Liquid Engine Test Facilities Assessment

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Abbreviations:

AEC	Advanced Expander Combustor
AEDC	Arnold Engineering Development Center
AFRL	Air Force Research Laboratory
ARRE	Advanced Reusable Rocket Engine
BMDO	Ballistic Missile Defense Organization
CALT	Chinese Academy of Launch Vehicle Technology
CBC	Common Booster Core
DASA	Daimler Chrysler Aerospace
DLR	Deutsche Forshungsanstalt fur Luft and Raumfahrt
DOD	Department of Defense
EELV	Evolved Expendable Launch Vehicle
ELV	Expendable Launch Vehicle
GRC	Glenn Research Center
GSLV	Geosynchronous Satellite Launch Vehicle
ICBM	Intercontinental Ballistic Missile
IDLH	Immediately Dangerous to Life and Health
IHPRPT	Integrated High Payoff Rocket Propulsion Technology
IPD	Integrated Powerhead Development
Isp	Specific Impulse
IHM	Integrated Health Management
LCPE	Low Cost Pintle Engine
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MFSC	Marshall Space Flight Center
MPTA	Main Propulsion Test Article
MMH	Monomethylhydrazine (CH3NHNH2)
MR	Mixture Ratio
NTO	Nitrogen tetroxide (N2O4)
NAWC	Naval Air Weapons Center
NTC	Noshiro Test Center
Pc	Liquid Engine Chamber Pressure
RGHP	Rocket Grade Hydrogen Peroxide
RLV	Reusable Launch Vehicle
RP	Rocket Propellant (standard US kerosene rocket fuel)
RTTC	Redstone Technical Test Center
SLBM	Sea Launched Ballistic Missile
SLREC	Shanxi Liquid Rocket Engine Company
SLV	Space Launch Vehicle
SMV	Space Maneuver Vehicle
SSC	John C. Stennis Space Center
SSME	Space Shuttle Main Engine
TPA	Turbopump Assembly
UTC	United Technology Corporation
UDMH	Unsymmetrical Dimethylhydrazine ((CH3)2NNH2)
USD	Upper Stage Demonstrator
WSTF	White Sands Test Facility

Introduction

Ground testing of liquid propulsion systems before flight operation has always been a critical player in mission success. While the overall goal for testing is program risk reduction, there are a variety of other reasons to conduct costly ground tests, namely

1. To validate design, analysis, manufacturing/ workmanship and modifications integrity.
2. To characterize system and component behavior (transients and steady state) at design point and off-design conditions in order to determine acceptable range limits (i.e., margin) for parameter values.
3. To experimentally determine component and subsystem thermo-chemical heat transfer and structural performance, and compare results with analytical models and design tools for validation and refinement.
4. To determine / demonstrate engine performance repeatability, durability and, if required, restart and turnaround time capability.
5. To demonstrate engine operational readiness and flight acceptance.
6. To reduce risk and increase confidence (reliability) in achieving mission success.
7. To characterize/demonstrate combustion stability and feed system coupled instability behavior.
8. To determine vehicle stage/engine interface compatibility and interaction (influence coefficients) performance.
9. To obtain data on wear rates and servicing requirements, especially for RLV engines, and identify engine areas that would benefit from product improvement either through redesign and/ To demonstrate thrust (throttling) and mixture ratio excursion capabilities and performance.
10. or application of new technologies.
11. To understand component/subsystem performance in an integrated environment and the relationship between control system inputs and key engine parameter responses.

Design requirements for emerging systems into the next decade will become more demanding though funding for new liquid rocket development has become more constrained. Propulsion systems for new vehicles are currently envisioned as highly reliable, re-usable, and/or fully integrated with a health monitoring system. These engines are also expected to exhibit quick post flight turnaround with minimal maintenance. The ensuing demands on domestic rocket engine test facilities to accommodate verification of any or all of these new requirements will require thoughtful planning on the part of facility managers.

Over the years, a variety of test facilities have been established to test liquid rocket engines. Given the high cost of maintaining such facilities, there has been interest in re-examining how best to utilize existing assets. In that regard, the John C. Stennis Space Center (SSC) requested that The Aerospace Corporation examine the current testing capability of all existing large liquid engine test facilities located in the United States. That information, along with projected liquid rocket engine development, was used to provide SSC with a future needs assessment for liquid rocket engine testing in the coming decade. SSC is the primary NASA large liquid rocket engine test facility in the United States. SSC facilities currently support development, checkout and continuous product improvement efforts on a variety of engines, such as the Space Shuttle SSME, the EELV RS-68 and the X-33 Aerospike (XRS-2200), as well as technology demonstration programs for future engine systems.

The requested assessment effort was comprised of two tasks. The first task was to construct projected test needs for liquid rocket propulsion system in the coming decade (2001-2010). As a first step in our test needs examination, liquid engine test facility utilization data was collected for past programs. Previous test program experience was reviewed against drivers such as engine design maturity and operating conditions to determine if trends exist to assist in the forecast of future program needs. The final step for task one was to develop a test needs forecast based on previous as well as anticipated future liquid rocket propulsion test program requirements.

Task two was to examine current and future liquid rocket propulsion test facility utilization and assess future facility requirements. This task began by constructing an overall picture of current government (NASA, DOD) and commercial liquid propulsion test facilities capabilities for sea level and upper stage propulsion systems. A test need roadmap was also assembled based on potential propulsion systems out to 2010. These two data items were used to examine projected US test facility utilization, both planned and projected, for possible support shortfalls or excess capacity.

Executive Summary

The John C. Stennis Space Center (SSC) requested The Aerospace Corporation to examine the current testing capability of all existing large liquid engine test facilities located in the United States. That information along with projected liquid rocket engine development was used to examine future liquid rocket engine testing facilities needs in the coming decade.

Current domestic liquid engine test facilities capabilities, when examined against engine concepts for the coming decade, indicate there are ample facilities offering altitude simulation during test. In addition, it was observed that many contractor facilities have limited ambient test capability of larger thrust engines under current consideration. Finally, it was concluded that diminished contractor participation engine development testing will drive this activity to the government sector. Only three facilities are seen as key contributors to engine testing in the coming decade, namely SSC, MSFC, and AFRL.

Past rocket engine test experience was evaluated as a possible resource for projecting future engine test needs. A database comprised of various engine models and the level of testing performed to flight qualify those systems for their first flight was constructed. For comparison purposes in this study, development and qualification efforts were totaled and treated as one test program. Based on experience with past Air Force programs, the time on the test stand accounts for typically 50% or more of the total program time. Historical data show that the time to design and develop new engines has increased over the last 40 years, most likely due to scarcer resources in today's funding environment.

A projection of future needs based on past successful programs yields a program scope of 15 engines, 400 firings, and 40,000 seconds as a future minimum test program requirement. Historical data suggests that test scope does not appear to be constrained by propellant class. Based on mission success, there also does not appear to be a requirement to change test program scope whether testing a low or high-pressure engine. This study has concluded that emerging propulsion system requirements for high reliability, high operability, low maintenance, and integrated engine health monitoring will significantly impact current resources of domestic liquid engine test facilities.

A desire for 'aircraft type operations' will result in a higher emphasis on full duration testing for engine reliability demonstration and durability verification. Demonstration will require test facilities to adjust their normal operations to mimic the 'hands-off' approach anticipated with the new vehicles. A requirement for low maintenance operations will result in launch site personnel becoming more actively involved with engine designers to refine engine serviceability and operability requirements. These personnel will also be required to assist in transfer of their operability experience to future flight ground crews.

If a reusable engine health monitoring system is desired, there is a need to improve test instrumentation and develop on-site, near real-time data processing to facilitate database construction. Should engine health monitoring be deemed a system priority in the coming decade, initiatives should be undertaken to develop an industry standard on system architecture, qualification, and verification for reusable liquid engines. Opportunity should also be taken, where possible, to obtain common measurements for test and flight data systems.

Stage testing can be used to validate system design and manufacturing. Test facility requirements for stage testing should include the ability to merge full scale vehicle stages and

interfaces with flight data systems, preferably at the earliest possible period of system development.

Component testing is an integral part of engine development. Facility planning for a new program should include the following considerations. Propellant flow rate capabilities and capacities must accommodate full power testing of turbopump assemblies to sufficient duration to fully map performance and verify design capabilities. Preburner testing requires sufficient flow rate and pressure to reach both minimum and full power. Injector testing will require propellant flow rate capabilities, pressure, and flow capacity to accommodate minimum and full power testing with sufficient duration to collect performance data. Injector, preburner, and thrust chamber development will also require bomb testing for instability characterization.

An engine test bed can augment component level testing and reduce risk to the engine development program. Facility systems that have control capabilities similar to flight engines with accurate, repeatable timing and control are highly desirable.

The present cost-constrained atmosphere surrounding new engine development will probably require new programs to employ either multi-position facilities or increased configuration management across several facilities testing the same engine. In order to optimize data interchange, it would be advantageous to establish guidelines for concurrent testing of an engine system at different facilities. Development of standardized interfaces and test skid designs for test facilities would also prove advantageous by providing greater flexibility in relocating test articles to new locations due to unforeseen events or schedule conflicts.

Key test facilities deemed vital to the national interest will require appropriate funding during slack test periods to ensure they remain intact and are properly maintained for future use. Equally important are the retention of skilled personnel to conduct component and system testing. Erosion of such skills can lead to schedule and cost delays during major propulsion system development.

Finally, there is no apparent need to expand the current national capability in peroxide engine system testing until there is a substantial program commitment for such systems.

Test Needs Discussion and Evaluation

Historical Perspective

Past rocket engine test experience can be a valuable resource for projecting future engine test needs. The following contains a summary of engine test programs for many of the liquid oxygen (LOX) kerosene and LOX/hydrogen rocket engines developed for space launch systems. Further detailed information can be found in References 1 and 2. The United States and Russia are the most prevalent developers of LOX/kerosene engines, whereas the United States, Russia, Japan, China, and Europe have developed hydrogen systems. India has also developed some hydrogen engine capabilities but little details are available. Other propellant classes were not studied, as the data for kerosene and hydrogen engine test programs were more readily available. Application to other propellant classes will be discussed later.

Tables 1 through 8 contain a database of various engine models and the level of testing performed to flight qualify the systems for the first flight. Not all historical engine models could be included because of information limitations. Where there was conflicting information in the literature a judgement of the validity of the data source was applied. Because each engine manufacturer uses different terms to describe the phase of the development process, a common definition is provided here. For this report, feasibility testing refers to testing of breadboard engines, previous models, or prototype engines that were used for engineering data gathering for completion of the design process. Development testing refers to testing of hardware that closely resembles the flight hardware to explore the operating capabilities of the system. Qualification refers to testing of flight quality hardware presented as formal evidence of flight readiness. In practice, because of engine complexity, the flight readiness of rocket engines is typically judged based on both the development and qualification efforts. As a result, the development and qualification efforts are totaled and treated as one test program.

Tables 1 through 4 summarize the engine performance parameters for the engine programs considered. Tables 5 through 8 summarize the test program details in addition to the flight success rates for each engine model. The number of firings reported is intended to reflect all test firings including aborts. There may be some inconsistency however, since some manufacturers may count test aborts separately. For program cost and schedule purposes, aborted tests are equally important and should be included, but they may in fact add little value to engine confidence. The period of development was based on the date of program start to the end of qualification. Often the actual time on the test stand was not provided and is a strong function of the number of test stands dedicated to the test effort. Based on experience with past Air Force programs, the time on the test accounts for typically 50% or more of the total program time. In describing the number of engines required for testing, each manufacturer tracks the number of engines differently. Some manufacturers consider rebuilt engines as significant changes in pedigree, while others will change build numbers to reflect a change in test venue alone. An attempt was made to report only new engines in Tables 1-4 to maintain consistency. The use of rebuilt engines is indicated by the "+" symbol to indicate that additional engines were used. The quoted engine life is based on manufacturer quotes. Nominal flight burn times are also listed where available.

The data in Tables 5 through 8 are trended in Figures 1 through 15. The Figures are presented for new as well as evolved engines. Several conclusions can be drawn from the historical engine test trends as well as comparison of past test programs to flight success rates. One must keep in mind however that there is considerable scatter in the data presented and the guidelines provided are for program concept planning purposes only. Actual engine test programs are highly dependent on the level of technology insertion, the evolutionary nature of the engine, the component test program, the reliability goals (including man rating), and the program constraints such as cost and schedule. In addition, the success rate is a function of the design and process reliabilities, the latter of which may not be influenced significantly by the test program. Some of these issues will be discussed later.

Design and Development Period

Figure 1 shows that despite noticeable improvements to processes associated with new engine development, the time to bring a new engine to operational status has increased over the last 40 years, most likely due to scarcer resources in today's funding environment. The early U.S. and Russian development efforts were predicated on essentially unlimited resources in preparation for the moon launch program as well as the Cold War. For example, early RL10 testing was performed on ten engine test stands. RL10 engine development is currently performed on one or two stands. The trends also indicate that about ten years were required for a new booster engine and that about seven years were required for a new upper stage engine. As noted earlier approximately half of this period is estimated as the on-stand test time. Figure 2 shows that evolved engines typically require 2-3 years for design and development but have considerable scatter from 1-5 years.

Test Seconds

Figures 3 and 4 show the historical trend for test seconds for new and evolved engines, respectively. In the last 20 years new booster engines required on average about 90,000 seconds of cumulative test time prior to first flight. The average corresponding time for upper stage engines was 28,000 seconds. There is considerable scatter in the data, as expected. Figures 5 shows the new engine flight success rate as a function of test seconds. It is apparent that lower success rates are associated with engines tested less than roughly 40,000 seconds. The recent historical trend for evolved engines indicates about 15,000 seconds of testing has been performed with a range of 716 to 20,000 seconds. Figure 6 shows the success rate relationship for evolved engines. The high degree of success for some evolved engines with test times lower than 40,000 seconds indicates that the degree of design evolution can significantly impact the test requirements.

Test Firings

Figures 7 and 8 show the historical trend for test firings for new and evolved engines, respectively. New booster engines required on average about 500 total test firings. New upper stage and evolved engines required an average of about 200 and 20 to 150 test firings respectively. When compared to the flight success rates, roughly 400 firings have been required to achieve a high success rate (Figure 9). Evolved engines have required 20-150 firings recently and again the trend with success rates in Figure 10 indicates a high success can be achieved with evolved engines using fewer firings than with new engines.

Test Engines

Figures 11 and 12 show the historical trend for number of new test engines for new and evolved engines, respectively. Rebuilt engines are not counted as part of this total. In the last 20 years most new programs have required fewer than 25 engines with the exception of the Russian RD-0120 and RD-171, which have required 80 engines or more. This is a result of the Russian design philosophy of designing engines to a lower life than other manufacturers. In the U.S., the engines are often designed to a longer life than required to minimize the number of test engines, and hence cost, required for a development program. For this effort the Russian engines will not be considered. The average new booster program required about 16 test engines, while upper stage engine programs required about 10 test engines during development. The flight success rate data in Figure 13 indicates about 15 engines are needed to achieve a higher success rate. The number of engines for evolved programs ranged from 1-11 and, like the other parameters, the success rate dependence in Figure 14 is weak for evolved engines.

Future Test Requirements

A summary of the above discussion is provided in Table 9. For new engine programs that might be used for the Second Generation RLV program, high reliability will certainly be important. As such, the flight success correlations in Table 9 are recommended as guidelines for scoping a concept test program. This yields a program scope of 15 engines, 400 firings, and 40,000 seconds as a minimum test requirement. It is interesting to note that this success-driven program would apply to both upper stage and booster engines. Conversely, historical trends suggest that upper stage engines have received less testing in general. This historical trend is driven by the fact that upper stages programs receive less program resources than booster stages programs. (In fact many cost models allocate cost based on hardware weight, which tends to favor the heavier booster stage.) Reduced testing of upper stages hardly seems warranted in light of the success rate information discussed earlier and in knowledge of the additional issues associated with upper stage operation such as extreme thermal environments and altitude operation.

Test stand requirements for a 400 firing program which last roughly 3-5 years on the test stand would require 2 firings per week. With program realities such as a low test rates initially, test stand down time, failure investigations, and anomaly resolutions, it is unlikely that a test rate of 2/week can be achieved continuously on a single stand for 3-5 years. Experience with past large engine programs indicates that lower test rates (0.5 to 1.5 tests per week per stand) should be planned initially. Therefore, any new engine program will require at least two stands and possibly three with full thrust and flow rate capabilities to meet program schedules. The use of multiple stands also brings forth requirements to standardize interfaces between the test stand and the engine (e.g., purge systems and ground start systems) so that stand-to-stand engine operational differences can be avoided. It should be noted here that it is also important to minimize interface differences from the test stands to the launch site for the same reason. Other multi-stand considerations include validating test stand thrust and flow rate measurements to avoid specific impulse biases. Use of common calibration procedures for flow meters and thrust cells would be beneficial.

To determine if there is a correlation of lower success rate with higher chamber pressure, new engine developments are plotted in Figure 15. The data indicate that there is no significant trend of reduced success rate with higher chamber pressure. This chart also implies that the testing requirements do not need to be modified for low or high pressure engines. Finally, the propellant class does not appear to be a significant factor. Thus, the projected requirements should apply to other propellant classes such as H2O2 and hypergols.

If cost or schedule becomes a significant driver in the test program, then history indicates that the testing will be reduced to meet the resources available, but not necessarily at the same flight success rate. Alternatively, there may a desire to test a 2nd Generation RLV engine similar to the test levels for the SSME, the world's first operational, man-rated, re-usable rocket engine. Table 7 indicates that the SSME was tested for over 700 firings and 110,000 seconds. The final test scope is often a compromise between the cost and schedule and a desire to build confidence in the engine operation once all of the failure modes are corrected. However, for planning purposes, 15 engines, 400 firings, and 40,000 seconds is reasonable based on historical success rates for man-rated and conventional engines. If additional man-rating engine requirements are imposed, additional testing may be required.

Future Facility Considerations

Integrated Health Management

IHM systems are generally seen as an essential element of the next generation of reusable launch vehicles. Such vehicles will be required to be highly operable with very short turn-around times, yet maintain low operational costs while demonstrating unprecedented levels of safety and reliability. As a first order requirement, these vehicle attributes will demand an engine health management system that can provide data streams necessary for efficient between-flight vehicle servicing. A higher order requirement may be that the system be sufficiently proactive during engine operation to sense any potentially hazardous or catastrophic anomalous conditions, diagnose the likelihood of impending engine failure, and initiate appropriate failure mitigation through appropriate system controllers.

Development and safety / reliability improvement verification of an engine health monitoring system will probably require testing and validation over a broad range of non-traditional test conditions. A number of these desired test conditions may involve an unacceptable level of risk for costly large-scale flight hardware, to say nothing of the risk to the test facility itself. Redundant control and more sophisticated redline backup systems will be needed to ensure that no serious harm comes to a facility or costly test hardware during testing at those performance envelope boundaries required to demonstrate an anomaly mitigation capability or engine durability projection. Pretest checkout procedures will also have to be more thorough, reliable, and automated. Software development and validation can be performed in a hardware-in-the-loop simulation laboratory similar to that employed at NASA MSFC in support of the SSME. Some of this testing should be performed on component test stands. The design or upgrade of new large component test facilities should take into account the requirements of validating and qualifying IHM subsystem requirements. In particular, the data requirements for the high frequency transients of those measurements affecting IHM sensors must be considered.

The efficient, economical use of reusable launch vehicles will also depend on precise tailoring of servicing and replacement procedures during turnaround operations. This means that the health management system must provide an accurate prognosis on the remaining useful life of components subject to wear and the best time for replacement and servicing. The development of the databases and trend lines to support these operations will first be developed on both the component and full engine test stands. The data acquisition systems of the test stands must be capable of not only supporting the development and qualification of the propulsion systems, but also their health management and servicing infrastructure. Components like sensors, connectors, distributed microprocessors, etc. also need to be tested in the set of environmental conditions such as vibration, shock, temperature, pressure, and heat transfer that they would be expected to simultaneously encounter in flight.

Data Transfer and Handling

The testing of large rocket engines, particularly during the development phase, can generate huge quantities of data. This is particularly true of high frequency data from vibration and acoustic measurements, which might require sampling rates up to the 100 KHz range. These measurements provide essential data on phenomena such as combustion stability, aeroelastic effects on turbomachinery, and other structural dynamic responses. On a large engine, a test might easily result in a data file of 10-50 Gigabytes.

Large government test facilities are remotely located from current major engine contractor design teams, and timely transmittal of test data files of this magnitude at present would require costly T3 lines. An alternative would be to have the bulk of the preprocessing (spectral analysis, etc.) performed at the test site, with ample back-up storage for the raw data, and with appropriate protection of proprietary data rights.

Integrated Systems Test

Experience has shown that failure drivers during engine flight operation are generally structural (e.g., fatigue, rupture) or functional (e.g., leak) in nature. These malfunctions are not always confined to the engine itself but can be manifested in interfaces with the vehicle, such as in the tank system delivering propellants to the engine, or electronic systems. Many of these failure drivers can be screened through a fully integrated propulsion system test, often referred to as a stage test. The philosophy of 'test as you fly' has gained acceptance as a good engineering practice. Stage testing was utilized on the Saturn launch vehicle and has also been recently used on the Delta IV, Atlas III, Ariane 5, and H-IIA launch vehicles.

The stage test allows better characterization of environments between an engine and its vehicle interfaces. Determining engine operation characteristics under realistic interface conditions is of primary interest to the engine designer. Stage testing provides useful information that can be used to validate system design and manufacturing. The integrated systems test gains increased significance for new reusable, low maintenance engine systems. Test facility requirements should include the ability to interface with flight data systems.

Reliability

A common desire in all new engine development is for high operational reliability. A good definition of reliability was that proposed by Blanchard (Ref. 5) and serves to illustrate the complexity of verifying reliability through an engine test program. Blanchard defines reliability as "the probability that a system or product will perform in a satisfactory manner for a given period of time when used under specified operating conditions." Accepting this definition, one first realizes that reliability is not a readily verifiable quantity since one is dealing with a probability. In today's cost constrained procurement environment, engine test programs are generally limited in scope and schedule. These constraints make it difficult to develop a sufficiently large test database to verify engine reliability with high confidence using conventional statistical models. Novel statistical approaches (Ref. 6) have been proposed in recent years in an attempt to circumvent test program cost limitations. However, allowing design changes or engine rework during the test program generally compromises those methods. In addition, the methods were developed under different engine design practices and operational readiness guidelines (e.g., single use and single start). The reality is that engine reliability must be constantly re-assessed as one acquires ground test and flight data.

The second test consideration associated with reliability is performance validation. This consideration requires engine testing conducted not only at or near but also beyond flight operational tests. An extension in test scope to address certification of additional engine characteristics (re-use, re-start, low maintenance) will require more engine on-stand time plus potentially a higher level of facility risk during the test program.

A third reliability consideration is an expectation of how long an engine will deliver expected performance. This time consideration can be viewed either as operation time or service life. Both considerations represent a durability issue with the later becoming increasingly important to those engine systems advertising significant re-use with minimal maintenance and fast operational turnaround. Durability is also a player in engine health monitoring.

The final consideration associated with reliability involves proper characterization of engine operating conditions. The complexity of emerging engine systems introduced by the use of new designs, materials and manufacturing methods requires a greater reliance on test instrumentation and data retrieval to validate engine performance expectations.

In summary, reliability requirements will impact facilities through engine run duration testing and operation beyond nominal operating conditions and increased data collection.

Operations

As mentioned above, some new vehicles for the next decade are expected to have rapid checkout and servicing capability. Rapid vehicle turnaround will, by necessity, require minimal servicing and inspection of the propulsion system. Demonstration of this design attribute prior to flight operation will require test facilities to adjust their normal operations to emulate the hands-off' approach anticipated with these new vehicles. Launch support crews will require closer involvement with engine designers to optimize servicing operations approaches and tooling. Engine test servicing experience will need to be transferred to field support crews.

In considering unique operations needs for test areas in the coming decade, one must make note of a growing interest in peroxide engines. Hydrogen peroxide for rocket engine testing can be broken into two categories based on concentration. A lower concentration is typically considered to be approximately 70% to 92% hydrogen peroxide. High concentration, often called Rocket Graded Hydrogen Peroxide ("RGHP"), is typically in the 96% to 100% range. Test operations with the two grades of peroxide are similar, with the greatest differences being the increasing sensitivity to contamination and high decomposition temperature with increasing concentration. Safety and handling techniques for peroxide are significantly different than with other storable propellants (e.g. NTO/MMH). Whereas peroxide requires continual venting to atmosphere, hydrazine derivatives and NTO are tightly sealed to prevent toxic vapors from escaping to surrounding areas. Completely closed systems are incorporated for toxic propellants, and unburned propellants must be disposed of through use of complex scrubbing systems. Conversely, decomposed peroxide vapors are benign (hydrogen/oxygen), and liquid peroxide can be diluted with water.

Material compatibility is a critical area of concern for peroxide storage and handling as it can have the most dramatic effect on peroxide decomposition rates. Among the concerns for compatibility are system contamination and surface area to volume ratios which must be minimized even with highly compatible materials.

The push to higher concentration hydrogen peroxide in future engine systems magnifies the need for peroxide engine test facilities to re-evaluate and maintain system cleanliness as well as maximize material compatibility. As the peroxide decomposition rate increases with increasing concentration, it is critical that test facilities also provide sufficient venting and water deluge cooling capability to prevent explosive pressurization.

Component Testing

Component testing is a critical part of an engine development program. Testing of components can provide valuable engineering information for final design of components and for the engine itself. Component testing may also be valuable for IHM data collection as discussed earlier. In addition, testing at the component level provides risk mitigation for costly engine tests if failure modes can be uncovered early. Component test requirements can also require significant facility investments to provide simulated engine environments such as high-pressure propellants and engine transient flow rates. Past test programs have tested turbopumps, injectors, thrust chamber assemblies, gas generators or preburners, igniters, valves, gimbal devices, and actuators. The level of testing for each of these components has varied considerably from program to program and, in addition, is not well documented in the open literature.

The increased use of computer design tools places greater reliance on component testing as a means to anchor the analytical models. This demand for data is expected to increase as engine systems attempt to integrate health monitoring into their design.

As a minimum, a new engine program can be expected to require facilities for turbopump tests, injector tests, and gas generator or preburner tests. Valve actuator testing is often performed at the supplier, and the other components require unique facilities on a case by case basis. The amount of testing is strongly influenced by the level of technology introduced into the part and the operational experience with the engine operating condition. Nonetheless, facility planning for a new program should include the following:

Turbopump requirements: Propellant flow rate capabilities and capacities must accommodate full power testing with sufficient duration to collect pump map data and verify design capabilities. Booster engine flow rates can approach 2000 lbs/sec or higher oxidizer flow. Test duration on the order of the expected flight duration (~200-500 seconds) is desirable but not always required to map performance and to find failure modes. For systems with low and high-pressure pumps, the high-pressure pumps will require 100-500 psig propellant feed systems. Hot gas heaters may be required to simulate turbine drive gases. In addition, precise flow control and throttling capability are required for pump mapping and off nominal margin testing. Facilities must also provide exhaust capabilities, e.g., a flare stack, for the unburned propellants. Unique instrumentation requirements include high frequency accelerometers (10 kHz and higher) and redundant pressure transducers, temperature probes, and flow meters. Proximity probes are also frequently used.

Preburner/Gas Generator requirements: High pressure propellants are required to simulate the burner feed pressures (can be as high as 8,000-10,000 psi). Sufficient flow rate capability to reach both minimum and full power flow rates would be needed for preburners. Run duration is often not a critical parameter other than to collect adequate performance data, unless erosion becomes an issue. Adaptable facilities are useful to permit injector interchange and burner length modifications. A water-cooled chamber may be required for injector testing. Unique instrumentation requirements include high frequency pressure transducers and accelerometers, and temperature rakes. Bomb testing for instability testing must also be accommodated. Optical probes for determining spectral content of the exhaust plume may also be useful.

Injector / Thrust Chamber requirements: Propellant flow rate capabilities and flow capacity must accommodate minimum and full power testing with sufficient duration to collect performance data. Run duration is often not a critical parameter other than to collect adequate performance data, unless injector erosion becomes an issue. Moderate to high propellant pressures are required. A water-cooled chamber may be required. Unique instrumentation requirements include high frequency pressure transducers and accelerometers, thrust measurement capability, and redundant pressure transducers, temperature probes, and flow meters. Bomb testing for instability testing must also be accommodated. Optical probes for determining spectral content of the exhaust plume may also be useful.

Nozzle Extension Testing Requirements: Upper stage and space engines can have nozzles with expansion ratios optimized for near or at vacuum conditions. The cost of ground testing such an engine in a full up configuration is generally very high but nonetheless deemed necessary for engine certification. The new Titan IV Stage II ablative nozzle and the original Titan II Stage II nozzle were qualified in a full size vacuum test cell at AEDC. Recent RL10B-2 engine 285: 1 nozzle qualification was performed at AEDC.

The extended nozzle design and associated qualification test plan can be tailored to reduce the total cost of testing. One option is to conduct some of the tests with a truncated nozzle, which enables use of an existing facility capability, to avoid damaging flow separation effects on the nozzle during test. This testing is supplemented with subscale testing to obtain proper nozzle performance scaling. However, a truncated nozzle test must be carefully designed to ensure the engine interface design can be validated with a proper interface environment simulation. The size of the nozzle truncation should depend on the nozzle structural and thermal design margins.

Test Bed Approach

The use of an engine test bed to test components may become part of future test programs to help reduce engine test costs. A test bed approach permits interchanging and testing of components on a work horse test engine. A work horse engine might be an engine with heavyweight, robust components or facility valves and plumbing but similar characteristics to the final design engine. Feasibility testing, as described in Tables 5 to 8, often employs a test bed approach. This approach has an advantage of proving components out on the test bed for added risk reduction prior to full-up engine testing. In addition component modifications and improvements or competing designs can be tested at the test bed level without putting valuable test engines at risk. In this manner the test bed can augment component level testing and reduce risk to the engine development program. The test bed approach has been used quite successfully in catalyst bed development for peroxide engines. The impact of this approach may place emphasis on facility systems that have control capabilities similar to flight engines with accurate, repeatable timing and control.

Test Facility Utilization

In order to formulate an assessment on the future utilization of liquid engine test facilities, one must first construct a picture of currently existing capabilities. The task was to survey all domestic engine test facilities (NASA, Government, and Commercial). However, several constraints were imposed on the survey due to the limited time available for task completion. The survey looked only at test stands having a thrust stand capability above 1000 lbf. Secondly, the survey looked primarily at liquid rocket engine test stands and exclude detailed review of engine component and subsystem test facilities. Finally, the survey excluded stands that are used to conduct tests on air breathing (i.e., RBCC) or spacecraft propulsion systems.

Survey results, tabulated on an Excel spreadsheet (See Appendix 1), are briefly summarized in the descriptions to follow. Thrust rating can reflect a concrete pad (CP), stand structural (ST), or stand measurement(SM) capability. Unless noted otherwise, quoted thrust rating on stands is assumed to reflect the maximum structural capability. References to stand pressure capability (low, medium, or high) pertain to the propellant delivery system from the run tank. Noted values are presented for comparison purposes and represent tank feed pressure for the oxidizer. More details of delivery capability are noted on the spreadsheet summaries in Appendix 1.

The descriptions to follow are based on the best information we could obtain from facility administrators or their associates. It must be noted that the business of testing rocket engines is a highly dynamic activity where existing assets can undergo changes to meet program needs. Therefore, one should view the information provided below as a starting point to pursue any future discussion with cognizant administrators on specific facility capabilities versus program needs.

Existing NASA Test Capabilities

John C. Stennis Space Center (SSC): Located in southwest Mississippi near the Mississippi-Louisiana border approximately 45 miles from New Orleans, Louisiana, SSC represents the primary NASA liquid rocket engine test facility. SSC has eleven active large liquid rocket test stands [Ref.7].

The A-Complex has two single-position, low pressure (250 psig) stands that can be employed for stage or engine assemblies using LOX/LH2 propellants. Both stands are thrusts rated at 1.1M-lbf and employ a vertical engine firing orientation. A-1 is an ambient test stand while A-2 has altitude simulation capability (512K-lbf @65K-ft) during engine testing. The A-Complex facility has the capability of receiving two LOX and LH2 storage barges at either stand along with providing sufficient pumping capacity for propellant transfer to significantly extended engine test duration.

The B-Complex has single dual position, low pressure (110 psig) stand employing a vertical test article firing orientation with a11M-lbf thrust rating. Both test positions are used for ambient stage or engine assemblies using LOX/LH2 propellants. The B-Complex facility has the capability of receiving three LOX and LH2 storage barges at either stand along with providing sufficient pumping capacity for propellant transfer to facilitate extended duration engine testing.

The E-Complex has three test facilities (E-1, E-2, E-3). This complex can deliver high flow rate (1800 lbm/sec) propellants at high and low pressures to facilitate testing of engine components such as gas generator and preburner driven TPAs. The E-1 facility has three test cells that can accommodate multiple programs at the same time. All cells employ a horizontal test article orientation during operation and contain support facilities to be self-sufficient. Cell 1 is a high pressure (7700 psig) component test stand that is thrust rated at 750K-lbf. The stand has a single axis thrust measurement system rated at 250K-lbf. Cells 2 and 3 are high (7765 psig) and low (295 psig) pressure stands that can be used to test an engine or component. Both stands are thrust rated at 60K-lbf and can handle test articles up to 30,000 lbs. in weight at angles up to 10° horizontal. Cell 3 is designed to test LOX-rich TPAs.

All cells are currently set up to test with LOX /LH2 propellants. Future plans are to add a high (7800 psig) and low (300 psig) pressure, RP-1 test capability to Cells 1 and 2.

The E-2 facility has two ambient test cells used for advanced component and engine testing. Cells 1 and 2 are thrust rated at 100K-lbf and 120 K-lbf respectively. Cell 1 employs a test article position at angles up to 10° horizontal during operation. Cell 1 is a low (150 psig) to high (9300 psig) pressure, LOX/LH2 or RP-1 stand that employs a vertical test article position. Cell 2 is a low (120 psig) pressure, LOX/RP-1 stand that can be used to test complete flight or flight-like stages. Each cell can support test articles up to 30,000 lbs in weight and has a thrust measurement system of 10 to 100 K-lbf.

The E-3 facility has two ambient test cells. A single axis, 10 or 25 K-lbf thrust measurement system can currently be installed in either cell. A 60 K-lbf thrust measurement system is a future facility upgrade. Both cells can be occupied simultaneously but share common support facilities which allows only one cell to test at a time. Propellants can be delivered at low (>1200 psig) to medium (>3500 psig) pressures. Cell 1 is a medium pressure (1500 psig) stand that is thrust rated at 60K-lbf. Cell 1 employs a horizontal test article orientation during operation and has been used to test hybrid propulsion systems. Cell 2 is a medium pressure (3500 psig) stand that is thrust rated at 25K-lbf. Cell 2 employs a vertical test article orientation and can be outfitted with a single axis thrust measurement system on one of the thrust takeout structures. Cell 2 is currently one of the few, if not the only locations to test emerging peroxide engines and associated components.

A new facility, called E-4, designed to static test air-breathing engines, such as Rocket-Based Combined Cycle engines, is currently under construction.

SSC has experience primarily with testing LOX/LH2 or hydrocarbon engines plus extensive expertise with the testing of peroxide and hybrid engines.

Marshal Space Flight Center (MSFC): Located in Huntsville, Alabama, the MSFC currently has four active liquid rocket engine test stands. All stands are ambient test facilities. The Advanced Engine Test Facility (TS-4670) is a low pressure (150 psig), two position, vertical nozzle down stand that can be used for LOX/LH2 or RP-1 engine and stage testing. Positions 1 and 2 have structural thrust ratings of 375 and 900K-lbf respectively. This stand was originally designed to test the Saturn S-1C engine stage cluster. More recently it was used for common core booster tests on the Atlas III launch vehicle. Both stand positions have thrust measurement capability.

The Hybrid & Engine Components Test Facility (TS-500) is a medium pressure (2000 psig), six position (11 & 24" LOX Hybrid, LOX& LH2 Bearing, Simple Turbopump, LOX & LH2 Component), stand. The stand is thrust rated at 40K-lbf and supports only testing with LOX/LH2 propellants.

The Component Test Facility (TS-116) is a high pressure (6000 psig), five-position stand used to test engine components, turbopumps, valves, cryogenic system components, and combustion devices. This facility is supports testing primarily with LOX/LH2 or RP-1 propellants and is designed to supply a large volume and high-pressure liquid and gas for test support. Multiple tests can be run simultaneously. Test article orientation can be either horizontal or vertical. The stand's large scale and subscale thrust rating is 750K-lbf and 60K-lbf respectively.

The Combustion Research Facility (TS-115) is a multipurpose, medium pressure (3000 psig), three position stand capable of testing small or sub-scale engine systems as well as combustion devices and cryogenic tanks. The stand has both cold and hot-fire positions and a thrust rating of 4K-lbf. This facility is supports testing with LOX/LH2 or RP-1, and methane propellants.

MFSC has experience with testing Hybrid, Cryogenic, and LOX/LH2 or hydrocarbon engines.

Glenn Research Center (GRC): Formerly known as Lewis Research Center, GRC is located primarily in Cleveland, Ohio. The facility has three liquid engine test stands. The currently inactive A-Stand (RETF-A) is an ambient test stand that is thrust rated at 50K-lbf. The also inactive B-Stand (RETF B) is thrust rated at 2K-lbf and provides altitude simulation capability (100K-ft) during test. These two, medium to high pressure (1500, 5000 psig) facilities support only testing with LOX/LH2 or RP-1 propellants.

The remaining B-2 stand, located in Plumbrook, Ohio is currently the primary engine test facility at GRC. This vertical stand, which can test engines and stages up to 200K-lbf thrust class, has the largest space environment chamber in the United States for altitude simulation capability (175K-ft) during test. This stand is a low pressure (90 psig) facility that supports testing with LOX/LH2 or storable propellants.

The test center has large engine experience primarily with LOX/LH2 or hydrocarbon systems.

White Sands Test Facility (WSTF): Located in Las Cruces, New Mexico, WSTF has six liquid engine stands operating. Three of those stands (TS-401, 403, and 405) are low pressure (300 psig) stands that employ a vertical test article orientation during operation. These stands are all thrust rated at 25K-lbf and have altitude simulation capability (100K-ft) during test. Stand 401 is configured to support cryogenic engine testing and has the capability to employ a slightly higher tank feed pressure (700 psig). TS-405 will also support testing at moderate pressure (1000 psig) but at reduced test duration.

The remaining three stands (TS-301, 328,and 402) are low pressure (300 psig) stands configured for ambient testing. TS-301 is a vertical nozzle down engine stand that is thrust rated at 25K-lbf. TS-328 and TS-402, which are thrust rated at 25K-lbf and 55K-lbf respectively, use a horizontal test article orientation during operation. There are two other areas that provide liquid engine testing of smaller engines or components. TS-302 is thrust rated at 1K-lbf and has altitude simulation capability. TS-405 is primarily a solid motor test stand but has a capability to test small hypergolic engines in the 1K-lbf thrust class. All of the WSTF stands support testing primarily with storable or hypergolic propellants for limited engine run duration. The exception is stand 401 that supports testing with LOX/LH2 or RP-1.

Existing Department of Defense Test Capabilities

Arnold Engineering Development Center (AEDC): Located in Tullahoma, Tennessee, the AEDC has two cells (TC J-3, TC J-4) for the testing of large, liquid rocket engines. Both cells are single position and employ a vertical engine firing orientation with altitude simulation capability (100K-ft) during an engine test. Test cell TC J-3 has a thrust rating of 200K-lbf and supports testing with LOX/RP-1, hypergolic, or storable propellants. The cell is equipped with LN2 cooled panels to enable temperature environmental simulation prior to test. The cell allows for the testing of high area ratio nozzles and can be configured to test small (1K-lbf) storable engines at low (1000 psig) tank feed pressures.

Test cell TC J-4 is thrust rated at 500K-lbf and supports testing with LOX/LH2, hypergolic, or storable propellants at low pressure (250 & 750psig). It is a comparatively large cell whose height can be extended to 125 feet. This cell has also been used to test solid motors and has a 1500K-lbf axial thrust measurement capability. The cell also has a temperature conditioning capability prior to test. This cell will be upgraded with larger propellant run tanks to facilitate extended run times during an engine test.

Air Force Research Laboratory (AFRL): Six large liquid engine test stands are located at Edwards, California. All liquid stands are currently inactive. Area 1-42 has one stand (Pad-B) which is thrust rated at 50K-lbf and employs a vertical engine firing orientation. The medium pressure (2400 psig) cell has altitude simulation capability during test and been used to test both liquid and solid propulsion systems.

Area 120 has three ambient stands (1A, 1B, 2A) that are all thrust rated at 1600K-lbf and support testing with LOX/LH2 or RP-1 propellants. Stands 1A and 1B are low pressure (165 psig) facilities and employ vertical engine firing orientation. Stand 2A is a high pressure (8000 psig) component test facility that employs a horizontal test article orientation during operation. Stand 1A was recently used to support EELV engine development. Pads 1B and 2A have been mothballed for some time. Pad 2A will be refurbished to support large liquid engine component development.

Area 1-125 has two low pressure (165 psig) test stands (1D and 1E) that are thrust rated at 1600K-lbf and employ a vertical engine firing orientation. Current plans are to refurbish the 1D stand to provide a LOX/Hydrocarbon capability to support new engine development initiatives for Reusable Launch Vehicle concepts under current consideration. Test stand 1E is in near identical condition as its 1D counterpart and is available to provide additional RP-1 engine test capability.

There are other liquid engine stands at AFRL but most have been inactive for some time and would take considerable time and money investment to re-activate.

Redstone Technical Test Center (RTTC): Located at Redstone Arsenal, Alabama the Redstone Technical Test Center is one of six centers in the U.S. Army's Test and Evaluation Command. Within RTTC, the Static Test Branch maintains one area (TA-5) for testing of liquid, solid, and hybrid motors. Liquid engine testing is conducted on twin ambient stands, TS-B1 or B2. These low pressure (100 psig) stands, each thrust rated at 500K-lbf, employ a vertical engine firing orientation and support testing only with hypergolic and storable propellants.

Naval Air Weapon Center – China Lake (NAWC): Located at China Lake, California the Naval Air Weapon Center maintains essentially two areas (Bay 4, T-Range) for the testing of liquid rocket motors. Bay 4 is a low pressure (100 psig) ambient test facility that is thrust rated at 100K-lbf. It has been used extensively for the testing of storable and hybrid engines. The T-Range has two low pressure (1000 psig) ambient test cells, thrust rated at 100K-lbf. NAWC test experience is primarily with storable and hybrid liquid engines. They have considerable expertise in solid motor testing. Recent activity at NAWC has included some consideration on enabling peroxide engine test capability development.

Existing Commercial Test Capabilities

Gencorp Aerojet: Located in Rancho Cordova, California, Aerojet maintains four areas for testing liquid rocket motors. The A-Zone area has four liquid engine stands (TS A-5, -6, -7, -8), all of which employ a horizontal test article orientation during operation. The A-5, A-6, and A-7 stands are used for ambient propulsion system testing. The three stands are all thrust rated at 10K-lbf. TS A-5 is a medium pressure (1200 psig) stand. The dimensionally smaller TS A-6 and -7 stands are high pressure (5500 psig) facilities used primarily for turbomachinery testing. The fourth stand, TS A-8, is a high pressure (5500 psig) facility that is thrust rated at 20K-lbf with altitude simulation (30K-ft) capability during test.

The E-Zone area has three liquid engine stands (TS E-4, -5, -6). The E–4 stand, which allows ambient testing in either a horizontal or vertical position, is a medium pressure (3100 psig) facility that is thrust rated at 240K-lbf. The E-5 stand is a low pressure (185 psig) facility that employs a vertical engine firing orientation and is thrust rated at 700K-lbf. This stand also has altitude simulation (150K-ft) capability during test. The TS E-6 stand is an ambient, high pressure (5600 psig) facility that employs a horizontal test article orientation during operation. TS E-6 is thrust rated at 200K-lbf.

The G-Zone area has seven stands, three of which are inactive. TS G-1, -2, -3, -8 are restricted to ambient testing of engine systems using storable propellants. In addition, all four stands have propellant temperature conditioning capability prior to test operation. Stands TS G-1 and TS G-2 are both thrust rated at 500K-lbf. TS G-1 is a dual position stand while stands TS G-2 and TS G-3 employ only vertical engine firing orientation. TS G-2 is a low pressure (179 psig) stand. TS G-3 is a low pressure (89 psig) stand with a thrust rating of 105K-lbf. All three stands, which are co-located next to one another, are currently dedicated to Titan launch program support. These stands are to be removed at the conclusion of the Titan program. TS G-8 is a low pressure (710 psig) stand that is thrust rated at 10K-lbf and employs a horizontal test article orientation during operation. The stand currently supports testing of the second stage Delta II engine (AJ-118).

The J-Zone area has ten stands for testing liquid engines. This area has two independently operating control rooms linked to a central data storage facility. TS J-4 and J-5 have altitude simulation capability (150K-ft) during test operation while the other stands are ambient test facilities. All stands in this area, with the exception of TS J-2A, employ a horizontal test article orientation during operation. TS J-2A employs a vertical engine firing orientation. TS J-1 is a medium pressure stand (1440 psig) that is thrust rated at 50K-lbf. This stand is used primarily to fire storable liquid propellant engines and has temperature simulation capability prior to test operation. The high pressure (7000 psig) TS J-1A stand is thrust rated at 100K-lbf. This stand is used for research testing on cryogenic engines and associated components. TS J-2 is a high pressure (6000 psig) stand that is thrust rated at 20 K-lbf. This stand is used to test storable engines. This facility has a LN2-jacketed, 600 gallon cryogenic vessel that was used in the past for liquefied fluorine service. The low pressure (250 psig) TS J-2A stand is thrust rated at 20K-lbf and can be used to test battleship missile configurations or upper stages. The stand is limited to testing with storable propellants and has temperature-conditioning capability prior to test operation. Larger run tanks enables longer test duration. TS J-4 is a moderate pressure (812 psig) stand that is thrust rated at 20K-lbf and has temperature simulation capability prior to test operation. This stand is used primarily to fire storable liquid propellant engines. TS J-5 is a high pressure(6000 psig) stand that is thrust rated at 200K-lbf and used primarily to fire storable liquid propellant engines. TS J-5 has been upgraded to test peroxide engines. Test stands TS J-11 and J-12 are thrust rated at 10K-lbf while J-13 and J-14 are thrust rated at 1K-lbf. These medium pressure (1230 psig) stands are co-located in one long bay and share a common control room. TS J-11 was built to characterize the performance of pressure-fed thrust chamber assemblies. TS J-12 was used to develop storable propellant turbopumps. TS J-13, J-14 were constructed to support research in small storable, cryogenic engines.

Boeing Rocketdyne: Located in Santa Susana, California, Rocketdyne maintains over twenty test stands to assist in the development of their liquid rocket engines and associated components. Ten of these stands meet the criteria of this review. The Alfa area has two low pressure (80 psig) stands (Alfa –1, -3). Both are ambient facilities that employ a vertical test article orientation during test operation. Thrust ratings for these LOX/RP stands are 440K-lbf and 220K-lbf respectively. Alfa-1 is used to test the Atlas MA-5A engines while Alfa-2 is used to test the Delta II RS-27 engine.

The STL-IV area has four stands of interest to this study. These stands were used in support of Peacekeeper fourth stage engine and associated component development. Stands 29A and 29B are low pressure (660 psig) facilities that employ a horizontal test article test orientation during operation with altitude simulation (80K-ft) capability during test. The stands are thrust rated at 3 to 12K-lbf. The stands are limited to testing with storable propellant engine systems and have temperature conditioning capability prior to test operation. Stands 24A and 24B are thrust rated at 3K-lbf and limited to ambient testing of engines using storable propellants. These medium pressure (1440 psig) stands employ a vertical test article orientation during test operation and have temperature-conditioning capability prior to test operation. The 24B stand was used primarily for testing engine injectors and chambers.

Five stands in the Coca area are used to support SSME testing. The low pressure (110 psig) A-3 stand employs a vertical test article orientation during test operation and has temperature-conditioning capability prior to test operation. The LOX/LH2 only stand is thrust rated at 600 K-lbf and is used to for ambient testing of the SSME. Maximum test duration is 300 seconds. Stands 1A and 1B are high pressure (8500 psig) facilities used for ambient testing the SSME Turbopump and Preburners. Stands 4A and 4B are also high pressure (8500 psig) facilities used to test the SSME thrust chamber and powerhead. The CTL and ATPF areas stands are used solely for component testing.

Pratt & Whitney (P&W): Located in West Palm Beach, Florida, United Technologies/ Pratt & Whitney Division maintains two stands (TS E-6, TS E-8) for the testing of liquid rocket engines. These facilities support only LOX/LH2 propellants.

The Altitude Rocket Engine Test Stand (TS E-6) is a single position, low pressure (150 psig) test stand that is thrust rated at 30K-lbf (156 K-lbf structural) and employs a vertical engine firing orientation. The stand has altitude simulation capability (70K-ft) and is used solely for the development and acceptance testing of the RL10 upper stage engine.

The High Pressure Cryogenic and Rocket Engine Test Stand (TS E-8) is a dual position, ambient test stand. Position A is a component test stand that has been used to test high pressure, cryogenic turbopumps and SSME-ATD preburners. Position A is structurally rated for 500 K-lbf of thrust. Position B is used for engine testing and is thrust rated at 80K-lbf. Position B employs a horizontal test article orientation during operation and has thrust measurement capability to 35 K-lbf. TS E-8 can operate at high (8500 psig) and low (550 psig) pressure for an engine test. A two-stage steam injector is used on Position B to pull a vacuum on the test engine during engine start. The TS E-8 stands will continue to be used support testing of SSME turbopumps, the IHPRPT Upper Stage Demonstration engine, and most likely RL60 development.

TRW: Four liquid engine test facilities are maintained at the Vertical Engine Test Site (VETS) located in San Clemente, California. All of these low pressure (750 psig) stands employ a vertical engine test orientation and have limited engine test duration capability based on present run tanks (<750 gal). Stands A1 and A2 are thrust rated at 10.5K-lbf and have altitude simulation capability of 50 K-ft during test. Stands B1 and B2 are thrust rated at 50K-lbf and used for ambient engine testing. The PITS facility is operationally similar to the B1 and B2 stands. The High Altitude Test Site (HATS) is thrust rated at 10.5K-lbf and has altitude simulation capability of 100 K-ft during test.

Atlantic Research Corporation (ARC): Located in Niagara Falls, New York this company has one, low pressure (40 psig), ambient stand (D-3) for testing liquid rocket engines above 1K-lbf of thrust. The D-3 stand is thrust rated at 3K-lbf and can employ either a horizontal or vertical test article orientation during operation. The stand only supports testing of small, hypergolic or storable engine systems.

Rocket Propulsion System Test Facility (ERTC): This facility is located in Sorrocco, New Mexico. It is a relatively new facility with limited test capability and experience. Its prime customers have been Microcosm, who is developing the Scorpius launch vehicle; and Truax, who is developing the Excalibur family of launch vehicles. ERTC has two stands that support limited engine duration tests based on present run tanks (<500 gal). One stand is thrust rated at 8K-lbf while the second stand is thrust rated at 80K-lbf. Both low pressure (850 psig) stands are used for ambient engine tests, employ a horizontal test article orientation during operation, and at present only support testing of LOX/Hydrocarbon propellant systems. Expansion to accommodate peroxide engine testing may be undertaken in the future.

Future Liquid Engine Propulsion Systems

Table 10 presents a brief description of potential or emerging propulsion systems for the coming decade. Some systems are still anticipating funding for new or continuing development. Our examination has tried to include all engine systems that would require test facility support. In addition, the descriptions that follow rely heavily on contractor intent or expectation.

LOX / RP-1 Engines (2001-2010)

Table I provides our overview of propulsion systems using LOX / RP-1. The Delta II first stage RS-27A, currently in production, and the Atlas II MA-5 booster and sustainer engines which have completed production will require sustained test support for engine flight certification until replaced by new launch vehicle systems.

Low Cost Pintle Engine (LCPE): The LCPE is being developed by TRW. The engine is designed to be simple, easy-to-manufacture, and low-cost by using parts made from common steel alloys and standard industrial fabrication techniques. The engine utilizes ablative cooling instead of more expensive regenerative cooling, and features a single element coaxial pintle injector to introduce propellants into the combustion chamber. TRW has used this pintle injector design in nearly all of its bi-propellant liquid rocket engines. A 650K-lbf LOX/LH2 version of the LCPE was tested at the SSC. The proposed extension would be a 1M-lbf LOX/RP-1 derivative of that engine in support of second generation, reusable launch vehicles. Other potential applications are an engine to power an expendable liquid strap-on booster or a re-useable liquid fly-back booster.

AJAX: The AJAX engine uses an oxygen-rich, single preburner, staged, combustion cycle. The engine is being developed at the concept level as a joint venture between Pratt Whitney and Aerojet in support of second generation, reusable launch vehicles. AJAX utilizes a simple, lightweight, single shaft turbopump configuration. The 1000K-lbf-class engine is designed to be a low maintenance and incorporates a throttling system. The engine is designed for low turnaround time between flights and has a projected time between overhaul estimated to exceed thirty missions. AJAX will incorporate integrated controls and a health management system to enhance its safety and maintainability.

RD-180: The RD-180 engine was selected by Lockheed Martin Aerospace to power the first stage of their Atlas III and Atlas V series of ELV's. The engine is a two thrust chamber derivative of the RD-170 engine that currently is employed as first stage propulsion for the Russian Zenit launch vehicle. The oxygen-rich, staged combustion RD-180 was developed and is currently being tested by NPO Energomash. This 933 K-lbf class engine is being marketed in the US under a joint partnership agreement with Pratt & Whitney (UTC). Under current US Air Force EELV contract guidelines, Pratt & Whitney is required to co- produce RD-180 engines in support of all government Atlas V launches. At present, this requirement is under further review. Atlas III Common Core Booster testing was conducted at the MSFC 4670 test stand in 1998. This facility, which is currently inactive, would be a strong possibility to support new engine testing should RD-180 engine co-production become a reality. At present, a decision on co-production has been delayed until 2008.

NK-33/-43: Built by ND Kuznetsov Joint Stock Company Scientific-Technical Complex of Samara Russia, the NK-33 and NK-43 engines are upgraded versions of the NK-15 and NK-15B engines which were intended to be used on the Russian N-1 launcher. The oxygen rich, staged combustion NK-33 and NK-43 engines are designed to provide improved thrust, reliability, and a restart capability. The engines, which are being marketed commercially by GenCorp Aerojet of Sacramento, CA., are still the highest performing LOX / RP (kerosene) rocket engines ever produced. They have a rated vacuum thrust of 379K-lbf and 395K-lbf respectively. Kistler Aerospace intends to use the NK-33 and NK-43 engines for their K-1 launch vehicle. Aerojet has also been in discussions with NASDA regarding using the NK-33 engine as the first stage of the NASDA upgraded J-class ELV. Kelly Space and Technology of San Bernardino, CA has also indicated interest in the NK-33 engines for the first stage of their Astroliner RLV. A slightly modified Russian NK-33 was tested at the Aerojet E-4 test stand. Discussions are underway to potentially transfer further testing of the Aerojet modified versions of these engines to AFRL Area 120, Test Stand 1D.

IHPRPT HC Boost Demo: The IHPRPT (Integrated High Payoff Rocket Propulsion Technology) 250 K-lbf thrust class Hydrocarbon Boost Demonstrator is expected to be a high performance hydrocarbon/LOX rocket engine utilizing the oxidizer-rich staged combustion cycle. The IHPRPT goal is to develop a rocket engine with a trajectory averaged thrust-to-weight (T/W) exceeding 154 and a trajectory averaged Isp greater than 332 seconds. Selected materials and processes are to be sufficiently mature to meet a 2005 demonstration date.

TRUAX MA-3: The MA-3 engine is a pressure-fed, de-rated Atlas LR-89 engine. This engine operates at thrust levels between 37.5 and 100 K-lbf. The engine will be employed to provide first stage power to the Excalibur launch vehicle currently marketed by TRUAX Engineering. The Excalibur will be used as a suborbital, liquid fueled, reusable ballistic missile target vehicle. Current plans are to conduct engine testing at the SSC E2 area, cell 2 starting in late March 2002.

LOX / LH2 Engines (2001-2010)

Table 10 provides our projection of emerging propulsion systems using LOX / LH2 in the next decade. The Shuttle SSME will require sustained test support for anticipated upgrades and engine flight certification. The RL10A-4-1 will also require continued flight certification testing during its continued production over the coming decade. New concepts are as follows.

COBRA: The COBRA engine uses a fuel-rich, single pre-burner, staged, combustion cycle. The engine is being developed as a joint venture between Pratt Whitney and Aerojet in support of second generation, reusable launch vehicles. COBRA will utilize flight-certified SSME Block II turbopumps and a double containment, fail safe powerhead, hot gas system. The 500-800 K-lbf thrust class engine is designed to be a low maintenance system. COBRA is advertised to exhibit low turnaround time between flights and have a projected time between overhaul estimated to exceed fifty missions. The engine will also incorporate integrated controls and a health management system to enhance its safety and maintainability.

Cobra preburner tests will be conducted at the SSC E-Complex, Cell E-1 starting in late 2002. Subscale main injector tests will be conducted at MFSC TS-116 starting in mid-2002. Hot-fire engine testing is anticipated beginning in 2004. Engine test location has not been determined.

RS-83: Boeing's Rocketdyne Division will develop The RS-83 engine. The engine is being designed as a main propulsion article for a two stage, reusable shuttle replacement vehicle. Nicknamed ''Mongoose', this engine is a competitor to the aforementioned COBRA engine. The RS-83 is envisioned as employing a fuel-rich, staged combustion cycle which will draw heavily from current SSME and RS-68 heritage.

RLX: The RLX engine employs an inherently self-limiting, split expander cycle. The engine is being developed currently at the concept level as a joint venture between Pratt Whitney and Aerojet in support of second generation, reusable launch vehicles. RLX is designed for a multiple start capability. The powerhead valve arrangement enables automated pre- and post-flight leak checks. The 100-300 K-lbf thrust class engine is designed to be low maintenance and exhibit low turnaround time between flights. The projected time between overhaul is expected to exceed fifty missions. The engine will also incorporate integrated controls and a health management system to enhance its safety and maintainability. Component and engine test locations have not been determined.

XRS-2200: The XRS-2200 Aerospike engine was designed to propel the Lockheed Martin Skunk Works X-33 Technology Demonstrator. An upgraded RS-2200 was selected to power

VentureStar, Lockheed Martin's next generation RLV. Both engines use a gas generator cycle. The XRS-2200 is a 266K-lbf thrust class engine.

The linear aerospike engine employs a common turbo-pump and a bank of liquid oxygen / hydrogen thrusters aligned along the top edge the thrust ramp. The ramp acts as one half of the rocket nozzle. Ambient atmosphere acts as the other. As the launch vehicle ascends during its trajectory, decreasing air density allows the effective nozzle area ratio of the aerospike engine to increase. The end result of this altitude-compensating nozzle is very high engine performance along the entire vehicle trajectory. This engine has completed testing at the SSC A-1 facility. At present, the X-33 program has no sponsor. This engine requires this test stand should further testing be desired. However, this stand is scheduled to support SSME Block III testing in December 2001 following XRX-2200 dismount. The SSC A-2 stand that normally supports SSME testing will be down until December 2002 for refurbishment.

IHPRPT Phase I Upper Stage Demonstrator: The Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program is developing an upper stage engine demonstrator (USD) to demonstrate LOX/LH2 technologies that meet IHPRPT Phase I upper stage goals for performance, operability, cost and reliability. Pratt & Whitney is the Phase I USD contractor for this 50 K-lbf thrust demonstrator. The IHPRPT funded hardware includes the Advanced Liquid Hydrogen (ALH) pump with hydrostatic bearings and radial inflow turbine and the Advanced Expander Combustor (AEC) with high conductivity copper alloy tubular chamber with a structural jacket. Pratt & Whitney is providing the Advanced Liquid Oxygen pump, the AEC injector and the electronic engine controller for the electromechanical valves. Testing of the hardware is taking place at Pratt & Whitney. Follow-on demonstrators have not been determined at this point.

IHPRPT Phase I Cryoboost Demonstrator: The Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program is developing a LOX/LH2 booster engine demonstrator to demonstrate IHPRPT Phase I booster engine goals for LOX/LH2 engines. The 250 K-lbf thrust Integrated Powerhead Demonstrator (IPD) is a full-flow staged combustion engine in which an oxygen rich preburner drives the oxygen turbopump and a fuel rich preburner drives the fuel turbopump. Hydrostatic bearings and oxygen rich technologies are part of the demonstrator to meet Phase I goals for performance, operability, cost and reliability. Testing of the hardware is planned for SSC in 2001 and 2002.

MB-60: Boeing Rocketdyne and Mitsubishi Heavy Industries, Ltd. have teamed to develop a new family of cryogenic upper stage engines designated as MB-XX. The commercially planned MB-60 is designed to provide high-performance, affordable, low-risk upper stage propulsion. The 60K-lbf thrust class expander cycle engine is the first member of the MB-XX family and is targeted for use on an advanced Boeing Delta IV launch vehicle. The engine will be available to support flight operations in 2005. Component (turbopumps, fuel boost pump) testing for the MB-60 will be conducted at the SSC E-Complex, Cell 2 starting in 2003. The engine will be tested at GRC, SPF B-2 starting in late 2002.

<u>RL-60:</u> The RL-60 engine is intended for a cryogenic upper stage. The engine is currently under development by Pratt & Whitney of West Palm Beach, Florida. Projections are that this advanced engine will be available in 2005 for several different launch vehicles. The 50 to 65 K-lbf thrust class RL-60 employs an expander cycle and is approximately the same size as the RL-10, allowing for direct substitution with minimal vehicle modifications.

<u>RL10B-2:</u> The upgraded, cryogenic Pratt & Whitney RL10B-2 engine is based on the reliable RL10 engine. The RL10B-2 engine is being developed for the Delta II and Delta IV launch vehicles. The engine employs an extendable exit cone for increased performance. The basic engine and turbo pump are unchanged relative to the RL10 family of engines. However, the RL10B-2 engine gimbal system will use electromechanical actuators to increase engine reliability while reducing engine cost and weight. The 25K-lbf thrust class engine can accommodate more than one restart. Engine tests with the extended nozzle will be conducted at AEDC during 2001 for Delta IV certification. Production engine acceptance tests without the nozzle extension are conducted on the Pratt & Whitney E-8 stand.

<u>RS-68:</u> The 650 K-lbf thrust class RS-68 engine employs a gas generator cycle. This Boeing Rocketdyne engine was developed to provide main stage propulsion for the Delta IV ELV. The engine has been designed to be simple and inexpensive to build. The RS-68 utilizes a simple design approach to drastically reduce the total part count when compared to engines of equivalent size or performance.

Development testing has been conducted at both SSC and AFRL. The AFRL testing, was conducted at Area 120 Pad 1A. That testing has concluded. RS-68 engine verification testing is still proceeding at the SSC B-Complex. That complex will most likely be used for production engine acceptance tests as well.

Peroxide Engines (2001-2010)

Table 10 provides our overview of propulsion systems using Peroxide/ RP-1. Several engines represent old designs but with improved injector efficiency and oxidizer catalyst bed performance.

<u>Advanced Reusable Rocket Engine (AREE):</u> Aerojet will develop an Advanced Reusable Rocket Engine that utilizes non-toxic, hydrogen peroxide as a propellant. The engine is being designed as a reusable, non-toxic, upper stage engine for SMV technology demonstration. The expected 12 K-lbf thrust class engine will use a closed cycle to provide high performance and throttle capability. The ARRE employs a lightweight composite nozzle extension and will use advanced injection concepts, fabrication processes and chamber materials. The ARRE program is expected to start in May 2001 and run through April 2005. Hot fire engine demonstration is anticipated to take place in approximately four years. Development testing of the ARRE and all its components will most likely be initially conducted at Aerojet's Sacramento facility. At present, there are no plans to incorporate this engine into a vehicle.

__AR2-3A:__ The AR2-3A engine is derived from the AR2-3 engine developed by Rocketdyne in the early 1960s. The original AR2-3 was installed on an F-104 fighter aircraft in order to conduct high altitude demonstration flights as a part of the NASA space program. As a slightly upgraded version of that engine, the AR2-3A was selected to power the Boeing X-37 demonstration vehicle. With several recently proposed further upgrades, the engine is expected to achieve an 8K-lbf thrust class rating. The 6.6 K-lbf version of that engine has been tested with JP8 fuel and 90% H2O2. New catalyst bed development supports movement to 98% H2O2 to meet SMV requirements. The AR2-3A was tested at the SSC E-Complex, Cell 3. Though the X-37 program is currently without a sponsor, any further engine testing would most likely be at the SSC E-Complex, Cell 3.

__RS-82:__ The Boeing Rocketdyne RS-82 engine represents a, non-toxic upper stage engine for SMV. The 12 K-lbf thrust class, throttleable engine employs a pump-fed, gas generator cycle. This engine, designed for long life, uses 98% H2O2 and RP-1. Boeing has planned a variety of component tests (catalyst bed, injector) at the SSC E-Complex, Cell 3 in support of this engine's development. It would be anticipated that any engine tests would be conducted at the SSC E-Complex, Cell E-3 as well. This engine was a competitor to the ARRE and as yet has no outside sponsor for further development though component testing is expected to continue.

__LR40:__ The LR40 is a closed cycle engine developed by General Kinetics in the late 1950s as a USN aircraft assist rocket. The engine was designed to be man-rated, throttleable, and restartable in any orientation. Though the engine has been fully qualified, it is currently out of production. With incorporation of proposed upgrades, the engine is expected to fall in the 15 K-lbf thrust class. This engine, which presently has no development sponsor, is a potentially competitor to the ARRE and RS-82.

Other Engines (2001-2010)

BMDO Target: Aerojet was awarded a $350,000 subcontract from Orbital Sciences Corporation to develop a new liquid propulsion engine for Ballistic Missile Defense Organization target vehicles. The engine is part of a high-fidelity, cost-effective booster stage for BMDO that Orbital is developing under contract with the U.S. Army Space and Missile Defense Command. The target vehicle is expected to be operational by the middle of the decade.

Shuttle Main Engine Upgrade: Aerojet has won an eight-month, $5 million contract from NASA to study development of a channel wall nozzle to replace the current tube nozzle used in the Space Shuttle Main Engine (SSME).

The current SSME nozzle is constructed by brazing together more than 1,000 specially shaped tube. During engine operation, hydrogen flows through the inside of these tubes to cool the nozzle and gasify hydrogen. The proposed channel wall nozzle will have less components and incorporate cooling slots milled directly into the nozzle structure to act as individual hydrogen coolant channels when an outer jacket is attached. The channel wall nozzle offers a significant increase in SSME nozzle reliability and faster, more consistent production at lower cost than the current tube nozzle. NASA's requirements are that the channel wall nozzle must be capable of 55 flights, 27,000 seconds of operation and one abort flight.

Aerojet is competing with Rocketdyne for possible selection to design and fabricate nozzles for the next SSME upgrade. Other potential upgrades include a new larger throat combustion chamber to reduce system operating pressures and temperatures, and an Advanced Health Management System to enhance anomaly detection and mitigation during engine operation.

RS-72: The 12.45 K-lbf thrust class RS-72 engine employs a pump-fed, gas generator cycle. This Boeing Rocketdyne engine was developed as a joint venture with Daimler Chrysler Aerospace to provide upper stage propulsion for American and European launch vehicles. The engine is a derivative of the DASA Aestus now flying on the Ariane V launch vehicle. The RS-72 exhibits increased performance through an integrated powerpack evolved from the Boeing Rocketdyne XR-132 engine. The RS-72 does not have a program commitment as of this date so future test requirements are uncertain.

RS-76 The 900 K-lbf thrust class LOX / Kerosene RS-76 engine employs a pump-fed, oxygen-rich, staged combustion cycle. This Boeing Rocketdyne engine was developed as a man-rated, reuseable design to support the Liquid Flyback Booster development for the Space Shuttle. A design goal of this engine was to improve reliability and reduce cost through a reduction in total part count. The RS-76 does not have a program commitment as of this date so future test requirements are uncertain.

Nontraditional Systems There are several nontraditional propulsion system concepts that may need testing in the future. They include tri-propellant engines, gelled propellants, endothermic fuels, multiphase propellants, slush cryogens, and hybrid motors. Each of these has some unique handling and testing requirements, most of which can be accommodated if proper facility planning is done ahead of time (e.g.: allowing space on a cryogenic engine test stand for the future addition of a hydrocarbon propellant supply system to test tri-propellant engines). Developing a solid generic understanding of the combustion and combustion stability processes characteristic of these new propulsion systems also calls for innovation in new robust sensor technologies.

Evaluation of Facility Utilization

Current domestic liquid engine test facilities capabilities (Appendix 1) were examined against engine concepts presented in Table 10. Note that some of the engines shown in Table 10, though reflecting a stated intent of a contractor, have yet to secure a program commitment or funding for full development. If some of these concepts are discarded, there could be less demand for engine test facilities. In addition, the evaluation to follow does not reflect demand on existing test facilities from current or future engine acceptance programs. Also, the facilities comments to follow do not consider utilization from advanced component testing. Finally, an assumption was made that a designated an intent to test an engine at a certain location will proceed as planned. If we exclude consideration of engines that have set a test location, the following observations can be made with regard to engine programs that have no set test location:

First, there appears to be sufficient capacity between NASA and DOD test facilities to meet all needs in the coming decade assuming currently planned facility activation and upgrades are funded. There appears to be a low demand in the coming decade for engine testing with altitude simulation. For those engines that require altitude testing, the existing NASA and DOD facilities will more than meet the anticipated need. Contractor altitude simulation facilities are of limited utility based on commitments to other program or run time limitations if extended duration engine testing becomes a test requirement.

Several engine components in the coming decade will require a facility capability for testing under high tank feed pressure. Again, there are multiple domestic facilities to meet this need. However, only the NASA (SSC, MSFC) and AFRL facilities appear to have the additional capability to offer extended run duration to those engine systems if it becomes a test requirement. As mentioned earlier, AFRL Stand 2A is currently being re-activated for large engine component testing.

The demand for stage testing will likely increase in the coming decade if the engines under consideration are to become operational. Stage testing appears to be best accommodated in the near term by existing NASA facilities at SSC and MSFC. Additional capability, if required, is being developed at AFRL as well. The GRC B2 facility offers stage test capability for those upper stage engines requiring altitude simulation.

Based on the engines considered and the tightening financial resources for engine development, we see low utilization for most contractor engine system test facilities. Some contractor facilities (TRW, ARC, EMRTC) are not sufficient to test at the engine thrust levels under consideration for the coming decade. It is anticipated that the other major engine contractors (P&W, Aerojet, Boeing) will use their facilities for component development and opt to utilize government facilities, when possible, for engine system testing.

There will most likely be no utilization of liquid engine test facilities at RTTC or NWAC in the coming decade. The test cells at AEDC, which are used where altitude simulation is required during engine test, could possibly be used for ambient testing of engines. However, the cost would be prohibitive compared to other existing ambient facilities. The AEDC J-4 stand could be used for an altitude test on the NK-43 engine, though a full run demonstration would require increased tank capacity. AFRL is developing or now has the capability to support ambient testing of many of the larger engines in the coming decade.

Utilization of WSTF facilities for liquid engine testing is expected to be low in the coming decade. The Boeing RS-72 engine could use WSTF should altitude simulation become a test requirement. Utilization of the GRC B2 stand should be low to moderate depending on proposed upper stage engine programs proceeding beyond concept design. MSFC facilities should see moderate engine test utilization in the coming decade based on the likelihood of a stronger stage test requirement. SSC will continue to see moderate to heavy demand for all their engines test facilities, particularly in those areas supporting peroxide engine development.

Evaluation of Facility Needs

Evaluation of the future facilities needs has yielded the following findings:

Facilities planning for future engine development test programs should plan on 15 engines, 400 firings and 40,000 seconds of test time for new booster and upper stage engine designs. This estimate is based on past programs and success rates achieved in practice. Commercially developed programs where cost and schedule may compete with reliability demonstration may be smaller in scope. Historical data suggests that the test scope does not appear to be influenced by propellant class. Based on mission success, there also does not appear to be a requirement to change test program scope whether testing a low or high-pressure engine. One must caveat these observations with the disclaimer that those engines examined were not required to meet some of the emerging requirements for high operability, low maintenance, and multiple restart.

To meet reliability goals for 2nd generation engine systems, test planners should expect to include margin testing as a major element in future new engine programs. Testing beyond specification limits may also be required to collect sufficient data for failure modes testing and IHM. Margin testing in thrust and mixture ratio may impact facility requirements and capabilities depending on the margins required.

Though the development of engine health monitoring systems will eventually require testing of sensors, imbedded microprocessors, software, etc., in realistic engine flight environment, instrumentation development should proceed at the component testing level. Data acquisition systems at test facilities should be re-examined in terms of their ability to support verification of an engine health management system and servicing infrastructure. The increased use of health monitoring and management to extend the life of rocket engines and the need to quickly evaluate and turn-around test results will necessitate the increased collection and rapid evaluation of high-frequency engine data. Data systems should be developed to allow for digitizing and cataloging of high-frequency measurements such that test results can be retrieved and analyzed rapidly at the test or launch site.

Qualification and certification of a proactive engine health management system will require integrated tests performed at a number of off-nominal, and potentially hazardous, conditions. Test facilities should be reviewed for highly reliable if not redundant control and redline backup systems to accommodate such testing without safety compromised to the facility and its personnel.

Integrated systems testing is the recommended approach to characterize the environments between an engine and its vehicle interfaces. Test facilities should work in concert with the launch sites to merge, as much as possible, test and flight data systems. Such a merged system will assist in flight data interpretation which gains increasing importance for re-usable, rapid turnaround vehicles.

Analytical techniques have significantly improved in the last few years, but the increased emphasis on high engine reliability and operability dictates that a greater amount of highly instrumented testing will be needed to develop and qualify new propulsion systems. Although we have a number of high quality, static test stands of various sizes today, new programs most often involve a extensive effort to reconfigure any of these stands to accept a new engine. The added requirement to generate integrated propulsion system data, such as multi- engine interactions, pogo systems, etc., usually requires further extensive modifications. Ideally, integrated system development testing would be done on an assembly similar to the Space Shuttle MPTA, with final qualification test performed with the actual vehicle, as with the Delta IV CBC. Early operational data on engine servicing, checkout, and replacement can also be obtained with such test articles.

The present cost constrained atmosphere surrounding new engine development will probably require new programs to employ either multi-position facilities or increased configuration management across facilities testing the same engine. The multi-position approach has been tried in the RS-68 program. The SSC B-Complex B-2 stand currently used for certification testing on that engine was configured to receive two engines. The intent was to gain the ability to conduct side-by-side tests on successive days with both engine systems drawing support from a common propellant feed and instrumentation system. This approach has been marginally successful for attaining an improved test rate. It was determined during that demonstration that reconfiguration of instrumentation to support the desired engine test schedule was time consuming, which offset the advantage of side-by-side testing. Technology was not the impediment but rather schedule constraints plus the cost needed to set up the facility to take full advantage of side-by-side testing. However, this testing approach has merit and warrants further consideration for new programs. Where practical, development of standardized interfaces and test skid designs for test facilities could prove advantageous by providing greater flexibility in relocating test articles to new locations due to unforeseen events or schedule conflicts.

Increased demand for data to support emerging engine requirements for quick turnaround time with minimal maintenance will require proactive test center involvement. Test and launch site personnel will need to actively interface with engine designers to facilitate operations issues with flight engines.

There is currently only one facility (SSC E3-Complex) specifically designed to test sizeable peroxide engines. As further additional engine requirements (e.g., health monitoring, re-use, and low maintainability) are added, one quickly surmises that even that facility will require significant upgrades to keep pace with potential demand. We do not see a need for expanding the current national capability in peroxide engine testing until a program commitment is present. At present there is a greater need for continued materials and component testing for these systems.

Facilities for booster scale turbomachinery component hot-fire testing under flight-like conditions are limited. Should national interest dictate two or more large liquid engines be developed, qualified and certified at the same time, test facilities could be seriously stressed. Major liquid engine developers have limited capability to test the turbomachinery prior to a full engine test. AFRL component test facilities do exist in varying degrees of readiness. As mentioned earlier, Pad 2A is being readied to support large liquid engine component development. However, other AFRL assets would require a substantial funding to reactivate for component testing.

It is recognized that liquid engine test facilities and associated organizational infrastructures are costly to maintain. As a consequence, when major engine development / production programs are completed, the supporting test facility runs the risk of being scavenged to support other programs. Thus, when one or more new major projects are started, a substantial capital investment may be required to restore these facilities. One possible solution is for the government to designate key facilities as vital to the national interest and, as such, assume stewardship during slack test periods. Government stewardship would require appropriate funding to ensure critical test assets remain intact and are properly maintained for future use. Of equal importance is the retention of skilled personnel to conduct component and system testing. Erosion of such expertise can lead to significant schedule and cost delays during major propulsion system development.

Recommendations

1. Establish an industry standard on IHM system architecture as well as minimum qualification, and verification test requirements before engine systems attempt to integrate health monitoring (IHM) into their design.
2. Incorporate near real-time data processing at test locations to facilitate IHM development. Re-examine current facilities for redundant redline control authority to assure safety during testing with active IHM systems.
3. Develop commonality between test and flight data processing systems to the maximum practical extent.
4. Minimize interface differences from the test stands to the launch site. When using multiple stands for engine development, standardize interfaces between the test stand and the engine (e.g., purge systems and ground start systems) so that stand-to-stand engine operational differences can be avoided. Validate the consistency of test stand thrust and flow rate measurements when using multiple stands during engine development. Where possible, use common calibration procedures for flow meters and thrust cells when testing engines at multiple locations.
5. Establish government stewardship of key national test facilities during slack periods with appropriate funding to ensure critical assets remain intact and are properly maintained. Establish a study group to examine potential skills retention issues at test facilities.
6. Consider consolidation of altitude test facilities.

Appendix 1-Domestic Liquid Engine Test Stands

DOD Test Assets (Page 1 of 1)

Arnold Engineering Development Center (Tullahoma, TN) : www.arnold.af.mil — contact Chris Smith (931) 454-6100 chris.smith@arnold.army.mil

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Propellant Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
TC J-3	Vertical	200 500	125 100	A50 LN2 LOX Hydrazines N2O4 RP-1	1700 28000 6600 4000 4000 1350 200 6600	1300 150 1000 1200 1200 1300 1000 1000		12 ft3 GH2 @2400 psi	80 KSPS (aggregate)	Cell equipped with LN2-cooled panels for temperature (20-130 °F) simulation during test. Stand allows testing of high area ratio (100) nozzles. Stand can be used to test small (1Klbf) storable engines.
TC-J-4	Vertical	500	100	A50 N2O4 LH2 LOX	350 350 10000 4000	750 750 250 250			250 KSPS (aggregate)	Facility has design limit of 1500 Klbf (axial), lower limit due to force measurement capability. Facility has also been used to test solid motors. Test cell equipped with temperature conditioning system (50-110 °F) Planned upgrades for LRE testing are as follows: H2O...2700K to 4200K gal total capacity, LOX... 4K to 18K gal capacity LH2... 10K to 42K gal total capacity, RT ... 198 to 1000 secs

Air Force Research Laboratory (Edwards, CA) : www.pr.afrl.af.mil — contact Robert Drake (661) 275-5542 Robert.drake@edwards.af.mil

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
Area 1-42 B-Cell	Vertical	50	90 to 120	solids/liquids MMH	500 gals	2,400	430	1,500 scf GN2 & 600 scf He	128 ch Cyber 16 ch datamax, plus	Stand has been used to test both solid motors and liquid engines.
Area 1-120 1A	Vertical / Down	1600	Ambient	RP-1 LH2 LOX	60000 90000 75000	165 165 165		1600 ft3 GH2 @ 10000 psi 1340 ft3 GHe @ 6000 psi 2850 ft3 GN2 @ 4000 psi 1000 gal Propane @ 250 psi	Dedicated 448 Analog Channels 270 Digital Channels 300 Real-Time Display Channels 50K sps/ch with 56 ch	Engine and Turbopump testing capability.
2A	Horizontal (15 ° down)	1600	Ambient	RP-1 LH2 LOX	2000 3800 2000	6600 7500 8000	28K gal LN2 @ 20 psi 28K gal LH2 @ 100 psi 28K gal LOX @ 20 psi	1600 ft3 GH2 @ 10000 psi 1340 ft3 GHe @ 6000 psi 5010 ft3 GN2 @ 6000 psi 1000 gal Propane @ 250 psi	Planned system 256 Analog Channels 360 Digital Channels 200 Real-Time Display Channels 50K sps/ch with 160 ch	Will be used to support large liquid engine component testing.
1B	Vertical / Down	1600	Ambient	RP-1	60000	165			None	
Area 1-125 1D, 1E	Vertical / Down	1600	Ambient	RP-1 LOX	75000 90000	165 165	13K gal LH2 @ 50 psi	3500 ft3 GN2 @ 3700 psi	Dedicated system planned 384 Analog Channels 270 Digital Channels 200 Real-Time Display Channels 50K sps/ch with 96 ch	Stand 1D will be convrted to LOX/LH2 capability. Stand 1E will remain LOX/RP-1 capability.

Redstone Technical Test Center (Huntsville, AL): www.atc.army.mil/~rttc — contact William M. Lies (205) 876-5324 Mlies@rttc.redstone.army.mil

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
TS-8	Vertical	500	Ambient	IRFNA RP-1 UDMH N2O4 Hydrazines	1600 lbm 1000 lbm 1000lbm 1600 lbm 1000 lbm	100 100 100 100 100			1500 Digital 100 Analog	

Naval Air Warfare Center (China Lake, CA): www.nawc.navy.mil — contact Paul Gorish (760) 939-7252 gorishps@navair.navy.mil

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
Bay 4		100	Ambient	Hydrazines IRFNA	150 150	3000 3000		300 ft3 GN2 @ 6000		
T-Range Cell 1 & 2		100	Ambient	JP LOX LP	100 1000 100	2000 2000		300 ft3 GOX @ 2000		

Stennis Space Center (SSC, MS): www.ssc.nasa.gov — contact Fred Patterson (228) 688-50000 fred.patterson@ssc.nasa.gov

	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Propellant Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
A Complex: A-1	1100	Ambient	LH2 LOX	110000 (VJ) 40000 (VJ) 5500 (Non VJ)	66.5 250 125	(2) 240000 gal LH2 Barges (2) 94000 gal LOX Barges	(2) 600 ft3 GH2 @ 5000 psi (2) 1500 ft3 Air @ 4600 psi 950 ft3 Air @ 2879 psi 1500 ft3 GHe @ 4753 psi 1500 ft3 GN2 @ 4678 psi 1500 ft3 GN2 @ 4576psi 1500 ft3 GN2 @ 4578 psi 1500 ft3 GN2 @ 4500 psi	400 low speed analog @50 sps 180 high speed analog @ 20K-sps HF analog tape recorders	Docking facilities for two LOX and/or LH2 barges per stand. 10" LOX transfer line from barge to stand, 12" dia. LOX line from run tank to TA. 12" LH2 transfer lines from barge to stand, stand to TA. LOX barge transfer pumps rated at 1250 gal/min @250 to 350 psig. LH2 barge transfer at a rate of 5000 gal/min @ 65 psig. Each stand has its own lifting crane (75-tons, rated @37.5-tons), 5-ton jib crane. A-2 stand uses self-pumping diffuser for altitude simulation test.
A-2		65	LH2 LOX	110000 (VJ) 40000 (VJ) 5500 (Non VJ)	66.5 250 125				
B Complex: B-1	750	Ambient	LH2 LOX	90000 (VJ) 49550 (VJ)	66 110	(3) 240000 gal LH2 Barges (3) 94000 gal LOX Barges	2500 ft3 GH2 @ 3375 psi 600 ft3 GH2 @ 5600 psi 600 ft3 GH2 @ 6600 psi 1500 ft3 GHe @ 4725 psi	B1: 512low speed analog @ 50 sps 180 high speed analog @ 20K-sps FM analog tape recorders	Docking facilities for three LOX and/or LH2 barges per stand. 14" LOX transfer line from barge to stand, 12" dia. LOX line from run tank to TA. 10" LH2 transfer lines from barge to stand, 12" stand to TA. LOX barge transfer pumps rated at1250 gal/min @250 to 510350 psig. LH2 barge transfer at a rate of 5000 gal/min @ 65 psig. RP-1 transfer rate at 10 to 1000 gal/min @100 psi max. Both stands share a main derrick lifting crane (200-tons, rated @37.5-tons), 20-ton jib crane and a 175-ton auxiliary crane (rated @ 37.5 tons).
B-2	1100	Ambient				28000 gal (VJ) @ 135 psig 15000 gal	(4) 750 ft3 GN2 @ 6600 psi 950 ft3 Air @ 2917 psi 1065 ft3 Air @ 4814 psi 1500 ft3 Air @ 4693 psi	B2: multiplexing for 256 active channels, 320 channel capacity 128 high frequency@100 Ksps low frequency @ 100 sps	
E Complex E-1: Cell 1	750	Ambient	LH2	6000 15000	8500 385	50000 gal LH2@ 35 psig 28000 gal LOX @ 165 psig 28000 gal LN2 @ 165 psig	(2) 625 ft3 GH2 @ 13500 psi (2) 750 ft3 GH2 @ 6600 psi 1500 ft3 GHe @ 4500 psi (2) 695 ft3 GN2 @ 15000 psi 1500 ft3 GN2 @ 4500 psi	500 low speed analog @500K-sps 96 high speed digital @ 100 K-sps	The three test cells can accomadate multiple programs at the same time. Each cell contains support to be self sufficient. A ten ton overhead bridge crane spans all three cells. A 5-ton crane provides lifting behind the facility blast wall. Cell 2 primarily used to test TPAs up to 3000 lbs in weight. Cell 3 is designed to test LOX-rich TPAs up to 3000 lbs in weight. TPAs can be tested at angles up to 10° horizontal. E-1 also has a hydraulic system for actuating special equipment. The facility has a 4000 GPM water deluge system.
Cell 2	60	Ambient	LOX	2600 11200	8500 400				
Cell 3	60	Ambient							
E-2: Cell 1	60	Ambient	LOX RP-1 RP-1/DIH20	3000 10150 500 850 145 500 145	150 165 8500 1800 4000 8500 6000		(2) 750 ft3 GH2 @ 6600 psi 625 ft3 GH2 @ 15000 psi 247 ft3 GN2 @ 15000 psi 1375 ft3 GN2 @ 5667 psi 1375 ft3 GO2 @ 4600 psi	360 low speed analog @200 Ksps 32 high speed digital @ 100 Ksps	Provides support for advanced component and engine testing. Stand has 2-ton jib crane. The facility has a 4000 GPM water deluge system if E-1 facility is not operating. E-2 also has a hydraulic system for actuating special equipment. E-2 can support test articles up 3000 lbs in weight.
Cell 2	100	Ambient	LOX RP-1	13000 3000 15000 2200	250 70 14 70		Site (1.5" line) GN2 @ 4500 psi Site (1.5" line) GHe @ 4500 psi		
E-3: Cell 1	60	Ambient	LOX	100	2000	250 gal RP/JP@ 1500 psig 600 gal LOX@ 60 psig	Site (3" line) GH2 @ 3000 psi Site (Tube Bank) GHe @ 3000 psi Site (1.5" line) GN2 @ 4500 psi	80 low speed analog@1.2Ksps 20-30 high speed analog@ 80K sps	Both cells can be occupied simultaneously but share facility support so only one cell can test at a time. Cell 1 has a 5-ton overhead crane. Both cells have a single-axis 10 K-lbf thrust measurement system.
Cell 2	25	Ambient	H2O2 RP/JP	500 250	1500 1800	4500 gal. H2O2	Site (3" line) GH2 @ 6000 psi Site (1.5" line) GN2 @ 4500 psi		

NASA Assets (Page 2 of 3)

Marshall Space Flight Center (Huntsville, AL) : www.msfc.nasa.gov ---- contact John Wiley (256) 544-8994 john.wiley@mfsc.nasa.gov

	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Propellant Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
TS-115 (3 positions) Combustion Research Facility (CRF) *Positions: Two Horizontal and One Vertical*	4	Ambient	LH2/ Methane RP-1/H2O LOX RP-1/ Methane	500, 2200 500 500 20	3000/1500 3000 3000 3000	25000 gal LOX 500 gal H2O @ 3000 psig	Site(3" line) GN2@4200 psi GH2 Trailer - 236 ft3, 4200 psi GHe Trailer - 236 ft3, 4200 psi GOX Trailer - 236 ft3, 2400 psi Site (1.5" line) Misle-Grade Air at 3500 psi	500 low-speed digital @ 100 sps 16 high-speed digital @ 1000 Ksps 40 analog tape channels	Open Steel Structure, one "hot fire" position. Future plans to add cold flow test position. Facility used for small scale combustion device testing. Two horizontal and one Vertical Hot Fire test positions.
TS-116: (5 positions) Component Test Facility (CFT) *(Positions: Turbine Blade, acoustic model, turbopump, high flow water, and engine)*	60,760	Ambient	LH2 / LCH4 LH2 LOX RP-1 / H20	2200, 2000 2200 , 2000 3000, 2000 3000, 3000	5000, 8500 5000 , 8500 5000, 6000 5000, 2700	28000 gal LOX 14000 gal LOX	1250 ft3 GH2 @15000 psi 600 ft3 GH2@10000 psi 1250 ft3 GN2 @ 10000 psi 700 ft3 GN2 @ 8000 psi Site (two 1.5" lines) Misle-Grade Air at 3500 psi Site(3" line) GN2@4200 psi Site(1.5" line) GHe @4200 psi Site(1.5" line) GH2@4200 psi	1000 low-speed digital @ 100 sps 96 high-speed digital @1000 Ksps 32 high-speed digital @ 250 Ksps 216 analog tape channels	Open steel structure, primarily used for subscale testing. Five test positions (one vertical and four horizontal). Facility equipped to test sytem components, turbopumps, valves, cryo propellant components, and other combustion devices. Can run multiple tests simultaneously. Environmental simulation capability. Storage of 700,000,000 gal of industrial water for fire control and cooling. Fire control is 110,000 GPM@150 psig, cooling is 200,000 GPM@150 psig. Facility has several hydraulic systems for test support.
TS-500: (6 positions) Hybrid&Engine Components Test Facility *(Positions: 24" LOX Hybrid, 11" LOX Hybrid, LOX Bearing, LH2 Bearing, SimplexTurbopump, and LH2 / LOX Component)*	40	Ambient	LH2 LOX	5000 3000	2000 2000	28000	Site(3" line) GH2@4200 psi Site(3" line) GN2@4200 psi Site(3" line) GHe @4200 psi Site (1.5" line) Misle-Grade Air at 3500 psi	500 Low-speed digital 32 High-speed digital @ 250,000 samples / sec 84 analog tape channels	Open steel structure, primarily used for subscale testing. Two Hybrid/Solid test positions (24" and 11"). LOX and LH2 Component Test Positions for valves, ducts and small tanks.
TS-4670: (2 Positions) Advanced Engine Test Facility (AETF)	375	Ambient	LH2 LOX RP-1	75000 23000 14000	60 150 150	450000 gal LH2@ 100 psig 78000 gal LOX@100 psig 20000 gal RP-1	11400 ft3 GH2 @ 3100 psi 90 ft3 GHe @ 10000 psi 2500 ft3 GHe @ 4200 psi 3750 ft3 GN2 @ 4200 psi Site (1.5" line) Misle-Grade Air at 3500 psi	750 low speed digital @100 sps 200 analog tape channels 64 high speed digital @ 250Ksps	The "Other Gases" and "Data System" assets listed for Position #1 supply both positions on 4670. This stand is capable of engine and vehicle stage testing.
	900	Ambient	LOX RP-1	12000 6000	130 130				

Glenn Research Center (Cleveland, OH): www.grc.nasa.gov — contact Robert Kozar (419) 621-3205 robert.kozar@grc.nasa.gov

	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Propellant Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
RETF A	50	Ambient	LH2	1000	5000				
				1200	1500				
			LOX	400	1500				
				400	8000				
			RP-1	600	4670				
RETF B	2	100	LH2	1000	5000				
				1200	1500				
			LOX	400	1500				
				400	5000				
			RP-1	600	4670				
GRC B2	400	175	LH2	34000	90				
			LOX	12000	90				
			Hydrazines	4000	90				
			N2O4	6000	90				

White Sands Test Facility	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Propellant Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
(Las Cruces, NM) : www.wstf.nasa.gov ---- contact Robert Kowalski (505) 524-5175 rkowalsk@wstf.nasa.gov									
TS-301	25	Ambient	N2O4 Hydrazines A50 UDMH	2000 2000	300 300		GN2 @ 3000, 1000 & 150 psi GHe @ 6000 & 1800 psi	177 Analog 200 Analog-to-Digital 200 Discrete Event 140 Control System	Multifunctional atmospheric stand, three levels Articulating test article mount Article & chamber Temp. Conditioning 40-120 °F Removable enclosure for large article installation
TS - 328	25	Ambient	N2O4 Hydrazines A50 UDMH	800 800	300 300		(Same as TS-301)	120 Analog 304 Analog-to-Digital 200 Discrete Event 140 Control System	Currently configured for hypergolic propellant systems, has removable environmental enclosure
TS-401	25	100	LH2 LOX Hydrazines N2O4 Hydrocarbon A50 UDMH	28000 4200, 13500 2000 2000 500000 Portable Portable	50 & 100 720, 90 600 600 400		400 ft3 GO2 @ 6000 psi GN2 @ 800 & 150 psi GHe @ 6000 & 3000 psi	380 Analog 309 Analog-to-Digital 256 Discrete Event 300 Control System	Currently configured for cryogenic engine testing Multiaxis Thrust Measurement Article & chamber Temp. Conditioning 40-120 F Nine foot Diameter Vacuum Isolation(Gate) Valve Nine foot entrance diameter steam injectors 24-inch bypass valve for cell venting Three interior levels can be reconfigured to reqs.
TS-402	55	Ambient	A50 UDMH				GN2 @ 800 & 150 psi GHe @ 6000 & 3000 psi	(Same as TS-401)	Removable enclosure for large article installation Article & chamber Temp. Conditioning 40-120 F
TS-403	20	100	N2O4 Hydrazines A50 UDMH	2000 2000 Portable Portable	300 300		GN2 @ 800 & 150 psi GHe @ 6000 & 3000 psi	410 Analog 415 Analog-to-Digital 256 Discrete Event 300 Control System	(Same as TS-401)
TS-405	25 (solid) 1 (Liquid)	100	N2O4 Hydrazines A50 UDMH	2000 100 2000 100 Portable Portable	300 1000 300 1000		GN2 @ 800 & 150 psi GHe @ 3000 psi	130 Analog 415 Analog-to-Digital 256 Discrete Event 50 Control System	Currently a solid motor stand, can test spin rates to 120 rpm, thrust to Article & chamber Temp. Conditioning 20-110 F
TS-901		100	Variable A50 UDMH						

Aerojet (Ranco Cordova, CA): www.aerojet.com — contact Rick Simonsen (916) 355-6024, Rick.simonsen@aerojet.com
(All stands operate under environmental permits issued by Sacramento County)

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Propellant Storage (gal)	Other Pressurants	Data System (Shared or dedicated)	Notes
A-ZONE TS A-5	Horizontal	10	Ambient	Ethanol LOX	127 250	1400 1200	 1500	100 ft3 GO2 @ 4000 psi 50 ft3 GH2 @ 4000 psi	192 Digital Channels 40 Real-Time Display Channels 20,000 KHz Max Frequency	
TS A-6,7	Horizontal	10	Ambient	LH2 CH4 LO2	180 50	6000 6000 5500	3000 3000 1500	78 ft3 GH2 @ 10000 psi 16 ft3 GHe @ 10000 psi 106 ft3 GO2 @ 6000 psi 60 ft3 GN2 @ 3600 psi 1800 gal LN2 @ 200 psi		Engine and turbomachnery testing capability.
TS A-8	Horizontal	20	30	LH2 CH4 LOX	150 50	5500 5500	3000 3000 1500	60 ft3 GH2 @ 6000 psi 16 ft3 GHe @ 10000 psi 374 ft3 GO2 @ 5000 psi 650 ft3 GN2 @ 3600 psi 35 ft3 H2O @ 3600 psi		Cryogenic & Turbopump Testing capability. Two axis thrust measurement capability.
E-ZONE TS E-4	Horizontal (17°) Vertical / Down	300 240	Ambient	RP-1 , CH4 LOX	540 540	3100 3100	21360 & 6400 13200	3900 ft3 GN2 @ 3500 psi 2800 ft3 GN2 @ 5000 psi 1800 gal LN2 @ 200 psi	256 Digital Channels 50 Real-Time Display Channels 20,000 KHz Max Frequency	
TS E-5	Vertical / Down	700	Ambient	RP-1 LH2 LOX	19800 10000 20000	185 200 185	 28000 24400	1300 ft3 GN2 @ 6800 psi 1300 ft3 GH2 @ 6800 psi		Storable propellant conditioning capability. No direct thrust measurement capability.
TS E-6	Horizontal	200	Ambient	LH2 LO2	600 300	5600 5600	10000 24400			Cryogenic engine and component test capability.
G-ZONE TS G-1 (Stands 4,5,&6 inactive)	Horizontal & Vertical	500	Ambient	A-50 N2O4	748, 6650 127, 4385	1500, 110 1400, 110	21360 & 14500 21360 & 14500	2800 ft3 GN2 @ 3500 psi	256 Digital Channels 50 Real-Time Display Channels 20,000 KHz Max Frequency	Storable propellant conditioning capability. Storable engine & Turbopump Testing capability
TS G-2	Vertical / Down	500	Ambient	A-50 N2O4	19570 22900	185 179				Storable propellant conditioning capability.
TS G-3	Vertical / Down	105	Ambient	A-50 N2O4	12000 14000	65 89				Storable propellant conditioning capability.
TS G-8	Horizontal	20	Ambient	A-50 N2O4	851 1300	1750 710				Storable propellant conditioning capability.
J-ZONE TS J-1	Horizontal	50	Ambient	A-50, MMH N2O4	127 200	1440 1440		400 gal H2O @ 3560 psi	480 Digital Channels 78 Real-Time Display Channels 20,000 KHz Max Frequency	Storable & Cryogenic engine test capability. Two pressure intensifiers(80,150 gal) for high propellant pressurization(5-6000 psi)
TS J-1A	Horizontal	20 - 100	Ambient	LH2 LO2 RP-1	150 80 80	3500, 7000 7000 5000		260 ft3 GH2 @ 4700 psi 680 ft3 GO2 @ 3500 psi	J-Zone has three control rooms linked to a common data storage facility.	Primarily a research engine test facility. Two pressure intensifiers(80,150 gal) for high propellant pressurization(5-6000 psi)
TS J-2	Horizontal	20	Ambient	MMH N2O4	28 28	6000 6000	13300 7410	63.6 ft3 GHe @ 6000 psi		LN2-jacketed, vacuum insulated, 600 gal. cryogenic vessel at this stand.
TS J-2A	Vertical/Stage	20	Ambient	A-50 N2O4	1055 1324	250 250	7410 7410			Battleship stage configurations only.
TS J-4	Horizontal	20	150	MMH N2O4	1254 2464	1275 812	13300	3900 ft3 GN2 @ 5000 psi 1300 ft3 GN2 @ 3500 psi		Cell / Propellant conditioning capability.
TS J-5,J-5A	Horizontal	200	150	MMH N2O4	400 400	6000 6000		1300 ft3 GN2 @ 5000 psi 1300 ft3 GO2 @ 5000 psi 4000 gal H2O @ 1800 psi		Recently upgraded to test peroxide engines.
TS J-11,12 J-13 J-14	Horizontal	10 1 1	Ambient Ambient 85	MMH N2O4	450, 70, 8 350, 35, 8	985/10000 1235/10000		4000 gal H2O @ 1800 psi		J-11 supports TC development, J-12 TPAs supports research for small (1K-lbf) storable engines.

Commercial Assets (Page 2 of 3)

Pratt & Whitney (West Palm Beach, FL) : **www.pwa.com** — contact Russ Joyner (561) 796-3159

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
TS E-6 (Altitude Rocket Engine Test Facility)	Vertical / Down	30 (SM) 156 (ST) 500 (PC)	80	LH2 LO2 LN2	10000 3000, 4000	150 150, 100	90000 14000 39000	220000 scf GH2 @ 5000 psi 73000 scf GHe @ 5000 psi 145000 scf GN2 @ 5000 psi 145000 scf GN2 @ 5000 psi 7500 gal/min H2O	110 Analog (36 O'graph,42 FM,32 HS) 320 High-Speed Digital (100 sps) 256 Real-time Display Channels 10,000 KHz Max Frequency	Stand structure is about 105 ft. tall. Thrust measurement accuracy to 0.5%. 8000 ft2 dedicated assembly/insp. area. Supersonic diffuser assisted with steam ejectors (three 2-stage units) used to pull vacuum.
TS E-8 (High Pressure Cryogenic Test Facility)	Horizontal	35 (SM) 80 (ST) 500 (PC)	Ambient	LH2 LO2 LN2 CH4	2400, 22000 900, 5000 1000, 6500	8500, 275 8500, 550 250, 250	160000 37000 39000	1800000 ft3 GH2 @ 9900 psi 220000 scf GH2 @ 5000 psi 250000 scf GHe @ 5000 psi 480000 scf GN2 @ 9900 psi 145000 scf GN2 @ 5000 psi 7500 gal/min H2O	78 Analog(18 O'graph,28 FM,32 HS) 256 High-Speed Digital (100 sps) 448 Real-time Display Channels 30,000 KHz Max Frequency	Stand has 500 K lbf structural capability. 13000 ft2 dedicated assembly/insp. area. Uses steam ejectors to pull vacuum for engine start.

Rocket Propulsion System Test Facility (Formerly EMRTC) (Los Alomos, NM) : **www.emrtc.nmt.edu** — contact Jim Forster (505) 835-5312, jim@emrtc.nmt.edu

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
RETS	Horizontal (15°)	8	Ambient	Kerosene LO2	200 370	850		50000 ft3 GN2 @ 2700 psi	96-128 Channels 32 Real-time Display Channels	
	Horizontal	80	Ambient	Kerosene LO2 H202	220 370 pending	730		50000 ft3 GN2 @ 2700 psi		

Boeing Rocketdyne (Santa Suzana, CA) : **www.boeing.com** — contact Thomas R. Tarn(818) 586-6245, Thomas.r.tarn@West.boeing.com

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
Alpha-1 Alpha-3	Vertical / Down	440 220	Ambient	LO2 RP-1	7000 7000	80 80		352000 scf GN2 @ 3000 psi 37000 scf GHe @ 2600 psi	28 Analog Channels 192 Digital Channels 45 Real-time Display Channels 50,000 KHz Max Frequency	
Bravo 2A,B,C				LO2 RP-1	6000 6000	3000 3000	40000 30000	6580scf GN2 @ 3000 psi 2000 scf GHe @ 2600 psi 20000 gal @ 150 psi	28 Analog Channels 192 Digital Channels 45 Real-time Display Channels 50,000 KHz Max Frequency	Ambient turbopump test facility. Closed Loop RP,H20 system with 45Kgal catch tank.
ST-4 29A,B	Horizontal	3,12	80	NTO MMH	1600 1600	660 660		1148 scf GN2 @ 3000 psi 53 scf GHe @ 5000 psi	10 Analog Channels 119 Digital Channels 108 Real-time Display Channels 50,000 KHz Max Frequency	Propellant conditioning capability.
24A	Vertical / Down	3	Ambient	NTO MMH	83 83				39 Analog Channels 95 Digital Channels 108 Real-time Display Channels 50,000 KHz Max Frequency	Propellant conditioning capability.
24B	Vertical / Down	3	Ambient	NTO MMH	360 360	1440 1440		1148 scf GN2 @ 3000 psi 53 scf GHe @ 5000 psi	14 Analog Channels 55 Digital Channels 108 Real-time Display Channels 50,000 KHz Max Frequency	Chamber and thrust injector test facility. Propellant conditioning capability.
COCA A-3	Vertical / Down	600	Ambient	LO2 LH2	45000 90000	110 55		3750 ft3 GN2 @ 5000 psi 600 ft3 GHe @ 5000 psi 4700 ft3 GH2 @ 2000 psi	108 Analog Channels 512 Digital Channels 74 Real-time Display Channels 20,000 KHz Max Frequency	
1A /1B			Ambient	LO2 LH2	2000 38000	8500 8500	90000 45000	5246 ft3 GN2 @ 10500 psi 3750 ft3 GN2 @ 5000 psi 600 ft3 GHe @ 5000 psi 4700 ft3 GH2 @ 2000 psi	108 Analog Channels 512 Digital Channels 74 Real-time Display Channels 20,000 KHz Max Frequency	Turbopump, Preburner test facility
4A /4B	Vertical / Down	600	Ambient	LO2 LH2	1200 1200	8500 8500		5246 ft3 GN2 @ 10500 psi 600 ft3 GHe @ 5000 psi 2800 ft3 GH2 @ 14000 psi	108 Analog Channels 400 Digital Channels 74 Real-time Display Channels 20,000 KHz Max Frequency	Thrust Chamber, Powerhead Test facility
CTL-5 3B,4A	Horizontal		Ambient	LO2 LH2	1200	2000	25 32, 45	460 ft3 GN2 @ 5000 psi 1410 ft3 GH2 @ 5000 psi	100 Digital Channels 20 Real-time Display Channels 14,000 KHz Max Frequency	Pump Testing Facility. 17500 hp, 44000 rpm electric drive
4B	Horizontal		Ambient	LH2	1200	2000		560 ft3 GN2 @ 5000 psi 1410 ft3 GH2 @ 5000 psi	100 Digital Channels 20 Real-time Display Channels 14,000 KHz Max Frequency	GG-driven turbine testing facility. Catch tanks for closed loop operation

Commercial Assets (Page 3 of 3)

TRW (San Clemente, CA) : **www.trw.com** — contact Jon Auguston (714) 361-7000

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
VETS A1, A2	Vertical	10.5	50	LO2 Fuel LN2	1000 1000 3600	750 750 15		500 ft3 GN2 @ 2200 psi	128 Analog Channels 128 Digital Channels 24 Real-time Display Channels 10,000 KHz Max Frequency	Propellant conditioning capability (-40-120 °F) (2) Single stage ejectors driven by blowdown steam system (44 or 75 lbs.sec)
B1 ,B2	Vertical	50	Ambient	LO2 Fuel LN2	1000 1000 3600	750 750 15		500 ft3 GN2 @ 2200 psi		
PITS	Vertical	50	Ambient	LO2 Fuel LN2	1000 1000 3600	750 750 15		500 ft3 GN2 @ 2200 psi		
HATS	Vertical	10.5	100	Fuel Oxidizer	1200 1200	750 750	16000	2244 ft3 GN2 @ 2200 psi 1200 gal Alcohol@700 psi		Propellant conditioning capability (-40-120 °F) Two stage,chemical steam system diffuser

Atlantic Research Corporation (Niagra Falls, NY) : **www.arc.com** — contact

	Firing Orientation	Max Thrust (Klbf.)	Altitude (Kft.)	Propellant	Run Tank Volume (gal)	Tank Feed Pressure (psig.)	Fuel Storage (gal)	Other - gases	Data System (Shared or dedicated)	Notes
D-3	Horizontal or Vertical	3	Ambient	N2O4 MMH IRFNA	4000 4000 4000	40 40 40		500 ft3 GN2 @ 2200 psi	30 Analog Channels 186 Digital Channels 19 Real-time Display Channels 2KHz Max Frequency	Four gal., 3000 psi piston tanks for 'gel' props.

General Dynamics (Redmond, WA) : **www.marquardt.com** — contact

										Notes
										Marquardt was bought by Primex, which then was bought by General Dynamics (Ordnance and Tactical Systems Division). The hydrogen peroxide and biprop facilities are being dismantled and shipped to Redmond, Wash., where they may be reassembled. The Van Nuys facility is going to be abandoned, and the air-breathing test facilities will probably be destroyed. Some of the nozzles have been sold to AEDC, and WPAFB may have some intererest in some components.

Appendix 2

Foreign Test Facility Notes

An attempt has been made to gather information on foreign liquid engine test facilities. The following information represents a collection of notes gathered through numerous Internet searches and published papers. Though attempts have been made to cross check all information, the reader is cautioned that much of the data cannot readily be validated as to accuracy. Therefor, the information to follow should be viewed primarily as qualitative in nature.

Russian Facilities

Energomash NPO: NPO has developed over 50 types of rocket engines and has experience in a variety of propellants including LOX/alcohol, lox/kerosene, HNO3/N2O4-UDMH, and LOX/LH2. In partnership with Pratt&Whitney (USA) they are currently the prime supplier for the main propulsion system for the Atlas 5 launcher. As a private enterprise, they possess 83 test stands, four of which can be used for comprehensive testing of engines and their associated components. Test facilities located at Khimky, Moscow employ over 1600 people and include facilities to conduct full up engine fire demonstrations as well as autonomous testing of various engine elements such as injectors and turbopumps. NPO has two stands for engine tests, each with a rated thrust capability of over 1000 tons. The stands are equipped with automated control with the capability of recording over 1000 parameters of the engine, test stand, and special storage tanks for propellants. NPO's capabilities also includes facilities for water and mineral oil "cold flow" testing of centrifugal pumps and regulating units. Also on-site are facilities for static and dynamic testing of pneumo-hydraulic control devices, as well as bearings and seal joints with limited simulation of actual operating conditions including axial and radial loads.

KB Khimmash: Khimmash is one of the leading Russian companies in the development of liquid fueled rocket engines. As a state enterprise subordinate to the Russian Space Agency, they have designed, developed, and tested over 120 engines for missiles and spacecraft. Specifically, they have delivered liquid propulsion engines with a thrust up to 100 K-lbf for rockets and kick stages. Their 11D49 engine was used as the second stage for the Kosmos 3M launcher. The 11D56/KVD-1 LOX/LH2 engine was used as the fifth stage of the upgraded N-1M launcher. A modified 11D56M engine is currently used on the Proton launcher as well as a kick stage for the Indian GSLV. They were also working with SEP (France) to develop an upper stage engine for the Ariane 5. Test facilities are located at Voskresensk, Moscow. Those facilities accommodate engine and engine assembly tests at simulated high-altitude conditions. Facilities also include pneumo-vacuum, hydraulic, gas dynamic, and vibro-dynamic testing of engines, engine assemblies, and associated components.

KB Khimavtomatiki, KBKhA: The main activity of KBKhA is the design and testing of over 30 types of liquid rocket engines used on ICBM's, SLBM's, SLV's, and satellites. Located in Voronezh, Russia, their accomplishments include third stage LOX/Kerosene engines for Vostok, Voskhod, and Soyuz. They also developed the 500K class stages 2 & 3 N2O4/UDMH

Proton engine. They have teamed with Aerojet (USA) to develop possible market opportunities for their RD-0120 engine. Testing facilities include at least two engine stands rated at 120 and 600 K-lbf respectively plus facilities for testing hydraulic systems, static structural strength, dynamics and vibration characterization, materials characterization, dynamic rotor balancing, component and subassemblies.

M.V.Keldysh Research Center: Keldysh cooperates with a wide variety of companies developing rocket engines, fuels, materials, and integrated space systems. Located in Onezhskaya, Moscow, this agency is a state enterprise that is subordinate to the Russian Space Agency. Facilities include accommodations for testing liquid rocket engines using LOX/Kerosene and LOX/liquid natural gas. They also have stands to investigate liquid engine stability, optimized altitude chamber design, and materials research.

GP Krasmashzavod: Located in Krasnoyarsk, Russia this diversified company was heavily involved in production of ICBM's and SLBM's. As a state enterprise, they also produce kick stages for heavy launch vehicles and liquid engines for spacecraft. Their experimental base include a complex of stands for static testing under loading (both internal and external pressure) and a complex of stands for test firing engines. Capabilities also include investigation of material properties and detailed non-destructive diagnostics.

NII Khimmash: Located north of Moscow, Russia, this facility is a lead institution for the ground testing and quality assurance of rocket and spacecraft propulsion systems. This state enterprise Institute has over 50 test stands to test rocket engines and associated components. In particular, test station #2 is a vertical stand that allows stage testing with dimensions up to 40 meters in height and 9 meters in diameter. Thrust stand rating is of the order of 2400 K-lbf. This stand was used for Block A testing of the Energia engines. Another facility is used for testing liquid engines and cryogenic systems with rated thrust up to 400 K-lbf. The B2A test stand at this facility was used for testing the RD-0120 LOX/LH2 engine developed by KBKhA for the Energiya Launch vehicle The altitude simulation facility allows hydrogen consumption from 15-300 kg/sec and nozzle exit pressures of .05 bar.

Samara Scientific and Technical Institute – Vintai: Located 50 KM from Samara, Russia, this company developed the RD-7 engine used on Soyuz as well as modified versions of engines for the N1-M launcher. The site has several stands that were used for NK-33/NK-43 development as well as NK-39.NK-31 development. The company is currently maintaining a co-production discussion with Aerojet (USA).

NIIMash (R&D Institute of Mechanical Engineering): Located at Nizhnyaya Salda in the Sverdlovsk Region, this organization has developed and produced a series of low-thrust rocket engines (LTREs) used for spacecraft stabilization, orientation, and orbit correction. In addition to LTRE research and manufacturing, this company has a large cryogenic engine facility capable of testing engines up to 67 K-lbf in thrust. This stand was used to develop the second stage main engine of the Energia launch vehicle.

French Facilities

SNECMA – Vernon: Located about an hour west of Paris, the Vernon site has over a dozen test facilities for Ariane engines, components, and subassemblies (bearings, valves, etc.). In particular, PF-1, PF-3, A48, and F22 are component test stands. PF-2 is an engine test stand. There are two PF41 stands used for cryogenic engine testing. The PF-50 stand is used for testing the Vulcain-2 engine for the Ariane 5 while the PF-52 stand was used to test the Vulcain-2 turbopumps.

<u>PF-50:</u> The PF-50 stand, which is identical to the P5 Stand at DLR in Lampoldshausen, began operation in September 1990 with testing of the Ariane 5 H-60 second stage engine. The entire PF-50 concrete structure stands 65 ft. high. The structure accommodates and protects test facility rooms. On the tower itself, there exists a steel structure with façade that provides space for the 200 m3 oxygen tank. Joining the tower on the side is a shaft to accommodate the 600 m3 hydrogen tank. The operations rooms and propellant tanks are separated from the test cell by a two meter thick wall. The walls of the test cell are hinged and the floor closed by an octagonal slab. Both are opened during tests. A rigid thrust frame holds the engine. A top-opened cone, located under the middle of the frame, transfers thrust from the engine. Propellant and supply lines as well as control and measurement cables pass through the cone to the engine. Test firings on the Vulcain engine have been conducted for nominal burn times of 590 seconds with some testing to 900 seconds for margin verification.

The oxygen tank has a 90K storage temperature while the hydrogen tank has a storage temperature of 20K. The oxygen tank is located up on the concrete tower at the right height to simulate correct geometric conditions in the Ariane 5 launcher. During a test, the liquid LH2 and LOX tanks are pressurized with gaseous hydrogen and nitrogen respectively. Propellants are conveyed through vacuum-insulated pipes to the engine turbopumps in the test cell. The propellant tanks are filled during test preparation from a propellant depot that is connected to the test stand by vacuum-insulated pipes as well. The LOX and LH2 storage tanks have a 210 m3 and 270 m3 capacity respectively. Liquid hydrogen is delivered by tankers with a capacity of 40 m3. Two tankers can be discharged into the storage tank at once, allowing delivery of approximately 200 m3 of LH2 per day. LOX is also delivered to the storage area by tankers with a capacity of 15 m3 per vehicle.

Both the engine and the test facility systems are supplied with various gases (nitrogen, hydrogen, helium and propane) at different pressures (up to 70 bars) and corresponding flow rates (up to several Kg/sec). The gas supply systems are integrated in the test facility. Cooling water is supplied to a jet guide tube and jet deflector at 2000 liters per second from water tanks through a one meter diameter pipe.

Measurement and test control are fully automated. The computer system and software technology are approximately ten years old. Transducer signals are adjusted by signal conditioning units programmed by the computer. Magnetic tape recorders are available for high-frequency signals. Magnetic tape recordings are evaluated by signal analysis software on a separate computer.

PF-41 Inaugurated in September1976, two PF-41 stands were used initially to test the Ariane-1 HM7 engine. Testing was limited to 248 seconds duration due to limited fuel tank capacity at the facility. Both stands employ a vertical test article firing orientation during operation and one has altitude simulation capability.

PF-52: This stand was built in 1988 and is currently being modified to test the new expander cycle VINCI engine for the Ariane 5 upper stage. PF-52 was previously used to develop the Vulcain and Vulcain 2 hydrogen turbopump and gas generator. This stand was capable of running turbopumps and gas generators together or independantly for 100 seconds. The stand will fill the much the same capacity for the VINCI turbopumps (LOX and LH2) as well as provide horizontal production acceptance engine level tests. The stand is equipped with both low and high pressure cryogenic systems and high pressure gaseous systems. The stand uses two 75 m3 LH2 run tanks for low pressure cryogenic systems. The turbopumps are fed with 10" diameter lines with fluid transfer obtained by GH2 tank pressurization. GH2 is held at ambient temperature in a 19 m3 storage facility held at 200 bar. LOX is supplied by two 35 m3 tanks, one of which is used during chill down, the other for pump supply. Lox supply to the turbopumps is also through 10" diameter lines with fluid transfer obtained by GN2 tank pressurization. GN2 is held at ambient temperature in a 12 m3 storage facility held at 200 bar. For high pressure cryogenic systems, LH2 is supplied by a 12m3 tank held at 400 bar with fluid transfer by high GH2 tank pressurization. The high pressure GH2 is supplied from two tanks, 20 m3 each, held at 800 bar. LOX is supplied for high pressure tests from a two m3 tank held at 400 bar with fluid transfer obtained by GN2 tank pressurization. The high pressure GN2 is supplied from one 6 m3 tank held at 800 bar. Data acquisition includes 600 low frequency measurement channels, 48 high frequency measurement channels, 1024 digital inputs on process events, 512 digital outputs on valve operation, and 32 analog outputs for control valve operation. Data acquisition rates can reach 1000 sps per channel on 256 grouped channels.

SEP-Melun-Villaroche: This test site has at least three test stands. The largest is a horizontal, cryogenic stand used to test the Ariane-1 HM7 engine. It is thrust rated for a maximum 450 K-lbf class engine and is quite similar to the Vernon PF-41 stand described above. A second stand is available for testing high thrust, storable (UDMH/N2O4) engines in the 180 K-lbf thrust class. A third test facility is available for small to medium sized cryogenic engines (LOX/LH2) in the 14 K-lbf class.

Villaroche also has a test rig for testing cryogenic turbopumps in the 15 K-lbf class, plus other smaller test benches for component or sub-assembly testing. A new test facility is under construction for testing the next generation cryogenic upper stage engines. This new facility will have altitude simulation capability.

ELA 3 French Guiana: The Ariane 5 is launched from the ELA 3 stand located in French Guiana. Cryogenic Main Stage development and qualification tests were conducted on the ELA 3 pad. A Nitrogen, LOX, and LH2 production plant is located near the ELA 3 facility to support engine testing if required.

German Facilities

DLR Lampoldshausen: This site has been used to conduct both development and acceptance test firings for the Ariane 4 Vulcain and Ariane 5 Vulcain-2 engines. The P3.2 stand was used to develop the Vulcain combustion chamber. The P5 stand (identical to the French PF-50 facility, see comments above) is currently used for Vulcain-2 thrust chamber, component, and engine testing. P5 has been rated to test engines up to 900 K-lbf and uses a high-pressure feed system with large propellant tanks to facilitate long duration testing. DLR has two high-altitude facilities, namely P1.5 and P4.2, the former of which will be replaced by P1.0, which is under construction. The P4 facility has two test cells. The P4.1 cell was intended for sea level testing and is thrust rated at 157 K-lbf. The P4.2 cell was designed for high-altitude test simulation though subsequent modification allows it to be used as a sea level stand as well. Current planning is to modify the P4.1 cell to facilitate vertical development test firings on the new, restartable, cryogenic, 35 K-lbf thrust class VINCI upper stage engine for the Ariane 5. The P4.2 cell is employed to test Aestus upper stage engine currently used on the Ariane 5. The P4 facility is supplied with high pressure (200 bars) nitrogen that is used to pressurize propellant run tanks and post test purge activity. The facility is also supplied with cooling water from several storage tanks. Transfer of water to the test site is via a one meter diameter line. There is also a 300 m3 water tank underneath a pump room for extinguishing purposes and to supply the steam generator supporting the P4.2 cell. Propellant storage tanks are located on either side of the test facility. Storage tanks are stainless steel with a capacity of 25 m3 at 5 bars. DLR also has a high pressure combustion research facility designated as P8. This facility has two identical test cells and is serviced by high pressure LOX and gaseous hydrogen. Test duration is 15 seconds at maximum propellant flow rates.

Japanese Facilities

Kakuda Propulsion Center: The center re-opened after expansion in 1980. The Center's expertise is in the development of LOX/LH2 engines. The main facilities of the Center include a high altitude simulation test stand, an integrated feed system test laboratory, and a tank thermal characteristics chamber. The engine test facility was used for horizontal testing of the LE-5A engine used on the HII launch vehicle.

Yoshinobu Launch Complex: Located at the Tanegashima Space Center, this complex was designed to test the HII LE-7A engine as well as launch the integrated vehicle. The engine test facility shares storage and supply accommodations for propellants (liquid hydrogen, liquid oxygen, helium, and nitrogen) as well as water and electricity with the launch complex. During testing, the engine is in a vertical position to simulate actual conditions at launch.

The liquid hydrogen storage facility has two globular, dual walled hydrogen tanks, each with a capacity of 540 m3. The overall hydrogen storage system is also assisted by two LH2 vaporizers , each with a capacity of 480 Nm3/hr. In addition there is one LH2 service tank (50m3), one GHe buffer tank (10m3), and five GH2 storage tanks (20m3). The engine test stand run tank has a capacity of 240 m3 and a catch tank of 20 m3.

The liquid oxygen storage system can service both launch operations as well as the engine test facility. Two LOX tanks are available, each with a capacity of 160 m3. The system is assisted by eight LOX vaporizers, each with a capacity of 4200 Nm/hr. The test stand run tank capacity is 85 m3. Continuous test firing of the LE-7A for 350 seconds is possible.

Noshiro Testing Center (NTC): This facility, opened in 1962, conducts ground tests primarily of solid rockets. The facility also has multipurpose vacuum firing test cells, a vertical liquid engine test stand, a cryogenic propellant test house, and various support facilities. This facility is heavily involved in the testing of theATREX-500 air turboramjet being developed for flyback booster concepts.

MHI Tashiro Test Center: This facility was used to conduct LE-5/5A/5B sea level and stage testing.

Indian Facilities

Liquid Propulsion Systems Center (LPSC): LPSC is responsible for R&D in liquid propulsion, earth storable and cryogenic engines, stages and associated components for launching spacecraft. Their test facilities are located at Mahendragiri in Tamil Nadu. The Principal Test Stand (PST) was commissioned in 1987 for the full duration (150 sec) testing of the testing of the PSLV L37.5 Vikas stage two engine. Altitude facilities are also available for testing the PSLV's 1.68 K-lbf motor. Current test activity is focused on a one ton cryogenic engine that is a subscale development unit for the 15 K-lbf thrust class engine intended for the

GSLV. Planned test duration for this subscale LOX/LH2 engine is 120 seconds. The test facility includes an integrated liquid hydrogen plant.

Chinese Facilities

The China Academy of Launch Vehicle Technology (CALT) near the town of Nan Yuan 15 km south of the capital develops/builds cryogenic engines. Shanxi Liquid Rocket Engine Company (SLREC) builds storable engines and also handles solid motors.

Very little information was found concerning Chinese liquid rocket engine test capability. There is reference to at least one, "multi-usage engine testbed', a large (59x41x22m) engine test-bed, a cryogenic engine test-bed, and a simulated high altitude testbed. In addition there is reference to a "full scale rocket test firing platform" which may be construed to be equivalent to a stage test facility, most likely located at the Jiuquan, Xichang, or Talyuan launch sites. Reference (1) states, "The Beijing Rocket Test Center 50 km southwest of Beijing maintains five major test stands. No 1 handles altitude testing of spacecraft thrusters up to 490 N, No 2 provides single-engine cryogenic facilities with No 4 accepting a complete H-8 cryogenic stage, and No 5 is devoted to hydrazine engines. Other test facilities are operated at the launch sites and SLREC probably has stands for storable engines. "

Table 1. Performance Data for LOX/Kerosene Booster Rocket Engines

Designation	Cycle	Thrust Lbf (kN)	MR	Pc psia (Mpa)	Isp Sec	Expansion Ratio	Throttle	Restarts
F-1	Gas Generator	1,522,000 SL (6770) 1,748,200 vac (7776)	2.27	982 (6.77)	265.4 SL 304.1 vac	16:1	100%	None
H-1	Gas Generator	205,000 SL (912) 230,170 vac (1024)	2.23	700 (4.83)	263 SL 295.3 vac	8:1	100%	None
LR87-AJ-1	Gas Generator	300,000 SL (1330)	1.91	580 (4.0)	249 SL	8:1	-	None
MA-3 Booster	Gas Generator	330,000 SL (1468)	-	-	250 SL	8:1	100%	None
MA-3 Sustainer	Gas Generator	57,000 SL (254)	-	-	214 SL	25:1	100%	None
MA-5 Booster	Gas Generator	377,500 SL (1679) 423,000 vac (1882)	2.25	639 (4.41)	259 SL 292 vac	8:1	100%	None
MA-5 Sustainer	Gas Generator	60,500 SL (269) 84,400 vac (375)	2.27 +/-15%	719 (4.96)	220 SL 309 vac	25:1	100%	None
MA-5A Booster	Gas Generator	429,500 SL (1911)	2.25	736 (5.07)	265 SL	8:1	100%	None
MA-5A Sustainer	Gas Generator	60,500 SL (269) 84,400 vac (375)	2.27 +/-15%	719 (4.96)	S 220 SL S 309 vac	25:1	100%	None
NK-15/-33	ORSC	339,000 SL (1510) 378,000 vac (1680)	2.55	2109 (14.54)	297 SL 331 vac	27.7:1	55-104%	None
RD-170/-171	ORSC	1,632,000 SL (7259) 1,777,000 vac (7904)	2.6	3560 (24.5)	309 SL 337 vac	36.4:1	50-100%	None
RD-180	ORSC	860,200 SL (3826) 933,400 vac (4152)	2.72	3722 (25.66)	337.8 vac	37:1	47-100%	None
RS-27	Gas Generator	207,000 SL (921) 231,700 vac (1031)	2.25	700 (4.83)	263 SL 295 vac	8:1	100%	None
RS-27A	Gas Generator	200,000 SL (890) 237,000 vac (1054)	2.245	700 (4.83)	255 SL 302 vac	12:1	100%	None

Table 2. Performance Data for LOX/Kerosene Upper Stage Rocket Engines

Designation	Cycle	Vac Thrust Lbf (kN)	MR	Pc psia (Mpa)	Vac Isp Sec	Expansion Ratio	Throttle	Restarts
LR91-AJ-1	Gas Generator	80,000 (356)	-	653 (4.5)	311	25:1	-	None
NK-15B/-43	ORSC	395,000 (1760)	2.6	2109 (14.54)	345	80:1	55-104%	None
RD-120	ORSC	187,400 (833.6)	2.6	2360 (16.3)	350	106:1	85-100%	None

Table 3. Performance Data for LOX/Hydrogen Booster Rocket Engines

Designation	Cycle	Vac Thrust lbf (kN)	MR	Pc psia (Mpa)	Isp sec	Expansion Ratio	Throttle	Restarts
LE-7	FRSC	243,000 (1080)	6.0	1840 (12.7)	446	52	-	None
RD-0120	FRSC	418,000 (1860)	6.0	2990 (20.6)	455.5	85.7	25-106%	None
SSME	FRSC	470,000 (2090)	6.0	3000 (20.7)	453.5	77.5	65-109%	Reusable
Vulcain	GG	257,400 (1145)	5.3	1600 (11.0)	430.6	45	-	None

Table 4. Performance Data for LOX/Hydrogen Upper Stage Rocket Engines

Designation	Cycle	Vac Thrust lbf (kN)	MR	Pc psia (Mpa)	Isp sec	Expansion Ratio	Throttle	Restarts
HM7A	GG	13,500 (60)	4.5	440 (3.0)	440.8	63.5	-	None
HM7B	GG	13,500 (60)	4.76	510 (3.5)			-	
J-2	GG	230,000 (1020)	4.5 ,5.5 nom	750 (5.2)	425	27.5	-	Multi
J-2S	Tap-off	265,000 (1180)	5.5	1200 (8.3)	436	40	17-100%, idle	Multi
LE-5	GG	23,150 (103)	5.5	524 (3.61)	449	140	-	One
LE-5A	Open Expander	27,400 (122)	5.0	577 (3.98)	452	130	idle	Multi
LE-5B	Open Expander	30,800 (137)	5.0	525 (3.62)	447	110	60%, idle	Multi
RL10A-1	Closed Expander	15,000 (66.7)	-	300 (2.1)	422	40	-	None
RL10A-3-3A	Closed Expander	16,500 (73.4)	4.4-5.6, 5.0 nom	475 (3.28)	444.4	61	-	Multi
RL10A-4	Closed Expander	20,800 (92.5)	4.9-5.8, 5.5 nom	578 (3.99)	449	84	-	Multi
RL10A-4-1	Closed Expander	22,300 (99.2)	4.9-5.8, 5.5 nom	610 (4.21)	450.5	84	-	Multi
RL10B-2	Closed Expander	24,750 (110)	5.88	633 (4.36)	466.5	285	-	Multi
YF-73	GG	9,910 (44.1)	5.0	389 (2.682)	420	40	-	One
YF-75	GG	17,600 (78.5)	5.0	532 (3.67)	440	80	-	One

Table 5. Booster LOX/Kerosene Engine Development and Qualification Testing Summary Including Flight Success Rates

Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Nominal Burn Time (secs)	Feasibility Engines	Feasibility Firings	Feasibility Seconds	Development including stage firings Engines	Development including stage firings Firings	Development including stage firings Seconds	Qualification including stage firings Engines	Qualification including stage firings Firings	Qualification including stage firings Seconds	Total Development and Qualification including stage firings Engines	Total Development and Qualification including stage firings Firings	Total Development and Qualification including stage firings Seconds	Flight Success Rate	Number of Engines Flown
F-1	8 yrs ('59-'66)	20 / 2250	165	-	-	-	-	-	-	2	34	>2255	56	2805†	252,958†	100.0%	65
H-1 165K	2 yrs ('58-'60)	-	165	-	-	-	-	-	-	-	-	-	17	85	-	100.0%	32
H-1 188K	3 yrs ('60-'62)	-	165	-	-	-	-	-	-	-	-	-	27	1,100	-	97.9%	48
H-1 200K	2 yrs ('63-'65)	-	165	-	-	-	-	-	-	-	-	-	48	1,700	-	N/A	0
H-1 205K	2 yrs ('65-'66)	-	165	-	-	-	-	-	-	-	-	-	16	800	-	100.0%	72
LR87-AJ-1	4 yrs ('55-'58)	-	138	-	-	-	-	-	-	1	46	3,579	-	-	-	-	-
MA-3 Booster	3 yrs ('58-'60	-	-	-	-	-	-	-	-	3	44	-	-	-	-	98.2%	279
MA-3 Sustainer	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	96.4%	138
MA-5 Booster	3 yrs ('61-'64)	-	174	-	-	-	-	-	-	-	-	-	-	-	-	98.7%	148
MA-5 Sustainer	3 yrs ('61-'64)		266	-	-	-	-	-	-	-	-	-	-	-	-	98.7%	148
MA-5A Booster	3 yr ('88-'91)	-	170	0	0	0	0	0	0	1	29	748	1	29	748	100.0%	51
MA-5A Sustainer	3 yr ('88-'91)		289	0	0	0	0	0	0	1	12	716	1	12	716	100.0%	51
NK-15/NK-15B	5 yrs ('64-'69)	1 / 110	110	-	-	-	-	-	-	-	-	-	199	450	40,200	97.7%	88*
NK-33 / NK-43	5 yrs ('69 - '74)	3 / 365	110	-	-	-	-	-	-	9	39	4,875	101	350	61,651	N/A	0
RD-171	10 yrs ('75-'85)	-	150	-	346	19,685	-	-	-	-	-	-	~80	~275	~25,000	95.9%	49
RD-180 (Atlas III)	3 yrs ('96-'99)	-	186	-	-	-	8+	70	10,956	4+	25	4,618	11+	95	15,574	100.0%	1
RD-180 (Atlas V)	1 yr ('99-'00)	-	230	-	-	-	3+	19	3,420	1	5	1,024	4+	24	4,444	N/A	0
RS-27	1 yr ('72)	-	265	-	-	-	-	-	-	-	-	-	-	-	-	100.0%	101
RS-27A	1 yr ('88)	-	265	0	0	0	0	0	0	1	22	-	1	22	-	100.0%	81

† = includes production due to lack of further information
* Two engines on the 1st flight were shutdown prior to liftoff and
2nd flight of 30 engines omitted since vehicle did not clear the tower

Table 6. Upper stage LOX/Kerosene Engine Development and Qualification Testing Summary Including Flight Success Rates

Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Nominal Burn Time (secs)	Feasibility			Development including stage firings			Qualification including stage firings			Total Development and Qualification including stage firings			Flight Success Rate	Number of Engines Flown
				Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds		
LR91-AJ-1	4 yrs ('55-'59)	-	225	-	-	-	-	-	-	1	39	2,933	-	-	-	-	-
NK-43	5 yrs ('69 - '74)	3 / 365		-	-	-	-	-	-	-	-	-	5	13	969	N/A	0
RD-120	10 yrs ('75-'85)	-	315	-	-	-	-	-	-	-	-	-	-	-	-	94.7%	38

Table 7. Booster LOX/LH2 Engine Development and Qualification Testing Summary Including Flight Success Rates

Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Burn Time (secs)	Feasibility			Development including stage firings			Qualification including stage firings			Total Development and Qualification including stage firings			Flight Success Rate	Numb of Engin Flow
				Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds	Engines	Firings	Seconds		
LE-7	11 years ('83–'94)	- / 1720	350	2	-	-	9	-	-	5	-	-	14	282	15,639	88.0%	8
RD-0120	11 years ('76-'87)	4 / 2000	460	-	-	-	-	-	-	3	-	-	90	793	163,000	100.0%	8
SSME†	9 years ('72-'81)	55 / 27,000	520	0	0	0	16+	627	77,135	4+	99	33,118	20+	726	110,253	99.7%	303
Vulcain	10 years ('85-'95)	20 / 6000	575	0	0	0	12+	-	-	2	-	-	14+	278	87,000	100.0%	7

† SSME includes production engines tested up to first flight

Table 8. Upper stage LOX/LH2 Engine Development and Qualification Testing Summary Including Flight Success Rates

Designation	Time from Program Start to Qualification	Engine Life (firings / secs)	Burn Time (secs)	Feasibility Engines	Feasibility Firings	Feasibility Seconds	Development including stage firings Engines	Development including stage firings Firings	Development including stage firings Seconds	Qualification including stage firings Engines	Qualification including stage firings Firings	Qualification including stage firings Seconds	Total Development and Qualification including stage firings Engines	Total Development and Qualification including stage firings Firings	Total Development and Qualification including stage firings Seconds	Flight Success Rate	Number of Engines Flown
HM7A	6 yrs ('73-'79)	-	570	-	-	-	-	-	-	-	-	-	11	-	25,000	90.0%	10
HM7B	3 yrs ('80-'83)	-	745	-	-	-	-	-	-	-	-	-	10	-	-	96.6%	118
J-2	6 yrs ('60-'66)	30 / 3750	450	-	-	-	36	1,700	116,000	2	30	3,807	38	1,730	120,000	97.7%	86
J-2S*	4 yrs ('65-'69)	30 / 3750	450	1	-	10,756	6	273	30,858	Development only			Development only			N/A	0
LE-5	8 yrs ('77-'85)	-	600	3	54	2,587	5	188	13,414	3	134	14,292	8	322	27,706	100.0%	9
LE-5A	5 yrs ('86-'91)	14 / 2920	535	0	0	0	2	66	6,918	2	52	9,238	4	118	16,156	86.0%	7
LE-5B	4 yrs ('95-'99)	16 / 2236	534	1	8	237	1	23	1,077	4	79	11,963	5	102	13,040	N/A	0
RL10A-1	3 yrs ('58-'61)	-	380	-	-	-	>230	-	-	-	-	-	>230	707	71,036	N/A	0
RL10A-3-3A	1 yr ('80-'81)	23 / 5800	600	0	0	0	4+	214	18,881	1	24	5,864	5+	238	24,745	97.6%	84
RL10A-4	3 yrs ('88-'91)	27 / 4000	400	3+	51	8,321	2+	73	15,055	1	38	5,265	3+	111	20,320	100.0%	34
RL10A-4-1	1 yr ('94)	28 / 3480	400	0	0	0	1	5	2,068	1	42	3,683	2	47	5,751	100.0%	49
RL10B-2	3 yrs ('95-'98)	15 / 3500	700	1	119	1,701	3+	125	11,605	1	30	4,044	4	155	15,649	50.0%	2
YF-73	7 yrs ('76-'83)	-	800	-	-	-	-	-	-	-	-	-	-	120	30,000	85.0%	13
YF-75	7 yrs ('86-'93)	-	500	-	-	-	-	-	-	-	-	-	-	-	28,000	100.0%	8

* J-2S was never qualified

Table 9. Test Program Summary

	Design and Develop Period	# of Test Seconds		# of Test Firings		# of New Test Engines	
	Recent Historical Trend	Recent Historical Trend	High Success Rate Trend	Recent Historical Trend	High Success Rate Trend	Recent Historical Trend	High Success Rate Trend
New Booster	10 yrs avg (9-11 yrs)	90,000 avg (16,000-163,000)	40,000	500 avg (280-800)	400	16* avg (14-20)*	15
New Upper Stage	7 yrs avg (6-8 yrs)	28,000 avg (25,000-30,000)	40,000	200 avg (120-320)	400	10 avg (8-11)	15
Evolved Booster	2 yrs avg (1-3 yrs)	7,000 avg (1,000-15,000)	-	40 avg (20-100)	-	4 avg (1-11)	-
Evolved Upper Stage	3 yrs avg (1-5 yrs)	15,000 avg (6,000-20,000)	-	100 avg (50-150)	-	5 avg (2-10)	-

* Ignores large number of Russian booster engines required. See text.

Table 10. Propulsion Needs For 2001-2010 Engines (Ref. 9)

Engine/ System	Application	Key	Contractor	Test Needs	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Currently Where Testing Planned	Other Needs	Cycle	Propellants	Vac Thrust (lbf)	Test Duration (sec)	Ox Req'd for Test Duration (lbm)	Fuel Req'd for Test Duration (lbm)
AJ10-118K	Production Delta II Stage II	P	Aerojet	Injector											Aerojet, G-8		Pressure Fed	N_2O_4/ Aerozine-50	9,800	150	3,000	1,579
IHPRPT	USD I Demo	LF	P&W	Engine											P&W E-8		Expander	LOX / LH2	50,000	200	19,005	3,168
IHPRPT	USD II Demo	NC	TBD	Turbopump, TCA, Engine											**TBD**	Altitude	Expander	LOX / LH2	50,000	200	19,005	3,168
IHPRPT	USD III Demo	NC	TBD	Turbopump, TCA, Engine											**TBD**	Altitude	Expander	LOX / LH2	50,000	200	19,005	3,168
IHPRPT	Cryoboost I Demo	LF	Rocketdyne/ Aerojet	Engine											SSC, E-Complex		FFSC	LOX / LH2	275,000	200	104,068	17,345
IHPRPT	Cryoboost II Demo	NC	TBD	Turbopump, TCA, preburner, Engine											**TBD**	High pressure supply (>7000 psia)	FFSC	LOX / LH2	275,000	200	102,041	17,007
IHPRPT	Cryoboost III Demo	NC	TBD	Turbopump, TCA, preburner, Engine											**TBD**	High pressure supply (>7000 psia)	FFSC	LOX / LH2	275,000	200	100,948	16,825
IHPRPT	HC Boost II Demo	NC	TBD	Engine											**TBD**		ORSC	LOX / RP-1	266,500	200	113,553	43,674
IHPRPT	HC Boost III Demo	NC	TBD	Turbopump, TCA, preburner, Engine											**TBD**	High pressure supply (>8000 psia)	ORSC	LOX / RP-1	266,500	200	111,578	42,915
XRS-2200	X33 Demo	NC	Rocketdyne	Engine											SSC, A-1		Gas Generator	LOX / LH2	266,000	500	258,116	46,930
MA-5A Booster	Production	P	Rocketdyne	Engine											RKD, Alfa-1		Gas Generator	LOX / RP-1	472,500	167	185,181	82,302
MA-5A Sustainer	Production	P	Rocketdyne	Engine											RKD, Alfa-1		Gas Generator	LOX / RP-1	84,150	368	70,479	29,738
MB-60	Development	LF	Rocketdyne	Turbopump, Chamber, Engine, Altitude, Stg Sim											GRC	Altitude, Stage sim	Expander	LOX / LH2	60,000	500	54,793	9,447
MB-60	Production	NC	Rocketdyne	Engine											GRC		Expander	LOX / LH2	60,000	500	54,793	9,447
NK-33 (AJ26-58)	Kistler and J-1 upgrade development	LF	Aerojet	Engine, Stg Sim											Aerojet	Stage sim	ORSC	LOX / RP-1	379,000	150	123,910	47,842
NK-33 (AJ26-58)	Production	NC	Aerojet	Engine											Aerojet		ORSC	LOX / RP-1	379,000	130	107,389	41,463
NK-43 (AJ26-60)	Kistler development	LF	Aerojet	Engine, altitude, Stg Sim											Aerojet	Altitude, Stage sim	ORSC	LOX / RP-1	395,000	250	205,603	80,629
NK-43 (AJ26-60)	Production	NC	Aerojet	Engine											Aerojet		ORSC	LOX / RP-1	395,000	210	172,707	67,728
ARRE	SMV Demo	LF	Aerojet	Injector, Gas Generator, Engine											Aerojet	Altitude, Stage sim	?	98% H_2O_2 / RP-1	12,000	500	16,250	2,500

Key: CO= Concept Only NC = No Contract LF = Limited Funding D = Development P = Production

Color Code: Green= Current Commitment, Yellow= Anticipated Commitment

Table 10. Propulsion Needs For 2001-2010 Engines (Continued)

Engine/ System	Application	Key	Contractor	Test Needs	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	Currently Where Testing Planned	Other Needs	Cycle	Propellants	Vac Thrust (lbf)	Test Duration (sec)	Ox Req'd for Test Duration (lbm)	Fuel Req'd for Test Duration (lbm)
AR2-3A	X-37 demo	LF	Rocketdyne	Engine											SSC, E-3	Altitude, Stage sim	Gas Generator	90% H2O2 / JP-8	6,600	500	11,626	1,789
RD-180	Co-Production demo	NC	P&W	Engine, TBD											TBD		ORSC	LOX / RP-1	933,400	250	506,096	185,697
RL60	Development	LF	P&W	Turbopump, Chamber, Engine, Altitude											TBD	Altitude, Stage sim	Expander	LOX / LH2	65,000	500	59,908	9,985
RL60	Production	NC	P&W	Engine											TBD	Altitude	Expander	LOX / LH2	65,000	500	59,908	9,985
RS-27A	Production	P	Rocketdyne	Engine											RKD, Alfa-2		Gas Generator	LOX / RP-1	237,000	265	143,876	64,087
RS-68	Production	P	Rocketdyne	Engine											SSC, B-Complex		Gas Generator	LOX / LH2	745	300	467	78
RS-72	Development	NC	Rocketdyne	Engine											TBD	Altitude, Stage sim	Gas Generator	N2O4 / MMH	12	300	7	4
RS-76	SLI Demo	LF	Rocketdyne	Turbopump, Chamber, preburner, Engine											TBD	Stage sim	ORSC	LOX / RP-1	1,000,000	250	533,428	197,566
RS-83	SLI Demo	CO	Rocketdyne	Turbopump, Chamber, preburner, Engine											TBD	Stage sim	FRSC	LOX/LH2	786,000	500	750,239	125,040
Cobra	SLI Demo	Co	P&W/Aerojet	Engine											TBD	Stage sim, IHM	FRSC	LOX/LH2	800,000	500	753,532	125,589
RLX	SLI Demo	CO	P&W/Aerojet	Turbopump, Chamber, Engine											TBD	Stage sim, IHM	Expander	LOX/LH2	300,000	500	285,714	47,619
SSME	Production	P	Rocketdyne	Engine											SSC		FRSC	LOX / LH2	470,000	500	443,675	73,946
SSME	Upgrade Development	LF	Rocketdyne, P&W Aerojet & others	Turbopumps, Chamber, Engine											SSC		FRSC	LOX / LH2	470,000	500	443,675	73,946
Titan LRE's	Production support	P	Aerojet	Engine											Aerojet		Gas Generator	N2O4/ Aerozine-50				
Truax MA-3	Demo	LF		Engine											SSC	Stage sim	Pressure Fed	LOX/RP-1				
LCPE	SLI Demo	NC	TRW	Engine											SSC	Stage sim	Gas Generator	LOX/RP-1	1,000,000	500	1,216,216	450,450
AJAX	Paper engine	CO	P&W/Aerojet	Turbopump, Chamber, Preburner, Engine											TBD	Stage sim, IHM	ORSC	LOX/RP-1	1,011,000	250	520,276	208,110
RL10A-4-1	Production	P	P&W	Engine											P&W E-8	Altitude	Expander	LOX / LH2	22,300	1000	41,839	7,607
RL10B-2	Production	P	P&W	Engine											P&W E-8, AEDC ('01)	Altitude	Expander	LOX / LH2	24,750	1000	45,489	7,736

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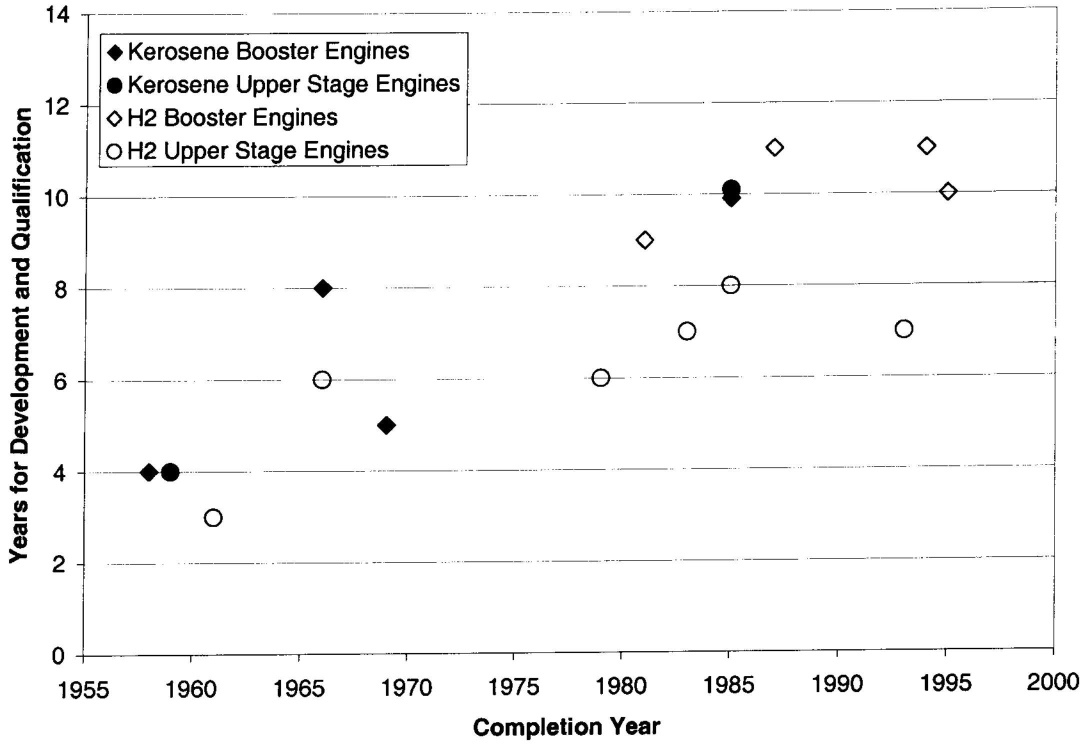

Figure 1. Years to develop and qualify new engine models

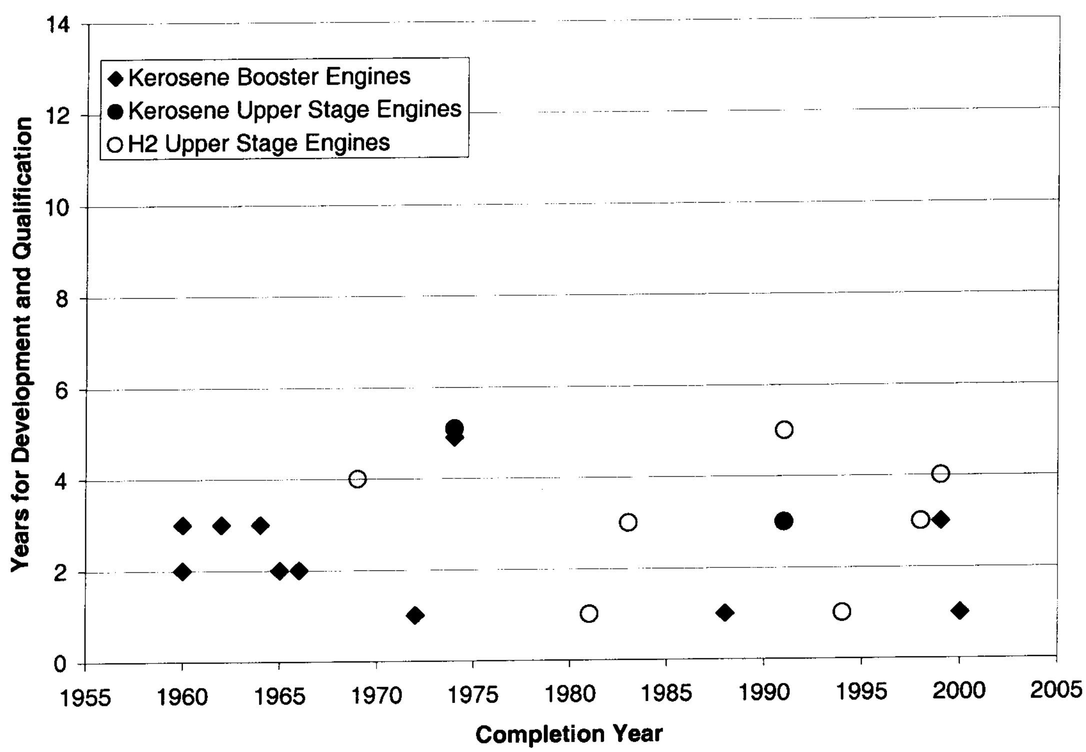

Figure 2. Years to develop and qualify evolved engine models

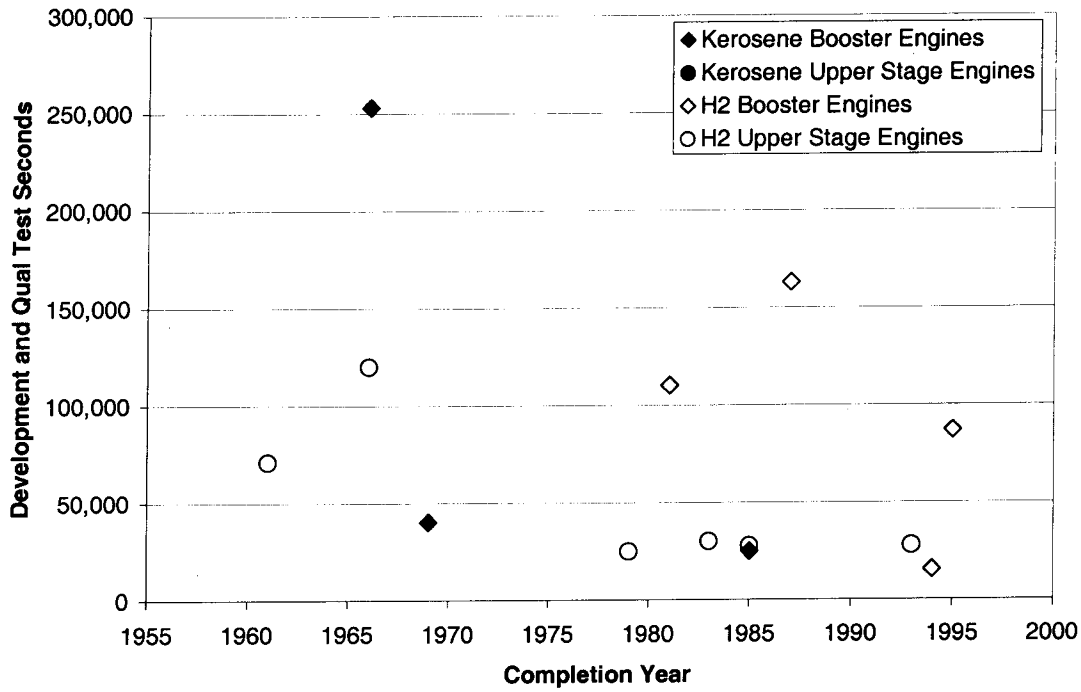

Figure 3. Number of test seconds for new engine models

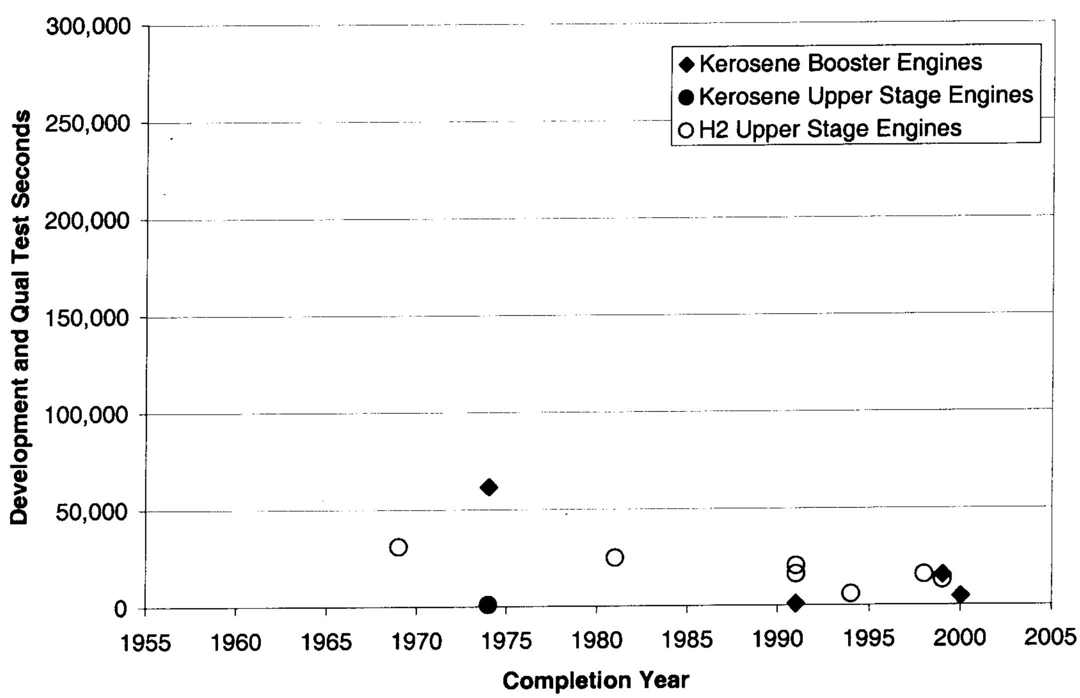

Figure 4. Number of test seconds for evolved engine models

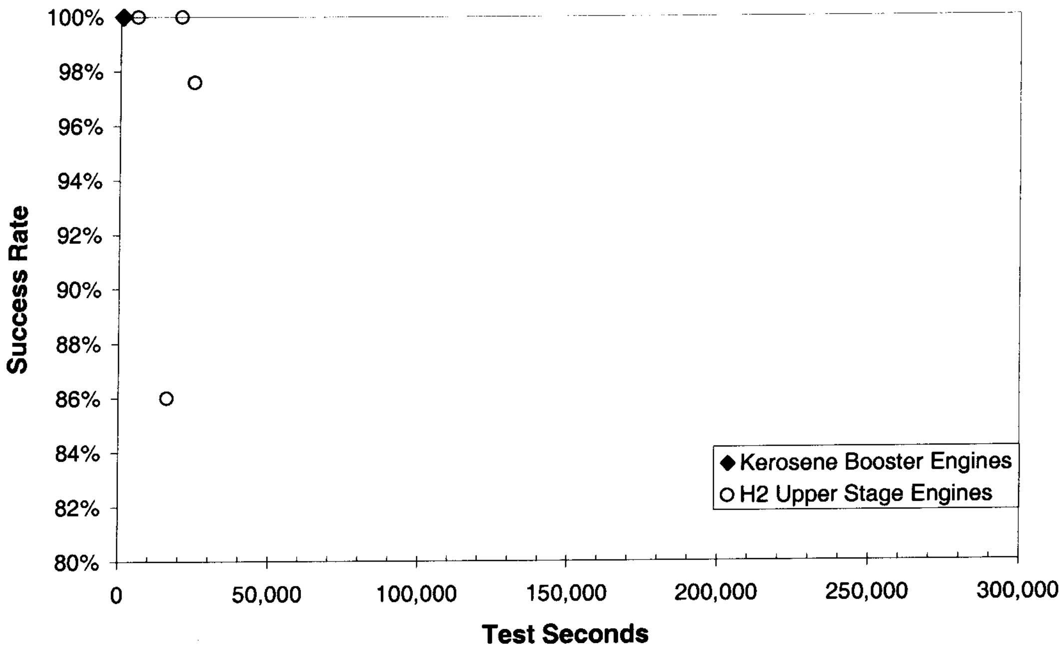

Figure 5. Success rate vs test seconds for new engine models

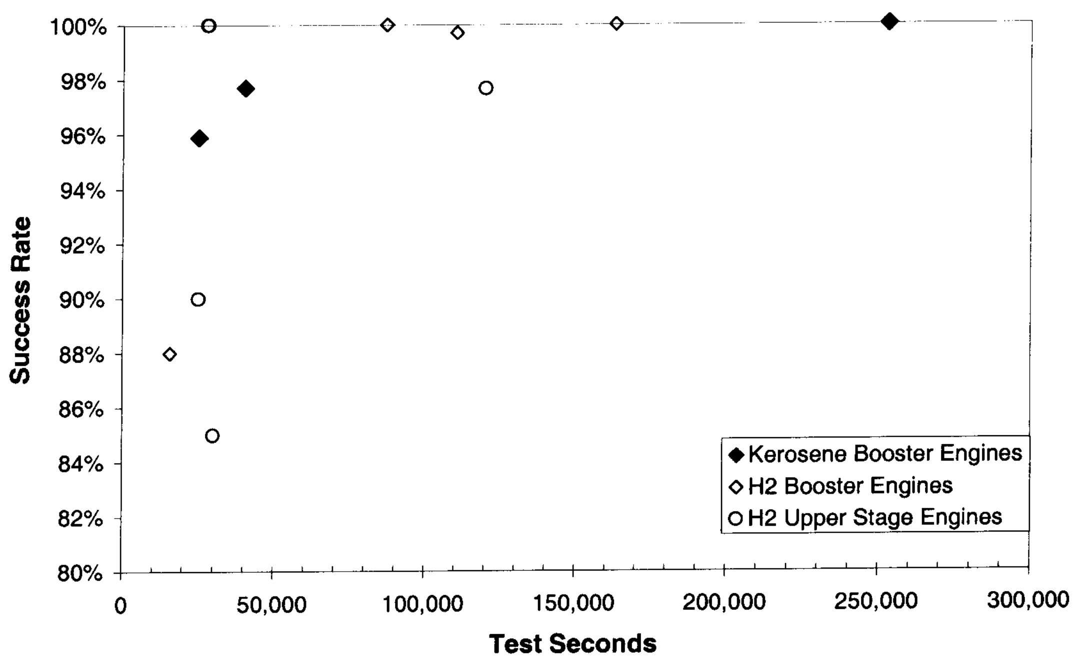

Figure 6. Success rate vs test seconds for evolved engine models

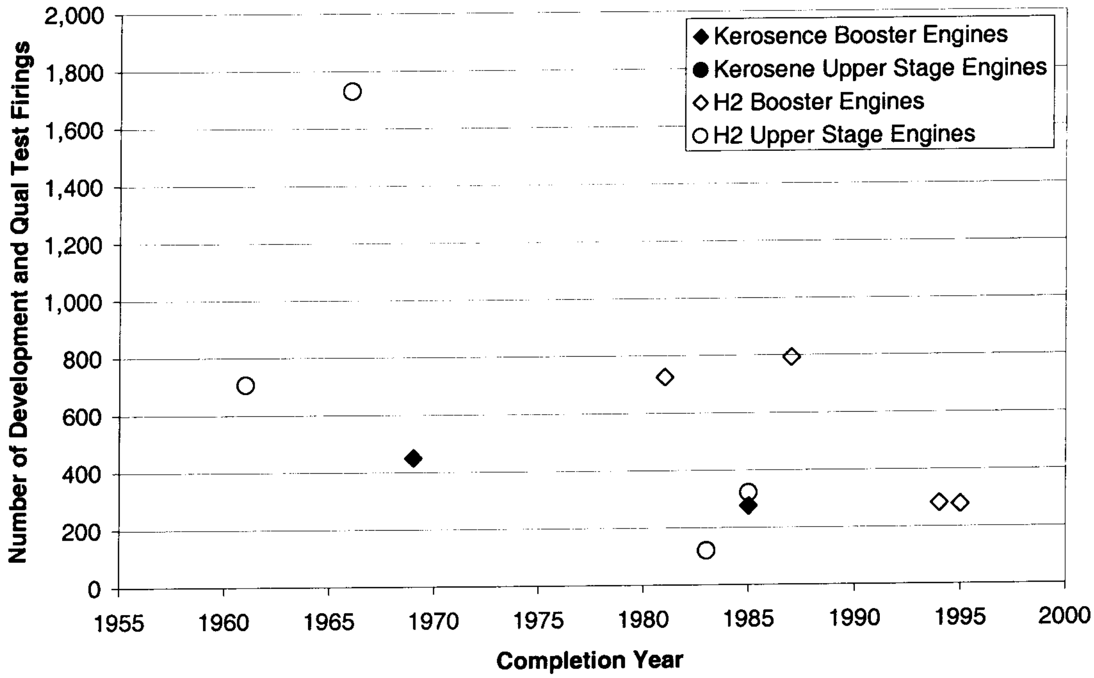

Figure 7. Number of test firings for new engine models

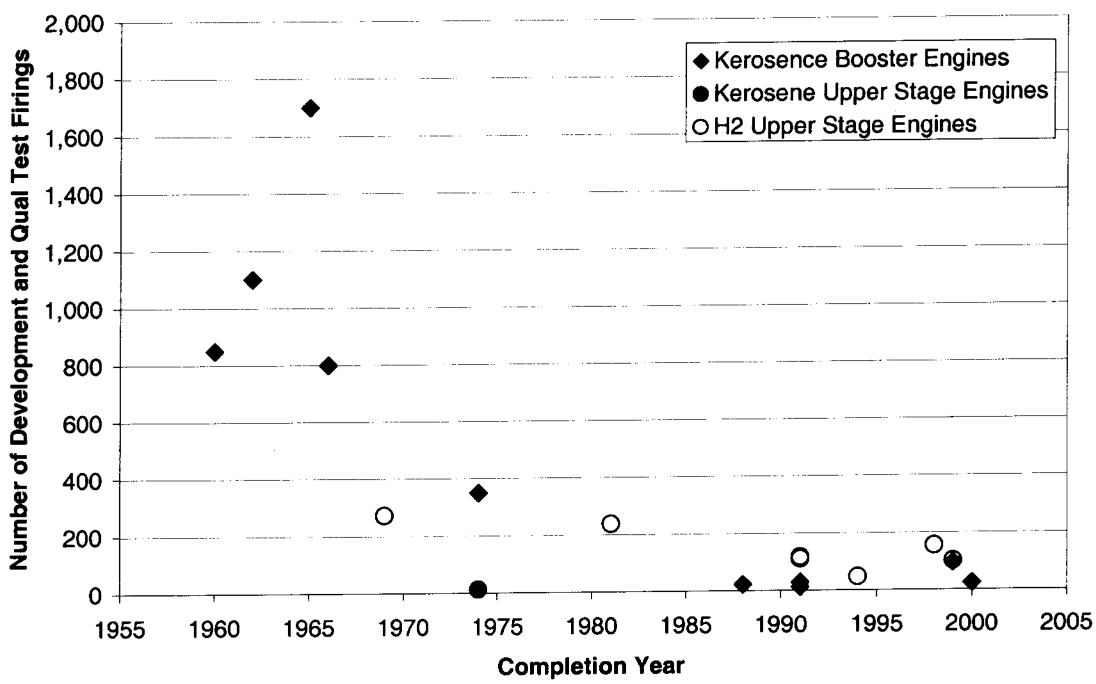

Figure 8. Number of test firings for evolved engine models

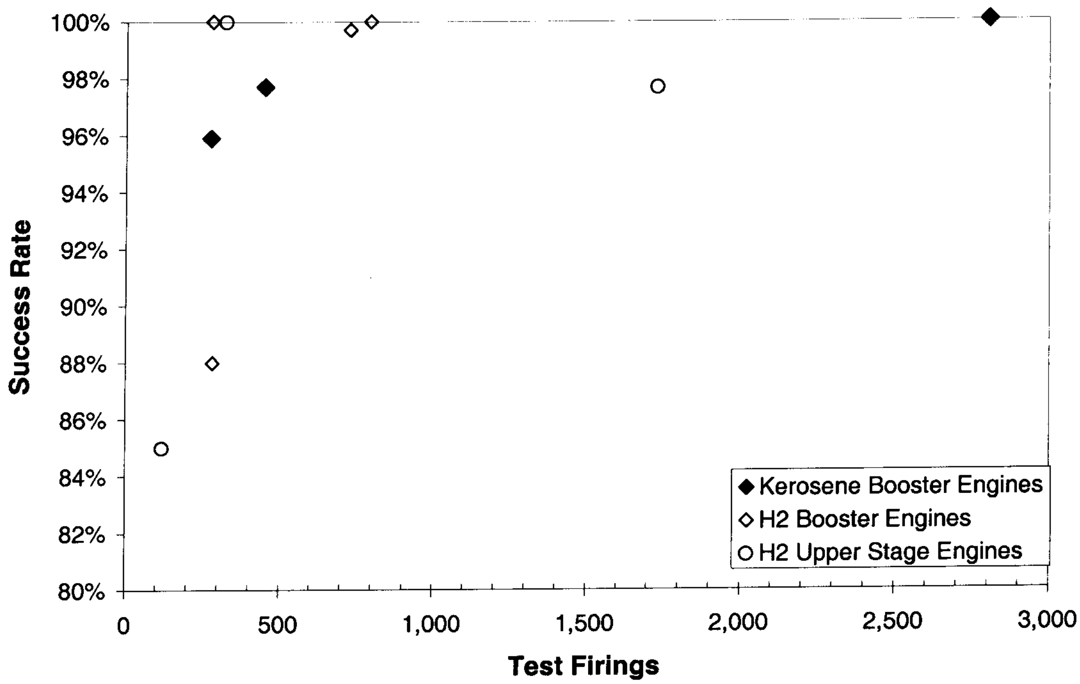

Figure 9. Success rate vs test firings for new engine models

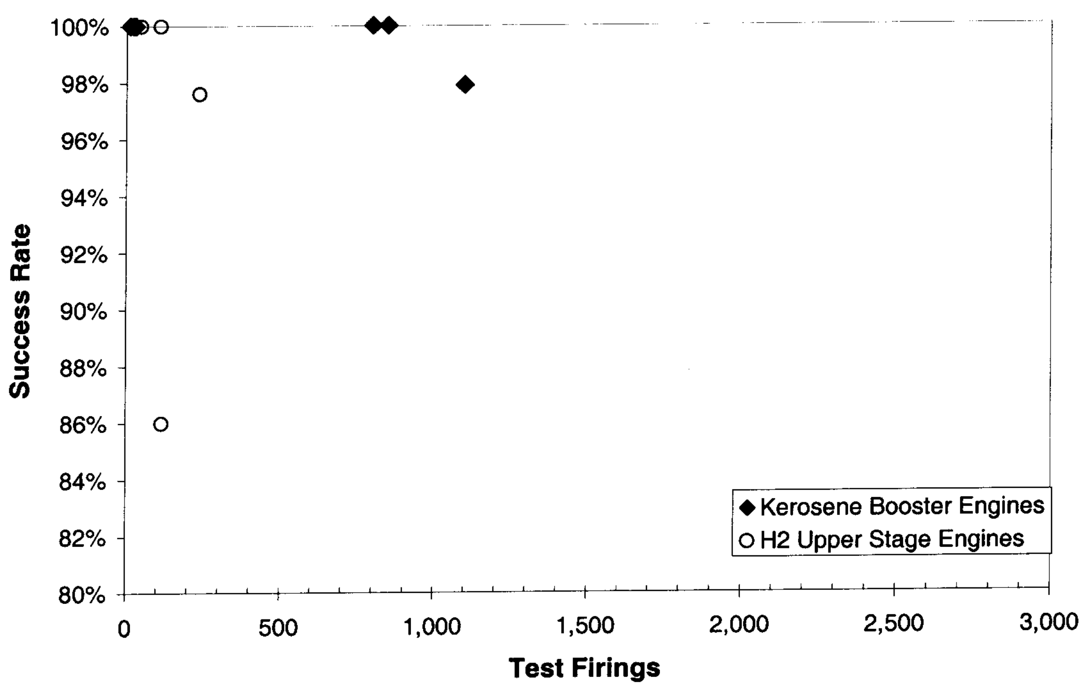

Figure 10. Success rate vs test firings for evolved engine models

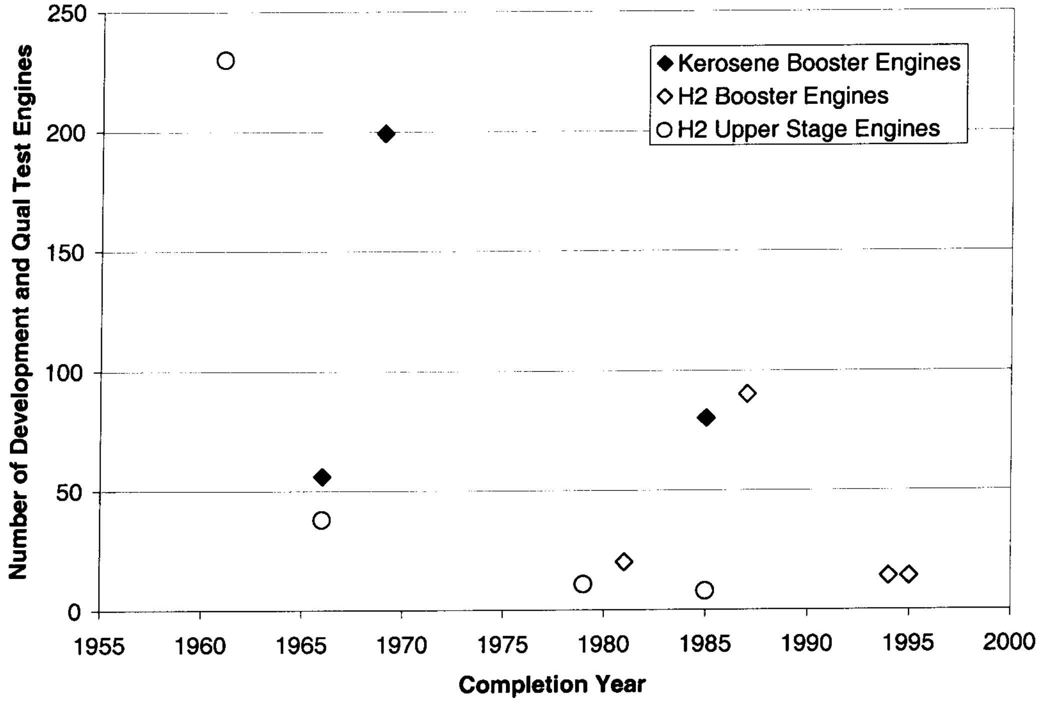

Figure 11. Number of test engines for new engine models

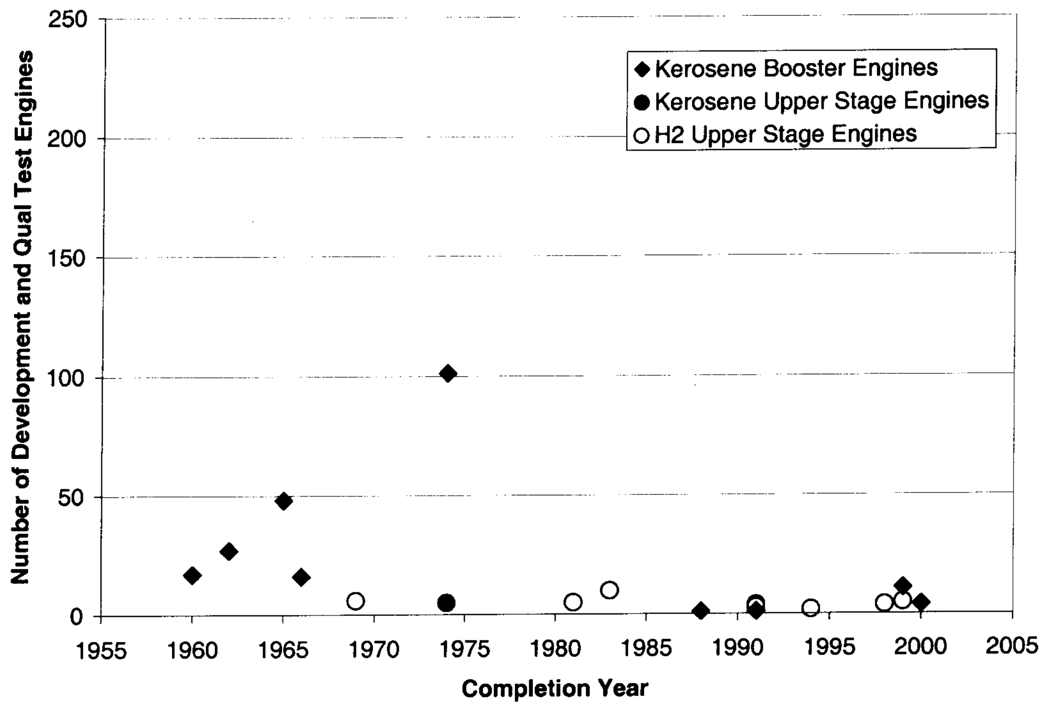

Figure 12. Number of test engines for evolved engine models

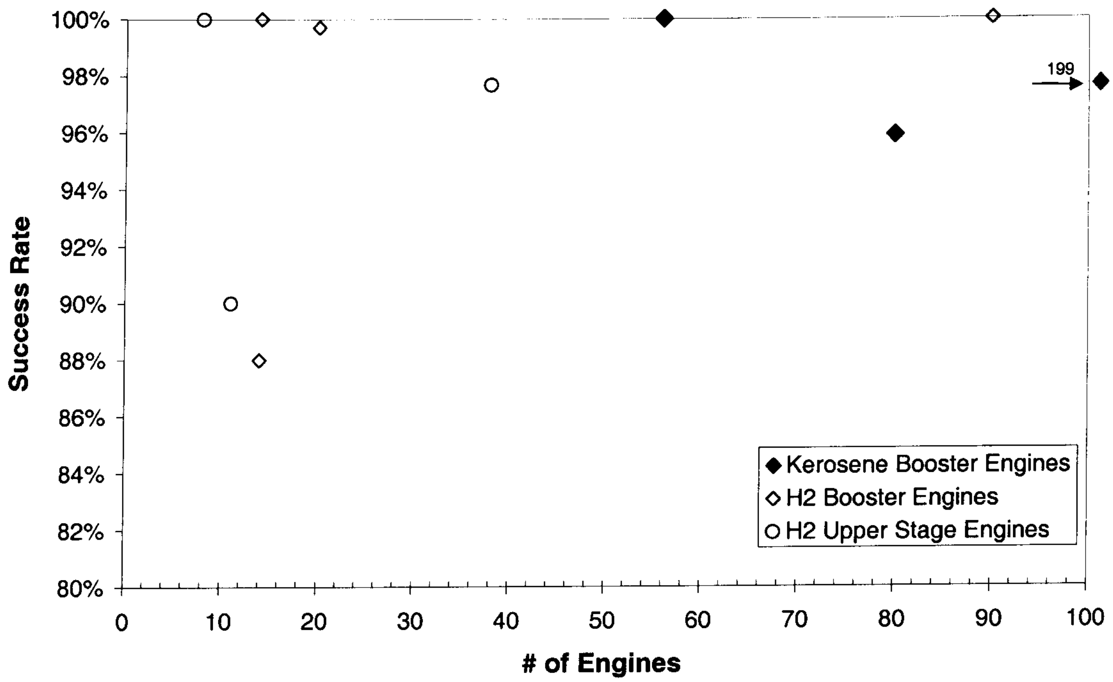

Figure 13. Success rate vs number of test engines for new engine models

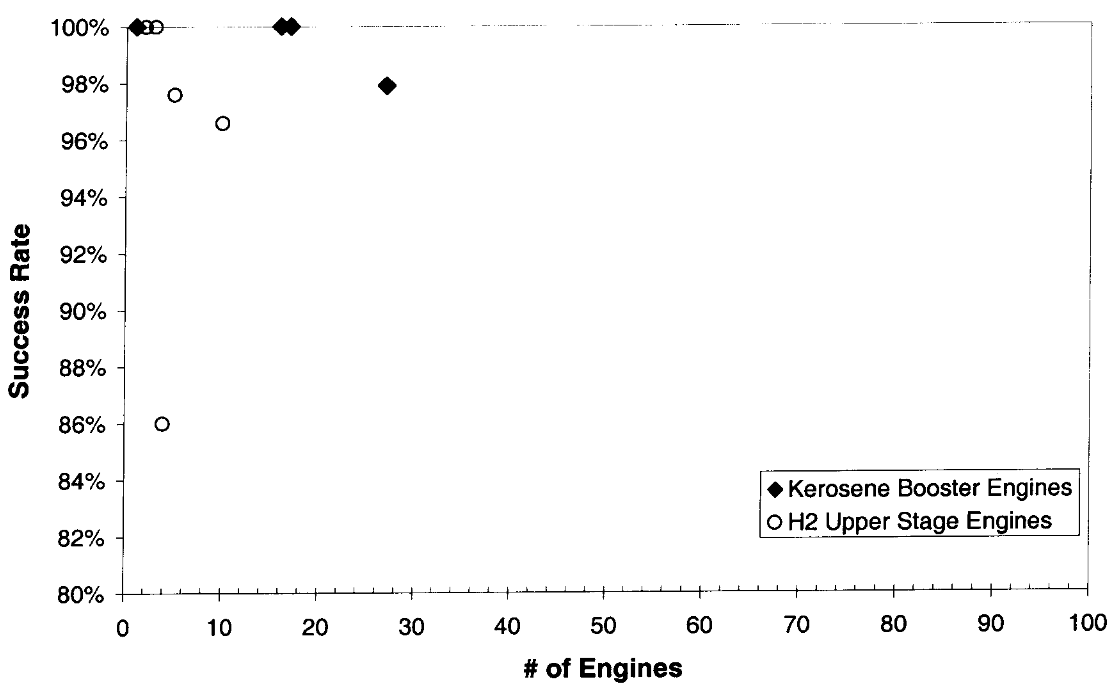

Figure 14. Success rate vs number of test engines for evolved engine models

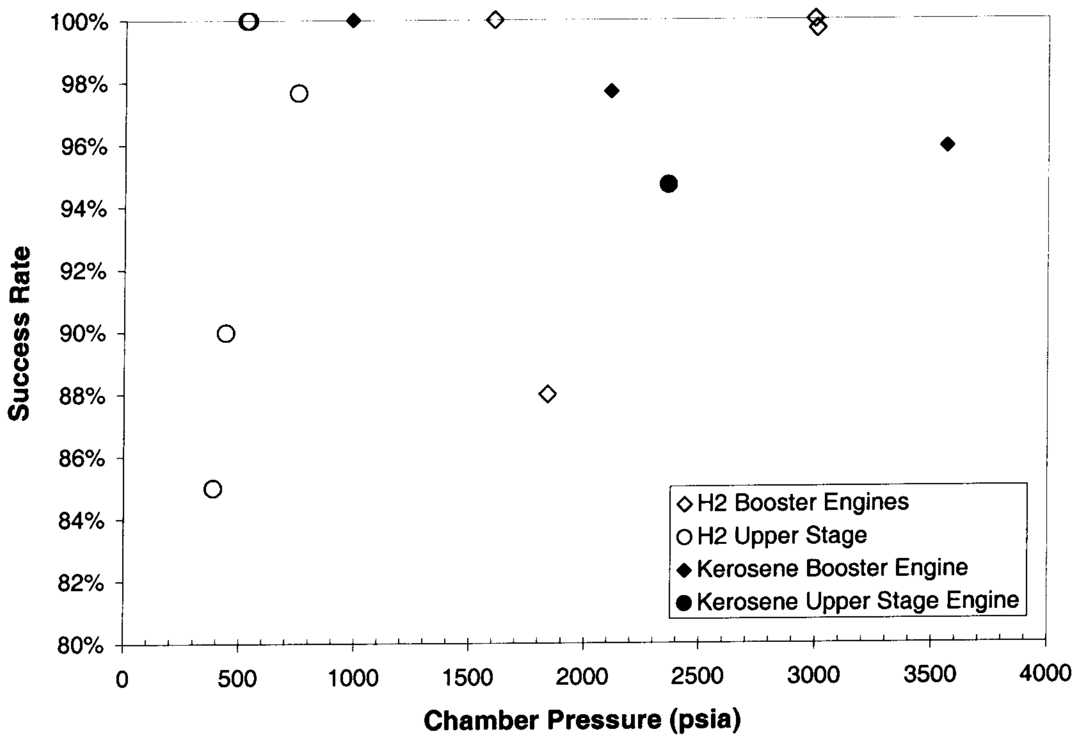

Figure 15. Success rate vs chamber pressure for new engines

References:

1. Emdee, J. L.; "A Survey of Development Test Programs for Hydrogen Oxygen Rocket Engines," AIAA-2001-0749, 29th AIAA Aerospace Sciences Meeting, Reno, NV, 2001.
2. Emdee, J. L.; "A Survey Of Development Test Programs For Lox/Kerosene Rocket Engines," AIAA-2001-3985, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Salt Lake City, UT, 2001.
3. Peery, S. and Minick, A.: "Design and Development of a 50K LOX/Hydrogen Upper Stage Demonstrator," 34th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, AIAA 98-3676, Cleveland, OH, 1998
4. USAF IPD brochure
5. Blanchard, B. and Fabrycky, W., "Systems Engineering and Analysis", Prentiss Hall, Englewood Cliffs, NJ, 1990
6. Liquid Rocket Engine Reliability Certification, Society of Automotive engineers, SAE ARP 4900, January 1996
7. Stennis Space Center Test Facilities Handbook, Fourth Edition, September 2001
8. Jane's Space Directory 2000-2001
9. SLI Propulsion Tasks, NASA Briefing, June 2001

General Web Sites

http://www.friends-partners.org/mwade/spaceflt.htm ...... Astronautix.com
http://hea-www.harvard.edu/~jcm/space/space.html .... Johnathon's Space Home Page
http://www.asi.org/adb/04/03/09/01/ .... Artemis Project Database
http://www.geocities.com/CapeCanaveral/Launchpad/1921/... Dragon In Space
http://www.fas.org/spp/guide/index.html .. Federation of American Scientists
http://yyy.tksc.nasda.go.jp/Home/Facilities/index_e.html .. NASDA Field Centers
http://www.slinews.com ..... Space Launch Initiative News
http://www.hq.nasa.gov/office/codei/nmlo/Pagelocations.htm .. NASA Locations
http://www.spaceandtech.com/spacedata .. Space Database
http://www.janes.com ..... Janes Space Directory

Foreign Web Sites

http://home.earthlink.net/~cliched/main_space.html ..... Soviet Space Site
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http://esapub/esrin.esa.it/rfs/rfs16/lieb16.htm ..... ESA
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http://www.geocities.com/CapeCanaveral/Launchpad/1921 ..... Go Taikonauts
http://www_tradoc.army.mil/dcscd/spaceweb .. Launch Systems and Launch Sites
http://www.nasda.go.jp/presskit/H-II_4_e/p-h2_6_e.html .. NASDA Launch and Control Facilities..
http://www.city.noshiro.akita.jp/eng/rocketeng.html ... Noshiro Rocket Testing Center

http://www.isas.ac.jp/e/about/center/ntc.html .. Noshiro Testing Center (NTC)
http://www.nasda.go.jp/home/facilities/e/kakuda2_e.html .. Kakuda Propulsion Center
http://www.aeroworldnet.com/1ra07217.htm .... Vintai Facilities
http://www.mcs.net/~rusaerog/space_centers.html .... Russian Space Centers
http://users.ev1.net/~larin/space_russia/niimash .... NIIMash
http://www.kerc.msk.ru/jpg/development/hre_e.shtml ..... Keldysh Research Center

NASA Web Sites

http://std.msfc.nasa.gov/capability/test_fac.html ...... MFSC
http://www.wstf.nasa.gov/Propulsion/Systems.htm ......WSTF
http://adam.grc.nasa.gov/plumbrookstation/pbtrial/prod02.htm ...... GRC
http://www.ssc.nasa.gov/propulsion .... SSC

DOD Web Sites

http://www.pr.afrl.af.mil/facilities/pr_west/index.html .... AFRL
http://www.atc.army.mil/~rttc .... RTTC
http://www.nawcwpns.navy.mil/r2/fs/Aeroheat.htm .... NAWC
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Commercial Web Sites

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http://www.boeing.com/defense-soace/space/propul ..... Boeing/RD
http://www.pratt-whitney.com ....United Technologies/Pratt&Whitney
http://www.trw.com/propulsion .... TRW
http://www.atlanticresearchcorp.com/test.html .... ARC
http://www.emrtc.nmt.edu/facilities/rts.html .... EMRTC

Related Reading

Matringe, L., "PF52 Test Stand for the New VINCI Rocket Engine", AIAA 2001-3383, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, 8-11 July 2001

Messer, B., Messe, E., Sewell, D., Lott, J., Sass, J., and Dutreix III, L., "Activation of the ELP UHP Propulsion Test Facility at Stennis Space Center, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, 8-11 July 2001

Bruce, R., Taylor, G., Beckmeyer, D., Ross, R., "Evolution of Hydrogen Peroxide Ground Test Capability", 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, 8-11 July 2001

Rahman, S., Gilbrech, R., Lightfoot, R., and Dawson, M., "Overview of Rocket Propulsion Testing at NASA Stennis Space Center", 11th Annual Symposium on Propulsion, Penn State University, 18 November 1999

Ryan, H.M., Solano, W., Holland, R., and Rahman, S., "Engineering the Future of Full-Scale Propulsion Testing", AIAA 2001-0746, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-1 January 2001

Dawson, M., "Development and Implementation of NASA's Lead Center for Rocket Propulsion Testing", AIAA 2001-0747, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-1 January 2001

Mendez, G., "Large Liquid Engine Test Facility", AIAA 2001-0608, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-1 January 2001

Santoro, R.J., Pal, S., and Woodward, R.D., "Rocket Testing at University Facilities", AIAA 2001-0748, 39th AIAA Aerospace Sciences Meeting & Exhibit, Reno, NV, 8-1 January 2001

"The New European Propulsion Standard", AIAA 2001-3967, 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, 8-11 July 2001

Turner, I.T., and Bajwa, A., "A Survey of Aircraft Engine Health Monitoring Systems", AIAA-99-2528, 1999

Zhu, H.W., Wang, K.C., and Chen, Q.Z., "A Statistical Approach to Fault Detection of Liquid Rocket Engine in Ground Test", 47th International Astronautical Conference, Beijing, China, October 1996

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