Large Liquid Rocket Testing – Strategies and Challenges

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Rocket propulsion development is enabled by rigorous ground testing in order to mitigate the propulsion systems risks that are inherent in space flight. This is true for virtually all propulsive devices of a space vehicle including liquid and solid rocket propulsion, chemical and non-chemical propulsion, boost stage and in-space propulsion and so forth. In particular, large liquid rocket propulsion development and testing over the past five decades of human and robotic space flight has involved a combination of component-level testing and engine-level testing to first demonstrate that the propulsion devices were designed to meet the specified requirements for the Earth to Orbit launchers that they powered. This was followed by a vigorous test campaign to demonstrate the designed propulsion articles over the required operational envelope, and over robust margins, such that a sufficiently reliable propulsion system is delivered prior to first flight.

It is possible that hundreds of tests, and on the order of a hundred thousand test seconds, are needed to achieve a high-reliability, flight-ready, liquid rocket engine system. This paper overviews aspects of earlier and recent experience of liquid rocket propulsion testing at NASA Stennis Space Center, where full scale flight engines and flight stages, as well as a significant amount of development testing has taken place in the past decade. The liquid rocket testing experience discussed includes testing of engine components (gas generators, preburners, thrust chambers, pumps, powerheads), as well as engine systems and complete stages. The number of tests, accumulated test seconds, and years of test stand occupancy needed to meet varying test objectives, will be selectively discussed and compared for the wide variety of ground test work that has been conducted at Stennis for subscale and full scale liquid rocket devices. Since rocket propulsion is a crucial long-lead element of any space system acquisition or development, the appropriate plan and strategy must be put in place at the outset of the development effort. A deferment of this test planning, or inattention to strategy, will compromise the ability of the development program to achieve its systems reliability requirements and/or its development milestones. It is important for the government leadership and support team, as well as the vehicle and propulsion development team, to give early consideration to this aspect of space propulsion and space transportation work.

Nomenclature

CPIA = Chemical Propulsion Information Agency
CBC   = Common booster core
DOD   = Department of Defense
DDTE = Design, development, test, and evaluation
ETO   = Earth to Orbit
GSE   = Ground support equipment
HYSR = Hybrid Sounding Rocket
LOX, LH = Liquid oxygen, liquid hydrogen
LRE   = Liquid rocket engine
MPTA = Main Propulsion Test Article
MSFC = Marshall Space Flight Center

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MTF   =   Mississippi Test Facility
NSTL   =   National Space Technologies Laboratory
PBS   =   Plum Brook Station
SRM   =   Solid rocket motor
SSC   =   Stennis Space Center
SSME   =   Space Shuttle Main Engine
STE   =   Special test equipment
TCA   =   Thrust chamber assembly
TRL   =   Technology readiness level (1 being lowest, to 9 being highest)
WSTF   =   White Sands Test Facility

I. Introduction

Liquid rocket engines (LRE), together with large solid rocket motors (SRM), represent the mainstay of capability for powering launchers whether heritage vehicles or more modern derivatives. A wide variety of liquid rocket engines (LRE) have been developed for boost stage and upper stage applications on so-called small, medium, and heavy lift launch vehicles where the individual engines range in thrust from approximately 10,000 lbf to over 1 Mlbf (Ref. 1). The range of test capability that has evolved and adapted to serve the test needs of these propulsion devices is equally varied, and includes small, medium, and large test stands that are architected to enable component-level (e.g. preburners, pumps), engine-level, or stage-level liquid propulsion testing. These test stands are typically equipped with the necessary propellant systems infrastructure, modern measurement systems, and other unique or necessary capabilities such as altitude simulation infrastructure. Traditionally, the primary users of the test capabilities are government organizations for government sponsored activities (e.g. NASA, and DOD entities), however, a wider user base is possible in the near future as more commercial ventures develop space launch vehicles, particularly in the small to medium launcher category. Specifics regarding test capabilities are generally well known to those who utilize them, and are databased and discussed from time to time in the open literature (for example see Ref. 2−9). Given this fact, the particulars of any given test site or test capability is not discussed here. Instead, the emphasis is on the test program or test project, its scope and extent, and the unique testing strategies chosen by the development and test team, and notable test facility challenges associated with that scope of work. The discussion is provided from the perspective of a test organization.

In order to underscore the fact that ground testing plays a central role in rocket propulsion development one can review the extent of testing on previously developed LRE propulsion for liquid oxygen (LOX), liquid hydrogen (LH), and kerosene propellants (see Ref. 10−11). One finds that hundreds of tests with multiple engine units, with accumulated durations of hundreds of thousands of test seconds, was typical for the many hydrogen and kerosene fueled engines developed and flown since the inception of human space flight. The testing community is keenly aware of the fact that a high level of readiness, flexibility and rigor must always be applied to accomplish such extensive manifests of ground test work in an expeditious, cost-effective, and safe manner at all times. In this context it is imperative that both the tester and the developer have the insight into the objectives and nature of test campaigns, as well as historical precedence, in order to effectively plan forthcoming propulsion testing programs as early as possible in the overall vehicle development process. It is important to mention that rocket propulsion development has not been a sustained Aerospace industry capability but instead is subject to the fluctuations of government policy and unpredictable market climates. As noted in Ref. 12, the US industrial and technology base for propulsion appears to have lagged behind the international community in the past two decades, and therefore with the recent reinvigoration of manned space exploration there is significant intellectual retooling that must take place in propulsion in general. It is in this context that this paper is presented.

II. Objectives of Liquid Propulsion Testing

The broad objectives of testing vary depending upon whether the test article is at low-, mid-, or high- technology readiness level (TRL[‡]), and consequently the test campaign may be quite different in terms of approach and timeline. For low-TRL work, with proof of concept hardware, the emphasis is on expeditious turnaround of varying hardware configurations with sufficient test results to warrant focused follow-on testing of a more sophisticated test article. For mid-TRL work, the emphasis appears to shift towards so-called "battleship" hardware that is mature enough to be a prototype design or early precursor. For high-TRL propulsion devices, either engine components or engine systems, the highest level of rigor is applied to both the facility and test article hardware, and a high degree of quality and confidence is expected of the testing activity in terms of safety and acceptability of the work. For the purpose of this paper, the remainder of the discussion is limited to mid-to-high TRL level work.

An overview of the potential ground test scope for a new propulsion design is given in Fig. 1. Assuming that the proof of concept is already in hand, the major development testing options likely involve a subscale combustion device that may be a pump, preburner, and/or thrust chamber with the desired attributes of the intended full scale combustion device. The data from the subscale component test is a reasonable risk reduction step that allows for the full scale hardware to be built and tested subsequently. Upon completion of all necessary full scale component testing, the integrated design may be tested as a unit, either powerhead or engine or both, and the data is then utilized to develop the confidence necessary to commit resources to the full scale flight-like prototype or a precursor demonstrator engine. Figure 1 further illustrates that the full scale development engine, and additional engine units are subjected to a qualification program (a.k.a. certification) that demonstrates the engine over its operating regimes including demonstration of operating margins and off-nominal performance or environmental extremes. The final testing step involves unit by unit acceptance testing prior to committing that specific hardware to a flight vehicle.

In the past decade, several rocket propulsion designs have progressed through several of the testing phases
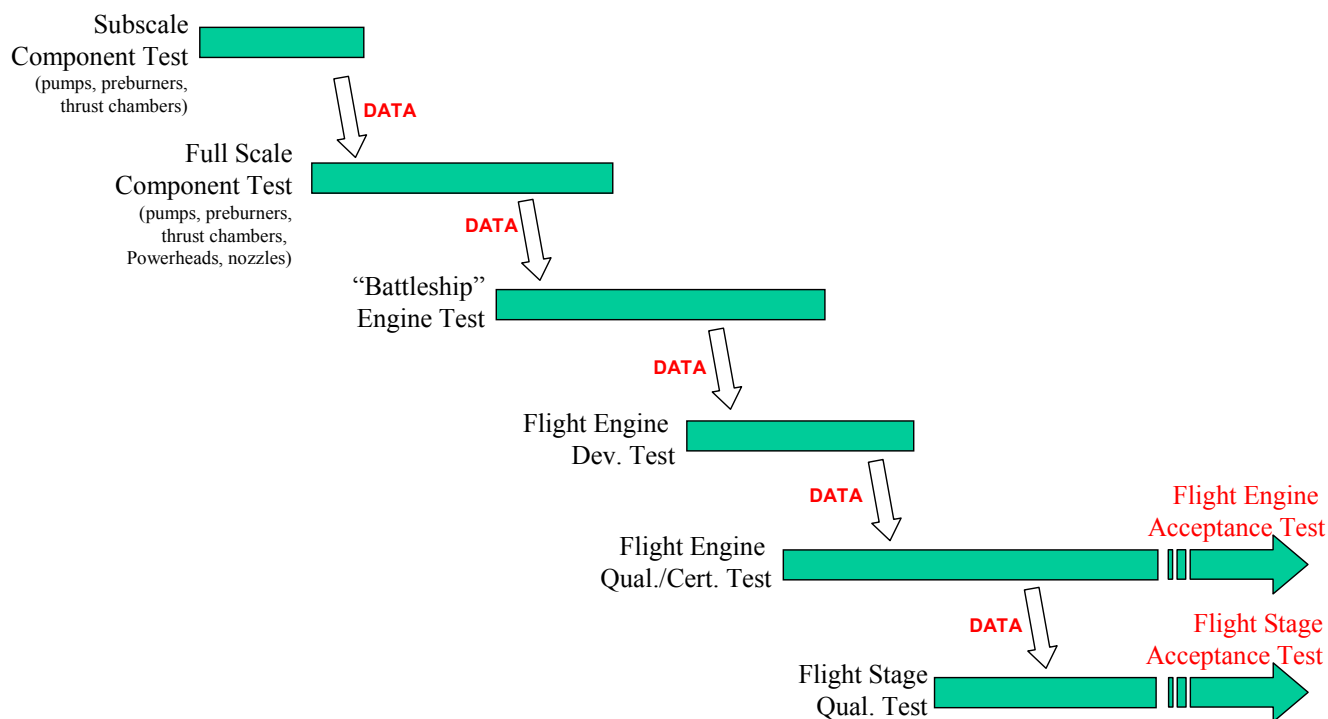
Figure 1. Notional representation of major elements of a test program (relative durations can vary).

[‡] The technology readiness level is a convenient scale to describe technology maturity, extending from 1 to 9; the subgroups of low TRL (1−3), mid TRL (4−6), and high TRL (7−9), are often used by government technologists for facilitating planning, discussions and reporting.

discussed above. These examples are discussed in the next section for the lessons they provide for future efforts.

Test organizations make every effort to forecast the trends in LRE test needs, and this is often challenging given the many development and evolution paths that liquid propulsion may take. For instance, it is known that launch vehicles relying upon either hydrogen or kerosene fueled engines will continue to be central to launch capability. However, the type of engine, its thrust class, and other attributes will not be known until architecture and other trade studies are completed and strategic decisions are reached regarding the national launch vehicle fleet. The current situation portends that either the Atlas and Delta ELV's could be evolved into heavy cargo lifters, and possibly even crewed vehicles, and therefore test facilities must be prepared to provide the potential test needs of the growth options stemming from these vehicle as outlined in Refs. 13−14. In other cases, a new propellant could be introduced into the traditional mix (e.g. liquid methane) and thus test facilities must plan in advance for all aspects of utilizing the new propellant choices.

III.   Survey of Selected LRE Test Campaigns

Several test projects and programs have been conducted at Stennis Space Center (SSC), Marshall Space Flight Center (MSFC), and elsewhere, in the past two decades (Ref. 3−4, 6, 8, 9). These include the successful development and certification activities for the Shuttle SSME engine, certification of the Delta IV RS-68 engine, and the testing of several other development engines such as MC-1, XRS-2200, and engine components for RS-76 and RS-84 designs, that did not evolve into flight engines for various reasons. It is instructive to examine all of these test projects/programs in a collective and comparative manner, and then distill some useful conclusions and observations pertinent to future test planning of developmental propulsion systems.

The LRE development and test strategy is generally conceived at the outset of the LRE development program, even as early as when the LRE design is being proposed as part of a formal contractor bid. Hence, several iterations of the scope and objectives of the testing will occur as the LRE design itself matures and more resources are brought to bear. Regardless, there is a common theme and evolution to the testing phases that accompany and enable design maturation as discussed in the following selective examples.

A. Development Testing of MC-1 Engine and Stage

During the 1990s, NASA managed and conducted the design, development, test and evaluation (DDTE) of the prototype hardware for a LOX/kerosene propelled rocket engine for the X-34 altitude launched flight test vehicle. The so-called MC-1 engine, originally named Fastrac, was a 64,000 pounds rated thrust (64 Klbf) device. As outlined in Ref. 15, an appreciable amount of engine testing (over 50 tests utilizing 4 engines) was accomplished between 1999 and 2001 in order to characterize and evaluate the MC-1 engine for the flight vehicle.

It is interesting to observe here that the development program involved the following *four* elements in the test campaign: (1) a component level test series of a LOX/kerosene pressure-fed thrust chamber, at NASA Marshall Space Flight Center (MSFC), (2) an engine system test series at NASA Stennis Space Center (SSC) and also at Rocketdyne Santa Susana facilities (in series), (3) a "battleship" stage test series with the so-called Propulsion Test Article (PTA) consisting of an integrated engine and flight size propellant tanks, and (4) an acceptance test series for the purpose of demonstrating that every manufactured engine was ready for flight. The first three series were accomplished essentially per plan, however, the critical latter phases of the testing (engine qualification/certification, and acceptance) did not take place since the X-34 vehicle flight test program was cancelled in 2001.

Each element of a test series is a risk reduction effort for the following phase of propulsion development, and involves a considered assessment of the "cost/benefit" involved. While the most technically comprehensive test program is highly desirable for technical risk reduction, the uncompromising constraints of cost and schedule commitments will preclude such an effort and testing scope may be reduced. For any given element of testing, its value to the rest of the development process is necessarily weighed against its cost in terms of risk reduction. For instance, the effort involved in conducting thrust chamber assembly (TCA) testing pays back

Figure 2. Hotfire testing of the MC-1 64 Klbf LOX/kerosene engine with its battleship stage installed vertically in the test stand (stage aft end is visible above the engine).

dividends in that ignition and stability characterization may be done earlier without the pump hardware that would be required for the engine level testing. Further, the risk of hardware or facility damage due to potential failure during TCA development testing is restricted to the component facility and would not perturb preparations for the engine test series to follow. (If it were the case that the TCA was already a well characterized existing design, then the TCA series would be not be as essential and the development might proceed directly to the engine level testing.) In the case of the MC-1 engine, the four elements of testing were essential demonstration steps prior to integration of main propulsion into the X-34 flight vehicle.

In terms of the test facility preparations, each element of testing involves careful choices and the earliest possible information on test article requirements is essential. In this example, the TCA testing required a facility with the propellant capability, supply pressure, and tank volumes to provide sufficient test duration to characterize the thrust chamber and ablative nozzle over a range of operating conditions. For the engine system test series, additional facility attributes were needed, namely, a dedicated location with the flexibility for providing both long and short run durations, propellant conditioning (to altitude start inlet conditions), pogo simulation, and adaptability to stage testing. Each of these presented challenges for special test equipment (STE) and other ground support equipment (GSE) that was ultimately the responsibility of SSC test site personnel at the B-2 stand.

The engine test series required either a vertical or canted engine installation, to avoid post-shutdown pooling of kerosene, and consequently this was incorporated into the test facility thrust structure adaptation for a downward canted engine. Conditioning of LOX was provided for by designing and fabricating a shell and tube heat exchanger sized exactly for this application, and the corresponding conditioning for the RP was possible through the use of an industrial grade heat exchanger. Additionally the implementation of temperature conditioning was a challenge in terms of the controls and measurement systems associated with the hardware and the tailored engine start sequence. The engine itself also contained flight avionics hardware and software that had to be interfaced to the test facility controls systems. For the stage test series, a significant challenge was the hardware installation and removal into the test stand, along with the integration of the stage structure to the test stand structure that required careful facility planning and implementation. While some of these were well understood in advance, their relative importance and impact on the test program was not fully appreciated until actual implementation and underscore the necessity for early definition if testing expectations are to be fully met.

B. Development Testing of Hybrid Sounding Rocket (HYSR) Hardware

Similar to the MC-1, a hybrid sounding rocket development effort was enabled through a test campaign at a different test location at SSC. In this case, the E-3 test facility was commissioned to perform both component and stage level testing of a 60 Klbf thrust class device. At almost the same thrust scale as the MC-1, this testing required only LOX propellant flow since the fuel was part of the motor test article supplied by the propulsion developers. Unlike the MC-1 stage, this was a pressure-fed stage without any pumps to incorporate into the motor.

The test campaign consisted of the following *three* elements: (1) a test series to demonstrate a novel ullage pressurization scheme for the simulated flight vehicle LOX tank, (2) a few tests of the hybrid motor itself, including its igniter system, and, (3) a "stage" test with a motor that was integrated with a customer-provided LOX supply tank (instead of the facility run tank). All the elements of testing were performed and provided the confidence to commit a flight design to a demonstration launch from the Wallops Flight Facility.

Figure 3. Hybrid sounding rocket (HYSR) test article installed at the E-3 Cell 1 test stand; solid fueled motor with liquid oxygen supply tank constitutes a simulated "stage."

For this development test effort, an expeditious and low cost proof-of-concept test campaign was accomplished. A minimum number of controls and instrumentation were requested, as would be the case for a highly reliable "turnkey" hybrid sounding rocket launch system. The horizontal motor thrust adaptor, with thrust measurement, was reused to test the simulated stage in an "L-shaped" configuration with the tank vertical as in flight, but the motor mounted horizontally in the same mount as the component level motor test. This is shown in Fig. 3. An interesting challenge in this case was that of making thrust measurement, therefore the thrust structure for the motor was designed to constrain vertical or lateral motion, yet allow for compliance along the motor axis, and hence the thrust measurement. Fortunately, the planned test firings were completed safely and the program achieved a successful launch from the Wallops range in December of 2002.

C. Development Testing of the XRS-2200 Engine

During the 1990s, NASA conducted a cooperative agreement with a prime contractor to develop the LOX/hydrogen powered X-33 flight test vehicle incorporating a so-called linear Aerospike engine. A prototype engine was developed with some innovative thrust chamber technology, but a well understood powerhead directly derived from the J-2S engine that was developed in the late 1960s. A significant amount of engine testing was accomplished between 1999 and 2001 in order to demonstrate the XRS-2200 engine technology.

For the X-33 program, the propulsion development involved at least the following *four* elements in the test campaign: (1) a component level test series with LOX/hydrogen thrust chambers at MSFC, (2) a powerhead or powerpack test series at SSC for the J-2S derived powerhead, (3) a single Aerospike engine test series complete with powerhead, thrust chambers, and linear Aerospike nozzle at SSC, and, (4) a dual-engine test series at the same test stand in a configuration representing the installation of the engines in the X-33 flight test vehicle. All four test series were accomplished, although unfortunately the dual-engine series was abruptly reduced due to the cancellation of the X-33 program.

The characterization of the thruster chambers both individually and with multiple thrusters was clearly a priority early step prior to igniting the entire engine at full scale. While the thrusters were characterized at NASA Marshall, the J2-S derived powerpack was tested at NASA Stennis A-1 stand as shown in Fig. 4. At the successful conclusion of these two separate series, the test stand was reconfigured twice to perform the engine system testing, first for a single engine (Ref. 8), and then for the dual-engine. Regrettably, the dual-engine series consisted only of 3 hotfires before the program was cancelled.

In terms of test facility challenges to accomplish XRS-2200 development, the major one was the conversion of an SSME test stand to a powerpack test capability, thus requiring a safe hydrogen and oxygen propellant dump system. After the powerpack test series, reconversion was then required to incorporate a thrust measurement system suitable for the unconventional XRS-2200 engine geometry. Finally, a second reconversion to adapt for dual engine hotfire required considerable careful effort for ensuring an adequate flame deflector configuration; the flame passageway and flame deflector originally designed for a circular bell nozzle had to be adapted to the linear configuration of the Aerospike. The outcome was that the dual engine was accommodated for a vertical hotfire but

Figure 4. Panoramic view of powerpack hotfire test at A-1 test stand at SSC. The gas generator exhaust is seen at left, and hydrogen burnoff through a facility flarestack at right, in picture.

Figure 5. Aerospike dual-engine hotfire test at A-1 test stand at SSC. The J-deflector flame bucket, below the engine deck, turns to the right in the picture to direct the flame.

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with the dual engine positioned diagonally across the entry into the flame bucket. For the dual engine test series, accurate bifurcation of both propellant ducts was necessary to provide suitable propellant flows split evenly to the dual engines. Further, the actuation profiles for the engines had to be conducted in the testing to demonstrate accuracy and control for the thrust vectoring role of the dual engine set. All of this was accomplished through the concerted efforts of a collaborative government and industry test site operations team.

D. SSME Engine Testing, and SSME MPTA "Stage" Test

The engine test history is well documented and does not need to be repeated here (Ref. 16). It is illustrative however to review some aspects of the local SSC experience for this engine test program that today continues to be critical to the national manned space flight capability. Unlike the developmental engines discussed above, the SSME is a human-rated engine and remains the most capable and advanced engine ever flown on US launchers. This 500,000 Klbf thrust class staged-combustion engine evolved from early work in the 1970s, to today's configuration often referred to as the SSME Block II upgraded version. Nevertheless, even a mature engine program like this must still undergo unit by unit ground testing prior to flight, and series of planned testing targeted for specific objectives like component level upgrades, or to further demonstrate component level or engine level reliability.

For SSME, the SSC test campaigns consisted of the following *four* elements: (1) engine level testing between 1975 and first flight STS-1, (2) an 18 test series with a 3 SSME cluster integrated with an ET called the Main Propulsion Test Article (MPTA), effectively a "stage," (3) an engine test series in the late 1980s and 1990s for the SSME Block I upgrade, and, (4) an engine test series in the 1990s for the SSME Block II upgrade (for specifics on Block I and II see Ref. 17). Unlike the Apollo program, each flight engine cluster is not tested as a threesome (in this case) or as a flight "stage" and the MPTA test capability for this was not preserved. Crucial precursor component work was performed

Figure 7. Installation of Shuttle ET into B-2 test stand at Stennis Space Center for MPTA stage test series (ET with 3 SSME engines).

elsewhere at contractor facilities (Rocketdyne Santa Susana Field Lab, and later Pratt and Whitney E-8 stand) to development test engine components and subsystems, and this is described in detail in Ref. 16.

The three decades of activity at SSC alone presented substantial challenges for all involved. A very brief synopsis is given here. The first order of business was the reconfiguration of the Apollo stage testing test stands A-1 and A-2 to engine test stands, which involved the addition of sufficiently large propellant run tanks. The requirement to provide the flight duration hotfires led to utilizing the propellant barges as "augmentations" of the run tanks at ground level, with pumping capability to fill the run tanks while the stand run tank is actively providing propellants during an engine test. A total of six LOX barges and three LH barges remain available today to serve this purpose.

A highly important aspect of test support to the SSME program was the ability to test at multiple test stands. At SSC, as many as three SSME test positions have been made available to maximize testing throughput and provide backup

Figure 6. Installation of multiple SSME engines into housing for the MPTA stage test series.

test capability in case of anomalies or failures of a test article or test position.

It is important to note that the SSME requires altitude simulation since much of its flight is at higher altitude. The A-2 test stand was thus equipped to provide a self-pumping diffuser that allows simulation of the low back pressure at up to 60,000 foot altitude. Each flight engine is tested in this diffuser-configured test stand so that the flight nozzle is subjected to a best-effort simulation of flight conditions.

Notably, over 2200 SSME engine test have been conducted at SSC between 1975 and 2004, averaging more than 70 tests per year. During these years, the test manifest has varied considerably so that anywhere from 1 to 3 test stands could be operating at any given time. Thus test stand refurbishment was scheduled to perform detailed inspections and repairs or renovations. On occasion, the need for one of the test stand (A-1) for other work (such as XRS-2200 Aerospike engine) caused all SSME testing to be conducted only on the A-2 stand, precluding a ready backup test capability available at A-1.

E. RS-68 Engine Testing and Delta IV CBC Stage Tests

The RS-68 is the most modern engine in the US liquid rocket propulsion fleet, and has successfully powered the Delta IV expendable launch vehicle. Unlike the SSME, it is not a human-rated engine but is nevertheless built to sufficiently high reliability for both its civil and military space launch manifest. At approximately 700,000 Klbf thrust, it is in fact more powerful than the SSME engine. The test program to provide a flight-ready engine is particularly of interest due to the recent precedent it sets for future testing programs.

For the RS-68 program, the propulsion development involved at least the following *four* elements in the test campaign: (1) component level test series for the gas generator at Rocketdyne, the main thrust chamber testing with LOX/hydrogen at MSFC, and a turbopump assembly cold flow test series, (2) an engine system level test series at NASA SSC, and development testing at AFRL, and, (3) a so-called common booster core (CBC) test series with an integrated flight stage incorporating a single RS-68. All were accomplished as planned and led to a successful first flight in November 2002. Interestingly, a combined stage with all three boosters side by side (Delta IV heavy configuration) was not performed and only characterized upon first flight of Delta IV heavy in December 2005.

In terms of test facility challenges at SSC for the engine test series and the stage testing, the following are noteworthy. The B-1 test position was modified to allow for two adjacent positions known as B-1A and B-1B in order to provide for greater flexibility and higher test rate at a single test stand. A thrust measurement system was procured for each test position rated to approximately twice the thrust level of the RS-68 itself in anticipation of future needs. Again the propellant barges were utilized to supply the RS-68 for the maximum flight duration test requirements just as is the case for the SSME.

The testing of the stage presented other challenges. The logistics of incorporating the stage into the stand and transporting it to and from SSC was a matter of major planning and careful execution. The canal system at SSC was a significant factor in that the stage was barged to Mississippi in a special carrier known as Delta Clipper and then hoisted into the B-2 side of the B test stand (see Fig. 8). Notably, this was the first flight stage incorporated into B-2 since the Apollo Saturn V stages in the early 1970s. Thrust measurement was not utilized for this stage test and is typically not part of stage testing scope.

Figure 8.   The Delta IV Common Booster Core is installed into B-2 test stand at SSC for stage test series (flight stage incorporating 1 RS-68 engine).

A highly successful test campaign was accomplished by the engine DDT&E team during this period and the work continues as a well honed process for acceptance testing each RS-68 flight engine. Occasionally additional testing is performed for special purposes. There are no current plans to do further stage testing. Unlike Apollo each flight stage is not tested before flight, and this has been the case usually for non-human-rated launch vehicles. Thus, the CBC stage test is the only stage-level ground test demonstration for the complete family of Delta IV vehicles including the small, medium, and so-called heavy lifters.

F. Integrated Powerhead Demonstrator (IPD) Engine Test Program

A major development has been underway for the past several years on an advanced technology staged combustion engine known as the Integrated Powerhead Demonstrator or IPD for short. At a nominal thrust level of approximately 240,000 Klbf thrust it is as challenging as any engine development effort ever undertaken in the US propulsion industry. As part of the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) activity, significant progress has been made in designing, fabricating and testing prototype engine hardware. The engine itself was at one time slated for the DC-X vehicle, but has since been continued only as a technology advancement effort. While detailed discussion of the overall program is given in Ref. 18, the following focuses on the implications for testing.

For the IPD program, the propulsion development involved at least the following *three* elements to date in the test campaign: (1) subscale component level work at various locations for key technology (e.g. gas/gas injectors, oxygen rich combustion), (2) large scale component level test series for the oxidizer and fuel pumps at NASA Stennis, and the oxidizer and fuel preburners at Aerojet test facilities, and (3) an engine system level test series at NASA Stennis. The first two elements have been accomplished (see Ref. 19−20), and the final element is currently underway. No further activity is presently baselined but is under consideration for furthering the IHPRPT goals.

A copious amount of knowledge has been gained through this propulsion technology development program, both from the propulsion developers perspective and from the standpoint of test site operations, engineering, and management personnel. In particular, the component-level test needs required facilitization that was state-of-the-art for component

Figure 9. IPD fuel pump cold-flow test at SSC E-1 stand (Cell 2); the high flow of gaseous hydrogen efflux is flared in front of the test cell upon exhaust by using exit igniters whereas the liquid hydrogen is disposed to the high pressure flarestack behind the test stand (not shown).

testing in the US. The fuel and oxidizer test campaigns involved the use of ultra-high pressure pressurization and propellant systems up to 1000 atmospheres. At high flowrates, high pressures, and cryogenic temperatures, virtually all aspects of the SSC test facility (E-1 test stand) were exercised in order to achieve safe and reliable test operations.

For the LOX pump cold-flow testing, it was first necessary to demonstrate pump characteristics as safely and as expeditiously as possible. Whereas pump cold-flow testing with LOX was discussed, the program chose to perform cold-flow testing solely with liquid nitrogen (LN2) as a cryogenic simulant and gaseous nitrogen to drive the turbine. This inherently difficult scope of testing was accomplished without issue, and was sufficient for analysis model verification against very unique test data.

For the turbopump's hotfire testing, a workhorse preburner was first demonstrated at highly oxygen-rich combustion conditions. The major challenge here was to ensure an effective ultra-high pressure run system for 8500 psia LOX supply, with its associated ancillary needs. This preburner was then integrated with the LOX pump into a "half-powerhead" for the purposes of oxidizer turbopump hotfire. The designed preburner was not yet ready and was to be tested at Aerojet in parallel with the pump at SSC. The fuel turbopump cold-flow and hotfire was also planned for SSC E-1, however, only the former was completed due to time and resource constraints. Once the engine preburners were demonstrated at Aerojet, and the turbopumps at SSC, the integrated engine was assembled for the development test series at E-1 stand, with a brand new injector and nozzle that will undergo hotfire for the first time on the integrated engine itself. This series constitutes the culmination of over a decade of activity on this development engine.
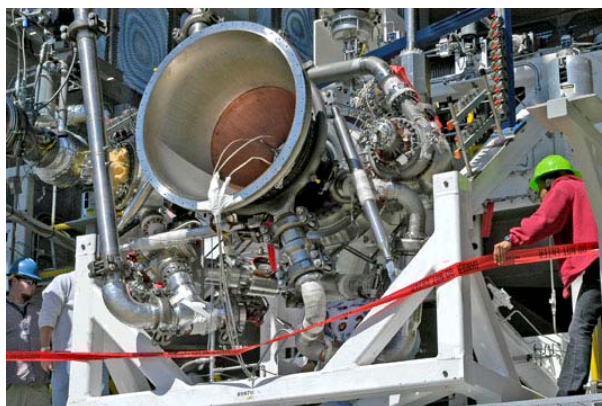
Figure 10. IPD engine is installed at SSC E-1 stand Cell 3 for a development test series.

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There were several noteworthy test facility challenges to enable and facilitate a safe and effective test program. First, the reliable operation of the test facility at ultra-high pressures was a critical aspect of all test operations, and robust systems and processes had to be crafted at the outset of the multiple test projects. This meant judicious and appropriate selection of all test components (high pressure bottles, tanks, valves, filters/screens, thrust structure, robust instrumentation, exhaust plume mitigation, and several ancillary system items too numerous to mention). It was not surprising that the existing stock of high value hardware was quickly depleted by being incorporated into a facility system or a critical spare.

Second, the IPD test program relied upon maximum use of multiple test locations in order to maximize parallel activity, to the extent that hardware availability and resources could allow. For instance, the engine preburners were demonstrated at the Aerojet facilities while a workhorse preburner was employed instead at SSC for the oxidizer turbopump hotfire; and further within SSC, the fuel and oxidizer turbopump test series were collocated at SSC E-1 in adjacent test cells, in order to effect almost parallel test setups, yet exploit the synergy of commonality where practical (cognizant test teams, engineering and operations processes, and hardware/software systems commonality).

A third major challenge for the test facility involved effective communications with a widely distributed community of stakeholders (technical and programmatic) including NASA and Air Force and their respective contractors. The use of electronic data management systems proved invaluable for tracking most aspects of technical progress by work teams located across the country. Technical change requests and approvals continue to be managed through these systems as are technical plans, drawings and data. The precedent set by IPD in this regard is likely to be adopted and further evolved in future work.

G. RS-84 Engine Development Test Program

As part of a recent technology initiative, a major thrust was made towards development of a LOX/kerosene booster engine prototype of approximately 1 Mlbf thrust scale, with potential growth options to as much at 1.5 Mlbf thrust comparable to the F-1 LOX/kerosene engine for the Saturn V. Unlike the F-1 however, the engine known as RS-84 was a staged combustion device for a reusable booster application, specifically an oxygen-rich staged combustion cycle. Although the effort is now cancelled, the test program planning was early and thorough in terms of high-level objectives and strategy.

For the RS-84 prototype development effort, the activity planned involved at least the following *three* elements in the test campaign: (1) subscale component level work at various locations for key technology (e.g. oxygen-rich LOX/kerosene combustion and chamber heat transfer), (2) near full-scale component level test series for the oxygen-rich preburner, the oxidizer and fuel turbopumps in cold-flow and hotfire, as well as a complete engine powerhead, and (3) several engine system level test series at multiples test locations. As a prototype engine development, the plans for stage level testing had not yet been formulated pending work on a launch vehicle application.

At SSC, the first major activity for RS-84 type of preburner combustion was its precursor demonstration of LOX/kerosene oxygen-rich (subscale) preburner combustion, under the RS-76 engine designation in 2000. The 2003 plans for RS-84 development consisted of further subscale testing of an improved subscale oxygen-rich preburner, closely followed by an integrated subscale preburner/chamber test to characterize thrust chamber performance, stability and heat transfer. Figure 11 shows the oxygen-rich preburner combustion exhaust emanating during a short duration steady state hotfire test.

The first large scale component test series was in planning at the time of program cancellation, namely for the high pressure preburner that would be the near full scale analog of

Figure 11. Subscale oxygen-rich preburner hotfire testing at E-2 test stand. Oxygen rich mixture ratio results in a white color plume at relatively low temperature.

Figure 12. High pressure and high flow engine component testing is enabled by large volume "ultra-high pressure" gas supply; here the E-1 stand nitrogen supply is augmented from 3 to 5 bottles to meet the needs for the largest test articles.

the one shown in Fig. 11. This preburner would like also provide the drive gas for the turbopump testing of both the fuel and oxidizer turbopumps either as separate test articles, or combined into an integrated powerhead test article. Tentative plans called for collocated component testing at E-1 stand and its 3 test cells immediately following the IPD component and engine test series.

During the planning discussions, several test facility challenges had already been surfaced and were in the process of being addressed. Among these the most notable are associated with the high flowrates, pressures and thrust loads of what would have been the largest staged combustion engine ever developed. The total LOX flow requirement through the preburner was over 2400 pounds mass per second. At ultra-high pressures, this translated into high LOX flow velocities and associated high demand on flowrates for the run tank pressurization. A design modification to the pressurization system was therefore engineered (both increased storage and increased flowrates) to accommodate this new demand where pressurization storage capacity was greatly augmented. A second major challenge involved completion of the planned upgrades for kerosene fuel systems, both low and high pressure, including run tanks, all major valves, and ancillary support systems with the associated instrumentation and controls. The upgrades were largely accomplished at the time of the RS-84 development program's cancellation, but will be of benefit to the next LOX/kerosene engine development effort.

A third major challenge involved thrust stand capability reinforcement for future main chamber testing up to 1 million pounds force. Although the stand is designed to handle a static load of this magnitude, the dynamics loads from chamber start and shutdown can be much higher and must be carefully analyzed and mitigated through structural improvements. Even the high pressure preburner imposes significant forces to the test cell that must be reacted through the primary test stand structural members. A related hurdle involved the requirement for a thrust chamber cant of at least 10 degrees for the TCA test series. This is necessary to preclude hazardous kerosene pooling in the injector and chamber (startup and shutdown cases), but causes a major plume exhaust mitigation issue in the vicinity of the test cell which must then be modified to accommodate the force/load, thermal, and acoustic conditions from such a large test article's energetic plume.

In closing this section, it is important to mention that many associated propulsion-to-vehicle interface technical issues can and should be addressed during large scale LRE testing. A few examples include such things as engine plume thermal and acoustic base region environments, interfaces with the vehicle main propulsion system (vibration propagation to the flight tanks, valves, and supply ducts, as well as system heat leaks and geysering concerns), vehicle pogo instability mitigation methods, and engine health monitoring through plume diagnostics of the exhaust plume. For the SSME engine, all of these have been examined during the course of the 3 decades of testing and some are still the subject of operational activity today. The X-33 program also availed itself of such targets of opportunity during the XRS-2200 engine test series to produce excellent base region plume effects data.

IV.   Test Project Preparation and Execution

The survey of LRE test campaigns describes the many variations of testing activity. This does not imply that these activities do not have a common process for preparation and implementation. In fact it is remarkable that there is a significant common basis for conducting test activity and it is of great advantage to development teams to be highly familiar with these elements.

A. Test Project Phases

As shown in Fig. 13, a life cycle for any individual test project, the process begins with a formulation phase with the development of test specific requirements, schedule/cost/technical options, and a decision of the test facility best suited for the testing and whether test facility refurbishments and/or upgrades are essential in order to initiate the testing scope. The formulation phase is soon accompanied by conceptual design and analysis engineering for all the necessary test systems (mechanical, electrical, structural, and instrumentation and controls, being the primary ones), and subsequently the detailed engineering to finalize the test approach. Long lead items are frequently procured as soon as the test engineering is mature enough to allow the commitment of resources, and all other test stand procurements, fabrication, and modification activities (both for hardware and software) ensue as soon as possible upon formal approval of the test stand engineering. Although test stand engineering is depicted as one horizontal bar, it actually represents the engineering for all test stand systems needed for the test series, namely the designs for any special test equipment for oxidizer, fuel, pressurization, controls, data readouts and post-processing, risk and hazard analyses, and so forth. The completion of design formally provides the "requirements" for much of the operational aspects including detailed test plans and procedures, test crew composition, data calibration and processing, safety controls, and more. The ultimate product of all the chain of activity in the figure is the production of highly accurate and repeatable data for the propulsion developer to assess the test article itself. Data reviews are
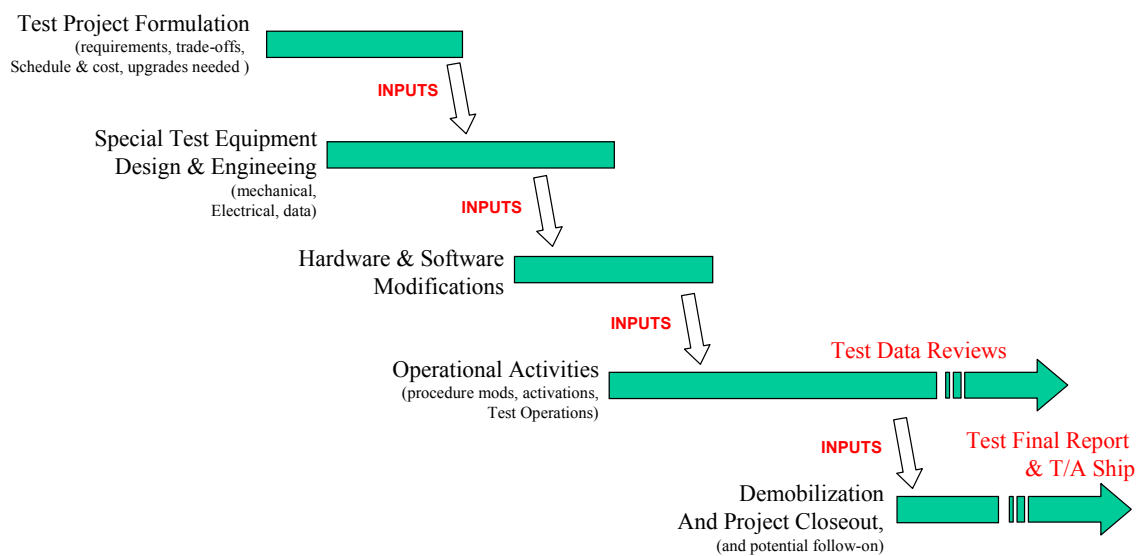
Figure 13. Life cycle representation of a typical test project.

the forum where the most important outcomes of testing are closely examined. Note that the authority to proceed to the next test is almost always contingent upon the outcome of the data reviews. At the conclusion of the formal test series, a final and necessary step is the safe demobilization of the test article and test facility equipment that is not to become a permanent part of the test facility itself. In many cases the test facility will prepare a closeout test report for the propulsion developer whereas in other cases that responsibility is retained by the test customer and their parent organization.

Overall, the process outlined in Fig. 13 is a microcosm of the overarching chain of events that is formally known as systems engineering, where in this case the organization performs a subset of work that can be referred to test systems engineering and operations that serves as a validation step and a risk reduction step for the LRE DDT&E. For clarity, a simplified representation of the test project life cycle was illustrated and discussed. Test site work documents at SSC and other sites codify in substantial detail how the process above is implemented locally.

It is well known that the majority of resources needed to perform testing are utilized during the test stand modification and operational phases, and due importance are given to these phases of the test project life cycle. It has been learned by experience however, that the earlier and equally critical phase of the life cycle is in fact the formulation phase when the test objectives, goals, facility requirements, testing approach and project and test site team roles and responsibilities are coordinated and negotiated. The importance of this part of the life cycle is frequently underestimated and insufficiently resourced. It is not only the strategy and requirements discussion that must be had in the formulation phase, but good forward planning can and should utilize engineering tools to perform conceptual designs and analyses to assess the feasibility and cost of doing a given test project. Given today's design and analysis tools, the early planning can and should be underpinned by test engineering. As an example, the future potential siting of launch vehicle stage test articles at the B test stand of SSC can be analyzed to a high degree of fidelity through the use of computer aided engineering tools at various levels of detail. Figure 14 depicts the B test stand with a notional stage installed at the B-2 side stage test position (left) and with oxidizer and fuel propellant tanks installed at the B-1 side engine position (right); the design is created in a dimensionally accurate computer model.

Installation and physical configuration is the beginning of a successively more detailed process for test systems engineering that will culminate in safe and reliable operations of the test series. As discussed earlier in Ref. 3, the concept will be refined according to specific test requirements and the engineering analysis outcomes and tradeoffs for meeting those requirements will ultimately be baselined in order to authorize the necessary procurement and buildup activities.

B. Major Testing Statistics

At SSC, and all other test sites, the process of Fig. 13 transpires and is either explicitly managed and implemented, or more or less implicitly performed to varying degrees of rigor. At this point, it is informative to examine outcomes for one test organization over its evolution. A recent compilation of test experience was made for all test activities performed at SSC since the origins of this test site. The historical test experience is summarized in Fig. 15, and includes the period from SSC inception as the Mississippi Test Facility (MTF) up to the end of calendar 2004.

The original testing at SSC was performed for Apollo flight stages, both qualification and acceptance. Although few in number, these involved highly complex tests given that most were flight articles to be launched from Cape Canaveral for crewed missions. Overall, 45 tests were accumulated on such stages across the A test stands and the B stand, and are a small fraction of the overall number today which exceeds 3300 individual tests of combustion devices, be they engine components, engine systems, or stages. Up until 2004, over 2200 tests have been accumulated

Figure 14. True scale computer graphics model of B test stand at NASA SSC; propellant barges (cylinders at left) are docked in the canal at the base of the stand as they would be for providing both fill and drain back capability to a qualification stage installed in the B-2 test position (left side in the stand structure).

on a large number of SSME engines, the only human-rated engine in the US national fleet, at the same test stands where Apollo stages were tested. Within the last 5 years the RS-68 engine that powers the Delta IV launch vehicle has been tested well over 150 times at the B-1 position of the B-stand with an excellent record of success and no major test incidents; its first flight stage was qualified upon completion of a 5 test series at B-2 position. The B test stand's B-2 position has primarily hosted stage tests; in particular the Apollo boost stages in the 1960s, and subsequently SSME MPTA, followed decades later by the developmental Fastrac PTA stage and then the CBC flight stage. While stage tests are few in quantity and infrequent, these tests represent some of the most important system-level pre-flight hotfire testing at full scale with flight articles.

Commissioned in the 1990s, the E Test Complex has added to the suite of SSC test facilities. Collectively, the 3 test stands comprise 7 test positions and have greatly augmented the ability to perform R&D testing of any TRL hardware. Specifically, more than 700 tests have been performed at this test area varying from small proof-of-concept devices to some complex and large test articles. Although the greatest number of E Test Complex test firings are attributed to E-3, there have been over 70 tests of large scale engine components that have successfully been accomplished by the test teams.

The only human-rated US-built engine today is the SSME, and SSC has conducted more tests to support this particular program than any other since inception. In particular this testing has supported over 100 Shuttle flights to date where every SSME engine has been acceptance tested as an individual unit prior to use on the flight vehicle. The 2200 or so tests of SSME may be further broken down in several ways to examine statistics of interest. One particularly informative view of the history is in terms of the test rate, in the case of SSME, year-by-year over 3 decades of work. Both completed tests and aborted/repeated tests are counted to produce the information of Fig. 16, where each data point represents an average test rate for the calendar year, i.e. calendar days from the first to final test of the year, divided by the number of tests.
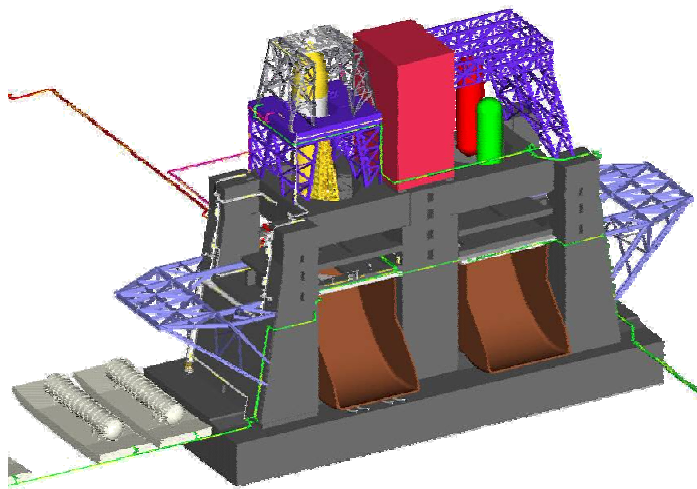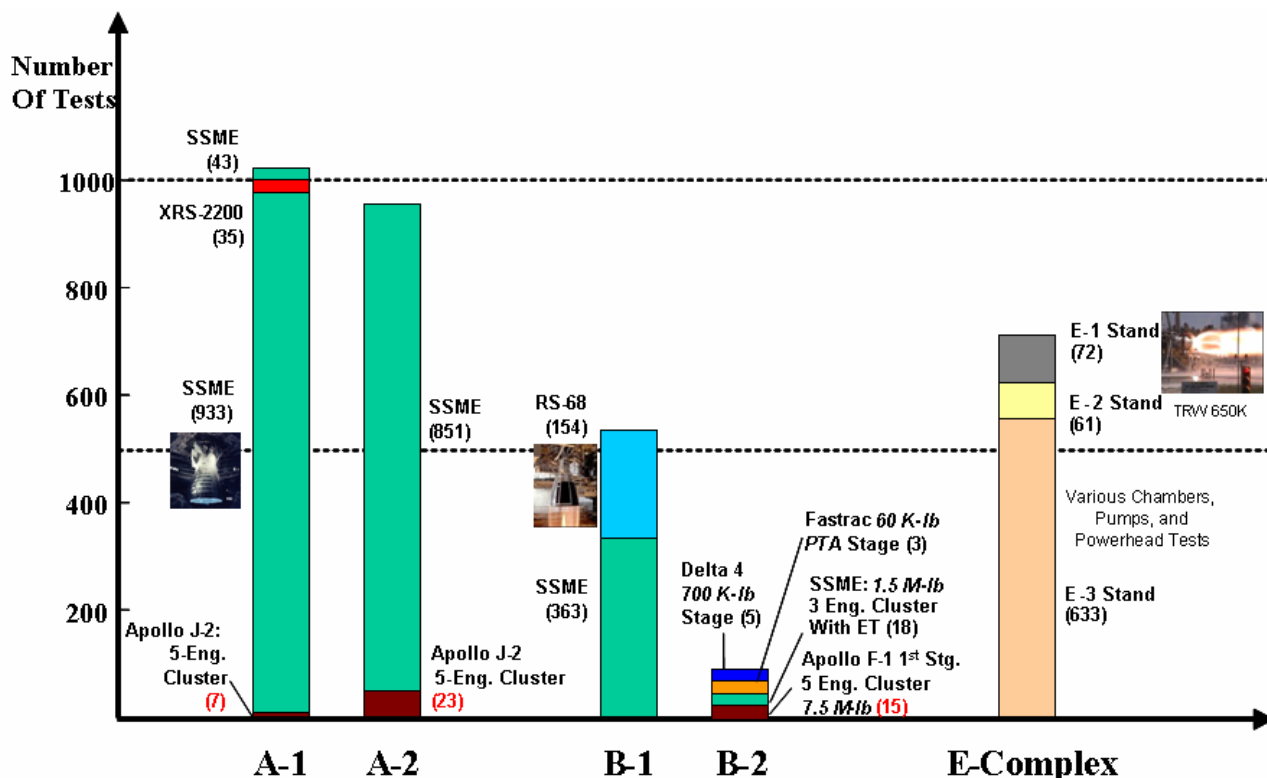
Figure 15. Total number of tests conducted (as of 12-31-04), by stand, at SSC). The numbers of tests for a certain test series is given in parentheses.

More often than not, two test stands were simultaneously dedicated to SSME engine testing. Between 1988 to 1997, this increased to three test stands due to the additional effort required to develop the Block II upgraded engine as well as support the Shuttle flights. Excluding the disruptions caused by the programmatic impacts from the two Shuttle losses of Challenger and Columbia, there has been an SSME test almost every week for decades, although the test rate has varied somewhat owing to differing circumstances. In the early years of the SSME program multiple engines and multiple hardware sets allowed for aggressive test rates with 2 SSC test stands active; tests at other sites (MSFC and Santa Susana) are not counted here. Excluding periods of test stand outage, for refurbishment maintenance and such, a peak rate of testing every 4 days was achieved when 3 test stands were available (A-1, A-2 and B-1). At this rate, as many as 90 SSME engine hotfires were conducted in a given calendar year at SSC. On a per stand basis, a test rate of 10 days between tests is a typical value. While any composite test rate is clearly an oversimplification that does not account for test complexity (routine acceptance tests, as compared to development tests, and more complex tests with altitude simulation diffuser and gimbaling and so forth), it is nevertheless a benchmark from which to set expectations for future test campaigns. Comparable statistics have been examined for the various other test series as well but is beyond the scope of this discussion.

In terms of individual test seconds, it is well understood that the test objectives and test stand capabilities will determine the duration of any individual test. For instance, component level tests may be relatively short ranging from 1 second to approximately 1 minute. Engine level tests are likely to be of longer duration to accumulate time on the test article and/or its components, ranging from 1 minute to as much as 10 minutes given sufficient test stand capability. Stage qualification tests of course will only be possible up to the point of stage tank depletion. In terms of accumulated test seconds for particular engine designs, it is noteworthy that heritage designs have accumulated on the order of hundred thousand seconds (all commissioned test sites combined) prior to first flight for human-rated systems. Per the analysis of Ref. 10-11, notable examples include the F-1 engine at 250,000 s (2805 tests), the J-2 upper stage engine at 120,000 seconds (1730 tests), and the SSME with 110,253 s (726 tests, per Ref. 16), to name a few. The most recent example of a newly developed flight engine, though not human-rated, is the RS-68 engine that was officially certified in record time after only 183 tests total occurring over multiple test sites (Boeing press release date Jan. 2002).
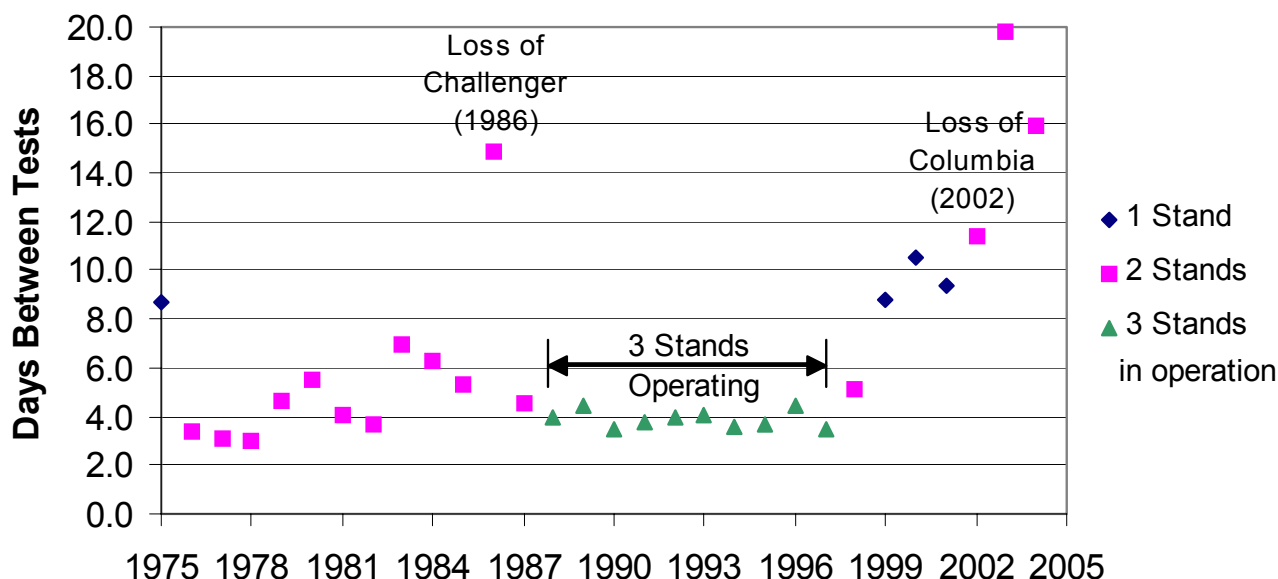
Figure 16. Testing rate for SSME at SSC, by number of stands operating.

Test seconds continue to be accumulated well beyond first flight. In the case of the SSME, there have been more test seconds since first flight than prior to first flight due to the engine upgrades and the many acceptance test firings. As of 2004, over 850000 test seconds may be attributed to ground testing of the SSME with the majority of those having occurred at the heritage A-1 and A-2 stands. In fact, test stands assume just as critical a role after an engine's first flight than before as the particular stand and its data sets become the comparator benchmark for subsequent engine test datasets obtained thereafter.

C. Planning for a Successful Test Campaign

Engine systems development is an infrequent occurrence given the large amount of resources that must be committed and the unique nature of the task. Nevertheless, developers and testers are often planning for advanced engine developments (e.g. Ref. 21-24). Few development teams can rely upon a formula or recipe for delivering a product under programmatic resource constraints and shifting priorities. Regardless, there are considerations in planning that can greatly aid the process, both for the development team and the test provider.

Based upon the discussion and examples in this paper, the following are noted for consideration. First, each and every element of a test campaign should be vetted between the development organization and the test organization(s) to make a considered assessment of its cost/benefit to the overall objective, with an emphasis on arriving at the appropriate mix and quantity of component, engine, and stage level testing. Second, the feasibility (both technical and programmatic) of test capability upgrades and customizations must be discussed at the earliest possible juncture in order to maximize the opportunity for a well-engineered test capability. Finally, the test sites' prior experience base with similar testing scope (or comparable planning) should be leveraged to expedite and facilitate the DDT&E plans. It is not too early to begin these actions, even as part of the bid and proposal activity well before having an official authority to proceed with the development.

Conclusion

In examining the various test projects and test campaigns collectively, and representative parts, both developers and their respective test capability providers should find some important guideposts and lessons that can facilitate future work on new or evolving liquid propulsion systems. For the present purpose, it is less important that a specific development program was successful or cancelled due to programmatic directions. It is essential to correlate the many similarities among them that show the way in terms of ground test based risk reduction as a means to mature a propulsion system for flight. A close partnership between propulsion developer and test provider during the

entire development life cycle is a necessary component of a successful rocket propulsion development and flight program.

Acknowledgments

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