AIAA 2002-3602

Propellant Densification for Shuttle: The SSME Perspective

William D. Greene and Dayna L. Boxx
NASA Marshall Space Flight Center, Huntsville, AL

Abstract

The subject of cryogenic propellant densification as a potential upgrade to the Space Shuttle is a subject that has been raised on several occasions over the last decade. Due to advancements in densification technology made as a part of and in parallel to the X-33 project, the subject was raised and studied once again in May 2001. Across the Space Shuttle program people from many disciplines converged to discuss issues and perform trade studies to determine whether densified propellants was worth pursuing. This paper discusses one of these areas, specifically the Space Shuttle Main Engine (SSME). The effects of propellant densification on steady state performance are presented along with discussions of potential transient performance issues. Engine component redesign and retrofit issues are discussed as well the high level requirements to modify the ground test stands to accommodate propellant densification hardware and tanks. And finally, the matter of programmatic concerns enters the subject at hand as part of a discussion of SSME recertification requirements. In the end, potential benefits to SSME performance can be demonstrated and, subject to the densification scheme chosen, there does not appear to insurmountable technical obstacles.

Nomenclature

Symbols

Isp	Specific impulse
$\dot{m}$	Mass flow rate
ΔP	Pressure drop
ρ	Fluid density
R	Flow resistance
R	Degrees Rankine
μ	Viscosity

Acronyms

DLH2	Densified LH2
DLO2	Densified LO2
ETT	External to tank densification
HPFP	High pressure fuel pump
HPFT	High pressure fuel turbine
HPOP	High pressure oxidizer pump
HPOT	High pressure oxidizer turbine
ITT	Internal to tank densification
LH2	Liquid hydrogen
LN2	Liquid nitrogen
LO2	Liquid oxygen
LPFP	Low pressure fuel pump
LPOP	Low pressure oxidizer pump
MR	Mixture ratio
NBS	National Bureau of Standards
RLV	Reusable Launch Vehicle
ROM	Rough order of magnitude
SSME	Space Shuttle Main Engine
SSTO	Single Stage to Orbit
TSH	Thermodynamic Suppression Head

Background

The concept of utilizing propellant densification within the Space Shuttle program is not an entirely novel proposition. In 1994, M.M. Fazah of NASA Marshall Space Flight Center [1] published an extensive report on the matter in which he examined propellant densification concepts, Shuttle infrastructure impacts, and ultimate potential payload gains. The conclusion of this report was that while payload gains were likely realizable, the cost of development and implementation was not justified by these gains.

Since the time of the Fazah report, a great deal of research and development work was undertaken in the area of propellant densification. References [2] through [7] represent a partial listing of published reports on the progress of this work most of which was funded under the auspices of the X-33 program and the single-stage-to-orbit Reusable Launch Vehicle (SSTO-RLV) studies. Further, this work was undertaken at different times and to differing degrees by Boeing, Lockheed Martin, NASA Glenn Research Center, and NASA Marshall Space Flight Center. Thus, continuing interest in the subject of propellant densification developed a broad base.

With the cancellation of the X-33 and SSTO-RLV programs in 2000, those working in the field of propellant densification were left with a great deal of developed technology but potentially no immediate application to a specific vehicle. This is how and when the subject arose of reexamining the utilization of propellant densification on the Space Shuttle.

In May 2001, a study was initiated to determine whether propellant densification was a viable potential upgrade to the Space Shuttle program. The broader results of this study will likely be reported elsewhere but it can be stated that the final conclusion was similar to the one made in 1994: it has potential, but even with the advances made, this potential does not justify the expense.

This report is focused on one particular aspect of the May 2001 study, the impacts and effects of densified propellants on the Space Shuttle Main Engine (SSME) program. That such a degree of specialization is possible bears testimony to the level of effort and manpower dedicated to the overall study.

In fact, it was likely due to this level of effort and due to the advancement in propellant densification technology that the final conclusions were inevitable. From a broad philosophical or conceptual level, the case for propellant densification is undeniable. But when forced to examine the details of both the existing system infrastructure that is to be retrofit and the requirements of a successful propellant densification process, the case becomes substantially more clouded. If the devil is in the details, then surely the devil is made of money.

Steady State Performance Adjustments

In evaluating the steady state performance of the SSME utilizing densified propellants it is necessary to first consider the global effects of colder, denser propellants on the system. The first global effect arises from the fact that in addition to being colder, densified propellants carry less energy available for eventual combustion.

As a first-order approximation to account for this effect of lower propellant available energies, an adiabatic frozen-flame analysis was conducted. Figure 1 shows the results for variations in both liquid hydrogen (LH2) and liquid oxygen (LO2) temperature. The y-axis in these plots is the percentage change in

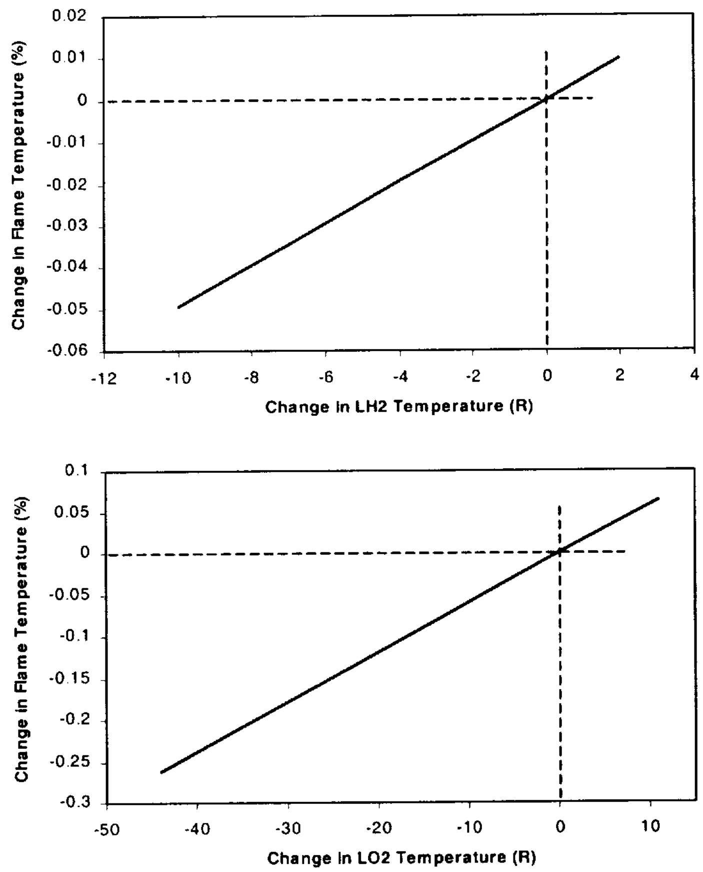

Figure 1. The Estimated Change in Adiabatic Flame Temperature Due to Propellant Densification of Both LH2 and LO2

adiabatic flame temperature. The corresponding change in system performance, specifically the combustion chamber characteristic velocity is proportional to the square root of this deficit in flame temperature [8]. Later, when the SSME Power Balance is used to analyze the engine cycle, these changes to the combustion performance will be incorporated.

The next global consideration is that of system resistances. The typical practice is to assign to various engine components fixed flow resistances or, in the case of throttling valves, fixed position versus resistance curves. Thus, the fluid pressure drops through the engine circuit become exclusively a function of fluid velocity and fluid density. The pressure drop equation takes the form as follows:

$$\Delta P = \frac{\dot{m}^2 \mathrm{R}}{\rho} \tag{1}$$

Where: ΔP = pressure drop
$\dot{m}$ = mass flow
R = flow resistance
ρ = flow density

With a little algebraic manipulation one finds that for a fixed geometry, this resistance factor is directly proportional to the standard fluid dynamics friction factor. Over the typical range of mainstage operation points, assuming that this flow resistance is fixed is a reasonably good assumption.

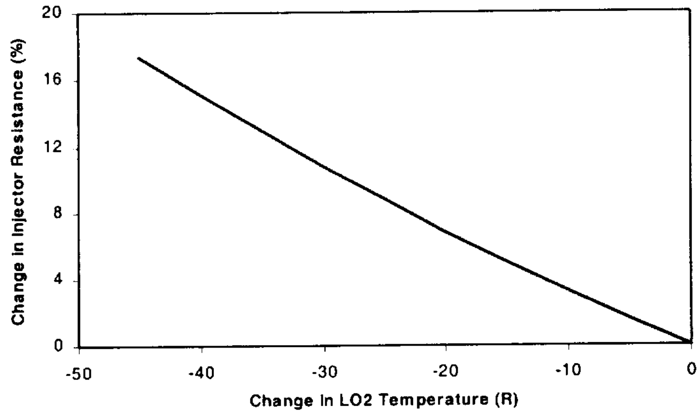

Figure 2. Approximate Change in Main Injector LO2 Flow Resistance with Densification

However, with the introduction of densified propellants, this assumption is weakened due to changes in propellant viscosity, particularly LO2.

Rather than attempt to track down every flow resistance within a steady state model of the SSME, for a first order approximation only those components with the largest pressure drops, the true system drivers, are examined. Due to the relatively small changes in LH2 viscosity over the range of temperatures under consideration, there is no component on the fuel side of the engine worthy of any effort. On the oxidizer side of the engine, however, one component stands out, the main injector. The two preburner injectors are fed by throttling control valves so any changes in pressure drop there can be overcome with valve position changes. But the main injector has no such compensating control factor directly upstream.

Using the 1911 Blasius approximation for friction factor for simplicity [9], and factoring out elements of fixed geometry and fixed overall mass flowrate (i.e., engine power level control point), the following relationship can be derived:

$$\frac{R_{dens}}{R_{nom}} = \left(\frac{\mu_{nom}}{\mu_{dens}}\right)^{1/4} \qquad (2)$$

Where: R_{dens} = flow resistance, densified
R_{nom} = flow resistance, nominal
μ_{dens} = viscosity, densified
μ_{nom} = viscosity, nominal

Figure 2 shows the results for this simple calculation using standard National Bureau of Standards (NBS) properties for LO2. It should be noted that there have been suggestions that LO2 viscosity changes are, in reality, more dramatic than reported by the NBS tables particularly in region below approximately 125R. Without a full characterization of this effect, however, it will not be considered here. Further, as will be discussed, it is difficult to justify the need for LO2 densification much below liquid nitrogen (LN2) temperatures around 140R.

Densification Combinations

Probably one of the most interesting trades to be performed when considering propellant combinations for a launch vehicle is the issue of the engine mixture ratio. Engine performance and durability are traded main

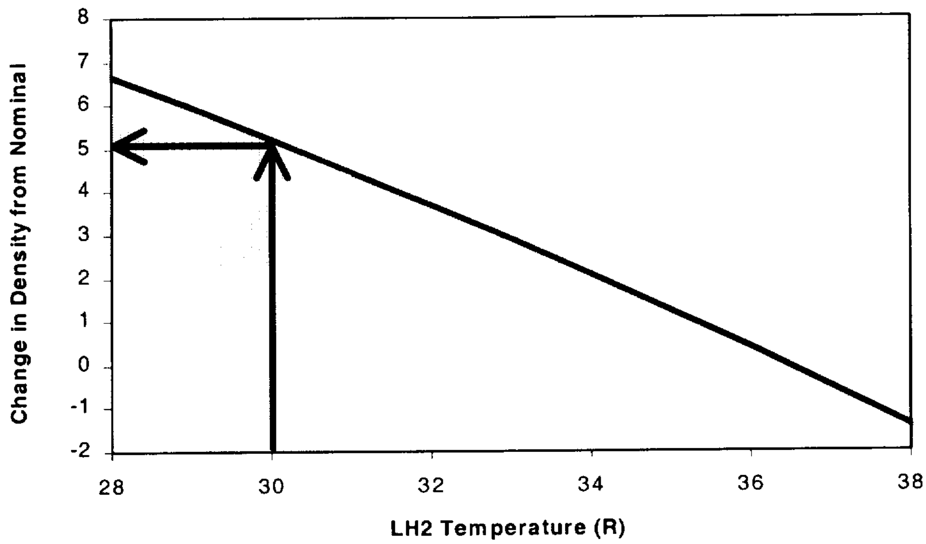

Figure 3. Densification of Liquid Hydrogen

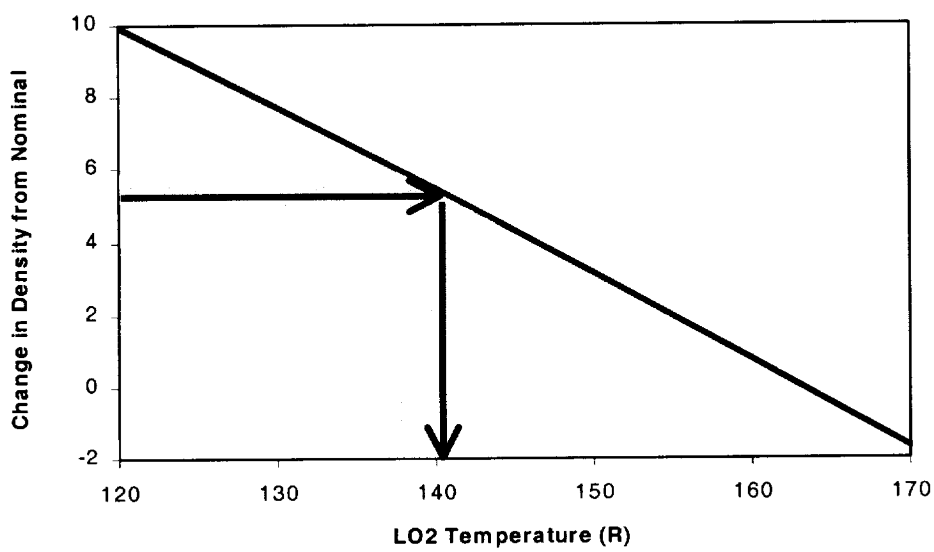

Figure 4. Densification of Liquid Oxygen

propulsion system, tanking, and trajectory requirements. However, such trades are most appropriate for a new vehicle system. In the case of densification for the Space Shuttle, retrofitting the existing hardware for the new propellant properties becomes necessary. With no flexibility on the side of recommending significant flight hardware modifications, a ground rule for this study, the whole issue of deciding upon a mixture ratio becomes simplified.

Further, there is little drive within the SSME community to consider mixture ratios significantly higher than the current nominal value. Higher engine mixture ratios translate to higher combustion temperatures throughout the engine and consequently lower life and reliability estimates. Also, higher engine mixture ratios also mean lower performance (i.e., specific impulse). For these reasons, only mixture ratios at or below the current nominal value are considered.

And finally, the last piece in the puzzle comes from densification technology itself. The ability to subcool the bulk temperature of a large volume of cryogenic liquid within a flight-weight tank is not without physical limitations. The typical magnitude of the ambient heat leak into non-vacuum jacketed tanks means that it is never possible to achieve a bulk densification equal to that of the ground-based propellant densification equipment. This effect is most dramatic with LH2 due to the greater heat transfer area and the lower total loaded LH2 mass, which results in relatively higher heat leaks in those tanks. While the final bulk average temperature of LH2 is dependent upon the details of the densification system, values of 29R to 31R are reasonable estimates for the current state-of-the-art.

Figure 3 shows the degree of densification achieved at this bulk average temperature of LH2 compared to the current nominal LH2 temperature. Using 30R as an optimistic but reasonable estimate for the bulk average temperature, one finds that the density of LH2 is increased by slightly more than 5%. This means that within the given volume of the Space Shuttle LH2 tank, 5% more LH2 can be loaded. Thus, in order to maintain a mixture ratio equal to the current mixture ratio, LO2 would have to also be densified by 5%.

Figure 4 shows a similar plot of the density change in LO2 with densification. Using the value of just over 5% densification, one finds that the appropriate LO2 temperature in approximately 140R. This temperature is coincidentally and conveniently just about the normal boiling point temperature for liquid nitrogen (LN2), a fluid often used in the densification process.

Thus, the two extremes for considering engine mixture ratio come from the following propellant combinations:

- Both LH2 and LO2 densified to 30R and 140R respectfully. Mixture ratio equal to the nominal value of 6.032.
- LH2 densified to 30R but LO2 unchanged. Mixture ratio reduced to approximately 5.75.

Obviously, there are an infinite number of intermediate points between these two values but for the purposes of this examination, these two extremes will be considered.

Steady State Power Balance Results

Using the Rocketdyne SSME Power Balance and the various input adjustments and propellant combinations derived above, the effects of propellant densification on various engine parameters can be examined. Figure 5 contains five plots summarizing many of the significant engine parameter changes.

The first changes to consider are the overall engine performance changes. When going to densified propellants but maintaining the same mixture ratio, the only effect is a slight suppression of the combustion efficiency resulting in a slight decrease in specific impulse (Isp). However, the thrust level remains essentially unchanged. If only LH2 densification is considered with the resultant decreased in mixture ratio, the Isp increases but the thrust level decreases. While the general wisdom of rocketry is that higher Isp is almost always good, there may be some trajectory circumstances, including abort scenario considerations, where this thrust change could be significant. This would be an area of further research should the Space Shuttle Program ever decide to go forward with densified propellants.

The parameters in the other three plots contained within Figure 5 pertain to internal engine parameters: pump discharge pressures, turbine discharge temperatures, and turbopump speeds. These parameters describe the robustness of the engine. In the most straightforward sense, the less stresses on the hardware--lower pressures, temperatures, and speeds--the greater the statistical reliability. Considering the history of the SSME, probably the most critical parameter is the high pressure turbine discharge temperatures. It can be seen that either scenario acts to reduce these values with the reduction being especially high in the case of the densified LH2 at a mixture ratio of 5.75. The only parameter that shows an increase across all three plots in the high pressure fuel pump (HPFP) discharge pressure for the densified LH2 case. This is due to the greater mass flow for the 5.75 mixture ratio offsetting the decrease in volume due to densification. However, this increase is quite small compared to the other reliability gains within the system.

The estimation of reliability values is always an imprecise activity. Attempts were made during the May 2001 study to quantify the reliability gains from the parameter changes illustrated in Figure 5. However, the results from these efforts were inconclusive. That leaves only the qualitative arguments as presented here. It is sufficient to say that the use of densified propellants within the SSME holds the potential for increasing reliability due to reductions in system stress parameters.

Transient Performance Issues

A detailed analysis of SSME transient performance, engine start, shutdown, and throttling, was not performed as part of the May 2001 examination of densified propellants for Space Shuttle. It would have been accomplished if the project had reached a sufficient maturity level, but the project was shelved before it got that far.

However, a discussion of potential issues was assembled [10] with the primary focus being engine start. A significant issue with the Block 2 SSME is the generation of temperature spikes in the two preburners during the start transient [11]. A great deal of work has been done to modify the SSME start sequence to minimize as much as possible the generation of these spikes, thereby ensuring greater life for the high pressure turbines. The densification of LO2 has the potential for making these spikes worse.

The SSME ignition sequence is based upon using the LO2 already within the engine at the time of engine start command. By controlling the temperature of this LO2, and therefore the density, it is possible to influence how much LO2 initially gets into the two preburners. Too much too soon and the result is high temperature spikes. Too little too late and the result is a failure to light or, possibly, a detonation event. Thus, deviations in either direction from the delicate balance currently achieved during SSME start have the potential of damaging hardware.

It would not be impossible to achieve this same balance with densified LO2, but what is envisioned is the need for a higher degree of active control. The conditions achieved today are extremely repeatable but largely obtained passively. In order to maintain these conditions, and thus ensure reliable and smooth ignition with colder LO2 temperatures at the engine inlet, more work is required. One suggestion would be to incorporate a two position, high/low, chilldown bleed system. By controlling the rate at which ambient heat leak into the engine is rejected, it may be possible to get back to today's internal engine conditions at start. Such a system, while

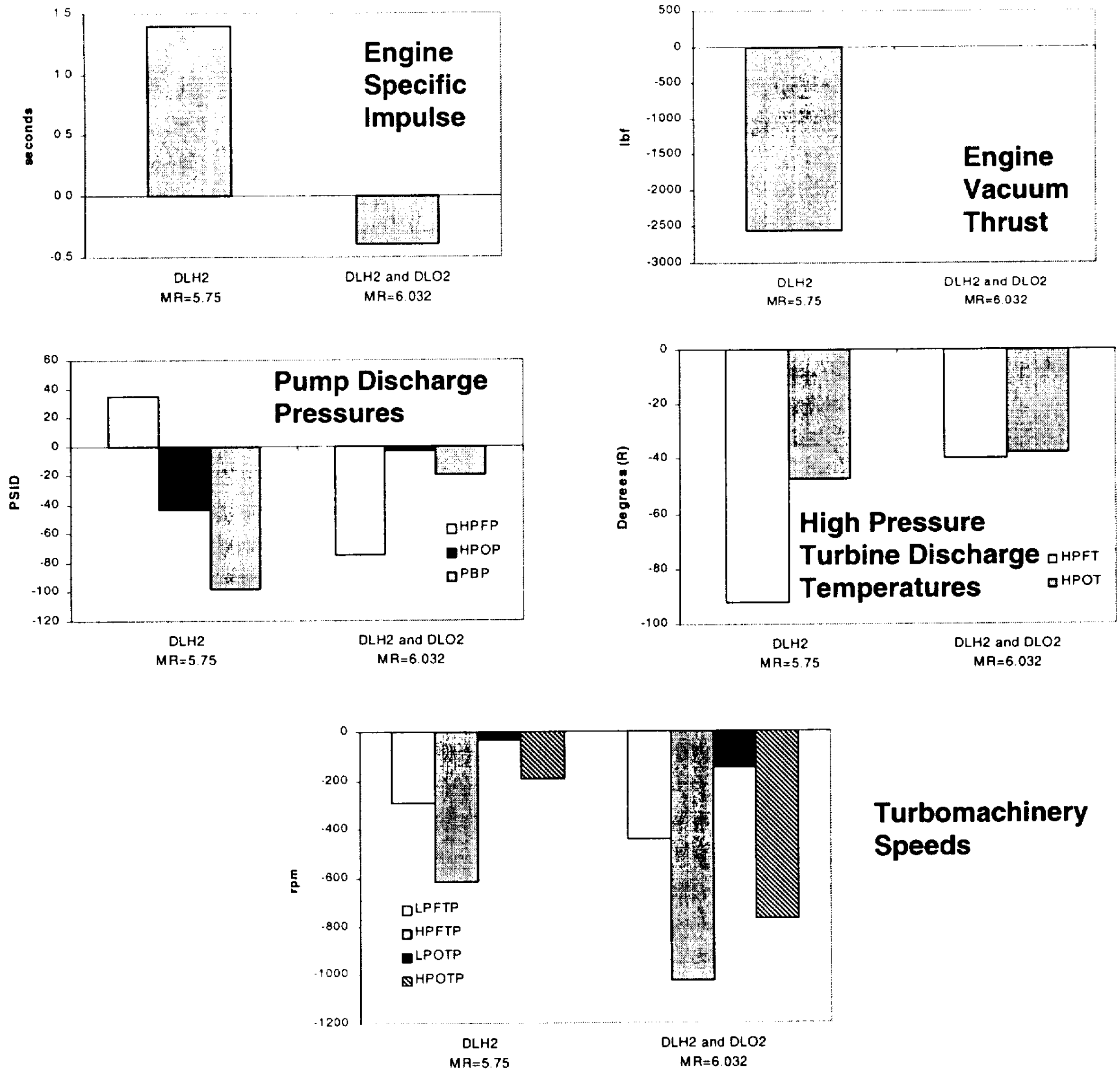

Figure 5. Steady State Effects of Propellant Densification on SSME Parameters

conceptually simple, would require extensive testing and retrofit of engine and facility equipment (test site and launch site).

At first glance there does not appear to be any issues with densified LH2 and the start sequence. It has even been suggested that the colder, denser LH2 would act to further minimize the ignition temperature spikes in the preburners [10], but such a benefit could only be verified by testing.

The final subject that falls roughly within the bounds of engine transient performance considerations is that of combustion stability. This, even more than engine start and shutdown, is an area lacking in detailed research to date. Again, the primary concern is the densified LO2.

The Block 2 SSME, unlike the original SSME, has no obvious combustion instability suppression devices in the main combustion chamber. The original SSME, and those launched for about fifteen years, had built-in acoustic cavities and main injector baffles. Through analysis and extensive testing, it was decided that these devices were not necessary as the engine was sequentially upgraded to the final point of the Block 2 design. Thus, if an instability mode should become a possibility with densified propellants, today's SSME stands unprotected.

The concern is centered upon the jet breakup, atomization, and mixing of densified LO2 as compared to normal boiling point LO2. The densified LO2 would be slower moving and heavier as it was injected into the chamber. Because the LH2 enters the main combustion chamber primarily in the form of a hot gas, there is little concern with regard to its changes in character, but the LO2 behavior remains something of an unknown.

It is possible that this concern in unfounded. Several tests with subcooled LO2 were conducted on the NASA Marshall Space Flight Center Technology Test Bed in the mid-90s. The engine inlet LO2 temperatures used for these tests were 15R to 20R higher than those being proposed here (i.e., at normal boiling point LN2 temperatures) and the SSME tested was of the older design with the instability suppression devices, but these tests were conducted safely with no apparent stability issues arising. Nevertheless, this remains an area requiring further research if densified propellants were ever truly implemented on the Space Shuttle program.

Component Redesign or Retrofit

Other than the potential hardware changes mentioned above (a two-stage chilldown bleed on the LO2 side and possibly combustion stability accoutrements) the only other obvious hardware change necessary to the SSME in order to use densified propellants is the application of insulation to prevent liquid air formation. Such insulation already exists on the LH2 side of the engine, but if densified LO2 is to be used then the LO2 side must be similarly outfitted. Whether this insulation would be required throughout the LO2 system or only on the colder, low-pressure portions would likely remain an issue to discover during development testing.

Another potential trouble area that would require a thorough examination through testing would be cavitation regimes the SSME low pressure fuel pump. While one of the benefits attributed to propellant densification is the lowering of fluid vapor pressures, thereby theoretically increasing margins to incipient cavitation, some concern has been expressed regarding reductions to the factor of Thermodynamic Suppression Head (TSH) (see [12], pg. 53-55 for discussion of TSH). The combined effect of lower vapor pressure and lower TSH may lead to a situation where there are no gains whatsoever in terms of actual engine operation capabilities due to the need to maintain adequate margins.

Engine Recertification

Assuming that the detailed technical issues resulting from the use of densified propellants on SSME can be overcome, there remain larger and more expensive programmatic issues to consider. The two most significant of these issues would be the need to recertify the SSME fleet for flight and making the necessary changes to the engine ground test stands to incorporate propellant densification.

Because the transition to densified propellants would be such a fundamental change to the SSME environments, as part of the May 2001 study and in coordination with the NASA SSME Project Office, it was determined that a standard Class A certification program would be necessary prior to the first flight. It was assumed under such a program the pre-certification development testing would be similar to past programs and include two engines covering roughly forty ground tests. The actual certification test series would consist of two engines, different from the development engines, and it too would span just over forty tests. For the purposes of planning, the details of these tests are not especially important but these tests are designed to cover a broad spectrum of conditions to ensure safe engine operation.

In concrete terms of making a rough order of magnitude (ROM) cost estimate, it was assumed that two of the four engines required to complete the development and certification program could be assembled from existing parts. The other two engines would likely come from the flight fleet and would have to be replaced with new hardware. Thus, the bill for accomplishing this testing would include two SSMEs and roughly eighty ground tests. Based upon 2001 dollars, the ROM cost for this bill comes to approximately $160 million.

Note that this value is only for certification of the existing SSME design. If significant modifications are necessary to the design, then the entire fleet of flight engines would have to be retrofitted with the new hardware (assuming a simple retrofit was possible) and there would likely be a requirement to conduct acceptance tests for each engine anew. This would tack at least another $15 million onto the test costs.

Test Stand and Launch Site Modifications

What the above ROM costs do not include are the modifications necessary to the ground test facilities needed to generate the vast quantities of densified propellants that would be required to conduct the testing. A detailed discussion of densified propellant production will not be presented here (see [1] through [7]) but a quick overview is in order.

For the purposes here, there are two methods of turning normal boiling point cryogenic propellants into sub-cooled, densifed propellants: internal to tank (ITT) and external to tank (ETT). In both cases, the idea is prepare the propellants prior to test. Currently there does not exist a technology capable of densifying propellants fast enough to support an engine firing real time.

ITT densification is depicted in a very simple schematic in Figure 6. Here, sub-cooling is achieved by reducing the tank pressure causing the fluid to boil and release heat until it reaches equilibrium. ETT densification, depicted in Figure 7, is accomplished by either transferring propellants from one tank to another through a densification unit or by recirculating fluid through a densification unit with a pump. The densification unit itself could use a variety of densification methods the most common of which is the use of sub-cooled cryogenic baths and heat exchangers.

The situation for SSME becomes a bit more complex due to the current setup at the NASA Stennis Space Center in Mississippi where SSME ground tests are conducted. For a typical, full duration ground test, propellants are supplied not only from the tanks located on the test stand, but also from barges located next to the test stand. Without propellant transfer from these barges, the ground test program could not fulfill the requirement of simulating flight-like mission durations on the test stand.

There are several possible solutions to overcome this complexity but all of them require significant facility modification:

- Densify both the stand run tanks and the barges in place. The problem with this solution is that it would require multiple densification systems and it is not clear that the barge fleet could be modified

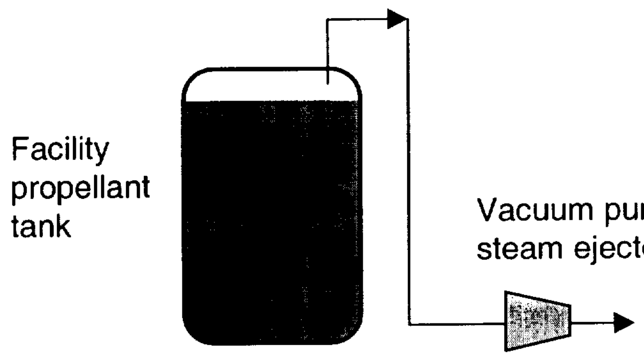

Figure 6. Simple Sketch of Internal to Tank (ITT) Propellant Densification

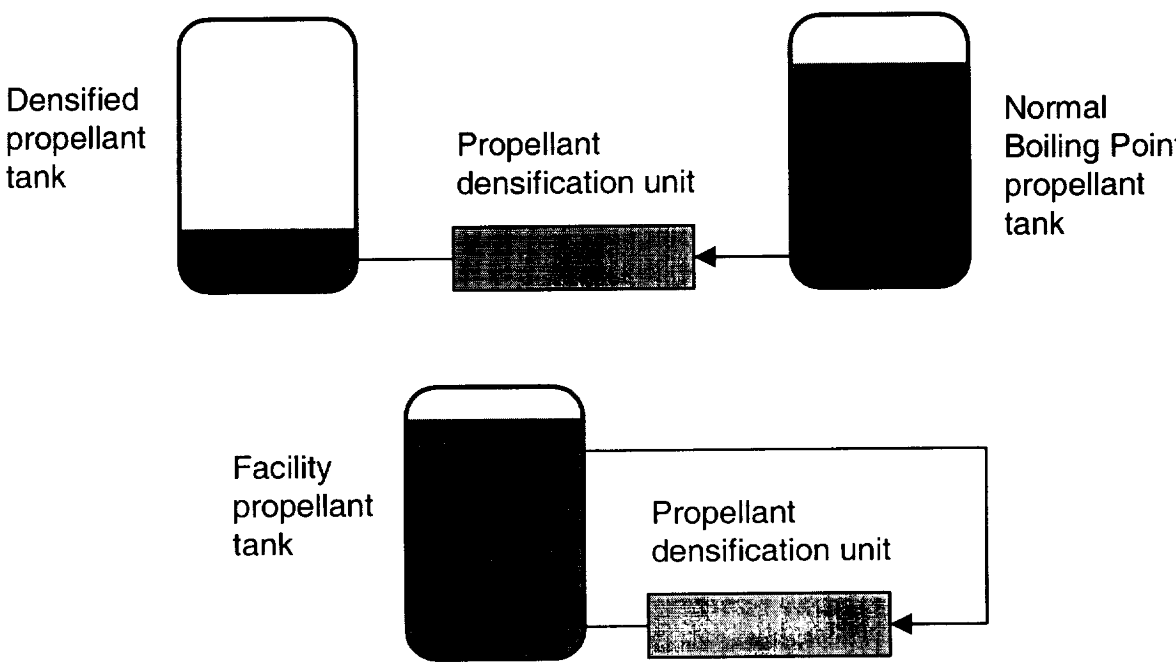

Figure 7. Simple Sketch of External to Tank (ETT) Propellant Densification Schemes

sufficiently to perform effective densification.

- Add supplemental, ground-based tanks to replace the barges. In this scenario, the propellant from the barges would be off-loaded to these new tanks and densified there. This would eliminate the problems with adapting the barges for densification but not the requirement for a separate densification system for the stand tanks. The exception to this would be if the supplemental tanks were large enough so that the stand tanks were redundant and could be back-filled with densified propellants immediately prior to test initiation. An illustration of such a system with ETT densification is shown in Figure 8.

- Replace the test stand tanks. This is the most straightforward choice but might be the most expensive. It would eliminate the necessity for propellant transfer in-run and would necessitate only a single densification system. Unfortunately, placing an ETT densification system onto the test stand might be problematic simply due to space concerns.

Because the May 2001 study of densification for the Space Shuttle did not proceed beyond the study phase, a final decision on the best way to modify the test facility was never agreed upon. Further, the study did not mature to the point of generating comparative cost figures. Presented here are simply some of the ideas discussed at the time.

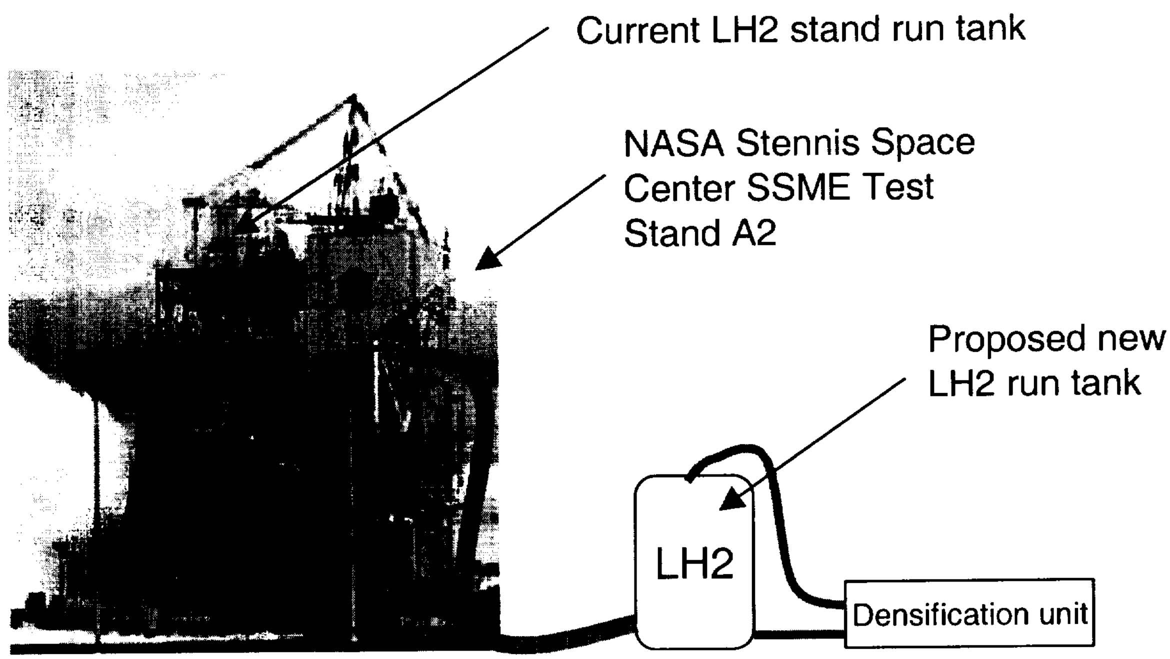

Figure 8. Internal to Tank (ITT) densification scheme with a new, ground-based supplemental liquid hydrogen tank.

Launch Site Modifications

This brief paper is dedicated to the narrow topic of the effects of propellant densification on the SSME program. A related topic that is not addressed is the modifications necessary to the launch site to accommodate the incorporation of densified propellants. It is at this point that all of the components and disciplines of the shuttle program come together

Summary / Conclusions

The Space Shuttle was not designed to use densified propellants. This is a statement of fact with repercussions throughout the program should the programmatic decision ever be made to pursue propellant densification as a system upgrade. There are potential effects in the tankage, in the feedlines, in the pressurization system, in trajectory development, and, of course, in the main engines.

Upon first glance, the predicted steady state SSME performance changes are nearly all in the positive direction. If both LH2 and LO2 densification are pursued, then there is a slight decrease in specific impulse performance but the decreases in internal stresses may well outweigh this factor. For the case of LH2 densification alone combined with the subsequent change to lower vehicle mixture ratio, there is actually an increase in specific impulse performance to be coupled with the decreases in internal component environments. From the standpoint of steady state performance alone, a pretty good case can be made that propellant densification for SSME has several advantages.

However, there may be a more difficult task to undertake in the realm of transient performance. To date, not a great deal of work has been dedicated to this subject, but it would appear that a chilldown procedure different than that used today would be necessary to ensure repeatable, benign engine starts. Potential fixes, such as a two-position relief system, likely would require modifications to both the engine and the facility (test and launch). Also, substantial development testing would have to be dedicated to this subject.

Other things that would have to be ironed out through development testing include an exploration of cavitation margins of the low pressure fuel pump with colder propellants and altered thermodynamic suppression head characteristics. If LO2 densification is pursued then the issue of combustion stability has to be addressed as well as increased insulation requirements for the LO2 system.

How the SSME test stands are to be modified to accommodate all of this necessary testing raises the specter of significant investments in new facility tanks and densification systems.

And finally, should all of these factors be overcome and the SSME and the Space Shuttle program become prepared to accept densified propellants, the expense of SSME recertification rises as a potential obstacle. While this is primarily a technical discussion, it is hard to ignore a requirement in the range of hundreds of millions of dollars.

Thus, the conclusion of this brief discussion, and that of the May 2001 study, is that there may be some benefits to the use of densified propellants within the SSME and that the most of the potential technical issues can likely be overcome. This suggests that for future launch vehicles propellant densification should be seriously considered as a baseline element of thereby reaping the benefits while avoiding the issues of retrofit and recertification. On the Space Shuttle program, howver, whether these benefits justify the time, effort, and cost is another question. For the time being the answer to that question remains no.

Acknowledgements

The authors would like to sincerely thank David Coote, Matt Marsh, and David Wilson for their valuable input to this paper.

References

1. Fazah, M. M., "STS Propellant Densification Feasibility Study" (NASA Technical Memorandum 108467)

2. Lak T., Lozano, M., and Tomsik, T., "Advancement in Cryogenic Propulsion System Performance through Propellant Densification" (AIAA-96-3123)

3. Tomsik, T., "Performance Tests of a Liquid Hydrogen Propellant Densification Ground System for the X33/RLV" (NASA Technical Memorandum 107469, AIAA-97-2976)

4. Greene, W. and Vaughan, D., "Simulation and Testing of In-Tank Propellant Densification For Launch Vehicles," AIAA-98-3688.

5. Anthony, M. and Greene, W., "Analytical Model of an Existing Propellant Densification Unit Heat Exchanger," AIAA-98-3689.

6. Greene, W., Knowles, T. and Tomsik, T., "Propellant Densification for Launch Vehicles: Simulation and Testing 1999," AIAA-99-2335

7. Jurns, J., Tomsik, T. and Greene, W., "Testing of Densified Liquid Hydrogen Stratification in a Scale Model Propellant Tank" (1999 Cryogenic Engineering and International Cryogenic Materials Conference, Montréal, Québec, Canada, and NASA Technical Memorandum 2001-209391)

8. Hill, P. and Peterson, C. Mechanics and Thermodynamics of Propulsion (Addison-Wesley Publishing Co., 1965).

9. White, F. Fluid Mechanics (McGraw-Hill, Inc., 1979).

10. Bradley, T. "Block II SSME Start Issues with Densified Propellants" (presentation by Boeing Rocketdyne to the Space Shuttle Propulsion System Integration Group, May 2001).

11. Greene, W.D. "Estimation Method for Block 2 SSME Preburner Ignition Temperature Spikes," AIAA-2001-3539.

12. Sobin, A.J. and Bissell, W.R., "Turbopump Systems for Liquid Rocket Engines," NASA SP-8107, Aug. 1974