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Propulsion for the 21st Century—RS-68

B. K. Wood
The Boeing Company
Rocketdyne Propulsion & Power
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PROPULSION FOR THE 21ST CENTURY—RS-68

Byron K. Wood
Vice President and General Manager
Rocketdyne Propulsion and Power
The Boeing Company

Abstract

The RS-68 is the first liquid propulsion system in the world to be developed from the ground up, based on Cost as the Independent Variable (CAIV). In its creation, it is the first new U.S. engine certified to fly since the Space Shuttle Main Engine over 20 years ago. Rocketdyne has a long, successful history of over 50 years in expendable propulsion systems, starting with the Redstone with over 85 flights, Atlas with over 569 flights, Thor/Delta with over 669 flights, and Saturn/Apollo first, second and third stages with over 32 flights. This heritage is, of course, complemented by the unmatched, reusable engine flight heritage of over 300 SSME engine launches and a million seconds of testing.

Overview

Conceptual studies of the RS-68 were an outgrowth of the NASA Space Transportation Main Engine (STME) Project begun in 1988. In that program, NASA and all major U.S. propulsion contractors collaborated in trade studies on propellants, cycles, size and lessons learned to focus on reduced development cost for a new multi-application engine (Figure 1) for the United States.

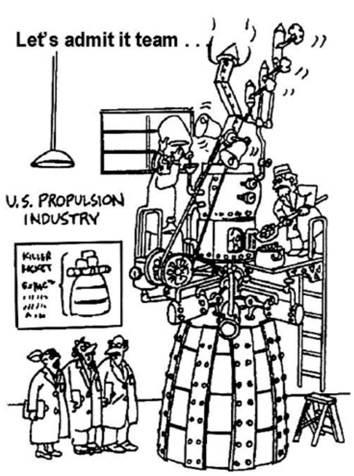

Figure 1. It's Time to Come Up with a New Engine

STME studies concentrated on a balance between cost and performance, but by the time the program was canceled in 1994 a new engine development cost projection of $1.1 billion with eight and one-half years to accomplish was on the table. Rocketdyne, recognizing that the price tag and cycle time would never be acceptable to the country, committed significant internal investment to establish an organizational culture, processes and tools to significantly beat the STME program forecast.

In 1995, the United States Air Force responded to escalating launch costs with a new program that called for a fresh generation of launch vehicles that could bring cost-to-orbit down by 25 to 50 percent. It was named the Evolved Expendable Launch Vehicle or EELV program.

In 1995, Rockwell International, Rocketdyne's then-parent company, made the decision to respond to the Air Force program in partnership with McDonnell Douglas in a new member of the Delta "family," which had decades of successful launches behind it. Powering the Delta IV would be the RS-68 from Rocketdyne Propulsion and Power. It was not until after the Boeing acquisition of Rockwell, and then McDonnell Douglas, that the foresight for significant private industry investment in a new rocket engine came into being—this based on the firm belief and in-place evidence that Rocketdyne could truly do the job for less than that projected for STME.

In 1997, RS-68 development was started and the engine completed certification for its use on Delta IV in 2001. Indeed, beating the STME projection was accomplished by a factor of two!

The engine was developed/certified via eight new—plus four rebuild—engines, accumulating 183 tests and 18,945 seconds of operation. In addition, five engines were run beyond the maximum mission duty cycle endurance factor limit and three engines were run to over three times the maximum flight duty cycle and 105 percent power, validating its reuse potential.

The first launch is targeted for summer 2002 from the Cape Canaveral Air Force Station, Florida, from a new launch pad built by Boeing. Similar capability will be in place on the west coast at Vandenberg.

The RS-68 is used in a Delta IV Common Booster Core (CBC). A single CBC plus various solid strap-on variants provides a wide range in payload capability. A Delta IV Heavy Lift version employs three CBCs in tandem using three RS-68s. See Figure 2.

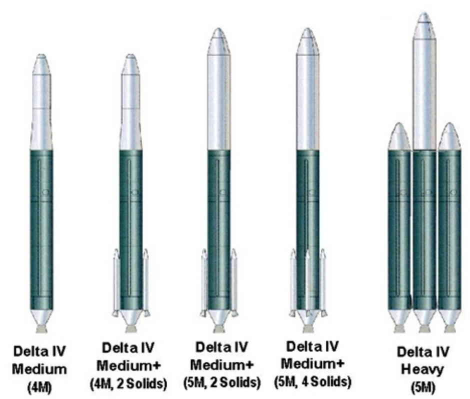

Figure 2. Delta IV Launch Family

For all Delta IV applications, the engine is started to full power and verified within limits before committing to launch. This is accomplished via the on-board engine electronic control unit and health monitoring system. This system provides for rigorous real-time start preparation monitoring of engine sensors and real-time monitoring of critical parameters prior to liftoff, with authority for launch abort. The system provides full redundancy after liftoff, with control unit switch-over.

In-flight operation uses power settings of 101 or 58 percent in various standard mission profiles, with burn durations between 250 and 350 seconds. Two-power level operation simplifies control and component complexity, thereby contributing to reduced cost.

And after all, it was all about cost. Compared to the SSME the RS-68 has 80 percent fewer parts and is produced for 92 percent less touch labor (Figure 3), in conjunction with a small focused supplier base, yielding a recurring cost one-fourteenth that of an SSME.

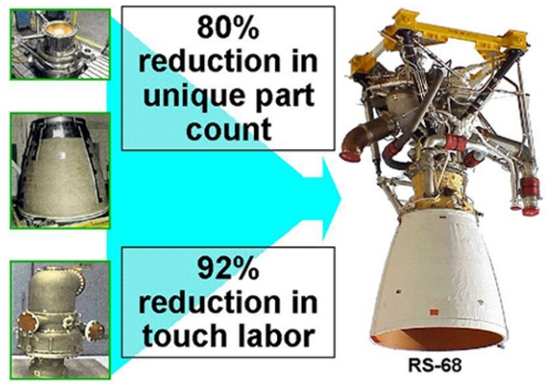

Figure 3. Design Simplification Payoff

A New Way of Doing Business

To meet the demands of the Air Force, and the Boeing-targeted commercial launch market as well, the RS-68 had to be created in an environment where cost was the truly independent variable (Figure 4).

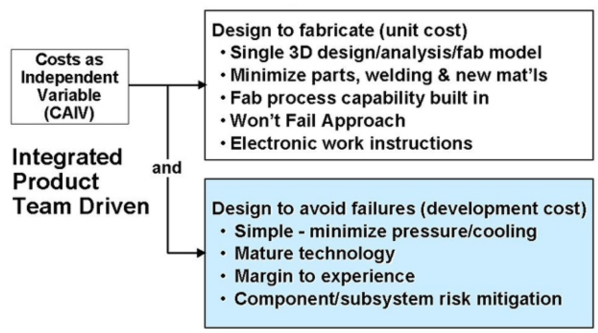

Figure 4. Cost as Independent Variable (CAIV) Key Elements

There were justifiable concerns whether a new rocket engine could apply new development and manufacturing methods that supported the Delta IV business plan. But by applying improved processes and building on the tremendous successes of unmanned and manned space flight programs, the RS-68 program has set new standards for low cost and reduced cycle time for liquid rocket development.

With flight certification now complete and a stream of flight engines in delivery, the metrics for RS-68 development (Figure 5) are impressive—by any product development standards.

- Development costs reduced 5x
- Variable development costs reduced 10X
- Development / Cert cycle time reduced 2X
- Required engine tests decreased 3X
- Payload-to-orbit increased 2% over plan
- Design reliability goals surpassed
- Recurring cost reduced 14X

Figure 5. RS-68 Summary

All this was accomplished while meeting or exceeding all performance and design reliability goals for the engine and delivering a two-percent payload bonus.

The result: a fully certified engine providing reliable booster propulsion for the 21st century at unprecedented non-recurring cost (Figure 6).

Figure 6. Which Cost More to Develop?

Engine Specifics. The new RS-68 is capable of operating in—and transitioning between—full power level and minimum power level upon command from the vehicle. It also supplies pressurization gasses to vehicle fuel and oxidizer propellant tanks and thrust vector and roll control by gimbaling the thrust chamber assembly and the fuel turbine exhaust roll control nozzle (Figure 7).

	Full Power	Minimum Power
Thrust, vac (KN) (K kg-f/Klb-f)	3,341 341/751	1,922 197/432
Thrust, s/l (KN) (K kg-f/Klb-f)	2,918 299/656	1,499 153/337
Chamber pressure (MPa) (psia)	9.79 1,420	5.62 815
Engine mixture ratio	6.0	
I_{sp}, vacuum (sec)	409	
I_{sp}, sea level (sec)	357	

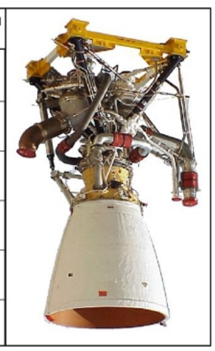

Figure 7. RS-68 Operating Characteristics

Turbopumps are single-shaft with direct drive turbines. Boost pumps are not required. High-pressure hot gases from the gas generator power in parallel the turbines, which employ integral machined bladed disks (blisk) (Figure 8). The thrust chamber/nozzle assembly consists of a combustion chamber and low-cost ablative nozzle; both implement existing, well-demonstrated technology.

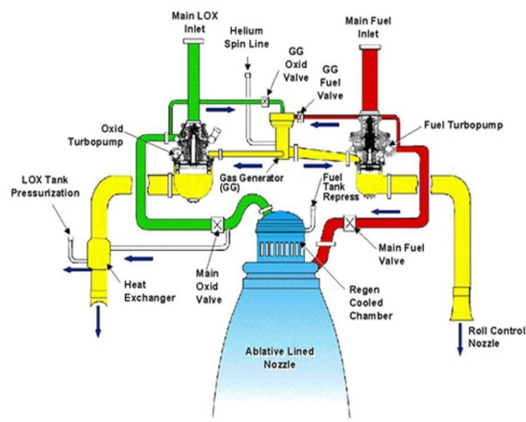

Figure 8. RS-68 Operating Schematic

While the main injector is similar in concept to the J-2 and SSME engines, it has been greatly simplified. This has been accomplished by reducing injector element density and using fewer unique parts. High-pressure ducting delivers pumped fuel and LOX to the injector/thrust chamber assembly, and shower head shaped ball valves with hydraulic actuators are used for control (Figure 9).

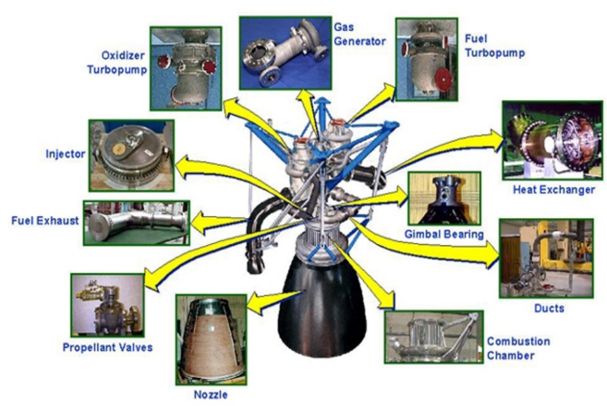

Figure 9. RS-68 Components

And finally, installation into the vehicle employs the proven design of Rocketdyne's RS-27 engine (Delta II). The RS-68 physical design (Figure 10) has pumps nested in a four-point attaching framework and the framework centered off the gimbal bearing at one end and fitted to the vehicle thrust section at the other. Outriggers attached to the combustion chamber allow gimbaling of the thrust chamber assembly during engine operation. Engine start, steady-state operation, throttling, and cutoff are controlled by an engine mounted controller. Gimbaled ducts (two) use flex sections instead of bellows flex ducts.

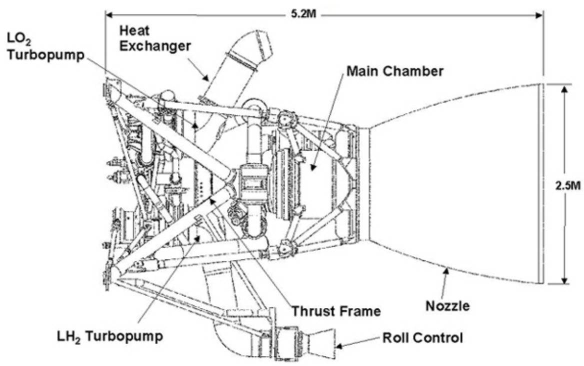

Figure 10. RS-68 Engine

Managing Development Risk

Propulsion is always a key risk item in the development of any new launch vehicle, so the Delta IV Team took a comprehensive, top-down, systems engineering approach (Figure 11) to identify and manage that aspect of the new booster engine risk.

Cost Risk	Depends on	Probability 1st time thru, PFTT
PFTT	Depends on	Producibility & design robustness to failures causing redesign
Producibility	Depends on	Number of unique parts & fab process capable design
Failures	Result from	Complexity, variability & technology reach
Impact of complexity variability & reach	Depends on	Design approach margin & risk mitigation plan technology

Robustness must be designed in

Figure 11. Propulsion Development Cost

In the cost trade space, the key is producibility and margin as chemical liquid propulsion approaches its limit in physics. Performance in relation to theoretical drives margin and together with weight they both drive simplicity and, therefore, producibility (Figure 12).

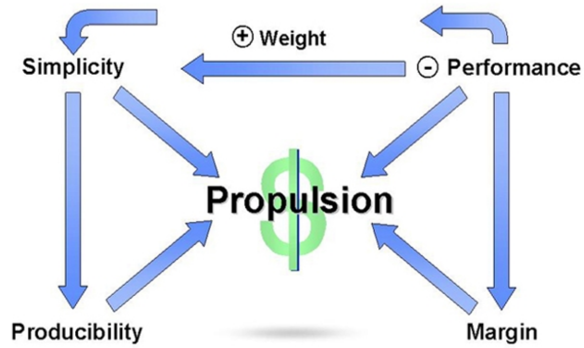

Figure 12. Cost Trade Space

A key decision in the process was the selection of the liquid oxygen/liquid hydrogen propellant architecture using STME as a point of departure (Figure 13). The inherent performance advantage provided in this application by the LO_2/LH_2 propellant combination enables a significant reduction in the performance demands on the booster engine. This allowed the team to employ a simple, gas generator operating cycle, with operating conditions commensurate with reducing risk and increasing reliability.

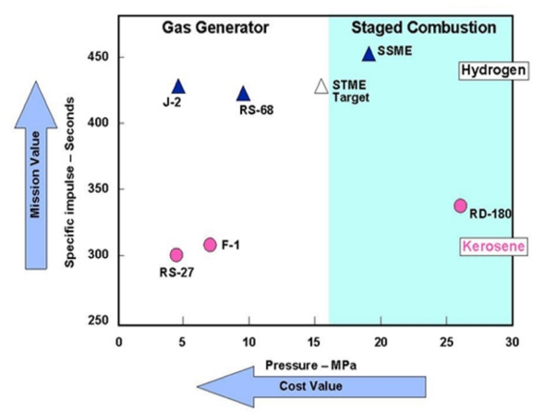

Figure 13. Best Value Trade Space

Based on this risk avoidance foundation, the team focused its efforts on a plan to find, quantify and mitigate risk.

Historically, about 75 percent of total engine development costs (Figure 14) are attributable to "Test-Fail-Fix" (TFF). Accordingly, the RS-68 program targeted reduction in those costs by driving down the typical risk level before the start of engine testing.

	Conceptual Design %	Final Design %	Validation Design %	Fail-Fix Design %	Total
Engineering & Mgmt. %	2	15	1	7	25
Hardware %			3	47	50
Test %			6	19	25
Total %	2	15	10	73	

Figure 14. Historical Development Cost Breakdown

A "TFF affordability objective" was established and used with Boeing's extensive engine test historical database, to estimate the approximate number of corrective actions that might be required during engine development. That database also provided a correlation that indicated the allowable risk factor level at the start of engine testing. The difference, then, between the program initiation risk factor and the “TFF affordable” risk factor established the magnitude of the risk mitigation activity for each component, as well as the engine system (Figure 15). This clearly defined where risk mitigation had to be employed prior to starting engine hot fire.

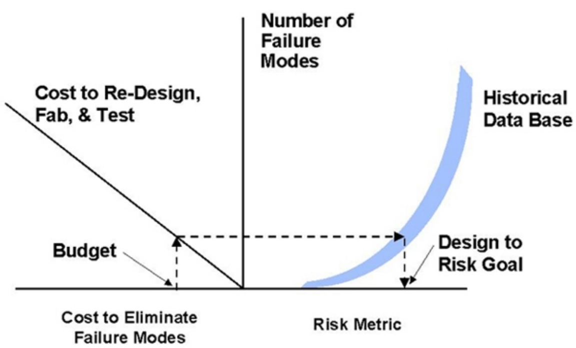

Figure 15. Design Failures Out

Risk quantification must take a realistic view of what the new design requires on a component and system basis with respect to clear known experience, areas where issues are typical when operating outside of experience and new, totally unknown issues that history says will occur when the envelope is pushed beyond demonstrated knowledge (Figure 16). In some cases even well anchored models and well characterized physics lack the fidelity to predict complex interactive problems stemming from both operational and fabrication process new ground.

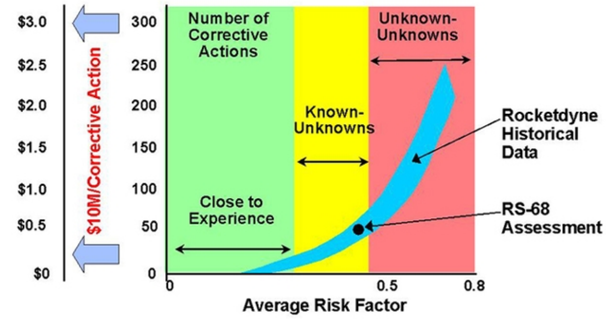

Figure 16. Risk Quantification

Key program risks (Figure 17) must be and were identified early, using a quantitative method which addressed both the likelihood of failure and the related consequences from a technical, cost and schedule perspective. Those risks were assessed by looking at technology maturity, operating environments knowledge, and manufacturing capability. Quantitative risk factors were defined for key components and the engine system as a whole. The quantitative factors were then directly correlated to Rocketdyne’s 40-year history of failure modes and documented cost.

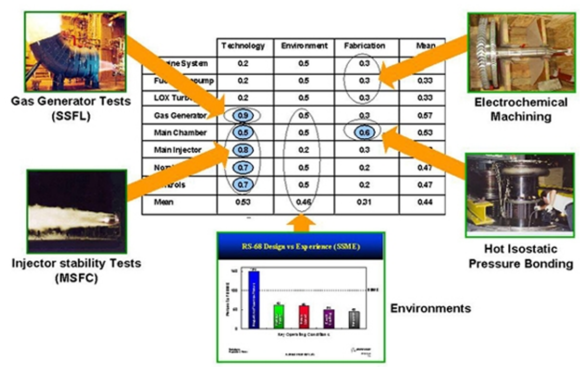

Figure 17. Mitigating “Identified” Risks

Early risk mitigation activities included incremental design reviews, manufacturing process demonstrations, component and subsystem verification testing and activation of multiple engine test facilities. During the initial design phase, both sub-scale and full-scale injector hot-fire testing was conducted to verify performance, stability and chamber compatibility. Critical main combustion chamber and turbopump fabrication processes were also demonstrated.

Gas generator, valve and turbopump component tests, as well as powerpack (gas generator and turbopump sub-assembly) tests, were conducted (Figures 18 and 19) to reduce risk and to evaluate design trades.

Figure 18. Gas Generator Risk Reduction Testing

Figure 19. Turbomachinery Power Pack Risk Reduction Testing

These tests, along with virtual design and analytical evaluations using 3-D models, progressively drove risk factors down in preparation for the start of engine development testing (Figure 20).

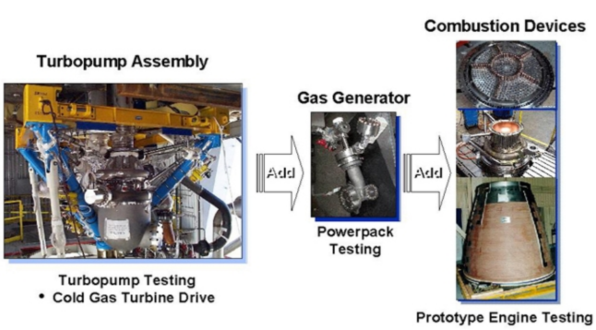

Figure 20. Incremental Test Approach

As the program progressed (Figure 21), identified risks were incrementally retired. This is not to say that there weren't setbacks along the way. As predicted from the experience base, problems requiring corrective action were encountered. These problems temporarily increased the levels of existing risks or identified previously unforeseen risks, but in each case, root causes were identified and mitigation plans established and successfully executed.

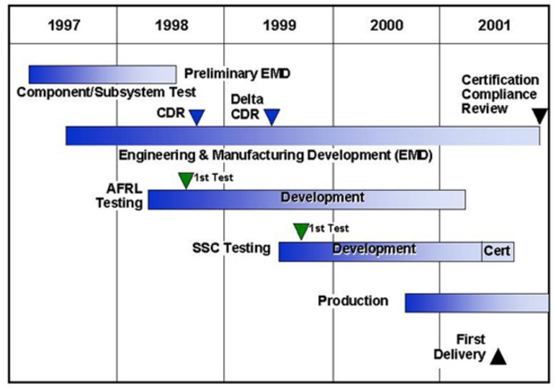

Figure 21. RS-68 Program

3-D Solid-Model-Based Virtual Design

In a sense, the RS-68 was created before it was created. That is, three-dimensional modeling and a wide array of analysis and design tools were implemented that were simply unavailable a generation ago when the Space Shuttle Main Engine was developed. Further, these tools and disciplines were used in new and cooperative ways by the larger RS-68 team in a parallel and integrated product development (IPD) environment that yielded extensive sharing of information among IPD members (Figure 22).

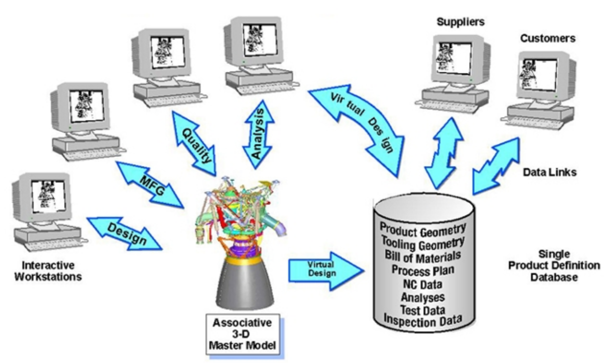

Figure 22. Digital Driven Design Environment

Moreover, the team shared a common 3-D-model geometry of each component, which allowed all team members to work from the same model to perform their unique analyses and update the design. As an example, 3-D unsteady CFD analysis was used for turbine evaluation, leading to better quantification of the dynamic environment and decisions early in the design as to the type of nozzles and or the need for damping features.

That analysis was then extended to manufacturing, for direct machining from the 3-D-geometry model Figure 23).

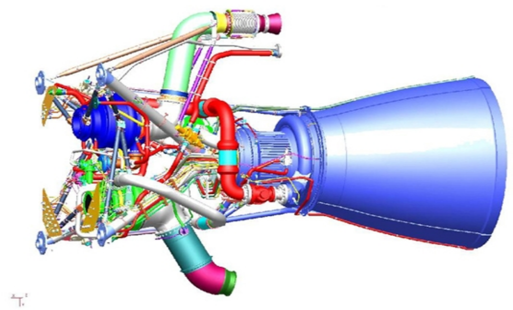

Figure 23. RS-68 Desktop 3D Engine Design Model

Effective mechanisms to accomplish this were implemented through the Rocketdyne Advanced Process Integration Development (RAPID) program (Figure 24). A key element was the model-centric Horizontally Integrated Design System (HIDS).

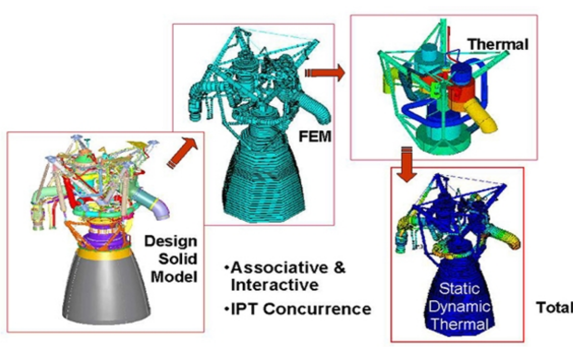

Figure 24. RS-68 Virtual Design

An important element to implementing this strategy was the adoption of concurrent engineering, led by an integrated product team leader (Figures 25 and 26). The integrated product team (IPT) leader must be skilled in monitoring numerous metrics such as cost, weight, performance, life and quality.

As an example, early in the design of a turbopump shaft, a HIDS 3-D model for the casting core was fabricated directly and sent to the casting vendor to begin casting trials. Using these cores, the vendor was

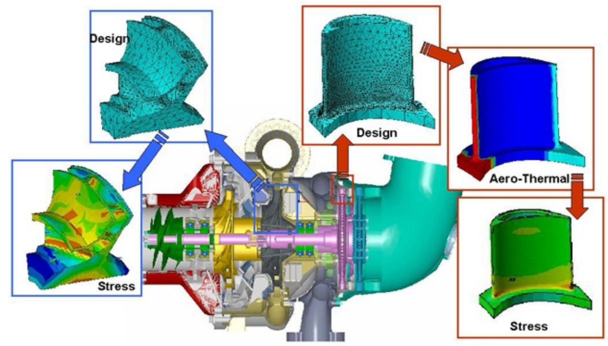

Figure 25. RS-68 Design Tools

able to optimize gating and have a direct impact on part design through the incorporation of specific features that ensured better core burnout or fill. Then, as the component design was completed, the core was updated and the probability of a first-time useable part was increased.

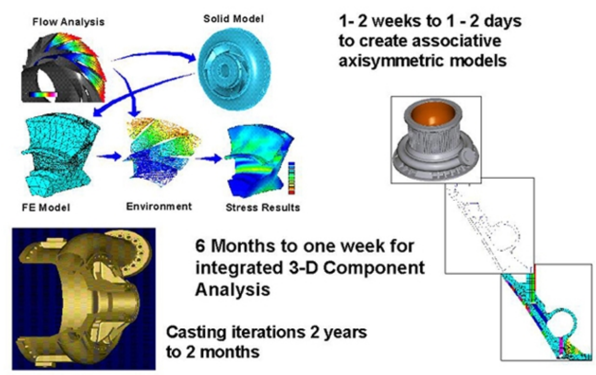

Figure 26. Model Analysis Cycle Time

It is clear that through the use of castings to integrate multiple parts into one piece and technologies that provide the same or improved functionality with reduced parts (Figure 27), cost has been significantly reduced.

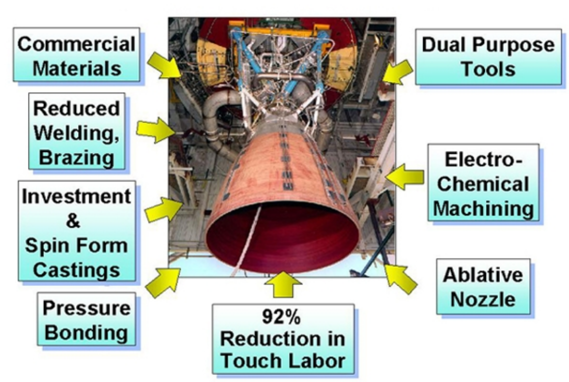

Figure 27. RS-68 Low Cost Fabrication

And integral with the process was that key suppliers were predetermined, and participated as design team members in the early decision making phase of the program—instead of waiting until the detailed design was nearly complete.

New Manufacturing Approaches

Closely following a new approach to design, the RS-68 program also implemented new manufacturing processes that themselves are a generation removed from existing conventions. Lower costs were attained by finding ways to drastically reduce parts count, along with the touch labor required to fabricate them. Welding was reduced compared to the SSME by 85 percent.

Rapid Prototyping—Large Scale Castings. The process of manufacturing super-alloy castings using a rapid prototyping was paramount in the development of high strength engine parts with greatly reduced cycle times.

Three-dimensional Pro-Engineer model databases were generated for each cast part. Each model database was then converted into soft tooling, using the stereo lithography (SLA) process. The reduced cycle time of the SLA process permitted the fabrication of the soft tooling to proceed quickly, along with the development and modification of the tool in real time. The SLA patterns are then used to generate molds to produce the metal casting. Each casting was manufactured with a single metal pour, integrating internal flow passages for the working fluids and coolant media.

HIP-bonded chamber. Fabrication and assembly of the RS-68 engine thrust chamber (Figure 28) represents the longest lead hardware for the engine. Major components included a hot gas liner, throat support,

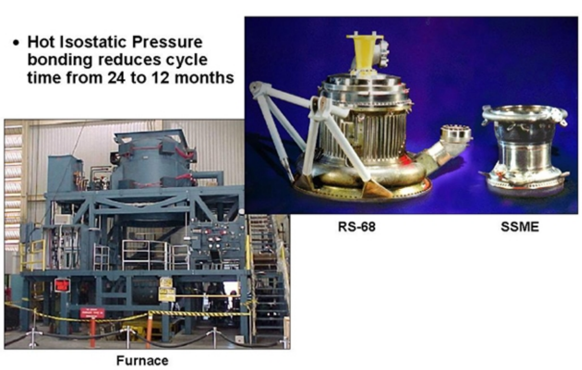

Figure 28. RS-68 Main Chamber Fabrication

structural jacket and manifold. Uniform pressure applied to brazed surfaces with no tooling results in a high quality joined part, with minimal hardware processing time.

Ablative nozzle. Low cost, proven fabrication technologies and a short fabrication cycle time were the key criteria used in the selection of the ablative nozzle for the engine. This approach allowed the majority of development tests to be conducted without a nozzle.

Blisks. A bladed disk—or "blisk"—design was selected for the RS-68 turbines to drive the turbopumps (Figure 29). Two turbopumps are used, one for the fuel (liquid hydrogen) and one for the oxidizer (liquid

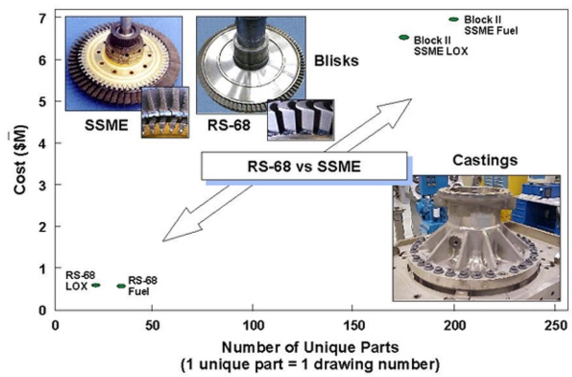

Figure 29. Turbomachinery Design Simplification

oxygen). In line with the plan, low cost and reduced cycle time were key criteria in the selection of the turbine blisk design. Individual blades are machined from a monolithic disk forging using electrochemical machining (ECM) processes.

Testing and Design Verification

As design concepts solidified into hardware, components were tested as proof of design. The thrust chamber injector was tested at the Marshall Space Flight Center, while the gas generator was tested at the Santa Susana Field Laboratory. During that time, the 1A test stand at the Air Force Research Laboratory (AFRL) was prepared to perform the blow-down and hot-fire testing of the turbopump test article (TPTA) power pack. After TPTA removal, the first RS-68 prototype engine was installed and tested. Development testing (Figure 30) was aggressively pursued, providing confirmation of start, mainstage, low and high power level operation,

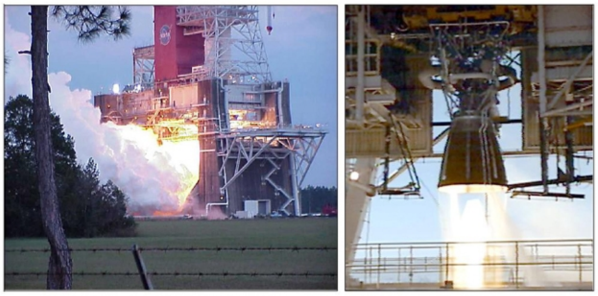

Figure 30. RS-68 Engine Test Program

shutdown and “out-of-envelope” inlet pressures. The engine made use of tandem SSME valves and various components were simulated by orifices.

Full flight design configured engine testing (Figure 31) was started in 1998.

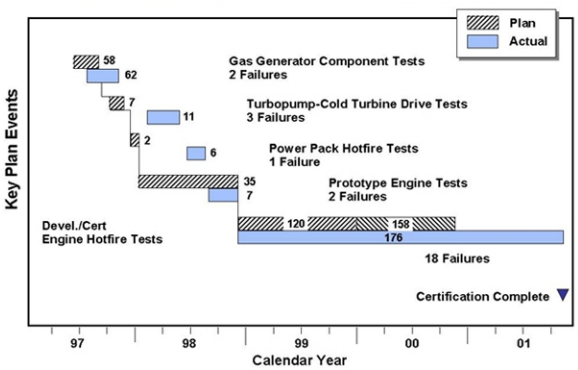

Figure 31. RS-68 Development Test Program Results

At the Stennis Space Center (SSC), the B test complex (Figure 32) was adapted for exclusive use by Boeing. The B1 test position was outfitted with two engine mount positions, using common tankage and controls, and was equipped to handle high flow rates of liquid oxygen and liquid hydrogen. Nearby propellant off-load area and canal systems provide quick access to large quantities of propellant, allowing rapid turn around between tests and provide for longer duration testing required for certification. The B-2 side of the B test stand was modified to restrain and test the entire Common Booster Core Vehicle with the RS 68 Engine.

Again, with a significantly reduced development cycle and lowered costs in mind, the test development and engine certification process was put on the fast track. In the time period of early 2001 development, certification

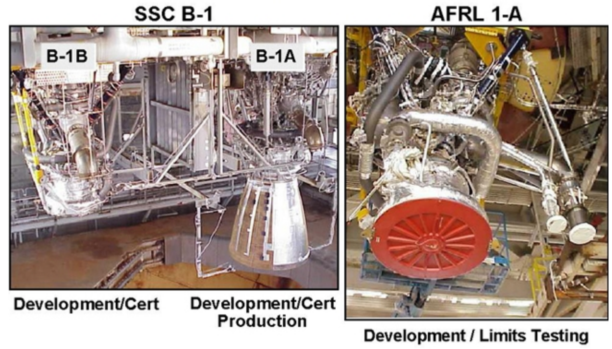

Figure 32. RS-68 Test Facilities

and vehicle qualification testing was occurring simultaneously at three test positions. The results were spectacular, especially when compared to historical precedent.

Development and certification time for the RS-68 engine was one-half the cycle time required to develop and certify previous rocket engines. That was realized by breaking the test-fail-fix cycle and using an objective based variable test/time approach, with component-level testing and won’t-fail designs and processes. Use of facilities at Boeing Rocketdyne, Marshall Space Flight Center, the Air Force Research Laboratory (AFRL) and Stennis Space Center (SSC), were key to conduct detailed component, subassembly and subsystem testing. These facilities were able to simulate engine and mission operating nominal and limit conditions.

Engine analytical models became key tools that set the test, engine and facility operating points and limits settings; these were used to simulate nominal and off nominal operating conditions.

Robust start, shutdown and transition to steady-state operation sequences were developed and demonstrated in record time. In fact, full power testing (Figure 33) was achieved in only 27 tests—one-fifth the number of tests required on prior engine development programs. It took almost a year, but a key lesson learned here was lack of enough up-front hardware. With spares this goal would have been met in less than 100 days.

Engine full-power capability was demonstrated in the first 27 tests, essential to moving forward with an objective-based test program. The objective-based approach focused on specific engine and mission requirements and operating regimes. Test duration and

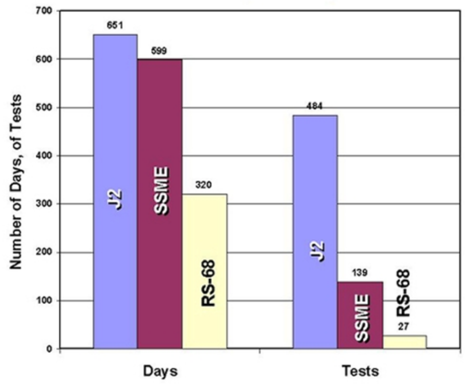

Figure 33. Full-Power Test Capability Milestones

the total number of tests (Figure 34) were adjusted based on verification and certification of these objectives.

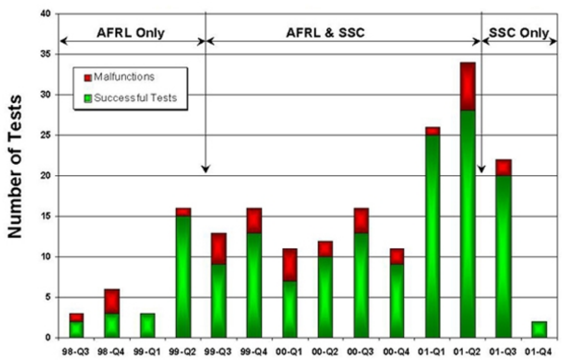

Figure 34. RS-68 Engine Development Test History

The engine and facility digital control systems were designed to provide flexibility and adjustability to optimize engine performance and test facility capability. This flexible and adjustable architecture meant that multiple objectives could be accomplished on one test. A Taguchi methods/design of experiment approach was employed to establish the specific operating set points needed to verify an objective. The objective-based approach and flexible robust tools led to RS-68 first flight certification in only 183 tests.

Issues discovered at the engine test level were reduced by an order of magnitude from previous large engine development programs. Fail-fix cycle costs as a percent of total program were reduced from 75 to 30 percent, saving more than a billion dollars. Still, this was greater than originally planned, which resulted in a one-year schedule slip. A disciplined issue resolution process was employed to determine root causes and high confidence corrective action.

One of the most significant and costly problems was a thrust shortfall of 15 percent below requirements (Figure 35). This was caused primarily by lower-than-anticipated turbomachinery efficiency and higher system resistances.

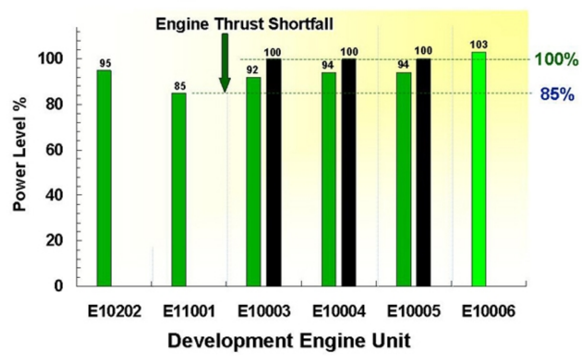

Figure 35. Engine Thrust Shortfall

In April of 2000, the resolution team established a design change plan and schedule for a 20-percent improvement. The plan was executed on schedule, exceeded the target and allowed a rated thrust increase and increase in payload-to-orbit (Figure 36).

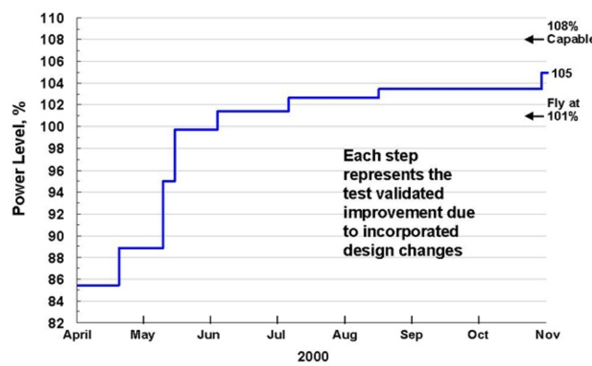

Figure 36. Thrust Recovery Demonstrated

Other significant issues resolved (Figure 37) were associated with fatigue life and damping of turbine blisks (integral blade and disk), FOD induced fatigue cracking in the oxidizer turbine drive duct, and higher than anticipated nozzle ablation rates. All of these failures represented issues in the unknown-unknown category because of design approaches geared to reduce cost but setting operation outside experience. Disappointing at the time, these issues have contributed to much higher fidelity models applicable to future engine designs.

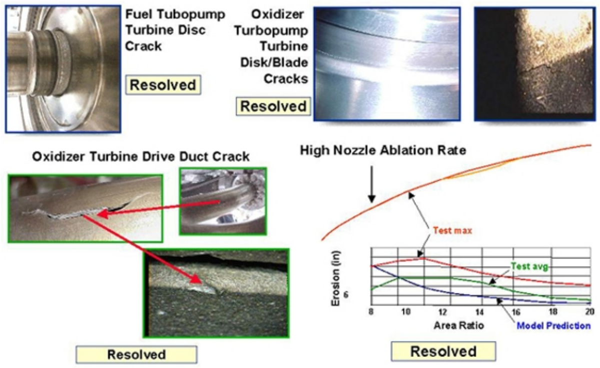

Figure 37. RS-68 Development Issues Resolved

Despite the issues, the robustness of the engine design allowed certification for first flight (Figure 38) to be completed in a record fewer number of tests (a factor of nine less than the F-1 and a factor of three less than the SSME).

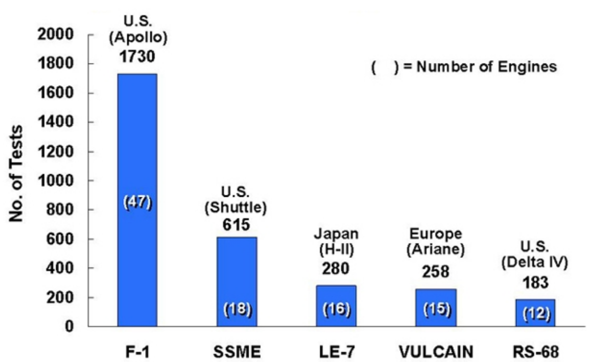

Figure 38. Engines/Tests: First Flight Certification

Design simplification also paid off in terms of reduction in the number of premature engine test cuts (Figure 39). The rate was reduced by more than a factor of four and the total number reduced by a factor of eight. No major engine-wide failures occurred compared to 12 on the SSME.

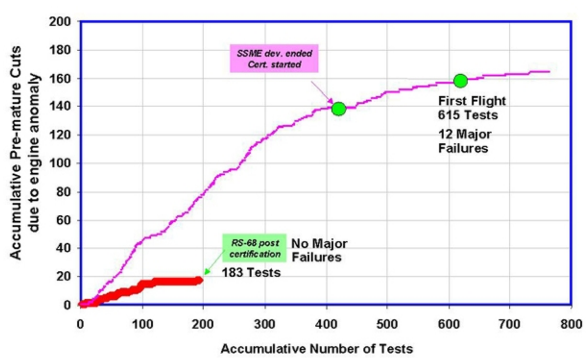

Figure 39. Test Premature Shutdowns

Engine flight life was set at 8 starts and 1,200 seconds. Yet during the development and certification program (Figure 40), five engines exceeded twice the flight life requirement, including three that were tested to over three times the required flight life.

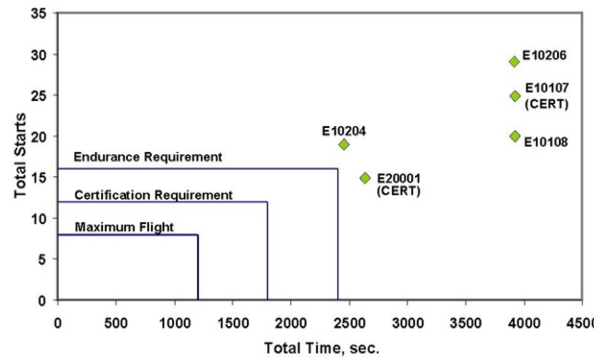

Figure 40. RS-68 Endurance Margin

Testing beyond the "corners of the box" demonstrated significant margin to the required flight operation. Moreover, the engine was hot-fire gimbal tested over twice the number of required flight gimbal cycles. Engine thrust levels of 105 percent and mixture ratio extremes of 5.3 and 8.5 further pushed the envelope well past nominal flight operation of 101 percent thrust and 6.0 mixture ratio. This "push-the-envelope approach" and the robust hardware meant more could be done with less (Figure 41). The RS-68 was fully certified to fly using only 12 engines.

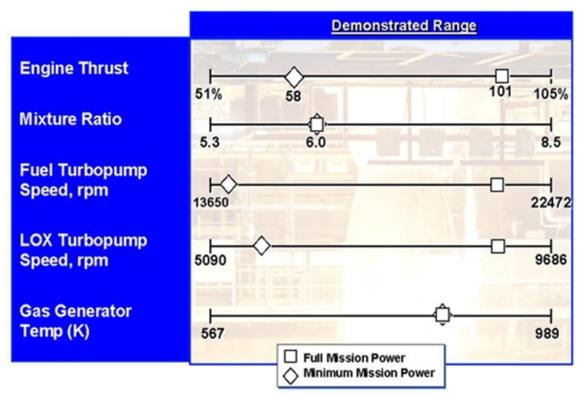

Figure 41. RS-68 Operational Margin

But even prior to system hot-fire testing, component qualification testing was also used to supplement engine level testing and decrease the risk to engine level testing.

Component qualification tests (Figure 42) were based upon failure modes, effects analysis and component complexity and therefore able to simulate engine environments. In addition, a vibration testing approach consistent with 40 years of manned-rated booster rocket engine experience was implemented. This included testing for electronic devices such as the engine control unit (ECU), main propellant valves, flex ducts, primary structures and the engine gimbal bearing. As an example, this testing successfully demonstrated margins of four times the required gimbal cycles for flexible components and 25 percent above maximum predicted loads for primary structures, and vibration testing of the ECU demonstrated margin up to twice the predicted environment for over three times the expected flight engine duration.

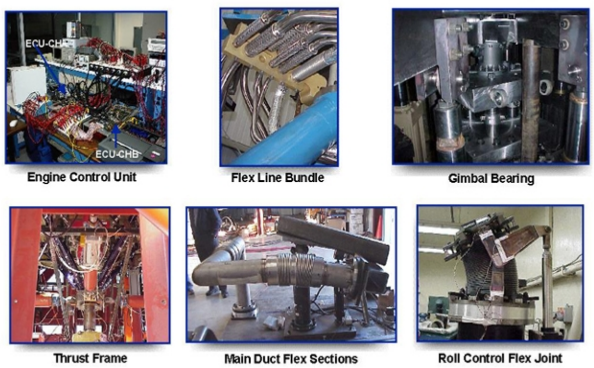

Figure 42. Component Qualification Testing

High reliability. Predicted flight reliability for the RS-68 engine is based on a comparative design assessment process that accounts for part count and complexity, fabrication and inspection capability, and relative severity of operating environments, which has been compared to the SSME baseline (Figure 43). There, appropriate adjustments are made to account for the three-engine SSME cluster with engine-out capability.

Bottom Line Development Cost. Normalized non-recurring development costs (Figure 44) were reduced by a factor of five, enabled primarily by the factor of 10 reduction in variable development costs (fail-fix issues).

Although great strides were made in development cost and cycle time reduction, opportunities for improvement (lessons learned) include better estimates of the scope of test stand activation and having adequate reserves for the level of predicted issues (Figure 45). Funding constraints resulted in lack of adequate ready-now backup hardware when issues did occur. Use of "slave" hardware early in the test program required additional design effort, and created peripheral issues and delayed discovery of real failure modes.

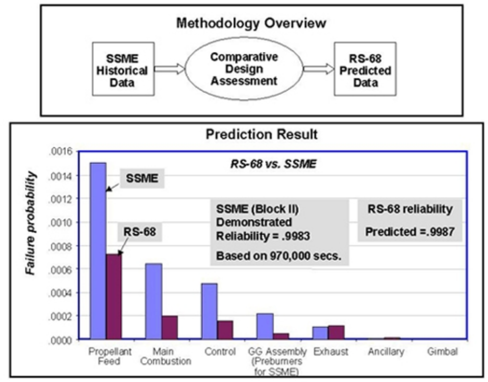

Figure 43. RS-68 Anchored Reliability

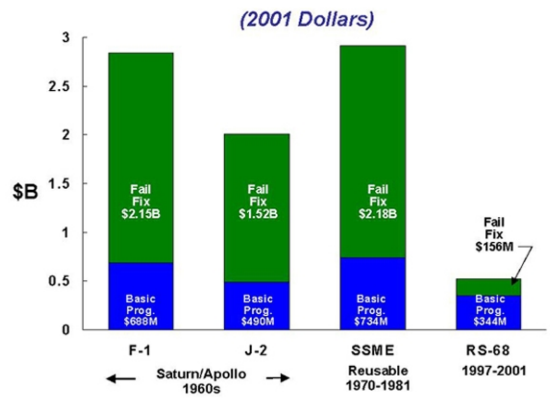

Figure 44. Non-Recurring Development Cost (2001 Dollars)

- Underestimated the cost and time to modify and activate new test positions
- Didn't carry full fail-fix model cost estimate as reserve
  - Historical data predicted 30 failure modes. Budgeted for 10. Actual: 26.
- Let funding make the program hardware poor up front
- Use of slave hardware in early testing increased design effort, delayed discovery of real failure modes and created new ones
- No provisions for on-stand removal of turbopumps

Figure 45. Lessons Learned

CBC Integration Testing. Finally, the RS-68 was fully integrated with the Delta IV Common Booster Core (CBC) design for integrated system testing (Figure 46). Integrated trade studies optimized the vehicle design and vehicle operation requirements to ensure the engine was truly developed and tested as it would fly. This fully integrated approach paved the way for a very successful CBC static hot fire test series.

Figure 46. CBC Hot-fire Testing (Test What You Fly)

A fully functional CBC with an RS-68 was hot-fire tested at SSC five times. During the series, engine chill and vehicle propellant loading was demonstrated, engine-vehicle communication was verified, operational sequences were finalized and engine hot-fire showed that the engine was indeed ready for flight (Figure 47).

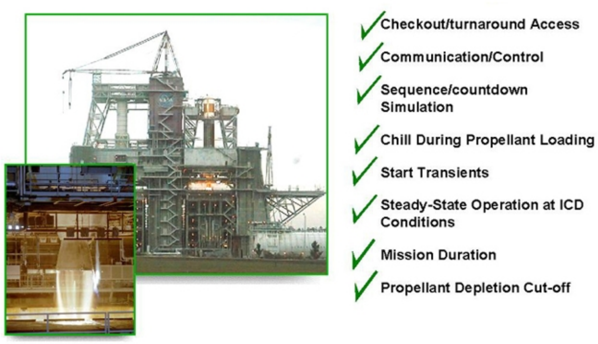

Figure 47. Common Booster Core Testing

<u>Streamlining Production and Test</u>

With certification now established, the business of bringing the RS-68 to the marketplace is already under way (Figure 48).

Boeing/Rocketdyne, over the last five years, has invested over $35 million in state-of-the-art fabrication facilities and equipment directed at key RS-68 manufacturing cost reduction processes. These include single set-up, multi-axis vertical turning centers, a new hot-isostatic-press furnace, multi-station turbomachinery assembly centers and a multi-channel combustion chamber slotter.

Figure 48. RS-68 Production Investment

Engine assembly is performed in a new facility located at the Stennis Space Center for optimum efficiency and low cost.

The Engine Assembly Facility (Figure 49) was designed using Lean Assembly Analysis Techniques to provide optimum process flow of components, and deliverable RS-68 propulsion systems. The facility contains all the ancillary equipment required to assemble and process the engine. Proximity of the test facility to the assembly facility assures that minimum time is used to transport, test and process the RS-68 engines. This arrangement also promotes the sharing of personnel, equipment and information to minimize investments in capital and intellectual property.

Figure 49. SSC Engine Assembly Facility

<u>The Legacy</u>

With the first flight of the Delta IV, the RS-68 will initiate the arrival of rocket engine systems that have established cost as a primary factor.

As such, the launch business will be forever changed. Boeing Rocketdyne has demonstrated a new way to develop and deliver propulsion itself. The Boeing RS-68 was developed using state-of-the-art design tools, breakthrough fabrication approaches, and a cost-effective testing approach—a new standard for U.S. liquid rocket engine development and production cost effectiveness (Figure 50).

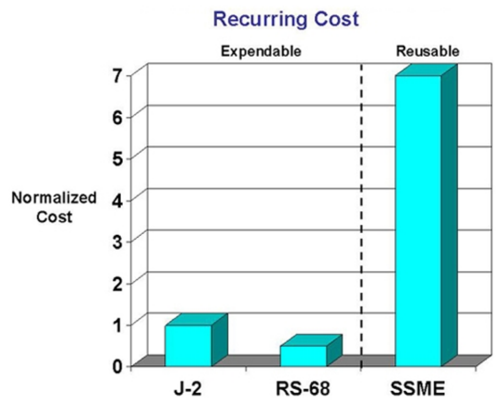

Figure 50. RS-68 Sets New Standards

Fully tested and flight certified (Figure 51), the RS-68 is poised to power affordable space lift capability well into the 21st century.

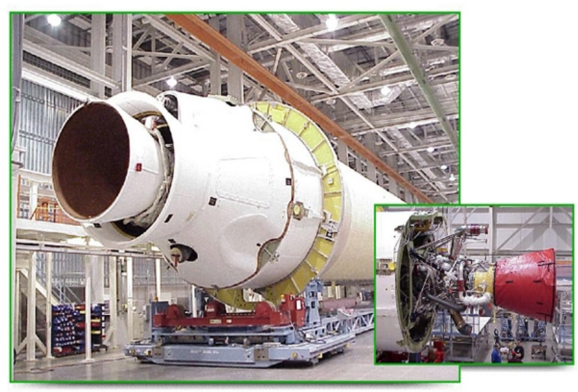

Figure 51. RS-68: Ready to Fly!

But also very important, it has trained a whole new generation of Rocketdyne liquid propulsion development, fabrication and test engineers and scientists (Figure 52). These men and women are prepared to maintain propulsion excellence for the United States and poised to step up to the clearly needed new propulsion challenges the nation must assume.

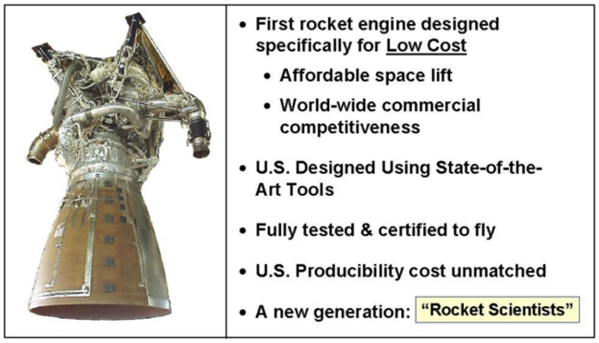

Figure 52. RS-68 Summary

Reference

AIAA 98-3208, "RS-68: What and How," B. K. Wood, The Boeing Company.

Acknowledgments

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