Conversion of the Space Shuttle Main Engine to the Full Flow Staged Combustion Cycle

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In the timeframe of 1983 NASA issued a call to industry for ideas to improve the Space Shuttle Main Engine (SSME). By that time the engine had disclosed a number of severe deficiencies in its design and operation. The problems were widespread across diverse technologies, and several were of criticality 1 levels of risk. In addition to technical issues, the first cost of the SSME hardware had risen by a large amount, making the cost of maintenance and operations extremely high as a result. The Shuttle Vehicle was plagued with its own problems as well.

Cryomec, a small company in Anaheim, CA responded to the NASA invitation and sponsored an initial evaluation of the SSME. Almost immediately in the study it was apparent that the SSME had been designed at essentially the physical limits in virtually all parameters. Stress limits, thermal limits, cavitation limits, bearing parameter limits, shaft dynamics limits, heat transfer limits, combustion limits, all showed that the design had been pushed to every limit of a given parameter, which was exacerbated by NASA finding it necessary to operate the engine at 109% of its design point to achieve flight objectives. In addition, incredible complexity had been incorporated in such critical items as the main injector, and such ordinary items as the hot gas collector ducting upon which the turbopumps were mounted. This latter subassembly featured a three-duct passage to deliver the exhaust gas flow from the LH2 TPA to the main injector, (the three ducts to minimize the pressure drop in the passage). Well after the SSME was flying, it was discovered that the middle duct was actually flowing in reverse due to a poorly understood dynamic flow field in the LH2 turbine exhaust, which was configured to make a 180 degree turn in an annulus after leaving the turbine.

The high operating temperature of the LH2 TPA turbine required the use of an alloy for the wheel that was subject to hydrogen embrittlement. The wheel was gold plated to protect it from hydrogen attack. After operation, flecks of gold sometimes were found, possibly indicating that the plating had been lost at a critical location. Expensive disassembly would then be required to allow full inspection.

The LOX TPA featured a complex double suction impeller, requiring a complex inlet that added to cavitation issues. Location of the LOX-cooled bearings near the impeller inlet, resulted in the bearings residing in sub-critical LOX as their coolant. Bearing-generated heat proved sufficient to cause the LOX to flash and vapor-lock the bearing set, so cooling could be lost. In one case at least, the ball bearing balls were found to be square and blue upon pump disassembly. The LOX TPA was driven by hydrogen-rich combustion products. A positive dynamic shaft seal arrangement was necessary to keep the LOX in the pump separate from the fuel-rich gas in the turbine. A helium purge system was provided for the necessary assurance of seal effectiveness. Approximately 2000 lb of high pressure helium was required for the seal purge on each flight.

The SSME uses boost pumps to improve the engine cavitation performance so tank pressure can be low. The boost pumps are hydraulically driven by bleed flow of liquid propellants from the main pumps. Approximately 10% of the flow is recirculated for the boost pump drive. This increases the power demand on the main TPAs, adds to the flowrate of the main pumps, inherently increasing their cavitation issues. The recirculated flow is heated by the inefficiencies in the hydraulic passages, which increases its vapor pressure and further aggravates the cavitation issues of the TPAs when the warm flow is reingested. Only a very small improvement is gained by the added weight, complexity and cost of the hydraulic-driven boost pump subsystems.

The main thrust chamber was designed for a chamber pressure of 3200 psia. A new alloy, NARLLOY_Z was formulated and fabricated into the Nation's first milled slot chamber. Incredibly expensive, it required a unique vacuum vapor deposition closeout of the exterior shell over the channels. The design was plagued with thermal ratcheting because of the proportions chosen for the ribs and lands. Thermal gradients were high enough to cause plastic yielding of the lands on each firing, leading to cracking of the lands.

The litany of such mis-guided engineering choices goes on to include the LOX post issues in the main injector, the extreme thermal transient caused by purging LH2 at -421°F out through a gas turbine still at full operating temperature (about 1550 F), a

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LOX superheater located in a fuel-rich hot gas duct, a main injector that produced a 5-6 percent mixture ratio disparity across the face, costly milled slot main chamber cooling channels that initially exhibited thermal ratcheting sufficient to induce fatigue cracking, LH2 pump impellers designed to be milled from single forgings of 6AL4V titanium material at $300,000 per each of the three stages, to obtain the necessary strength-to-weight required for the high tip speed needed to support the high (3000+) psia chamber pressure, turbine materials prone to hydrogen embrittlement, that had to be gold plated to hinder hydrogen attack.

In any event, we at Cryomec investigated the approach of converting the SSME from a Partial Flow Staged Combustion cycle to the Full Flow Staged Combustion (FFSC) cycle. In the process we coined the term FFSC to explain the difference from the SSME. The SSME uses less than 1/3 of its propellant mass flow to drive its turbomachinery. The engine runs at a mixture ratio of 6 so the hydrogen is 1/7th of the flow. It is essentially all burned at a mixture ratio of about 0.8:1 to generate the turbine drive gases, so roughly 2/7 of the total flow is used for turbine power. The low mass flowrate to the turbines requires high turbine inlet temperatures to produce the required power for the cycle. In the FFSC cycle both the LOX and LH2 are burned and all of the propellant mass flow is used to drive the turbines.

The benefits of the FFSC cycle are dramatic. The abundant mass flow allows major reductions in turbine drive gas temperature (at least 400F less in the LH2 turbine and even more in the LOX TPA). The drive gases are compatible with the pumped liquids so positive dynamic shaft seals are not needed, nor are the 2000 lb of GHe purge gas. The cool turbine drive gases have low nozzle spouting velocities, so lower turbine tip speeds can be used with associated reductions in centrifugal stresses. Cryomec proposed to reduce the chamber pressure to 2800 psia, and open the chamber throat to retain the same thrust. This further reduced the power demand of the feed system, and allowed the turbopumps to run slower. (Note: NASA eventually enlarged the chamber throat to ease the demand on the feed system. The boost pumps were converted to gas-driven turbines, allowing higher pressures to be developed and reducing the demand on the main pumps. The LOX pump was readily simplified to a single axial inlet impeller. The LOX cooled bearings were now in super-critical LOX so bearing coolant dryout could not occur. LOX could be allowed to enter the turbine housing, so only a liftoff dynamic shaft seal for initial chilldown was needed. The cool running LOX turbine became a simple impulse wheel, which takes all the pressure drop across the nozzle instead of pressure drop across the blades. Large wheel tip clearances can be tolerated for safety assurance with minimal performance penalty. The LOX pre-heater in the LOX TPA turbine exhaust is now in a compatible gas stream, eliminating a criticality 1 failure mode. The cool running turbine on the LH2 TPA was able to use A286 alloy for the turbine wheel, an alloy not subject to hydrogen embrittlement.

The turbopumps were redesigned to incorporate the preburners directly into the TPA housings, eliminating external ducting and saving weight and complexity. The LH2 turbopump was configured to incorporate a 4th stage impeller. Adding the fourth stage allowed the impeller tip speeds to be reduced to such a degree that the impellers could be cast from CP Titanium at a cost of about $10,000 each, instead of the $300,000 6AL4V Ti impellers needed before.

The main chamber remained cooled by LH2, but the heat transfer load was significantly reduced by the reduction in chamber pressure. This allowed the channel slots to be widened relative to the lands so greater elastic elongation length would be available to reduce/eliminate thermal ratcheting. Both propellants arrive at the main injector as pre-burned products of combustion at nearly the same pressure and modestly different temperatures. The propellants were to be injected as alternate thin sheets of oxidizer and fuel in radial slots or concentric rings of sheets. The high shear between the fast moving GH2 and the much slower moving GOX, and the large surface area exposure was expected to provide high C* efficiency, while the greatly reduced volumetric change from combustion of liquid oxidizer to gaseous oxidizer meant that the instantaneous quantity of oxygen in the chamber was reduced by roughly a factor of 10, making sustained combustion instability less likely. The injector was simple, light weight and inexpensive, being little more than a sheet metal weldment.

Most importantly, virtually all design parameters in the FFSC version of the SSME have significant margins. Furthermore, the technical advancements that have been made on the SSME can be beneficially incorporated into the FFSC version. Full advantage of advancements in bearings, materials, ignition, health monitoring, tooling, manufacturing methods, infrastructure elements, etc. can be gleaned productively. There was no major SSME issue that was not alleviated or eliminated by the switch to the FFSC cycle. Cryomec Propulsion Inc. pursued these studies and design activities at a cost to the company of approximately $300,000 per year from 1983 through 1986. The results of the work were presented widely to NASA Centers, NASA

Headquarters, various Air Force laboratories, and to the three main propulsion firms of that era. Many proposals were also submitted.

Eventually, the Air Force awarded contracts to Rocketdyne and Aerojet to jointly design and build the Integrated Powerhead Demonstrator (IPD). Unfortunately, they did not pursue the simple avenues based on the SSME Cryomec had found in their studies. Initially enamored with the FFSC cycle, a design with a Pc of 4000 psia was pursued. Many engineers in both companies contributed to the IPD, One of the Cryomec team was informer unofficially that the Air Force was aware that they were in violation of Cryomec Patents. The IPD ended up with a relatively costly and complicated test article that has not found use in a practical application.

At this time I have Conceptual Design drawings of all the modifications noted above, as well as many not listed. I also have much of the original study work leading to the various modifications suggested, as well as briefing materials. I hope this helps you to envision the potential to upgrade the SSME to a cost-effective workhorse engine giving high performance and reliable operation.