequent missions.[3]

The historic first lunar landing, Apollo 11 (AS-506), experienced a “small bulge” of pogo at 75 seconds into second stage, and four well-defined pogo occurrences were noted during Apollo 12 (AS-507), but they were thought to be nonlinearly limited.[3] The Apollo 12 vibration at the center engine had reached 8 g's and again concerns were raised for the vehicle's structural integrity, but analysis predicted that the 15 g structural limit would not be exceeded.[2]

In the meantime, the operational work arounds had given time for the pogo working group to refine its analyses and for the contractor to develop a helium-bleed toroidal pogo suppressor for the oxidizer side of the J-2 engine. The suppressor was not without its own risks as it wrapped around the oxidizer line near the pump and was filled after starting the engine. The oxidizer line frequency was expected to sweep bulkhead and crossbeam modes that could result in momentary resonance and instabilities, potentially triggering catastrophic nonlinearities. Suppressor failure modes were also a threat for only achieving partial filling and stability problems. Much detailed design and analysis was required before the pogo working group was satisfied the suppressor was ready for flight.[10]

The suppressor was available for Apollo 13 (AS-508), but there were concerns with the flight schedule, and the difficulties of installation, inspection, and verification on the waiting Apollo 13 Saturn V vehicle. These concerns and the favorable analysis prediction of nonlinearly limited vibration amplitude led to a decision to fly as-is, so no fix for pogo was implemented.[3]

Apollo 13 launched on April 11, 1970. During the second stage burn, two episodes of pogo occurred on the center J-2 engine as expected from previous missions, but the third occurrence diverged severely and acceleration at the engine attachment reached an estimated 34 g's (the accelerometer went out of range) before the engine's combustion chamber low-level pressure sensor commanded a shut down. A vivid comparison of previous missions with Apollo 13 data is provided by Ryan, as shown in Figure 10.[10] It was estimated in the post-flight investigation that only one more cycle of amplitude growth could have been sustained without catastrophic structural failure.

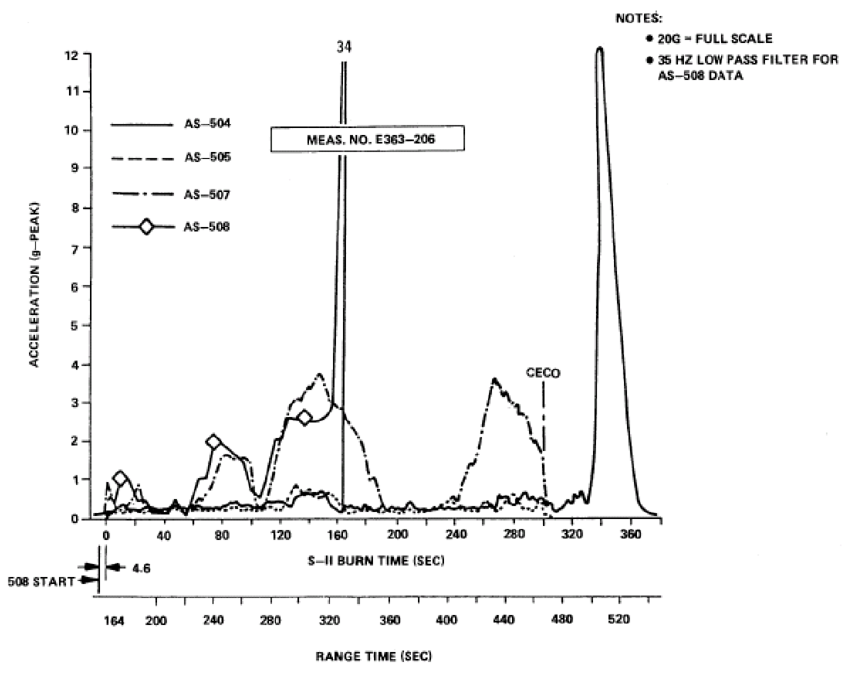

Figure 10. Comparison of center engine thrust pad accelerations[10]

The pogo community experienced yet another lesson about the limitations of their knowledge of the nonlinearities active in pogo, and NASA received a wake-up call that eliminated the “mini-pogo” thinking. The waiting pogo suppressor was installed on the center J-2 engine for all subsequent Apollo missions. No further pogo was experienced on the Apollo missions other than a few seconds of 10.5 Hz “buzz” at the end of second stage flight, and the lingering threat of another occurrence of third stage pogo. NASA continued to closely monitor the S-IVB third stage as it had been analyzed to be stable with low margins. Changes in spacecraft weights and dynamic characteristics were the major concern as heavier lunar modules were launched with Apollo missions 15, 16, and 17 carrying lunar rovers.[2,15]

1970 POGO STATE OF THE ART

The NASA pogo working group’s collective experience was summarized in an October 1970 monograph in the NASA Space Vehicle Design Criteria series, entitled “Prevention of Coupled Structure-Propulsion Instability (pogo)”, authored by Sheldon Rubin of the Aerospace Corporation for NASA’s Langley Research Center.[13]

Rubin summarized the state of the art, and provided criteria and recommended practices for mathematical modeling, preflight tests, stability analysis, corrective devices or modifications, and flight evaluation. Particularly noted were the large flight-to-flight variations in peak vibration levels that occur for nearly identical vehicles, illustrating the great sensitivity to small parameter deviations. Satisfactory flight performance was recommended as better ensured by eliminating the instability rather than attempting to accommodate or tolerate it. This marked a significant change in NASA’s thinking, treating pogo as an instability problem to be avoided, just as in flutter or control system instability, rather than as a design loads or vibration environment to be “managed”.

Knowledge of the problem was thought to be sufficient to avoid pogo entirely on new vehicles. The variation in amplitudes experienced was attributed to a slowly varying limit cycle controlled by nonlinear behavior due to damping in the longitudinal vehicle modes and the dynamic gain behavior of the engine pumps. But quantitative definition of these nonlinearities was considered lacking and put accurate prediction of the limit cycle behavior beyond the state of the art, although Rubin did refer to dissenting opinions.[14] So modelling was focused on predicting linear damping of the coupled system, and the rate of change of the system properties was considered slow enough to allow a sequential fixed-parameter analysis of successive flight times.

A low inertance accumulator located near the engine pump inlet was recommended as the most effective means of reducing the fundamental feedline resonant frequency below that of the first significant structural mode. Higher feedline modes were expected to remain above the fundamental structural mode. Examples of such installations as the Gemini and Saturn V I-C first stage implementations were provided as schematics and are reproduced in Figure 11.

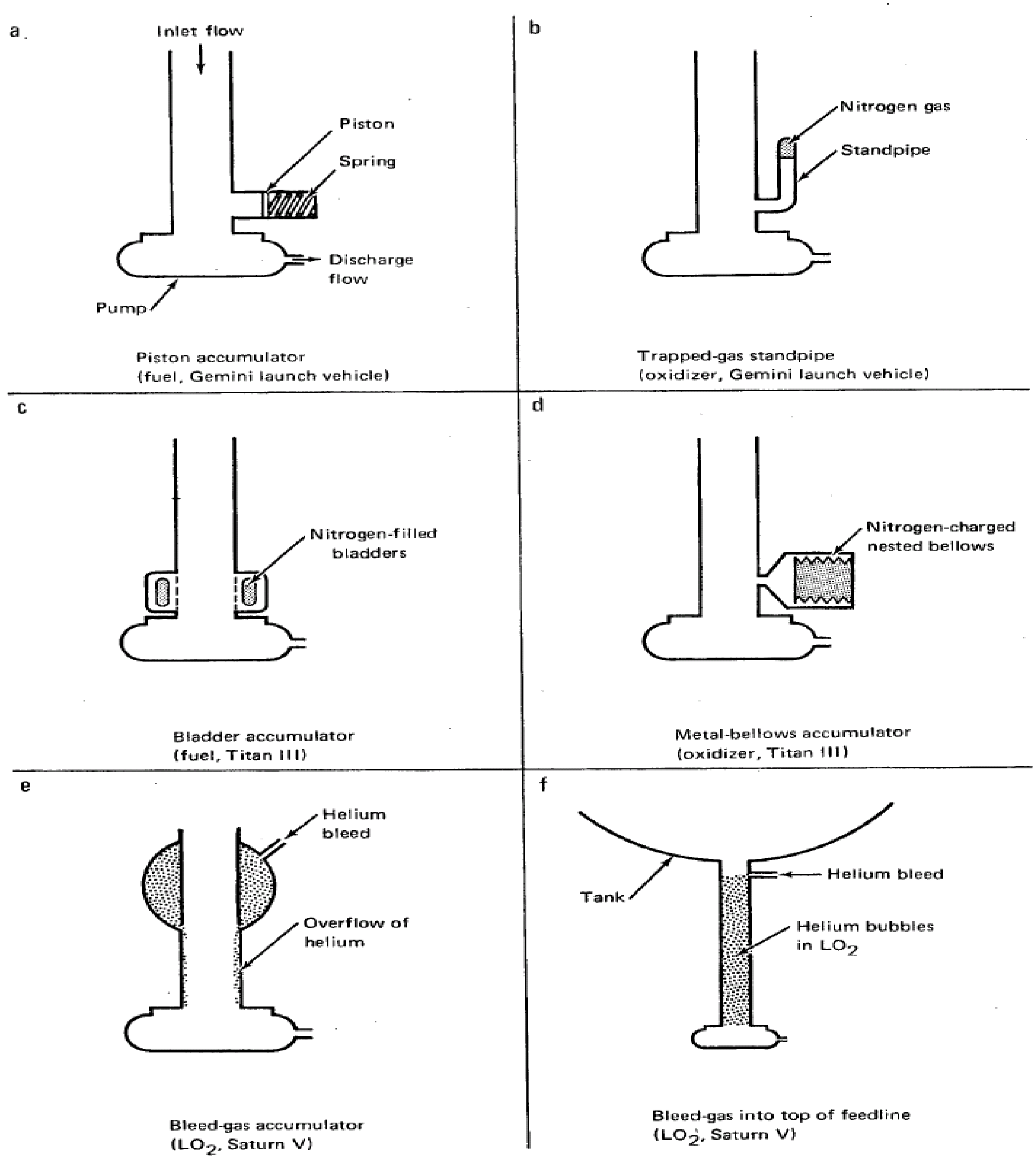

Figure 11. Pogo Suppression Devices[13]

Vehicle design criteria were proposed as: "The coupled structural and liquid propulsion system of the space vehicle shall be stable as determined by a suitable combination of analysis and test." The analysis was to be a linearized model of the coupled system demonstrating an adequate margin of stability, with accuracy substantiated by ground and flight test. Stability was to be demonstrated in terms of closed loop damping, or a damping gain margin expressed in decibels as the ratio of the actual structural damping to the structural damping required for neutral stability. Sensitivity analysis to phase shifts in the structural modes was also recommended. Instability was to be eliminated by appropriate modification of the coupled physical system.

The NASA criteria were introduced by Rubin to the technical community at a Space Transportation System Technology Symposium in July, 1970.[14] Included in that presentation was an interesting chart summarizing the collective industry experience with known pogo instabilities, included here as Figure 12.

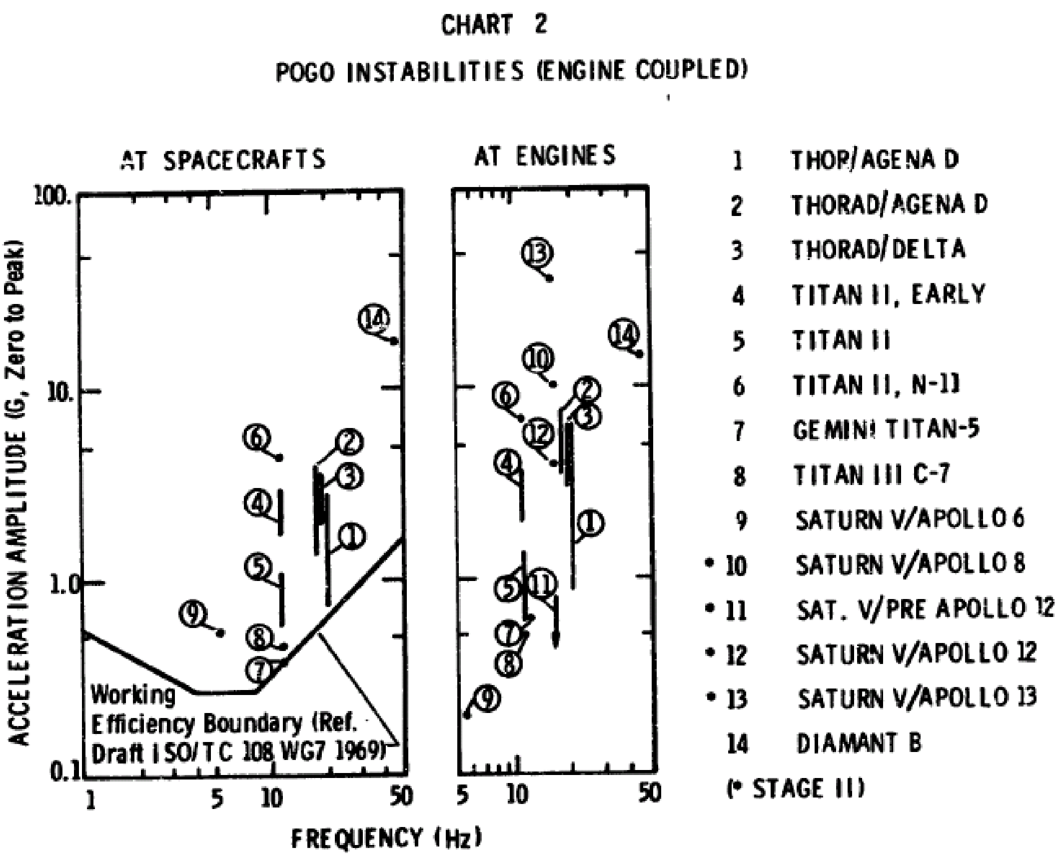

Figure 12: Pogo Experienced in Flight[14]

Rubin aptly summarized the new NASA appreciation for pogo as a major instability concern for all rocket-powered phases of spaceflight and emphasized the strong interplay of analysis and test, especially the need for flight test to realistically exercise the coupled system. Flight test was the final substantiation of the math model, but the inability to determine coupled-system damping during flight was recognized. Technology needs were listed as: transducers for propellant flow oscillations, development of test plans for comprehensive measurement of turbopump dynamics, evaluation of propellant tank modeling methods, and investigation of methods for in-flight excitation to measure coupled system damping.

Thus, the near failure of the S-II stage on Apollo 13 due to pogo instability has colored the NASA attitude toward pogo ever since, and pogo has subsequently been treated as a self-excited instability, such as wing flutter and flight control instability, that must be eliminated rather than as a dynamic loads or vibration environment.

SPACE SHUTTLE EXPERIENCE

The Space Shuttle Phase C/D development began in 1972 with the experience of Apollo 13 still fresh in memory of NASA program managers. The desired rapid turnaround of the Shuttle fleet also influenced the program management attitude regarding pogo. The Johnson Space Center’s first co-chair for the Shuttle pogo prevention panel, Dr. Hal Doiron, was told the problem should be fixed “with a sledge hammer”. Recurring pre-mission debates on whether different payload dynamics would erode small stability margins were going to be unacceptable to management. An operational approach similar to an airline was desired, just as wing flutter is not an issue for any flight within an aircraft’s operational envelope, and is not affected by structural dynamic cargo changes.[4,15]

Figure 13. Space Shuttle

A Pogo Integration Panel (PIP) was authorized by Space Shuttle Program Directive No. 25, dated July 16, 1974, to provide technical oversight to the numerous pogo prevention and integration activities. The PIP required membership from each of the hardware element organizations and met informally beginning in 1973 even before receiving its official charter. The Aerospace Corporation was tasked with the performance of independent pogo stability analyses in support of the PIP. Dr. Sheldon Rubin led this team and was also an active participant in the PIP. The PIP met on a regular basis to review and evaluate the technical activities described in the Pogo Prevention Plan and to exchange and coordinate technical information.[4]

A Pogo Prevention Plan (JSC-08130) was developed, following the guidance of NASA SP 8055, and approved by program management to organize the various analyses, tests and decisions necessary to develop and integrate a pogo suppression system. The Pogo Prevention Plan delineated activities into five basic elements: analytical development, testing, pogo suppressor development, verification analysis, and documentation. An elaborate test program was planned and executed to develop the data used in the verification analysis. The principle tests involved engine pulsing and suppressor development. The Space Shuttle's unique asymmetric four-body configuration created a challenge unlike any of NASA's previous vehicles, with aerodynamic surfaces, complex asymmetric structural modes, and advanced main engines firing continuously during ascent and during staging. This configuration resulted in complex asymmetric structural dynamic models requiring a comprehensive ground vibration test program for developing verification data.[4,15]

The pogo suppressor was designed as an integral part of the propulsion system for the first time, actually as part of the Space Shuttle Main Engine (SSME) between the low and high pressure liquid oxygen turbopumps, rather than added later to the propulsion feed line system as a remedial effort. Early designs had called for an accumulator at the inlet to the SSME low pressure oxygen turbopump, but this left a long oxidizer duct to interact with the downstream high pressure oxygen turbopump, and studies showed that despite the complications to SSME development, the optimal location for the suppressor was within the SSME at the high pressure turbopump inlet, operating as a broad band filter. Development of the SSME and pogo suppressor included Caltech research into pump dynamics, ONERA contribution of an ultrasonic flow meter, and the National Bureau of Standards evaluation and calibration of some required instrumentation.[2,3]

The suppressor itself is a spherical container about the size of a basketball charged with hot (400°F) gaseous oxygen for most of the flight (a helium charge is used prior to engine start). The high pressure liquid oxygen is separated from the gaseous oxygen by a baffle plate to prevent the liquid oxygen from splashing up into the gaseous oxygen and condensing the bubble. Essentially a Helmholtz resonator, it is designed to attenuate LOX flow oscillations into the high pressure turbopump in the 5-50 Hz frequency band for a "smooth" flow rate of LOX into the high pressure turbopump. The mixture of gaseous and liquid oxygen is continuously bled from the suppresser to control the gas volume and thereby the feed system dynamics that prevent pogo. Then the mixture is reintroduced into the feed line upstream of the engine so that all the gas condenses.[4,3]

The program requirements stipulated that the system closed loop damping had to be greater than zero for any worst-case combination of system parameter uncertainties. Important pogo structural modes were assumed to have only one-half percent damping as a worst-case, combined with worst-case distortions of mode shape (structural gain) and with the worst possible combinations of structural frequency and feedline propellant mode frequency. Conservatism was built into the analysis to address the uncertainties in the structural dynamic models and engine models. Uncertainty factors were applied to the modal gains, modal frequencies, suppressor inertance, suppressor compliance and SSME powerhead gain. In some cases it was also assumed that one suppressor was out.[4]

Pre-flight pogo stability analysis for missions STS-1 through STS-5 indicated that the Space Shuttle was pogo-free throughout the powered flight regime. Specific time points analyzed in the flight trajectory were:

Lift-Off (t = 0 sec.)

Max. dynamic pressure (t = 40 sec.)

Pre-SRB separation (t = 120 sec.)

Post-SRB separation (t = 125 sec.)

Boost (t = 254 sec.)

Boost (t = 418 sec.)

Prior to Main Engine Cut-off (t = 510 sec.)

The flight test program included instrumented flights on STS-1 through STS-5. The pogo instruments were basically pressure measurements installed in the liquid oxygen feedline and the SSMEs, and accelerometers on the Orbiter thrust structure. These measurements were augmented by other instruments used by other disciplines for their flight verification process. Examination of flight data indicated a pogo-free vehicle and the pogo flight measurement responses were as expected. No pogo oscillations were seen in the pressure measurements or in the thrust structure accelerations. The instrumentation verified that the suppressors were fully charged and operating throughout the boost phase of each flight. The flight data confirmed and validated the data developed in the ground test programs.

The pogo stability of the Space Shuttle is diligently monitored and verified to this day on a flight-by-flight basis to address concerns for any changes in structural dynamic properties, as from the changing payloads, structural fatigue of the Orbiter, or the upgrades to the SSME and the External Tank, that could affect the stability margins, particularly should a suppressor fail. Six operational measurements were approved and installed on all the Orbiters, consisting of three X-axis accelerometers on the SSME gimbal pads, and three sensors measuring the pressure of the liquid oxygen flow into the high pressure turbopump.[4]

FUTURE CHALLENGES

It's now been over 30 years since the beginning of development of the Space Shuttle and a new generation of engineers face the challenges of developing two new launch vehicles that must be verified pogo-free: the Ares I crew launch vehicle, with a first stage derived from the Space Shuttle Solid Rocket Booster (SRB) and a new upper stage utilizing a Saturn derived J-2X engine; and the Ares V cargo launch vehicle, with a core stage utilizing two Shuttle-derived SRBs, a Shuttle-derived External Tank and five RS-68 engines, and an upper stage with the J-2X engine.

Several excellent resources exist to help guide these efforts. The Boeing Company has captured the Space Shuttle Program pogo experience for NASA in a March, 2007 report by Duane Bastia and Dr. George Zupp.[4]

The NASA Marshall Spaceflight Center commissioned a May 2003 report by Dr. Hal Doiron to summarize the current state of the art in pogo prevention, providing a detailed learning guide for pogo stability analysis, and presenting a comprehensive discussion of pogo prevention activities.[15]

An earlier Aerospace Corporation state of the art report is also available by Oppenheim and Rubin.[16]

Fortunately, many of the gifted engineers that lived out the experiences discussed herein are also still available as consultants to this new generation. Drs. Doiron and Zupp, notable as the first and second (respectively) JSC co-chairs for the Space Shuttle Pogo Integration Panel are providing on-going consultation to the Constellation Program. Mr. Bob Ryan is still mentoring and teaching through the Marshall Spaceflight Center, and Mr. Sheldon Rubin also still consults on occasion, having passed his mantel for pogo expertise at the Aerospace Corporation to his protégé Mr. Kirk Dotson.

Looking to the future based on his Space Shuttle and subsequent EELV experience, Dr. Doiron emphasizes that a systems engineering effort is required if a pogo prevention effort is to be successful:

"The multi-disciplined nature of the pogo problem, involving in-depth knowledge of both structural and propulsion system dynamics analysis, requires a need for engineers involved to get out of the comfort zone of their structural or propulsion technical specialty. They must learn enough about the other specialties to conduct a successful pogo prevention effort in a multi-disciplined team environment. They must master new terminology and engineering concepts and principles, and embrace a shared spirit of cooperation and understanding for success in a melting pot of individual specialties. A successful pogo prevention effort will bring together experts, in a working team environment, from a number of specialized technical areas, including:

- Structural design
- Structural dynamics analysis
- Cryogenic fluids analysis
- Turbo- machinery performance, dynamics analysis, and test
- Rocket engine design and performance analysis
- Integrated propulsion system design analysis and test
- Structural and structural dynamics testing
- Specialized structural and fluids sensor technology
- Ground and flight test instrumentation system design
- Data acquisition
- Spectral analysis of forced response and random response data
- Control systems/structural interaction and stability analysis
- Vehicle trajectory and payload performance analysis
- Pogo stability analysis
- Pogo suppressor design"

With respect to the extensive pogo analysis and test verification efforts of the Space Shuttle, Dr. Doiron comments that "no cost was spared in Shuttle pogo stability verification. Therefore, the Shuttle experience probably represents the most thorough and costly pogo prevention program that will ever be required." It is his assertion that baselining a well designed, robust pogo suppressor at the outset of a launch vehicle development program is the most cost effective approach for pogo mitigation, with savings in pogo model test validation realized by piggy-backing these objectives on existing engine development and qualification tests, and eliminating at least the pogo modeling need for a full scale vehicle modal test.

A pogo suppressor is effectively baselined in the NASA plans for the Ares I vehicle, but given the previous flight history of the pogo phenomena and the many "learning opportunities" it has presented, many current and former NASA engineers are still cautious and skeptical of any short cuts to validation testing. Planning the details of the Ares vehicles' pogo verification should be an interesting debate.

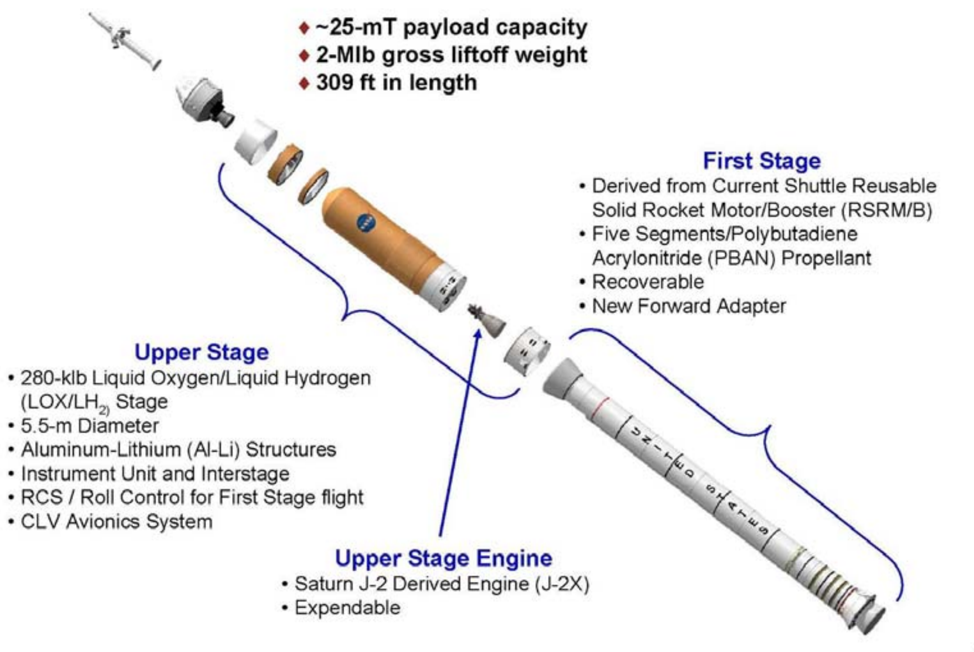

Figure 14. Ares I

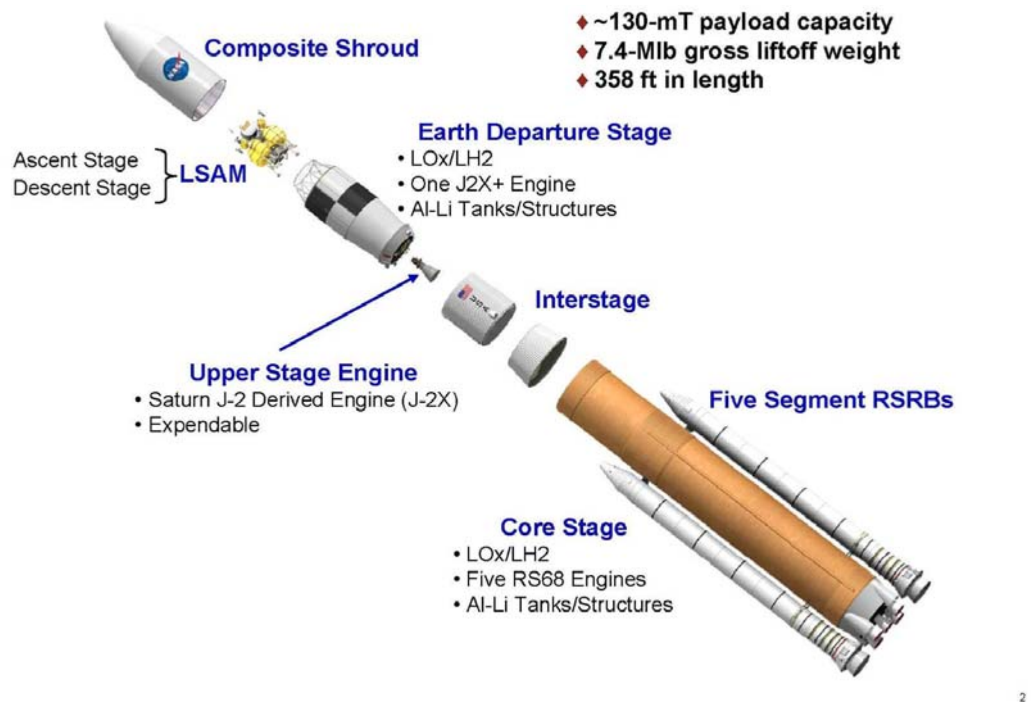

Figure 15. Ares V

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