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Abstract

STS-104, launched July 2001, marked the first flight of a single Block 2 Space Shuttle Main Engine (SSME). This new configuration of the SSME is the culmination of well over a decade of gradual engine system upgrades. The launch and mission were a success. However, in the process of post-launch data analysis a Main Propulsion System (MPS) anomaly was noted and tied directly to the shutdown of the Block 2 SSME. An investigation into this anomaly was organized across NASA facilities and across the various hardware component contractors. This paper is a very brief summary of the eventual understanding of the root causes of the anomaly and the process whereby an appropriate mitigation action was proposed. An analytical model of the High Pressure Fuel Pump (HPFP) and the low pressure fuel system of the SSME is presented to facilitate the presentation of this summary. The proposed mitigation action is discussed and, with the launch of STS-108 in November 2001, successfully demonstrated under flight conditions.

Nomenclature

Symbols

b_f	Frictional damping coefficient
b_v	Viscous damping coefficient
E_f	Frictional energy losses
J	Moment of inertia
M	Moment (general)
M_T	Turbine power moment
Ψ	Torque coefficient
ρ	Density
Ω	Rotational velocity

Acronyms

ET	External Tank
HPFP	High Pressure Fuel Pump
HPFTP	High Pressure Fuel Turbopump
HPFTP/AT	Advanced Technology High Pressure Fuel Turbopump
LPFD	Low Pressure Fuel Duct
LPFP	Low Pressure Fuel Pump
MFV	Main Fuel Valve
MPS	Main Propulsion System
SSME	Space Shuttle Main Engine
STS	Space Transportation System

Introduction

On 12 July 2001, Space Shuttle Mission STS-104 erupted from the pad at the NASA Kennedy Space Center. At the back of the Shuttle Orbiter Atlantis, as always, three Space Shuttle Main Engines (SSMEs) guided the orbiter into space. What was different for this flight was that one of those engines was of a new configuration. SSME unit number 2051 was the first Block 2 engine mounted and fired on the shuttle.

This was a watershed event in the quarter century history of the SSME project in that it represented the culmination of decades of design, test, redesign, intermittent starts and stops, and finally resounding success. The Block 2 SSME contains nearly all of the accumulated component improvement projects undertaken over the years including:

- Two Transfer Tube Phase 2+ Powerhead
- Single-Tube Heat Exchanger
- Large Throat Main Combustion Chamber
- Advanced Technology High Pressure Oxidizer Turbopump
- Advanced Technology High Pressure Fuel Turbopump (HPFTP/AT)

It is the last component listed above, the HPFTP/AT, that marked the final piece in the puzzle in the transition to the Block 2 engine. The design, development, and certification of this component undertaken by Pratt & Whitney in coordination with the NASA SSME Project Office took nearly a decade to complete. The final product of that process is a piece of hardware that is considerably more robust and potentially safer than its predecessor.

The first flight of the Block 2 SSME was, for the most part, pleasingly uneventful. The pre-start chill was nominal. The start transient and thrust buildup was nominal. Flight ascent (mainstage) operation was nominal. The throttling for the maximum aerodynamic loads

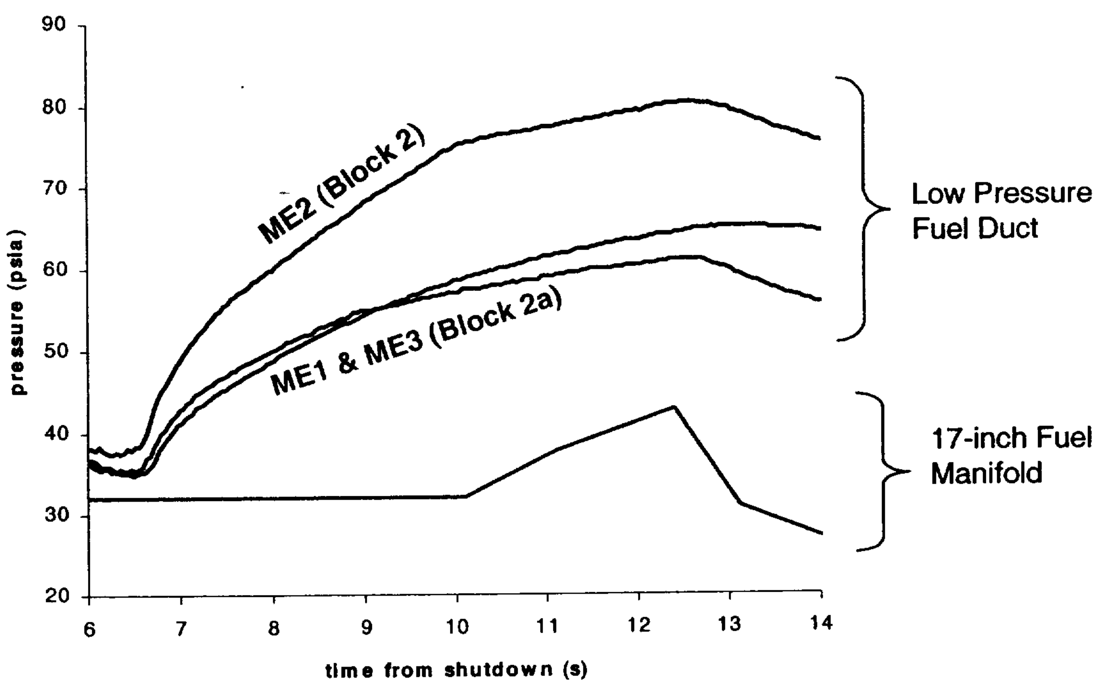

Figure 1. STS-104 Fuel System Post-Shutdown Pressures

and maximum vehicle acceleration was nominal. And, finally, engine shutdown after 512 seconds of hot fire was nominal. Almost.

The engineers examining the SSME flight data made the initial observation of the anomaly almost immediately. During the engine shutdown phase, about 10 seconds past engine shutdown command, it was noted that the pressure at the engine inlet and the pressure in the low pressure fuel duct were elevated for one engine. The magnitude of the peak was approximately 80 psia. Compared to the other two engines, both of which had peak pressures during the same time period in the vicinity of 65 psia, this stood out. The engine with the higher pressure was the Block 2 SSME. These pressure rises in the low pressure fuels ducts are illustrated in Figure 1.

Within the engine community, a differential pressure of approximately 15 psi was little more than a curiosity. Considering that elements in this particular subsystem experience pressures over 200 psia during operation and that certain components of the SSME experience pressures of over 7000 psia, it was understandably difficult to generate a great deal of excitement over 15 psi. The difference was attributed to an unforeseen yet benign integration difference due to the new HPFTP/AT. Within the engine system, there was no issue.

However, a concern was registered within the Main Propulsion System (MPS) integration community and only a couple of days later this pressure rise became categorized as an In-Flight Anomaly. In response, a team was formed across NASA and industry elements, and an investigation was launched.

Understanding the Problem

The root cause of the concern expressed by the engineers concerned with the MPS and the Orbiter can be traced within the simplified schematic of the MPS fuel system in Figure 2. During mainstage operation, the 17-inch disconnect valve, the three engine pre-valves, and the Main Fuel Valves (MFVs) within the engines are all open in order to feed fuel to the combustion chambers of the engines. During the engine shutdown sequence and the sequence that leads to separation of the Orbiter from the External Tank (ET), the valves close in this order:

- First the engine MFVs close to kill power to the engine.
- The orbiter pre-valves close to isolate the engines from the MPS.
- The 17-inch disconnect valve closes to prepare for ET separation.
- A dump valve opens to drain 17-manifold.

The pressure within the low pressure fuel systems of the engines (the three upper traces in Figure 1) start to rise upon closure of the pre-valves, approximately 6.5 seconds, because at that point there is a quantity of cryogenic liquid trapped between the pre-valves and the MFVs. Within that trapped volume of liquid both the Low Pressure Fuel Pump (LPFP) and the High Pressure Fuel Pump (HPFP) are still spinning imparting energy into the liquid. Further, there is a good bit of hardware within this system to re-chill back down to saturated low pressure fuel temperatures. This too adds energy into the liquid. A trapped cryogenic volume with energy input is an obvious way to create a pressure rise.

The pressure rise observed in the 17-inch manifold (the single lower curve in Figure 1) occurs upon closure of the 17-inch disconnect valve at approximately 10 seconds. Here again the valve closure sequence has created a trapped volume of cryogenic liquid, this time between the pre-valves and the 17-disconnect valve. The difference, however, is that there

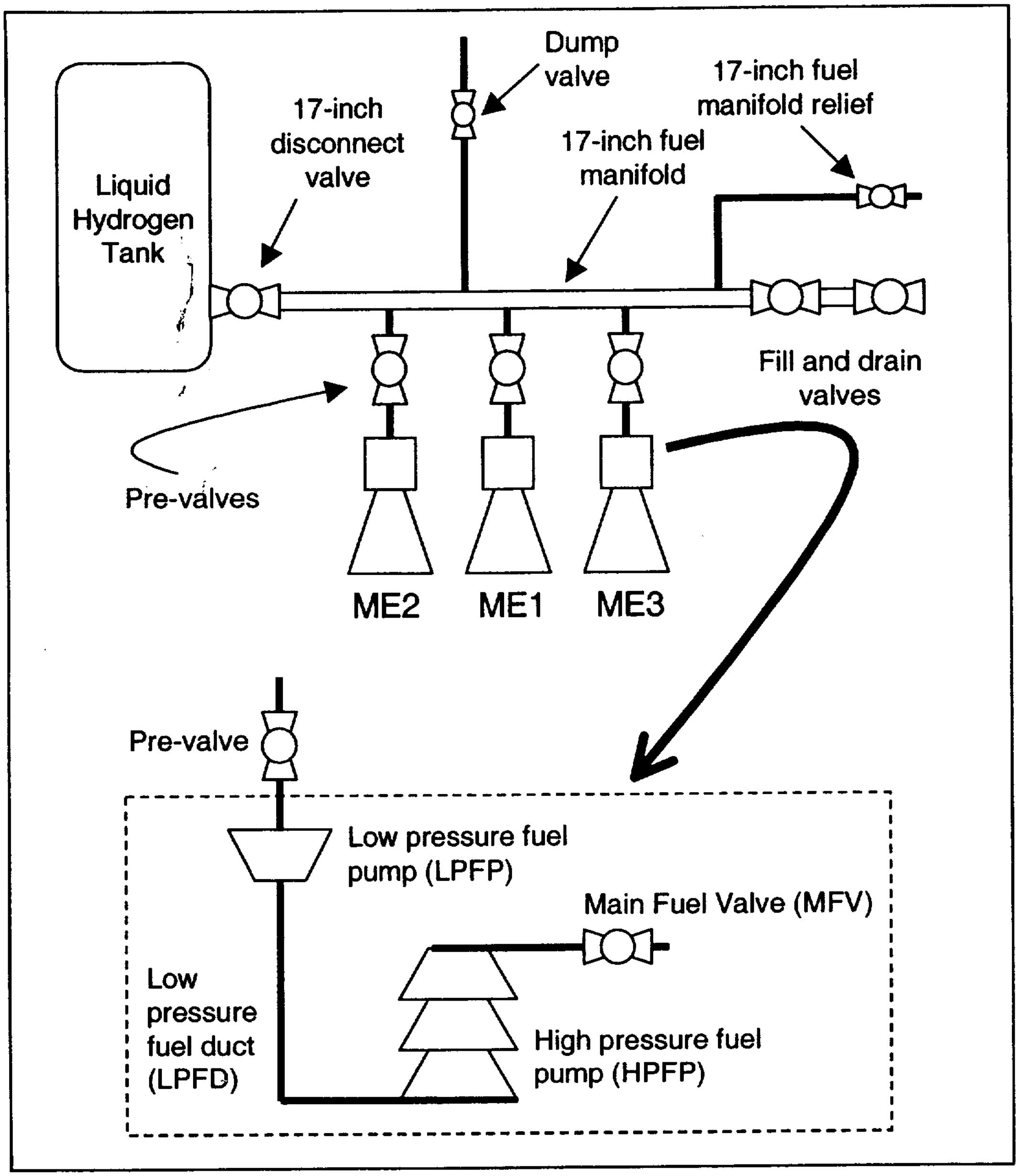

Figure 2 Simplified Schematic of the Shuttle Main Engine Fuel Feed System

are no spinning down pumps embedded within this volume. So the question becomes, why does the pressure rise within the 17-inch manifold?

The answer to that question can be found within the details of how the engine pre-valves function. Built into these valves is a redundant pressure relief system designed to protect against over pressurization of the engine feedlines. Thus, the very high pressure seen within the Block 2 SSME low pressure fuel system, over 80 psia, caused this relief system to operate and flow was initiated from the engine back up and into the trapped volume within the 17-inch manifold. Thus, the pressure continued to rise until the dump valve was activated. The pressure in the 17-

inch manifold reached a peak of 43 psia, the highest pressure observed in the history of the Shuttle flight program.

That is how and why the pressure rose. Why it was a concern for the MPS and Orbiter engineers has to do with the fact that the 17-inch manifold has a maximum operating pressure of 55 psia. If 43 psia was achieved with just one Block 2 SSME, what pressure would be achieved with three pre-valves relieving back into the manifold? The relief mechanism of the pre-valves is not controlled to tight tolerances in design or fabrication. What would have happened if the pre-valve in this case had relieved at a higher rate? Or had begun to relieve at a lower pressure? Taking these factors into consideration, it is quickly apparent that a number of plausible scenarios could be constructed in which the peak pressure within the 17-inch manifold exceeds its maximum operating pressure.

The final piece to the puzzle can be found within Figure 2. The 17-inch manifold has a single, non-redundant relief valve. While relief valve failures are rare, they are not inconceivable. Thus, there are a number of plausible scenarios for the development of high pressure and there is a single piece of hardware upon which the system must depend for protection. The system utilized in this manner is not "single fault tolerant," meaning that with the failure of a single component to operate properly there exists the possibility of catastrophic results.

It is a fundamental precept within the Shuttle program that vehicle systems remain single fault tolerant. This is why the STS-104 pressure surge became the subject of an in-depth investigation and why mitigation was necessary to ensure safety for future flights of the Space Shuttle.

Formulation of a Simple Model

Because the root cause of the entire investigation can be traced back to the generation of pressure within the low pressure fuel system during the engine shutdown sequence, an analytical model of this phenomenon is a useful tool for understanding the situation and ultimately for finding an appropriate resolution.

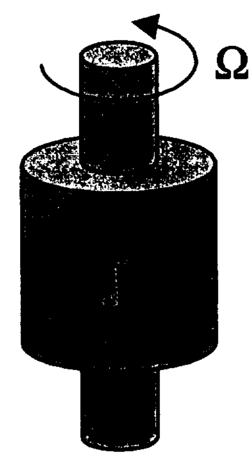

Figure 3 Representation of HPFP Rotor for Simple Model

The primary focus here is the spindown of the HPFP. The primary reason for this is that the change in the HPFP represents the only significant hardware configuration change between the Block 2 SSME and its predecessor, the Block 2a SSME. Figure 3 shows a simplistic representation of the spinning rotor. The other significant change had to do with a valve sequence change and is discussed below.

The basis for the model of the HPFP is the conservation of angular momentum as represented by the following equation:

$$\sum M = M_T + J\dot{\Omega} - b_v\Omega^2 - b_f\Omega = 0 \qquad (1)$$

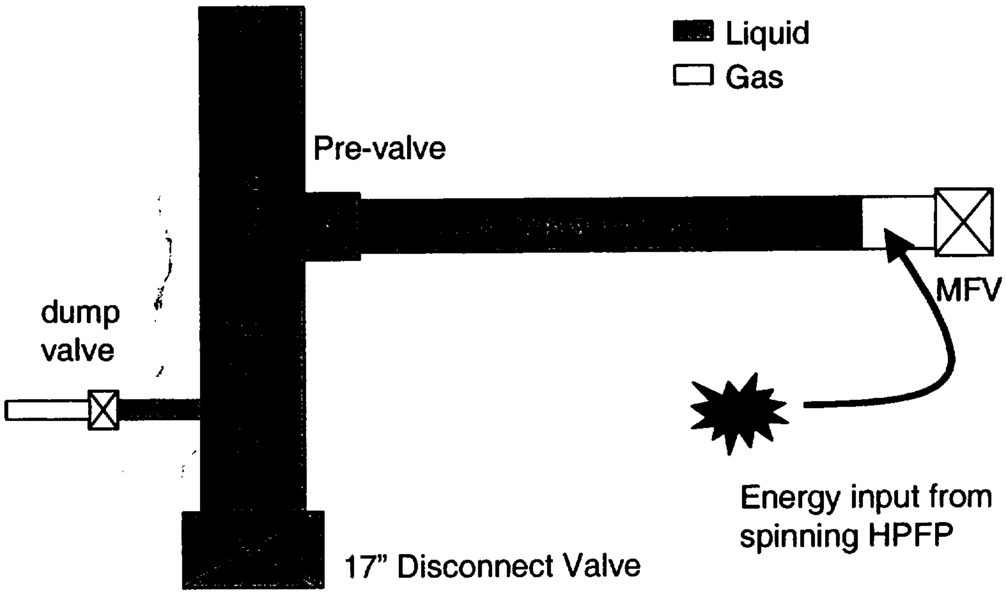

Figure 4. Simple Model Configuration of System Volumes

Where:

M_T Represents the turbine moment.

$J\dot{\Omega}$ Represents the rotor inertia.

$b_v\Omega^2$ Represents the viscous damping.

$b_f\Omega$ Represents the frictional losses.

Multiplying through Equation (1) by the HPFP speed yields the following, which is essentially the same equation but transformed to an expression of conservation of energy:

$$M_T\Omega + \frac{1}{2}\frac{d}{dt}\left(J\Omega^2\right) - \Psi\rho\Omega^3 - E_f = 0 \qquad (2)$$

Where:

$M_T\Omega$ Represents the turbine power.

$\frac{1}{2}\frac{d}{dt}\left(J\Omega^2\right)$ Represents the change in rotor angular energy.

$\Psi\rho\Omega^3$ Represents the viscous damping transformed into an expression of pumping energy via the Torque Coefficient.

E_f Represents the frictional energy losses.

Further simplifications can be made if it is assumed that the time of interest is exclusively after closure of the engine MFV. First, that simplifies the Torque Coefficient to a constant value since it is normally a function of the pump flow coefficient. Next, because this point is several seconds into the shutdown sequence, it is assumed that there is no power input from the turbine. Thus, Equation (2) becomes:

$$\frac{1}{2}\frac{d}{dt}\left(J\Omega^2\right) = \Psi\rho\Omega^3 + E_f \qquad (3)$$

This expression simply states that the loss of energy of the rotor is equal to the energy imparted to the fluid, the pumping energy, and the energy imparted to the hardware via friction. This equation is useful because the HPFP speed from the flight data and the constant Torque Coefficient for no-flow conditions is known.

The next consideration for the creation of a simple model is the system into which the HPFP delivers its energy. Figure 4 is a schematic of this system. There are, essentially, two volumes to consider. First, there is the volume on the engine side of the interface between the Pre-Valve and the MFV. Second, there is all the rest of the volume represented primarily by the 17-inch manifold. Further, within the engine volume there are liquid and vapor portions. The vapor is created by the HPFP energy input into the liquid. In typical rocket engineering parlance, this growing gas volume is the "boil-out" of the pump.

The final element of this model comes in the form of heat transfer. Again, preferring to keep this model as simple as possible, it is assumed that there is a constant, low-level heat transfer into the engine volume during the timeframe of interest. Also, there exists heat transfer in the form of soak back from the hardware of the energy listed in Equation 3 as frictional energy losses. Due to the complexities of the HPFP internal configuration, a straightforward, linear relationship was assumed and the transfer coefficient was determined empirically.

Results From the Simple Model

The focus of the analysis to be presented here is the Block 2 engine since this will be the sole engine configuration used for flight as of April 2002. Figure 5 shows the results from the simple model for the reconstruction of both the pressure in the low pressure fuel duct of the engine and the pressure in the 17-inch manifold for STS-104, Main Engine 2 (the Block 2 SSME). The implied assumption used here is that the observed pressure rise in the 17-inch manifold was due exclusively to the flow back across the pre-valve from this one engine.

As can be seen in Figure 5, the simple model does an excellent job of reconstructing the flight data. The data inputs required to generate this reconstruction are the spindown traces for both the LPFP and the HPFP.

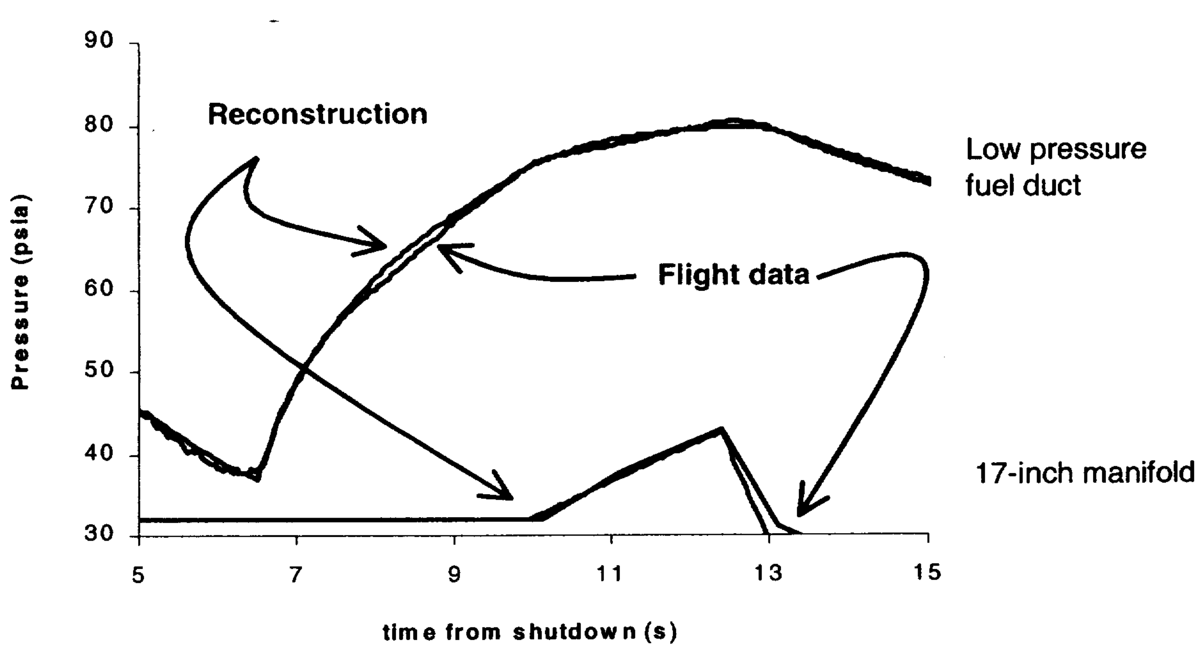

Figure 5. STS-104 Block 2 SSME Flight Data and Simple Model Reconstruction

It should be noted that despite the relatively good results from this simple model shown here, a much more detailed and comprehensive multiple-volume model was used for the actual reconstruction and mitigation action selection process during the investigation. This model was originally constructed by engineers at NASA Marshall Space Flight Center and later codified and documented by engineers at Boeing Huntingdon Beach.

Investigation Team Mandate

A team was formed to understand and resolve this anomaly. This team was comprised of the technical experts from each of the orbiter MPS subsystems drawn from both NASA and contractor organizations. The team was assembled on July 17, and given a mandate to come to the shuttle program with a mitigation action on August 30. This deadline was the latest that any changes could be effected for the launch of STS-108 scheduled for November. The team's mandate was clear: understand the root cause of the pressure rise, be capable of re-creating it using an analytical model, and provide the best mitigation action along with rationale for its selection.

The team first gathered all necessary data on the orbiter and SSME systems in question. This was done to completely understand the characteristics of the system as well as the subsystem interactions. A complete history of the operations of this system was compiled and thoroughly examined in order to completely understand the problem. As mentioned above, an analytical model was constructed to represent the actions of the system in the timeframe of interest. Once the model was mature, it would not only duplicate the pressure rise on STS-104, but also be able to predict effectiveness of mitigation plans.

Problem Resolution Process

The team then turned its attention to the resolution of the anomaly. In order to develop a plan for mitigation of this effect a number of proposed, "brainstormed" ideas were bounced against the realities of cost and launch schedule constraints. Obviously the best solution would be to build the hardware such that the pre-valve relieved in a more predictable and controlled manner or build the 17-inch manifold such that it was capable of withstanding higher pressure surges. Alternatively, a redundant relief valve could be added to the 17-inch manifold thereby eliminating the single point failure potential of the current configuration. However, considering the cost and launch schedule impacts of wholesale changes to the main propulsion systems for the entire orbiter fleet, all such orbiter hardware solutions were necessarily stillborn. They would only be called upon only when all other alternatives were exhausted.

On the other side of the interface, a number of suggestions were made as to how the engine hardware might be altered to minimize the post-shutdown pressure generation. The new Block 2 HPFTP/AT could possibly be reconfigured to spindown more like the older version of the HPFTP used on Block 2a. Perhaps the low pressure fuel duct could be built in such a way that it provided a pressure surge accumulator analogous to the POGO accumulator on the liquid oxygen side of the engine. While changes to engine hardware are not impossible to implement, as evidenced by the Block 2 SSME itself, they take several years and hundreds of millions of dollars to bring to flight-ready fruition. Again, hardware changes would only be considered after all other reasonable alternatives were explored.

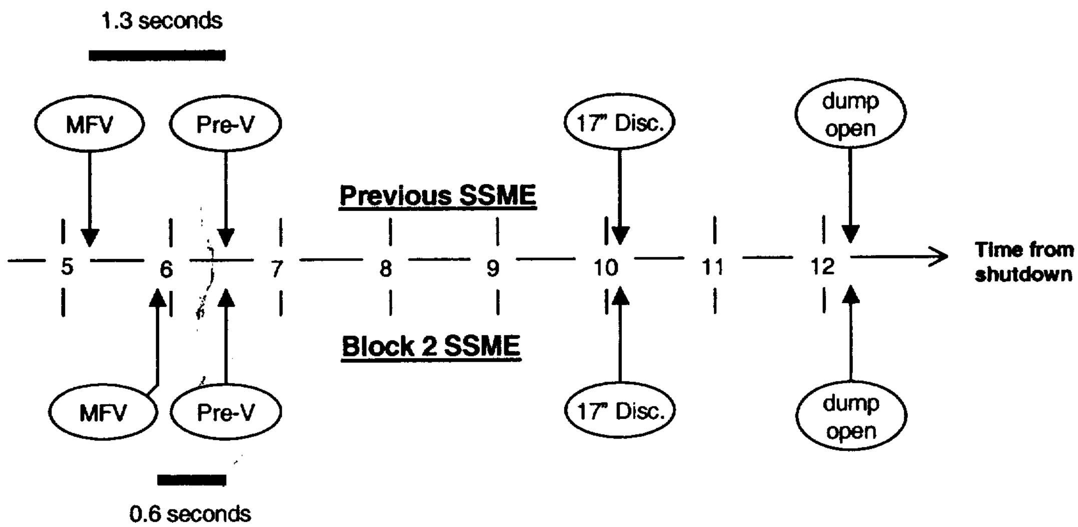

Figure 6. Post-Shutdown Valve Sequence Representation

So, with hardware options out of the picture with regard to reasonable considerations, there is no choice but to turn to software and operational sequence changes with the hope that this is a sufficient tool to get the job done.

This then leads to a discussion of success criteria. Or, in other words, what is good enough? It was decided, at minimum, because the 17-inch manifold has a maximum operating pressure of 55 psia, that nowhere in the system should a pressure value exceed this value prior to opening of the dump valve. Thus, even with substantial Pre-Valve relief coupled with a 17-inch manifold relief valve failure, there would be no possibility of exceeding the 17-inch manifold maximum operating pressure. A look back at Figure 1 highlights the fact that it was not only the Block 2 SSME low pressure fuel duct pressure that violated this criterion. Indeed, a historical review of all Shuttle data to date reveals that such a criterion has never been met across any of the previous SSME configurations. The Block 2 SSME data merely represents an extreme case that functioned to bring this case to the attention of the propulsion system community.

When it comes to engine shutdown the manifestation of software influence can be summarized by the valve sequence. Figure 6 is a representation of the shutdown valve sequence discussed earlier for previous incarnations of SSME and for the new Block 2 SSME. It can be seen that the order of the sequence has not changed with three valves closing, Main Fuel Valve (MFV), Pre-Valve (Pre-V), and the 17-inch Disconnect Valve (17" Disc), followed by the opening of the dump valve. The only change is the time span between MFV and Pre-Valve closures.

An examination of Figure 5, specifically the trace of pressure in the low pressure fuel system of the engine reveals that the pressure rise does not occur until the Pre-Valve is closed. Yet the flow of liquid hydrogen comes to a stop when the MFV is closed. Thus the time span in between represents a period within which there is energy input into the stagnant fluid from the spinning pumps and yet the fluid volume is uncontained. What one finds is that during this time span gas is being formed in the two fuel pumps, particularly in the HPFP. Later, when the Pre-Valve is closed it is hypothesized that this volume of gas acts as an accumulator to help absorb the onslaught of additional energy input into the closed volume.

Figure 7 shows several output traces from the simple model using STS-104 data as input. The highest trace is the reconstructed pressure data for the low pressure fuel duct. The trace labeled "MFV closure earlier" represents what would happen if the MFV closure time for the Block 2 SSME was moved back to where it had been for previous SSME configurations. The resulting peak pressure prior to the dump valve opening just after 12 seconds is reduced from the reconstructed flight data as would be expected based upon the discussion above relative to the formation of a gas accumulator. However, this peak still exceeds the 55 psia criterion.

A more radical suggestion would be to move the closure of the MFV out past the time of the Pre-Valve closure. In other words, close the Pre-Valve first and then close the MFV. While this is a fundamental change to the valve sequence order, the idea of providing a time period for gas accumulator growth prior to locking up the system remains the same. In Figure 7 the trace labeled "MFV closure later" represents the resulting pressure rise in the low pressure fuel duct when the MFV closure is delayed until 1.3 seconds beyond Pre-Valve closure. The value of 1.3 seconds was chosen as a demonstration example since that was the previous time span between MFV closure and Pre-Valve closure for previous configurations of SSME. The resulting peak pressure is significantly lower than the STS-104 flight reconstruction but still higher than the goal.

Before any more effort is expended on the issue of altering the MFV closure time it should be noted that such a change is not trivial technically or programmatically. It would require some level of development and recertification testing. With regard to the notion of moving the MFV closure time earlier, this ignores the fact that the MFV closure was changed for the Block 2 SSME with the intention of reducing the

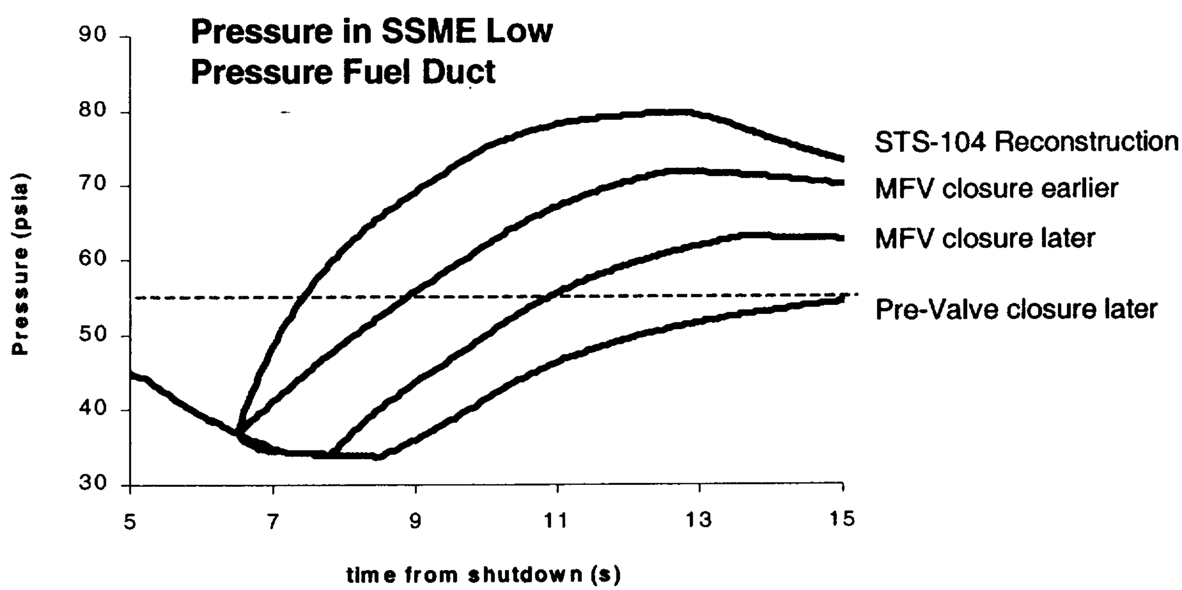

Figure 7. Simple Model Demonstration of Proposed Software Mitigation Options

environments within the new HPFTP/AT during shutdown. Changing the closure time back to its previous position may compromise specifically those hardware life issues that the Block 2 SSME was intended to address. Plus, according to the modeling results, it would not fulfill the success criterion.

With regard to the notion of moving the MFV closure to a point after Pre-Valve closure, the ramifications of this change could be significant. While it would likely be possible to delay the MFV closure long enough to achieve the stated goal in peak pressure reduction, what this change might do to the turbopumps is unclear. Further, there would be more liquid hydrogen dumped through the engine system than there is currently. The effects of this both in terms of the engine hardware and in terms of the vehicle are also unclear. In short, this change introduces a whole bevy of unknowns. In the world of operational systems, unknowns typically translate to time and money, and perhaps lots of both.

The other software alternative, referring again to the timeline in Figure 6, would be to delay closure of the Pre-Valve. Unlike the MFV changes, this suggestion is not isolated to the SSME but requires a change to the Orbiter Main Propulsion System software.

Ideally, what one would want to do is:

1. Increase the amount of time available to build the gaseous accumulator.
2. Decrease the time between system lock up and the opening of the dump valve.

These two objectives could be achieved simultaneously by shifting the Pre-Valve closure to later and keeping everything else the same. Unfortunately, due to the intricacies of the Orbiter software system and the necessary procedures between engine cutoff and ultimately separating from the expendable External Tank, this cannot be accomplished precisely. Instead, there does exist the possibility of delaying the entire sequence starting with the Pre-Valve closure. In other words, it is possible to slide the whole Orbiter valve schedule to the right. This scenario is

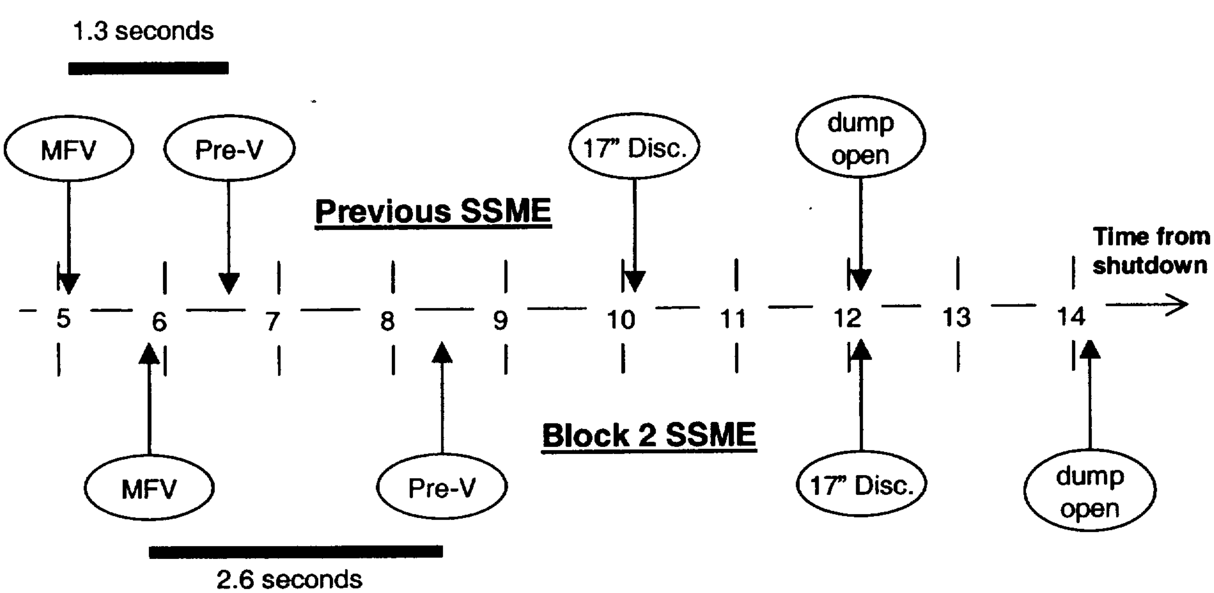

Figure 8. Proposed Valve Sequence Timeline Compared to Original Sequence Prior to Block 2 SSME

presented in timeline form in Figure 8. Here the Pre-Valve closure has been delayed by 2 seconds resulting in the closure of the 17-inch Disconnect Valve and the opening of the Dump Valve to also be delayed by 2 seconds. Further, this delay propagates all of the way through separation of the External Tank so that it too would be delayed by 2 seconds.

The result in terms of pressure rise trace in the low pressure fuel duct is illustrated in Figure 7 and labeled as "Pre-Valve closure later." The peak pressure at the time of the opening of the Dump Valve, now at just after 14 seconds, is below the 55 psia criterion goal. This scenario, assuming that it could be implemented on Shuttle, represents the best option to mitigate the pressure surge in the low pressure fuel duct of the SSME thereby safeguarding the 17-inch Manifold. It also provided the solution with the least impact to the Orbiter propulsion system.

Mitigation Demonstration: STS-108

The next opportunity to launch a Block 2 SSME after STS-104 came in November 2001 with STS-108. Due in part to the issue of the shutdown pressure rise observed on STS-104, it was decided to again fly with only a single Block 2 SSME but only if an appropriate pressure surge mitigation action had been identified and implemented.

STS-104 launched in mid-July. The best option for mitigating the pressure surge as discussed in the section above, delaying the valve sequence by 2 seconds, was identified by the investigation team by the end of August in fulfillment of the investigation team mandate. What is not discussed here is the fact that there are many different modes of SSME shutdown and vehicle contingency abort scenarios and all of these had to be addressed, explored, and analyzed prior to accepting the proposed mitigation action as the recommendation for flight. All of this analysis was accomplished prior to the end of August deadline.

Next comes the implementation of the recommendation. Just in terms of scheduling, getting the necessary software change into the Shuttle system in time to support the November launch of STS-108 was a Herculean task. However, prior to that, analyses had to be performed by the vehicle flight mechanics engineers to access the consequences of delaying External Tank separation by 2 seconds.

Thanks to the truly outstanding efforts of the entire Shuttle support crew including NASA, Boeing, Pratt & Whitney, United Space Alliance, and Lockheed Martin, the necessary evaluations were completed and STS-108 was cleared to fly with the next Block 2 SSME and with the proposed pressure surge mitigation action. The only identified consequences of the 2 second External Tank separation delay were some very small changes to the probabilities for Orbiter re-contact for some abort operation modes. These changes were deemed to be not statistically significant for STS-108. Later, generic analyses were conducted to demonstrate that there was little or no impact for all future flights.

Figure 9 shows the results from the STS-108 mission. Plotted are the predicted pressure trace from the simple model derived above with the 2-second Pre-valve closure delay and the actual flight data for the pressure in the low pressure fuel duct of the Block 2 SSME. It can be seen that the prediction and the actual data essentially fall on top of each other. Also shown are the peak pressure from STS-104 and the goal for STS-108 so that it can be confirmed that the mitigation action taken did indeed accomplish what was necessary.

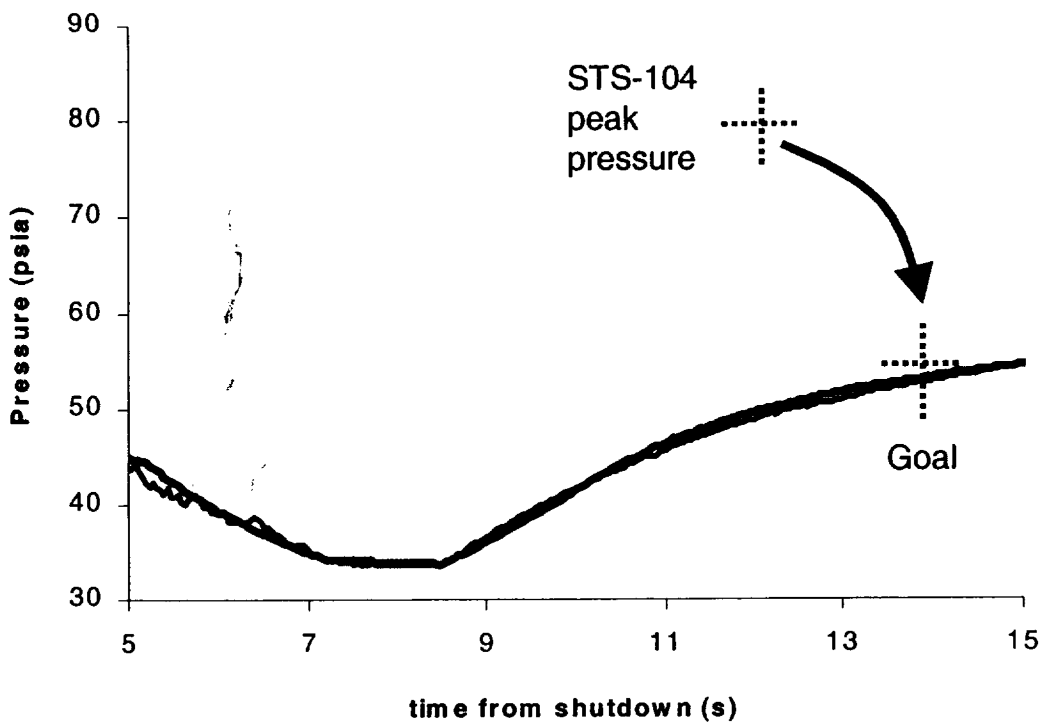

Figure 9. STS-108, Predicted and Actual Pressure in the Low Pressure Fuel Duct

Discussion

One question that was asked during the investigation and not yet addressed here was this: How did this integration issue slip through the cracks? The Block 2 SSME went through a rigorous evaluation process that included years of development testing, certification testing, and analytical modeling efforts in an attempt to avoid precisely the kind of surprises that occurred on STS-104.

One reason that this potential issue was missed relates back to the fact that even on previous configurations of SSME there existed pressure surges in flight as seen in Figure 1. Never before was much attention paid to this fact since there were only rare and low level instances of pressurization of the 17-inch manifold. The Block 2 SSME configuration did not create the issue, it only amplified the effects to the point of bringing them to the attention of the engineering corps.

Further, this pressure surge effect is not apparent in the ground test data. For neither the Block 2 SSME or for previous SSME configurations do the ground test results show pressure surges anywhere near those seen in flight. As opposed to the 30 to 50 psi surge changes seen in flight, on the ground a typical surge is on the order of 1 to 5 psi and this is independent of SSME configuration. Until this investigation was conducted into the STS-104 anomaly, no analysis was applied to understand why this was the case. It was simply attributed to flight effects and considered benign.

Qualitatively, there are three reasons why the SSME ground test data does not exhibit post-shutdown pressure surges.

First, the volume of the ground test system upstream of the engine interface is significantly larger than on the Orbiter. The larger volume acts as a larger pressure accumulator even when filled with liquid. Further, there exists the possibility of some volume of trapped gas within the facility between the Pre-Valve and the engine interface. Obviously this would only enhance the accumulator effect.

Second, due to convective heat transfer effects and afterburning in the nozzle present only on ground test shutdowns, there is significantly more power delivered to the turbines during the time period of interest. While it may be counterintuitive to suggest that higher turbine power translates to lower pressure surges, here again the gas accumulator effect dominates.

And third, the timing of the Pre-Valve closure has always been different than that which is used in flight. The closure time is approximately 7.9 seconds after shutdown as opposed to 6.5 seconds for STS-104 and previous flights. Due to the acknowledgement of the other inherent deficiencies in modeling the shutdown transient, no attempt was made on the test stand to precisely simulate Pre-Valve closure in flight.

The bottom line result from all of this discussion as to the differences between flight and ground test is the realization that the STS-104 anomaly was not predicted because the ground test data could not set off the alarms to suggest that a previously benign but never-analyzed curiosity could be transformed into a significant flight issue. Needless to say, this was a dramatic lesson for everyone involved.

Conclusions

The Space Shuttle flight STS-104 represented a significant milestone in the history of the Shuttle and SSME programs. The implementation of the Block 2 SSME is an enhancement to the safety and reliability of the vehicle. However, an unforeseen anomaly during engine shutdown tempered the post-flight celebration. In response to this anomaly an investigation team was formed, hardware characteristics were examined, analytical models were constructed, mitigation actions were explored, and finally the best action was recommended. All of this work was accomplished in a timely manner so that only four months later the next flight of the Block 2 SSME, STS-108, was a rousing success including a full demonstration of anomaly mitigation.

This paper has presented a discussion of the anomaly and its potential consequences. An approach to the construction of an analytical model was derived and compared to the flight data. A synopsis of the options for mitigation was presented along with the final choice and the results from that decision. And finally, a brief discussion of the broader lessons learned has been presented including the need to understand to some degree even those phenomena in the flight and ground test data considered benign. Unless you understand why something is benign, you cannot know under what conditions its status might change.

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