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# The MB-60 Cryogenic Upper Stage Engine - A World Class Propulsion System

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Mitsubishi Heavy Industries (MHI) and Pratt & Whitney Rocketdyne (PWR) have been co-developing the MB-60 cryogenic upper stage engine since 1999. This engine is sized to provide 267 kN (60 Klbf) of vacuum thrust using liquid hydrogen and liquid oxygen propellants. Key features of this engine include: robust/reliable design, high specific impulse, low weight, and multi-restart capability all combined in an affordable package. On the MB-60 engine, these design objectives are satisfied by combining components that draw on key technologies integrated into a system that is powered using the expander-bleed (or open expander) cycle. At the start of this joint international engine development effort, PWR and MHI focused on demonstrating those technologies that enabled attainment of the engine design goals and mitigated certain development risks. Key technologies that were demonstrated as part of this development effort included: a high performance injector, main combustion chamber (MCC) heat load and resistance characteristics, film cooled nozzle operation, and high performance fuel turbomachinery. In addition to these technology demonstration tests, a demonstrator engine combining all of these technologies was later assembled and tested successfully. This engine served to demonstrate the integrated performance of all the key components (with the exception of the nozzle). It also provided an opportunity to develop and demonstrate other integrated features of the engine. These integrated features included: high chamber pressure operation, the engine start and shutdown sequences, engine specific impulse, and the ability of the MHI/PWR team to co-develop an engine within the constraints imposed by government export regulations. The purpose of this paper will be to discuss each of the various technologies and features listed above in more detail as well as the results of the demonstrator engine test. This paper serves to document the world class capability of the MB-60 engine and establish its readiness for continued development.

**Key Words:** MB-60 Engine, Expander-Bleed Cycle, Upper Stage, Cryogenic Propellants

## 1. Introduction

Mitsubishi Heavy Industries (MHI) and Pratt and Whitney Rocketdyne (PWR) began work on the MB-60 engine in 1998. This work was facilitated by a technology assistance agreement (TAA) that enabled co-development of a 267 kN (60 Klbf) cryogenic upper stage engine. Work was divided 50/50 between PWR and MHI. PWR was responsible for the turbomachinery and the nozzle. MHI was responsible for the thrust chamber assembly (TCA), valves, controls, and ducts. System level tasks were performed jointly and it was agreed that engine assembly would be performed in the country in which it was to be delivered. Comparable capabilities of the two companies made it possible for both companies to be a system integrator under the constraints imposed by government export regulations. For example, engine system performance analysis was performed by two companies independently until the results matched. At that time, the engine was primarily intended as a commercially developed upgrade for use on an advanced upper stage (AUS) for the Delta IV launch vehicle. Early development efforts focused extensively on the fuel turbopump (FTP) and the TCA. Component level testing of the TCA was successfully completed at the 267 kN (60 Klbf) power level. These tests served to verify the performance of the injector and main combustion chamber at their original intended design condition. Additional information on these TCA tests is provided in Reference 1. Late in 2000, changes in the commercial launch market forced the termination of the AUS program and the engine effort was adjusted to focus on a lower thrust level (156 kN) more compatible with the existing Delta IV upper stage. At that time, a decision was made to develop and test a demonstrator engine in the 156-178 kN (35-40 klbf) thrust range. Testing of a demonstrator engine described later in this paper and in Reference 2 was conducted at this lower thrust level. The combination of full power component tests and demonstrator engine tests at the reduced thrust level, serve to verify the readiness of the key technologies needed to support MB-60 engine development.

## 2. Key Upper Stage Engine Technologies

The MB-60 is a LOX-hydrogen upper stage engine designed utilizing an expander-bleed power cycle. A simplified schematic of the system is provided in Figure 1. This cycle was selected based on: relative simplicity and development ease; high performance capability; and compact packaging (due to high chamber pressure capability). References 3 and 4 provide additional background and rationale for this cycle selection. There are a number of key engine technologies and

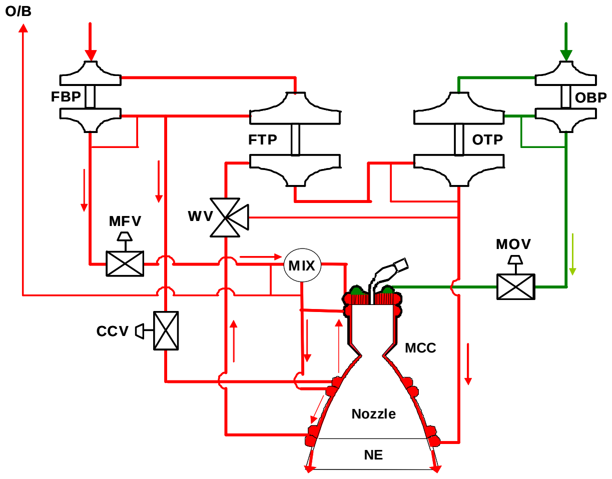

Figure 1: Typical Expander-Bleed Cycle Engine

capabilities that facilitate the design and development of this type of engine. These technologies include: high performance injector design, an advanced main combustion chamber, a film cooled nozzle extension, and high performance fuel turbomachinery. Each of these technologies is discussed in more detail in the following paragraphs.

## 2.1 High Performance Injector

High performance injector technology is necessary to attain very high specific impulse. Improved mixing and combustion in the main combustion chamber translates directly into higher engine specific impulse. Each percentage point improvement in combustion chamber energy release efficiency translates into approximately 5 seconds of additional specific impulse. Attaining such high performance in an expander-bleed cycle engine is particularly challenging due to the cycle's inherently low fuel injection temperature. This challenge was recognized early in the MB-60 program and an effort was performed by MHI to demonstrate injector performance at full scale. The development performed by MHI included both non-combusting and combusting single element testing as well as 3 different full size injectors tested at engine operating conditions. At the conclusion of the effort, an injector meeting the stringent MB-60 engine requirements was successfully demonstrated. Additional details of the injector testing are discussed in Reference 1.

## 2.2 Main Combustion Chamber

The main combustion chamber (MCC) is a key component that significantly impacts the operation of any expander cycle engine. This significance is based on the fact that energy to power the expander cycle is provided via heat transfer extracted from the combustion chamber. As a result, any expander cycle engine is highly sensitive to a shortfall in the heat transfer and excess coolant fluid pressure losses. If the heat transfer in the MCC is less than expected then the turbine inlet temperature and developed horsepower will also tend to be lower – resulting in a thrust shortfall. If the coolant (hydrogen) pressure loss is more then expected then additional turbopump power is required – also resulting in a thrust shortfall. MHI recognized the significance of MCC operation to the MB-60 engine and structured a development program to demonstrate the design. Full scale testing of the MCC was conducted in conjunction with the aforementioned injector. These development tests included testing of two full size MCC's at actual engine operating conditions. A total of 26 tests were conducted. The energy extracted from the MCC coolant circuits and the coolant pressure losses were measured. At the conclusion of the effort, an MCC meeting the MB-60 engine requirements was successfully demonstrated. Additional MCC performance results are discussed in Section 3 of this paper.

## 2.3 Film Cooled Nozzle Extension

The nozzle extension (NE) plays a key role in the overall performance of the engine. Not only must the nozzle extension provide an efficient means of expanding the engine's primary exhaust products, it must also provide a means to maximize the performance recovered from the low pressure turbine exhaust gases. The expander-bleed power cycle operates by extracting a portion of the heated high pressure fuel from the outlet of the thrust chamber coolant circuit and expanding those gases in turbines to generate the

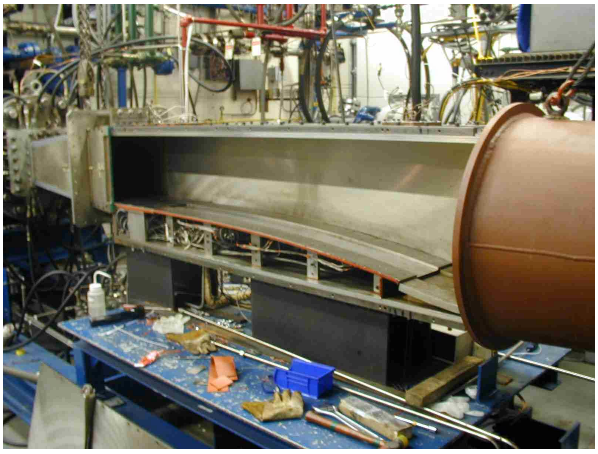

Figure 2: Nozzle Film Cooling Test Setup

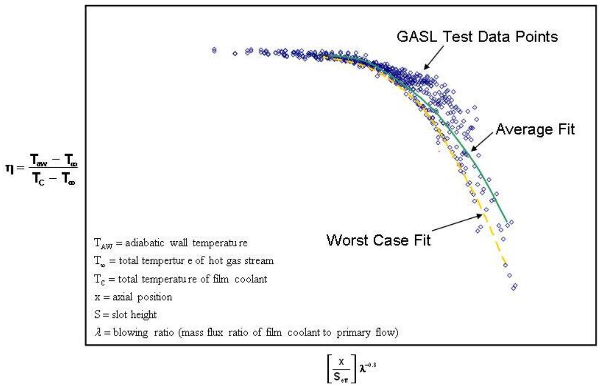

Figure 3: Nozzle Film Cooling Test Results

power required to operate the engine’s turbomachinery. After being discharged, the turbine exhaust fuel pressure is significantly less than the engine’s main combustion chamber pressure. Despite this low pressure, significant performance can still be recovered from these gases by accelerating them to supersonic velocity and injecting them into the nozzle. In this capacity, the gases can provide significant film cooling of the engine’s fixed nozzle extension and significant internal drag reduction for the engine’s primary exhaust flow. The film cooling effectiveness of the turbine drive gases when used in this manner is of critical importance to the design of the nozzle. Both the effectiveness and persistence of the coolant film influence the selection of the nozzle extension material, the length of the extension that can be effectively cooled, and axial location of the injection location. The choice of the nozzle extension material has a strong influence on the engine’s cost. An expensive carbon-carbon nozzle would be required if the film effectiveness is poor but a much lower cost metal nozzle can be used if the film effectiveness is sufficient. To address this question, PWR undertook an effort to characterize the effectiveness and persistence of the turbine exhaust gas film for the MB-60 engine application. This effort involved testing performed at the General Applied Science Laboratory (GASL) in Ronkonkoma, New York. Figure 2 shows a photograph of the test hardware. A total of 9 tests were conducted. Data from these tests confirmed the ability of the nozzle configuration to be cooled via this approach and subsequently served to anchor analysis models used to predict the NE’s thermal environment. Results are shown in Figure 3. Based on the results of these tests an economical sheet metal NE was baselined for the MB-60 engine.

Another important feature of the MB-60 engine nozzle is the configuration can be readily adapted to accommodate unique requirements of future launch vehicles. This adaptability is realized because the film cooled nozzle extension is a mechanically simple configuration isolated by design from the engine powerhead. As a result, the nozzle length and area ratio can be readily changed to match the unique set of requirements and/or stage geometric envelop. Such changes to the nozzle extension will influence the engine’s specific impulse and thrust but will not change the operating conditions of any other component. This feature enables the engine to be adapted to future launch vehicle configurations (after initial development testing is completed) without requiring extensive additional testing to re-demonstrate the durability of the powerhead and its components.

## 2.4 High Performance Fuel Turbopump

The fuel turbopump is a key component that significantly influences the design and operation of an expander-bleed cycle engine such as the MB-60. Power required to pump the liquid hydrogen fuel to the necessary operating pressure is significantly greater (more than 3X) than that required for the oxidizer side of the propellant feed system. As a result, the engine balance is highly sensitive to both the fuel pump and turbine component efficiencies. These efficiencies strongly influence the power required to balance the cycle and, in turn, drive the quantity of energy that must be extracted from the MCC. In addition, the pump’s discharge pressure and required power is driven strongly by the engine’s chamber pressure and the fuel feed system pressure losses. To satisfy these constraints, the MB-60 fuel pump was designed using a two stage centrifugal pump to generate the necessary discharge condition and a high efficiency, low blade aspect ratio supersonic impulse turbine design to extract the necessary power from the heated fuel. Other unique features of the MB-60 turbopump include: a hydrogen hydrostatic bearing to support the turbine end of the rotor and provide substantial rotor damping; and a primary seal package that was developed for PWR by Eagle Engineering Aerospace Company (Tokyo, Japan). A photograph of the fuel turbopump (FTP) is provided in Figure 4. Testing of this turbopump was carried out as part of the demonstrator engine test program discussed in Section 3 of this paper. Significant findings from the test program include: satisfactory pump performance; satisfactory hydrostatic bearing and rotordynamic damping as evidenced by the data provided in Figure 5; high turbine efficiency; and satisfactory rotor axial force balance and balance piston operation.

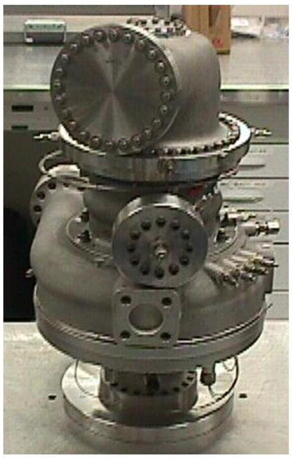

Figure 4: Fuel Turbopump (FTP) Assembly Completed

PWR’s MB-60 fuel turbine design baselines a high performance, supersonic impulse turbine. This high performance turbine configuration strongly enhances the overall performance of the engine by minimizing the flowrate required to drive the turbomachinery. This type of turbine is typical of designs baselined by PWR on engines in similar high pressure ratio turbine applications. Examples of engines where this technology is applied include both the RS-68 and the J-2X. Turbine operation was successfully demonstrated on the MB-XX demonstrator engine for this specific application. Additional information and observed

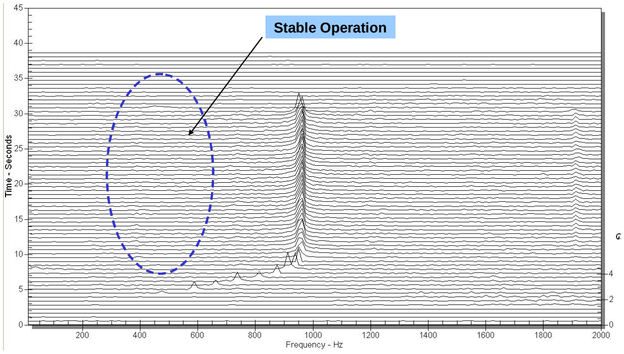

**Figure 5: MB-XX Fuel Turbopump Accelerometer Data**

performance is summarized in Table 2.

In the timeframe of 2000 to 2001, market forces drove the MB-XX program to focus on a smaller engine in the 156 kN (35 Klbf) thrust class. As a result, the existing 267 kN (60 Klbf) design was tuned to operate at the lower thrust level. The FTP was not re-designed or re-sized, rather the turbine nozzle and stator blade counts were changed to permit lower speed operation. Pump end bearing characteristics were also altered to insure acceptable rotordynamic margins at the lower operating speed. This modified turbopump configuration was ultimately tested as part of the demonstrator engine discussed in Section 3 of this paper. As a result of these changes, the thrust level of the demonstrator was limited to approximately 40 klbf. However, since the basic design was not altered, the changes required to convert the design back to the higher thrust level are minimal.

## 3. Demonstrator Engine and Test Results

MHI and PWR successfully assembled and tested the first MB-XX demonstrator engine in the summer of 2005. Testing was performed at the Tashiro Field Laboratory located in northern Japan. A total of 11 tests were conducted accumulating approximately 100 seconds of hot fire time on the engine. Safe start and shutdown transients were developed and demonstrated. Satisfactory fuel turbopump operation was demonstrated (the FTP was operated for the first time during these engine tests). Steady-state operation was conclusively demonstrated in the final test when a programmed duration of 30 seconds was attained. During that test, this expander cycle engine was operated at a chamber pressure of 9.0 MPa (1308 psia) corresponding to a thrust level of 165 kN (37 Klbf). A summary of all engine level testing that was conducted as part of this program in provided in Table 1.

The MB-XX engine was assembled using a flight-type injector, main combustion chamber assembly and fuel turbopump. These are the most significant components that most strongly influence the engine's design and performance. However, to minimize the cost of the effort, the remaining components were drawn from other compatible programs or commercial sources. As a result, key components such as the valves and the oxidizer turbopump were not flightweight or optimally sized for this application. Assembly of these heavier components impacted the mechanical arrangement of the demonstrator engine. This impact included adjusting the component arrangement to accommodate support structure that would not be required in a flight engine. Custom ducting was fabricated to connect all the components in this altered configuration. All testing was conducted at sea level conditions only and the film cooled nozzle extension was not installed for any of these tests. A layout of the engine is shown in Figure 6.

Table 1: MB-XX Demonstrator Engine Test Summary

| Test Number | Date | Duration (secs) | Max Pc (psia) | Summary |
|---|---|---|---|---|
| T60-027H | 6/20/05 | 1.2 | 0 | Chamber igniter development/characterization test. MOV not opened |
| T60-028H | 6/25/05 | 4.0 | 0 | Test terminated per plan as FTP discharge pressure exceeded target value of 210 psia. MOV not opened. Satisfactory FTP hydrostatic bearing lift-off and operation. Phase 1 of the program considered complete. |
| T60-029H | 6/30/05 | 4.8 | 620 | Test per plan as FTP discharge pressure exceeded target value of 840 psia. MOV opened for the first time and chamber ignition established. MFV opened to intermediate position. |
| T60-030H | 7/5/05 | 5.0 | 594 | Repeat of test -029 except MFV intermediate position adjusted to refine engine start sequence. Satisfactory FTP rotor axial force/balance piston operation demonstrated. Phase 2 considered complete. |
| T60-031H | 7/11/05 | 0.0 | 0 | Test terminated erroneously by observer prior to engine start (but after auto sequence start). |
| T60-032H | 7/13/05 | 6.0 | 780 | Test terminated during start sequence due to higher than expected transient MCC coolant outlet temperature. |
| T60-033H | 7/18/05 | 6.2 | 790 | Repeat of test -032 with adjusted MFV timing and revised MCC coolant temperature red line. Test was erroneously terminated by facility noise issue on vibration safety cutoff (VSC). |
| T60-034H | 7/22/05 | 9.9 | 1135 | Repeat of test -033. Engine orificing set to target 85% power level. Facility issue lead to early test termination as thrust was stabilizing. |
| T60-035H | 8/9/05 | 8.8 | 1327 | First attempt to run full power (thrust & MR control orifices changed). Facility issue lead to early test termination as thrust was stabilizing. |
| T60-036H | 8/12/05 | 17.0 | 1296 | First successful mainstage test. Conducted for programmed duration. Thrust control orifice size reduced slightly from prior test to target desired thrust level. |
| T60-037H | 9/21/05 | 30.0 | 1304 | "Show" test. Visitors from Tokyo embassy and JAXA present for the test. No change to engine orificing or valve sequence. |

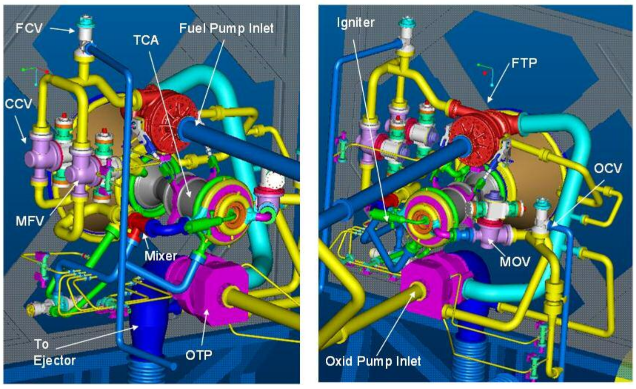

Figure 6: MB-XX Demonstrator Engine Mechanical Arrangement

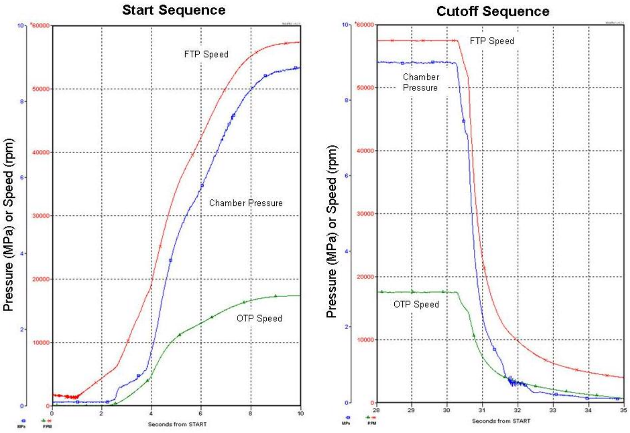

Figure 8: Typical MB-XX Demonstrator Engine Start and Cut-off Transients (Data from Test -037)

OTP design work at PWR was stopped in 2000 to concentrate available financial resources on the FTP. In order to move forward with the demo engine test activity, MHI elected to pursue the design and development of an OTP for this application. An ulterior motivation for this activity was also MHI's desire to improve its in-house turbopump design/development capability. The OTP was designed without assistance from PWR by MHI personnel relying on assistance from MHI R&D centers. Design requirements for this OTP were drawn from the MB-XX demonstrator engine operating point. A non-flightweight OTP configuration was ultimately designed and component tested at the Tashiro Field

Laboratory in 2004. This turbopump was designed for a maximum thrust level of approximately 156 kN (35 Klbf).

During the demonstrator engine test program a total of 11 tests were conducted. A summary of each of these tests is provided in Table 1. These tests served to verify satisfactory FTP operation, develop the engine start and shutdown sequences, and demonstrate performance of key engine components. The testing culminated with a very successful 30 second duration full power test. Key parameters from this final test are provided in Figure 7 and Figure 9. Steady-state operation of the engine was clearly attained during this final test as evidenced by the stability of all pressure and temperature data between 15 and 20 seconds after engine start. A typical engine balance (pressure, temperature and flow schedule) for the demonstrator engine is provided in Reference 2.

Successful start-up and shutdown transients were developed for the MB-XX demonstrator engine. These transients were developed using a combination of simulation tools and an incremental test approach. The test program was structured using a series of short tests to meet specific incremental test objectives. Data from each test was used to refine and improve simulation tools that, in turn, were used to predict behavior in subsequent tests. After each test, the sequencing of the various engine valves (actuation timing and rates) was adjusted based prior test experience, improved simulation, and the specific objectives planned for the next test. In this manner, safe and robust valve sequences were developed and demonstrated. Figure 8 illustrates typical engine start-up and shutdown characteristics.

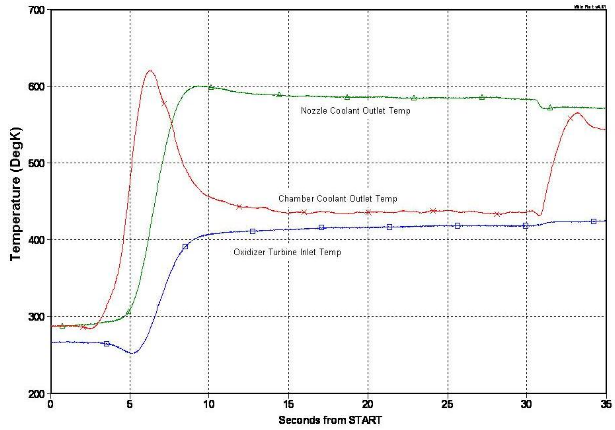

Figure 9: Demonstrator Engine Temperature Data from Test -037

Table 2: Performance of Engine Compared to Design Targets

| Parameter | MB-60 Target | Predicted Demo Engine Performance | Actual Demo Engine Performance |
|---|---|---|---|
| Thrust - Vac (kN) | 267 | 156 | 166 |
| Specific Impulse (secs) | 467.0 | 414.9 | 415.7 |
| Chamber Pressure – Inj End (MPa) | 13.9 | 9.31 | 8.99 |
| Combustion Chamber Energy Release Efficiency (%) | 99.5 | 98.6 | 99.3 |
| Fuel Pump Outlet Pressure (MPa) | 20.7 | 15.1 | 15.4 |
| Fuel Pump Speed (rpm) | 69,500 | 56,750 | 57,447 |
| Fuel Pump Efficiency (%) | 65.1 | 63.3 | 59.3 |
| Fuel Turbine Inlet Temperature (K) | 632 | 628 | 580 |
| Fuel Turbine Efficiency (%) | 52.4 | 46.1 | 54.4 |
| Normalized MCC Heat Load (kW) | 13,766 | 10,386 | 11,393 |
| MCC Pressure Drop (MPa) | 3.18 | 3.10 | 3.59 |
| Nozzle Heat Load (BTU/sec) | 2,826 | 2,016 | 1,989 |
| Nozzle Pressure Drop (MPa) | 1.00 | 0.51 | 0.54 |

The engine's specific impulse was measured during this test program to assess performance relative to expectations. However, since the engine was tested only at sea level conditions, without the full nozzle extension, and with dumped turbine exhaust gas there remains significant uncertainty in the performance numbers. The available data does provide an indication of acceptable injector and combustion chamber performance. This conclusion was reached by correcting measured site performance using TDK performance predictions for the as-tested regeneratively cooled nozzle configuration and comparing that derived number to the actual measured values. This comparison showed a level of energy release efficiency exceeding design targets at the demonstrator test condition. A summary of the relevant specific impulse data is provided in Figure 12 with additional tabular data provided in Table 2.

The performance and characteristics of both the MCC and nozzle cooling circuits was measured during this test program and compared to design expectations and component test data. Results confirm that expected heat loads and pressure drops for both coolant circuits were comparable to expectations (within plus or minus 15%). A comparison of demonstrator engine test data to expectations is shown graphically in Figure 11 and supplemented by tabular data in Table 2. These results show that the MCC heat load exceeded the design target by approximately 10%. The higher heat load also resulted in a correspondingly higher MCC pressure loss (approximately 15% over the design target. Performance for the nozzle portion of the cooling circuit was very close to the design targets for both the heat load and pressure drop. When combined these data give very high confidence that the 60K operating condition can be obtained.

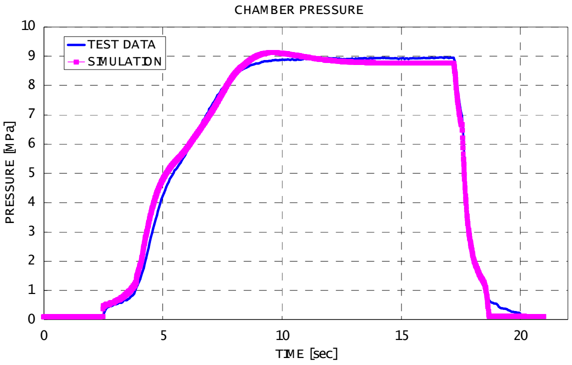

Figure 10: Comparison between Test Data and Simulation Results (Data from Test -038)

A summary of measured versus predicted performance for various key engine parameters is provided in Table 2.

Included in that table are the MB-60 engine design target values, the corresponding demonstrator engine predicted performance levels, and the actual demonstrator engine test results. These data confirm that the demonstrator engine operated much as expected and confirm that the design can be operated as predicted at the 267 kN (60 Klbf) thrust condition.

An interesting phenomenon observed during these tests was associated with the MCC coolant temperature transient behavior. The selected start and cutoff sequence resulted in significant increases in temperature (above the steady-state value) during both the start-up and shutdown transients (see Figure 9). This behavior is believed to be a characteristic of this expander cycle combined with the high chamber pressure design baseline. Since the coolant channel geometry is optimized for relatively dense coolant during steady-state high chamber pressure operation, the coolant channels are relatively restrictive during transient operation as the engine transitions from low pressure to high. This phenomenon resulted in the premature termination of one test (Test -032) during this program. The effect of these temperature transients on the chamber structural capability was evaluated and concluded to be harmless. It is believed that further optimization of the start and shutdown valve sequences can minimize or eliminate this phenomenon.

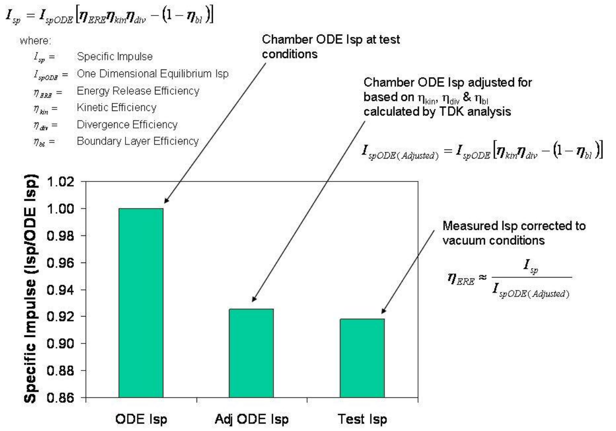

Figure 12: Specific Impulse Data from Test -037 Indicates High Energy Release Efficiency

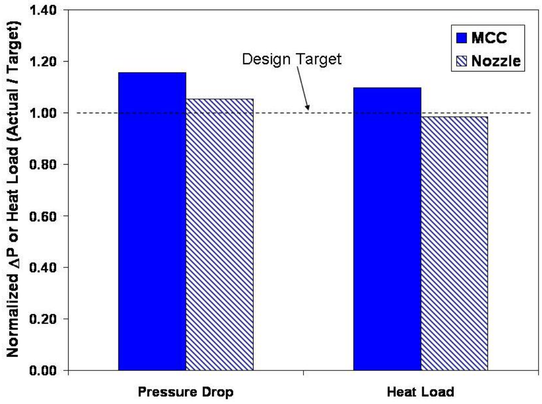

Figure 11: Steady-State Nozzle and MCC Heat Load and Pressure Consistent with Design Targets

## 8. Conclusions

Technologies necessary for the successful development of a high performance, expander-bleed cycle engine for application to the MB-60 engine have been demonstrated successfully at both the component and engine level. These demonstrated technologies include: high performance injector technology; design of the main combustion chamber; film cooled nozzle extension; and high performance turbomachinery. Key parts of the engine were assembled and tested successfully as part of a demonstrator engine during the summer of 2005. This was the first time that key MB-60 engine components were assembled and tested together as an engine. These tests proved to be highly successful. Over the course of 10 tests, fuel turbopump operation was characterized, a safe start sequence was developed, and steady-state engine operation at full power was demonstrated for 30 seconds. Performance of the various components was consistent with pre-test expectations. Characteristics of the main combustion chamber and performance of the main injector were evaluated. Operation of the FTP's hydrostatic bearing was satisfactory throughout the program. No significant hardware damage was incurred in any of the tests. All primary test objectives were obtained. Throughout the effort, all applicable export regulations, licensing requirements, and PWR internal control plans (regarding export control procedures) were followed.

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