The Past as Prologue:
A Look at Historical Flight Qualifications for Space Nuclear Systems

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ABSTRACT

Currently the U.S. is sponsoring production of radioisotope thermoelectric generators (RTGs) for the Cassini mission to Saturn; the SP-100 space nuclear reactor power system for NASA applications; a thermionic space reactor program for DoD applications as well as early work on nuclear propulsion. In an era of heightened public concern about having successful space ventures it is important that a full understanding be developed of what it means to "flight qualify" a space nuclear system. As a contribution to the ongoing work this paper reviews several qualification programs, including the general-purpose heat source radioisotope thermoelectric generators (GPHS-RTGs) as developed for the Galilee and Ulysses missions, the SNAP-10A space reactor, the Nuclear Engine for Rocket Vehicle Applications (NERVA), the F-1 chemical engine used on the Saturn-V, and the Space Shuttle Main Engines (SSMEs). Similarities and contrasts are noted.

INTRODUCTION

Currently the U.S. is sponsoring a number of studies or programs relating to the use of nuclear power and propulsion in space. Radioisotope thermoelectric generators (RTGs) will be produced for the Cassini mission to Saturn. NASA and DoE are involved in the SP-100 space nuclear reactor power system program which is being designed to span a range of applications from robotic science missions to human-operated planetary bases. Separately DoD is investigating several thermionic space reactor concepts for possible military applications. NASA and DoE in coordination with DoD have been investigating the use of nuclear propulsion for missions to Mars. DoD has been sponsoring a nuclear thermal propulsion program for possible use by the U.S. Air Force (USAF).

Each of these programs has different flight qualification standards which reflect to some extent different philosophies and applications. However, there are aspects of the use of space nuclear systems that are common. For example, to paraphrase Williams [1981]: Space nuclear power and propulsion systems ". . . differ from other products of technology in several critical respects. They are exposed to hostile environments unlike any on earth. They cannot be repaired once they are launched. Production of a particular craft has been limited to one or at most a few models. The designs challenge the state of the art and use the latest hardware, which must be proved for the space environment by thorough testing."

There is at present considerable emphasis on approaches which do things "faster, cheaper, better" without compromising safety. At the same time because of problems with some recent space missions there is a heightened public concern about having successful space ventures. Managers are thus caught between potentially opposing pressures. Calling attention to recent technological failures, Petroski [1992] has written: "But at the root of many such incidents may lie a much greater human error: the mistake of ignoring the fact that errors do occur in engineering and of forgoing tests that prove designs before the designs disprove themselves . . . Clearly a deliberate and controlled proof test can not only protect the public from the immediate physical trauma and the resulting psychological anxiety of an accident. It can also serve an objective of engineers: to regulate their own profession." As a contribution to the thinking, planning and discussion of flight qualification this paper reviews the qualification of several space systems, including the general-purpose heat source radioisotope thermoelectric generators (GPHS-RTGs) as developed for the Galileo and Ulysses missions, the SNAP-10A (Systems for

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Nuclear Auxiliary Power 10-A) space nuclear reactor, the Rover/NERVA (Nuclear Engine for Rocket Vehicle Applications) program, the F-1 chemical engine used on the Saturn-V for the Apollo missions to the Moon, and the Space Shuttle Main Engines (SSMEs). Similarities and contrasts will be noted.

ROVER/NERVA

Writings on the application of nuclear power to propulsion can be traced to the beginnings of the century leading to several studies in the 1930s and 1940s. By the 1950s it was clear that a nuclear rocket was feasible if certain materials and cryogenic propellant problems could be overcome. On 2 November 1955 DoD officially approved the start of the nuclear rocket program with an initial goal of demonstrating feasibility by 1959. While the Rover program (as it came to be known) was a move into uncharted technological territory it did have some basis in the NEPA (Nuclear Energy for the Propulsion of Aircraft) and ANP (Aircraft Nuclear Propulsion) programs [Dewar 1974].

In hindsight it often appears that the chosen design magically appeared out of nowhere; however, the final design of NERVA evolved from competing concepts and requirements. Initially the nuclear rocket was to be developed as an intercontinental ballistic missile (ICBM) for USAF and various concepts such as a 1500-MW, graphite ammonia-cooled reactor for an upper stage and a 10,000-MW liquid-hydrogen graphite reactor for a single stage were considered. By 1956 it was clear that chemical ICBMs could meet the ICBM requirements so in 1957 DoD redirected the program to the "propulsion of missiles, satellites, and the like" [Dewar 1974]. The nuclear rocket program finally got under way following a dual course: "a limited research program into advanced nuclear propulsion systems and materials, and a specific basic reactor testing effort called the KIWI program" [Dewar 1974]. Beginning in 1959 three 100-MW reactors in the Kiwi-A series were tested "to demonstrate that a high power density reactor could heat a propellant quickly and stably to high temperature; to establish basic testing procedures; and to determine the basics of the graphite-hydrogen interaction" [Dewar 1974]. By now NASA had entered the nuclear propulsion program and reoriented it toward a methodical step-by-step engineering program aimed at civilian applications. Next, in 1961, came the 1000-MW-class Kiwi-B series of tests which led to improved reactor fuels and structural supports. The first of the NRX (NERVA reactor experiment) tests closely resembled the Kiwi B4-E configuration. In parallel, efforts were under way to develop a liquid hydrogen pump. Figure 1 shows a model of NERVA and Figure 2 shows schematically the overall history of the Rover program. By 1969 a total of 20 reactor tests had been run of which 15 featured various "breadboard" engine test configurations; however, from 1964 on the program was largely focused on reactor technology [Dewar 1974, Gunn 1989, and Koenig 1986].

By this time man-rating and a reliability requirement of 0.995 at the 90% confidence level had been specified for NERVA.

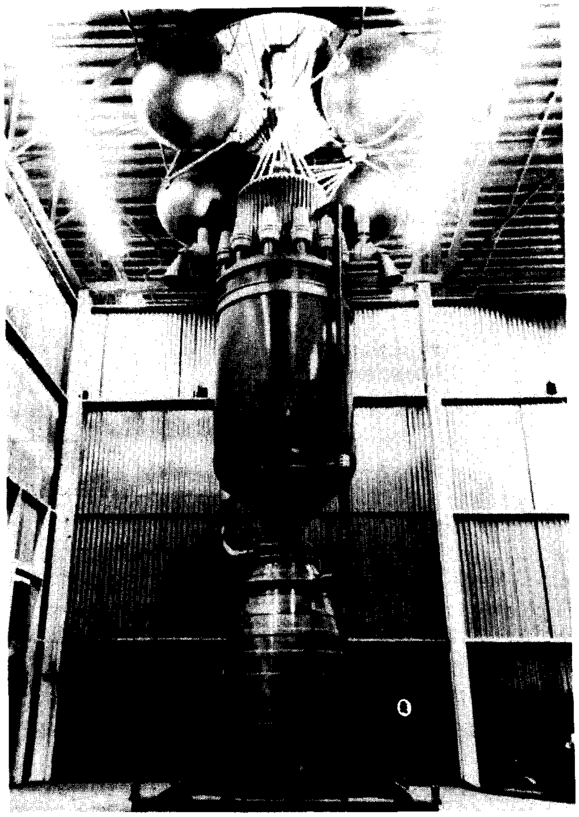


Fig. 1. Model of the NERVA Engine. NERVA was designed to produce 75,000 lbf of thrust at a specific impulse of 825 pounds force—sec/pounds mass and a 10-hour operating time with 60 start/stop cycles.

The engine test program was to include the following test series [SNPO-C 1971]:

- Development Tests to confirm design calculations and assumptions
- Preliminary Qualification Tests to demonstrate that the item functions as designed
- Formal Qualification Tests designed to demonstrate that the item satisfactorily meets the requirements of flight

For planning, three categories of tests were defined depending upon how the test was to be conducted: (1) whether test parameters and interfaces were simulated; (2) whether actual NERVA engine hardware was used; or (3) whether flight tests were run. In parallel with the engine test program was a component development program. To meet the overall requirements of the NERVA program (and leading to a flight test) five reactor assemblies were to be tested; three weight and envelope mockups (WEMUs) were to be built; and nine engines (one spare and one unfueled) were to be built. Overall, the program was based on a statistical/reliability approach [SNPO-C 1971].

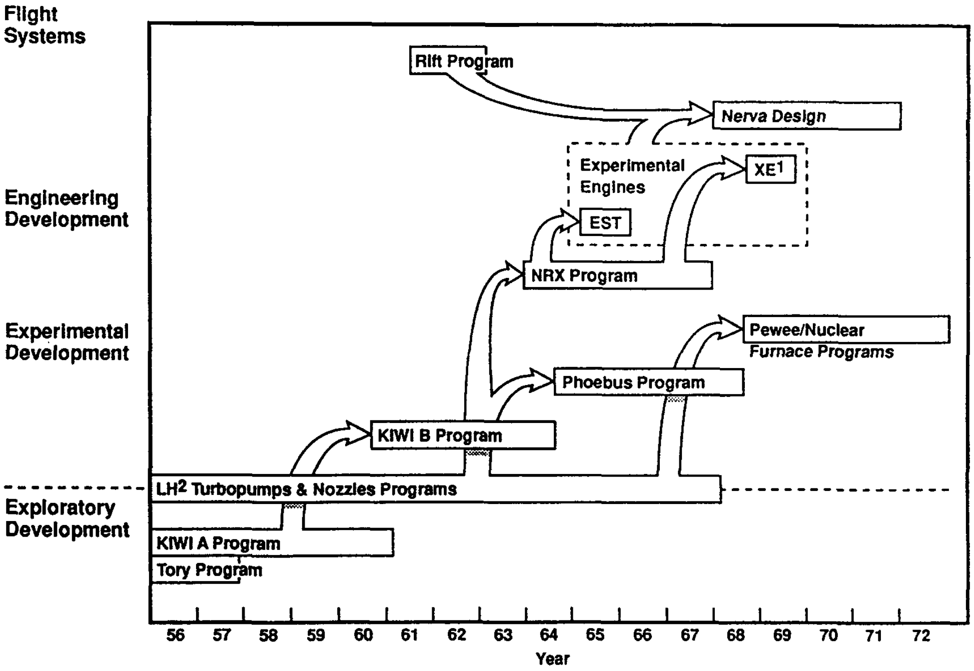


Fig. 2. Schematic Overview of the Rover Nuclear Rocket Program in which 20 Reactor Tests were Conducted

The reactors were assigned to (1) nuclear subsystem (NSS) development testing (R-1 and R-2); (2) NSS Preliminary Qualification (R-3); and (3) NSS Formal Qualification (R-4 and R-5). The WEMUs were to aid in developing and demonstrating handling, transportation, interfaces and facilities. The engines were assigned to (1) engine development testing (E-1); (2) Preliminary Qualification (E-2, E-3, and E-4); (3) Formal Qualification (E-5, E-6, and E-8; note: there was no E-7); (4) spare for Formal Qualification (E-X); (5) spare with unfueled reactor for Formal Qualification (E-C) [SNPO-C 1971]. The nuclear rocket program was terminated in 1973 before final qualification but the program did demonstrate the practicality of solid graphite reactor/nuclear rocket engines for future space propulsion requirements "using liquid hydrogen as the propellant, for thrust requirements ranging from 25,000 lbs to 250,000 lbs, with vacuum specific impulses of at least 850 seconds and with full engine throttle capability" [Gunn 1989].

In hindsight some have argued that a more methodical approach with greater emphasis on component and non-nuclear testing should have been pursued so that the more expensive full-up reactor and engine tests could be minimized. Certainly an early "nuclear furnace" for nuclear testing of the nuclear fuel separately from a full-scale NERVA reactor test would have been beneficial. However, it must be realized that the nuclear rocket program was truly in uncharted territory and it was essential to determine if reactors and engines could be made to work. Also, there were political and national security pressures that helped drive the program on an aggressive path.

SNAP-10A

The joint USAF-AEC (Atomic Energy Commission) SNAP-10A reactor program, which was formally initiated on 30 December 1960 with a design objective of 500 We at the end of a one-year life and a shielded system mass of 340 kg, can be traced back to the Project Feedback study conducted after World War II. Companies such as Rockwell had also conducted studies showing the feasibility of nuclear reactors for space power. These early concepts benefited from materials work sponsored by the NEPA and ANP programs. SNAP-10A also benefited from work on the SNAP-2 reactor program (which had two operating reactors, SER [SNAP Experimental Reactor] and S2DR [SNAP 2 Developmental Reactor]) and the SNAP-10 reactor program (which provided the early impetus for thermoelectric reactor systems). In addition, work on a higher power reactor (SNAP-8, which also had two versions: S8ER and S8DR) for NASA's applications provided information of use to the SNAP-10A program. With the benefit of five years of development work on the uranium/metal-hydride reactor concept, the SNAP-10A program went from start to flight in less than five years.

As noted in Staub 1967, "The overall SNAP-10A development program included basic technical development, prototype component testing, engineering integration into systems, final hardware qualification testing, and final component integration into prototype systems. The plan objectives were to establish technical feasibility, to uncover basic engineering problem areas at the earliest possible time, and to evaluate the necessity for parallel or backup

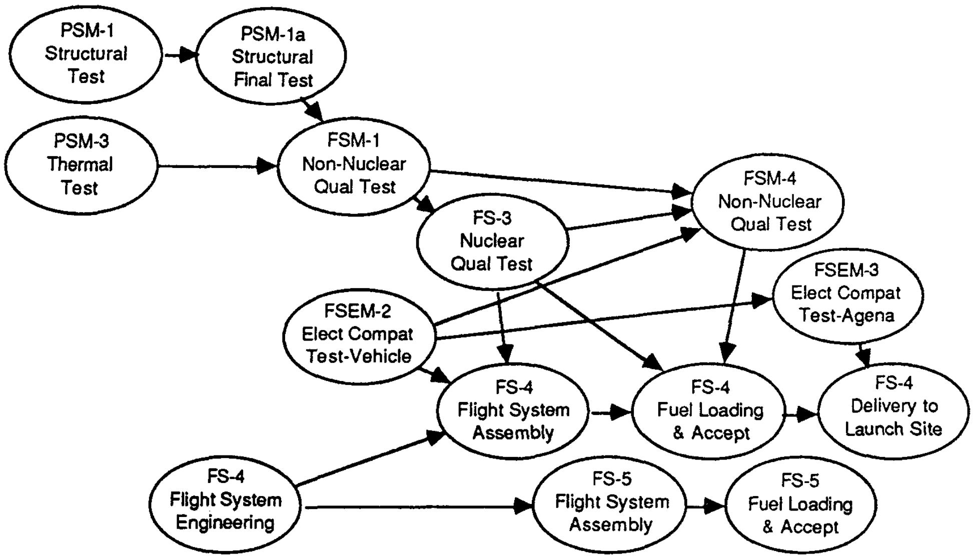


Fig. 3. System Development Sequence for the SNAP-10A Reactor

development, as well as specific areas requiring such development. The utilization of components, in contrast to complete systems for all of the basic development work resulted in significantly lower program cost and reduced the time cycle through testing, data feed back, refabrication, and retest." The SNAP-10A program included the following test and flight systems for the SNAPSHOT flight test on an Atlas-Agena booster combination (exclusive of the safety program) Staub 1967):

- PSM-1 – a prototype structural test system
- PSM-2 – an electrical analog simulator of the thermoelectric converter to be used in combined launch vehicle/SNAP-10A testing
- PSM-3 – a prototype thermal and hydraulic test system
- FSM-1 – an electrically heated nonnuclear qualification test system
- FSM-2 – originally an electrically heated prototype qualification test system to be delivered to the Agena contractor as part of a static firing test; later this unit became a non-power-producing electrical mockup (FSEM-2) to be used in combined Agena-SNAP-10A electrical and mechanical compatibility testing
- FSM-3 – originally an electrically heated qualification test system with flight hardware to be operated with the Agena in a combined thermal vacuum test; later, this unit became, like FSM-2, an electrical mockup (FSEM-3)
- FS-1 – a nuclear qualification test system
- FS-2 – originally this was to be the first flight system; later this became FSM-4, a second nonnuclear qualification test system with flight components

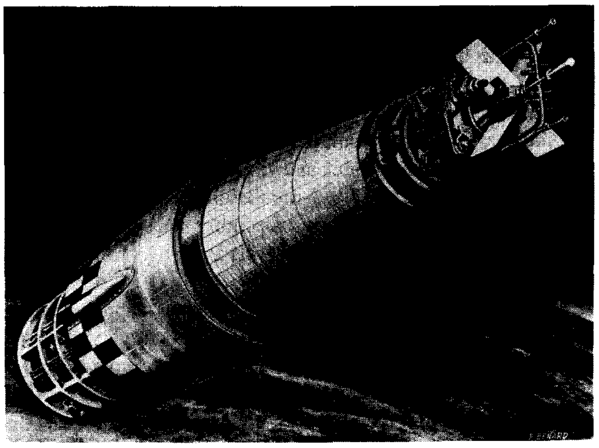


Fig. 4. Artist's Concept of the SNAP-10A Reactor and Agena Upper State in Orbit. The SNAP-10A was Designed to Produce 500 We for one Year. It was Launched on 3 April 1965.

- FS-3 – the second flight system
- FS-4 – a spare flight system
- FS-5 – a replacement for FS-2

The interrelationship of these test and flight systems is shown diagrammatically in Figure 3.

The PSM units provided basic system information early enough in the program to be fed back into the design of the

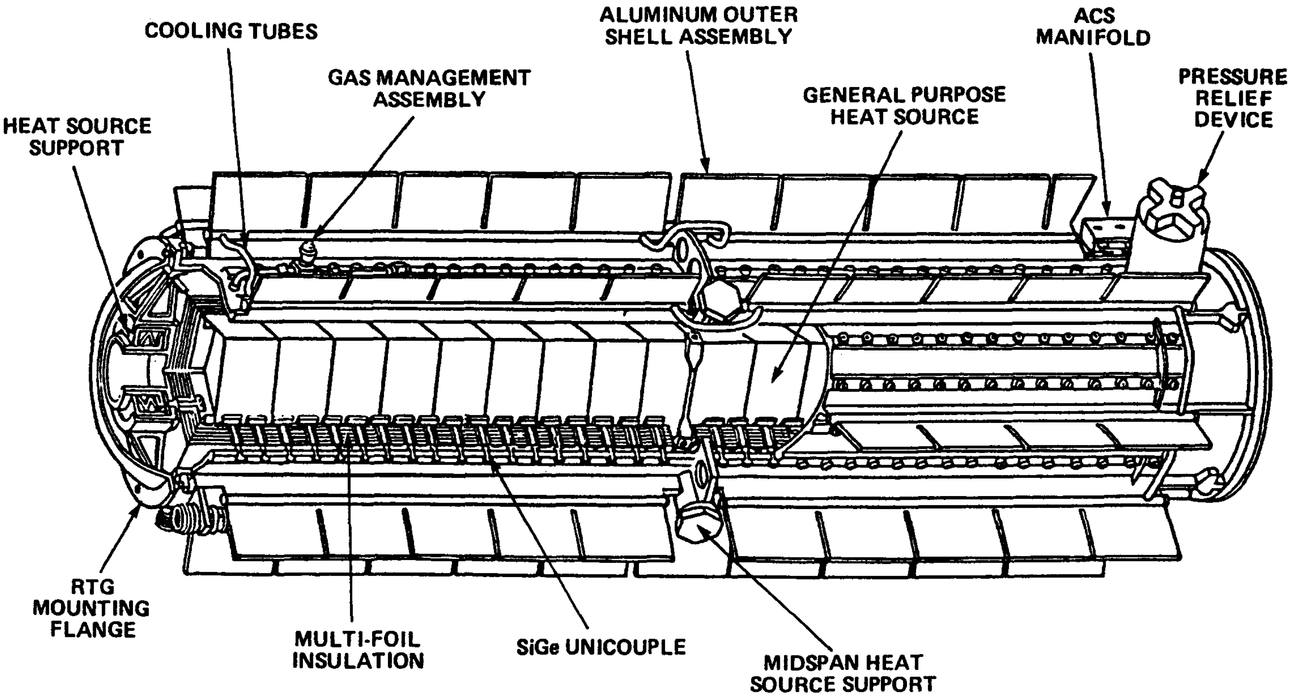


Fig. 5. Cutaway of the General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) Which is Now in Use on the Galileo and Ulysses Spacecraft. This is the Most Powerful Space RTG Ever Flown

systems. FSM-1, FS-3, and FSM-4 provided the necessary ground qualification systems data prior to flight in such areas as transport and launch shock and vibration; thermal-hydraulic performance; startup and self-regulation; diagnostic instrumentation; manufacturing, assembly, acceptance test, and checkout procedures; and ability to operate in a thermal vacuum environment [Staub 1967].

FSM-1 provided information on a number of prelaunch operations including sodium-potassium (NaK) fill. FSM-4 was used to demonstrate and qualify the factory-through-orbital operations. Both FSM-1 and FSM-4 demonstrated the compatibility among components integrated into a stable system. FSEM-2 and FSEM-3 were used to assess electrical compatibility between the SNAP-10A and the Agena vehicle. Both units uncovered compatibility problems which were solved [Staub 1967]. Among the lessons learned from SNAP-10A were that "Two nuclear reactor tests and a non-nuclear reactor mockup test were required to assure that design of reactor fuel elements, core vessel internals, and reflector subassemblies were ready for nuclear qualification and flight demonstration. Each test was required to verify design improvements, provided new information and was different than [sic] previous tests" [Schmidt 1988]. It was noted that "The experimental reactor test must be followed by a development reactor test and be completed before final design of the flight system. A non-nuclear mockup of the flight design containing flight components must be tested prior to start of the nuclear qualification test" [Schmidt 1988].

The FS-3 ground-test reactor began automatic startup on 22 January 1965 and completed the design objective of one year of continuous full-power operation on 22 January 1966. The reactor was actually run until 15 March 1966 allowing for several additional tests. FS-3 established a record at the time for the longest known continuous operation of a nuclear reactor system. FS-4, the world's first nuclear reactor electric power system for space applications, was launched on 3 April 1965 and started up as soon as confirmation was received of the desired orbit. Figure 4 is an artist's concept of the SNAP-10A reactor and Agena stage in orbit. After 43 days of successful operation, the reactor was automatically shut down as the result of a high-voltage failure sequence in the electrical system of the Agena spacecraft [Staub 1967].

A conservative design philosophy coupled with reliability analyses and the step-by-step use of component and early system test hardware allowed the SNAP-10A program to achieve a very high degree of reliability. It has been reported that "The significant success of the ground test qualification systems and of the flight test demonstration was due in large part to the conduct of the component qualification program" [Staub 1967]. (Note: The component qualification test program was completed in three years in conjunction with extensive development testing [Staub 1967].)

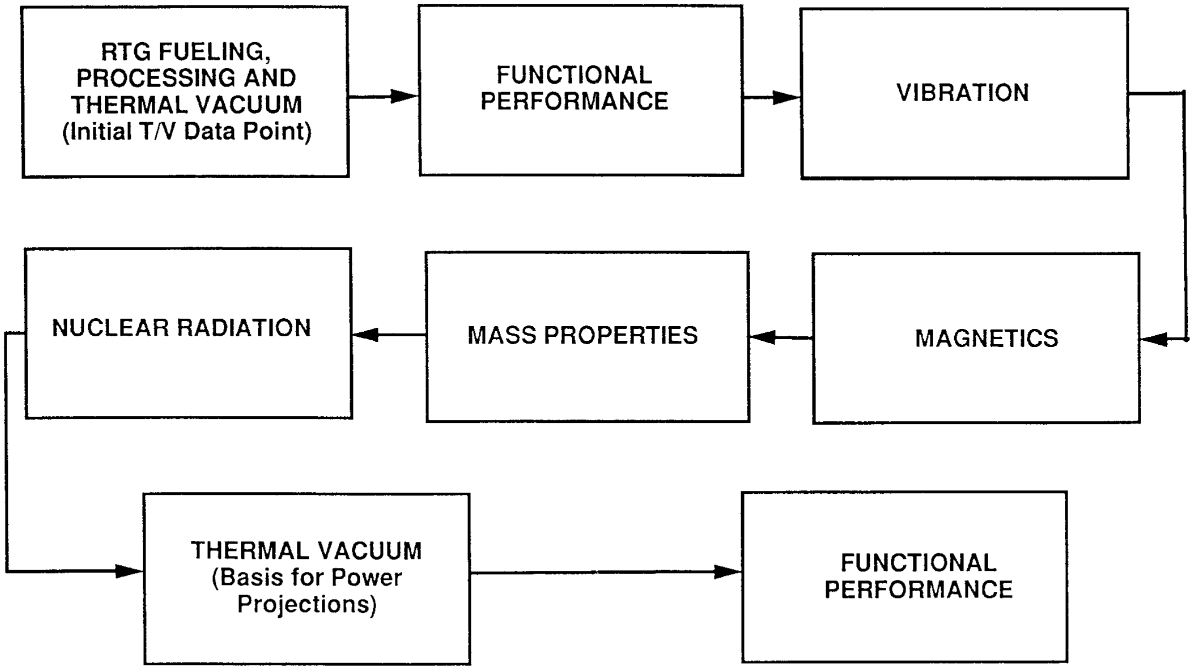


Fig. 6. Performance Sequence for the GPHS-RTG Assembly and Testing

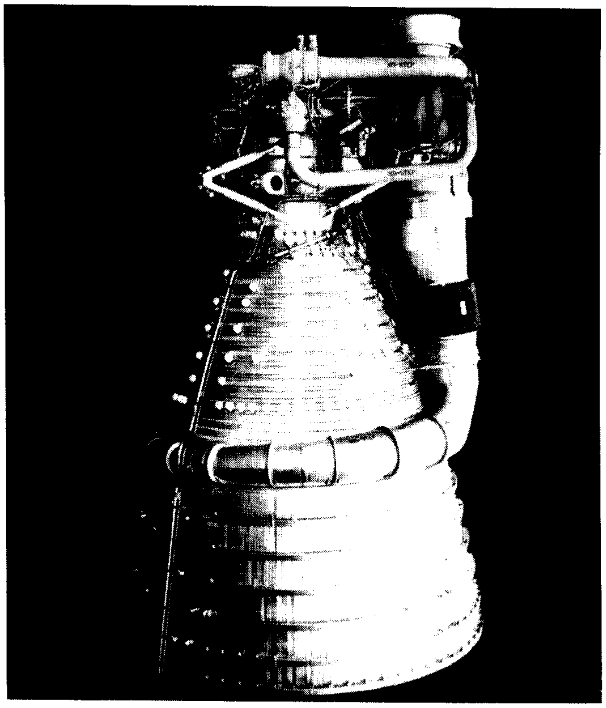


Fig. 7. Photograph of the F-1 Rocket Engine which was Used in the First State of the Saturn V Launch Vehicle for the Apollo Missions to the Moon. This is the Most Powerful Rocket Engine ever Operated

GPHS-RTG

The GPHS-RTG was developed to provide power (≥285 We) for the Galileo and Ulysses spacecraft as well as future spacecraft such as the Cassini spacecraft. As shown in Figure 5, the GPHS-RTG consists of two major components: the general-purpose heat source (GPHS) and the converter having an overall length of 114 cm and a mass of about 56 kg. The GPHS-RTG owes much of its heritage to the multi-hundred watt RTG (MHW-RTG) program that provided the RTGs for two USAF satellites (LES 8/9) and NASA's Voyagers 1/2 spacecraft. Nevertheless, the GPHS-RTG program was not without its problems, some of which were related to the larger design (the GPHS-RTG is almost twice the size of the MHW-RTG), some were related to starting production after several years of relative inactivity following the MHW-RTG program, and some were related to the new heat source design.

The design of the GPHS-RTG was controlled by the interface documents and specification requirements established between the developers and the users. Primary drivers came from the spacecraft requirements and the launch vehicle requirements, which led to tight requirements in the areas of power, structural (ability to withstand launch vibrations and pyrotechnic shock), magnetic field strength, mass properties (mass, center of mass, moments of inertia, products of inertia), pressurization, nuclear radiation, and general functional attributes (insulation resistance, internal resistance, pressure decay, nonsusceptibility to electrostatic discharging) [Bennett et al. 1986].

The test philosophy was to build and test hardware through increasing levels of assembly. First thermoelectric elements

Fig. 8. Montage of Photographs from the Apollo 11 Flight to the Moon—The First Manned Lunar Landing. On the Left is Shown the Huge Saturn V Lifting Off from the Kennedy Space Center Powered by the Mighty F-1 Rocket Engines

(unicouples) were built and tested, followed by the testing of six 18-couple modules. The full-scale Component Engineering Test (CET) units were built and tested for structural and mass properties. Next came the assembly and testing of the electrically heated Engineering Unit, which proved the design (after uncovering a vibration problem that was successfully solved), and the nuclear-heated Qualification Unit, which qualified the overall RTG design while allowing a checkout of the assembly and testing operations before the flight units were built. (The long-term thermal vacuum testing of the Qualification Unit has provided confidence in the long-term performance of the flight RTGs and in the analytical models.) Finally the four flight RTGs were assembled and tested. The overall performance sequence for GPHS-RTG assembly and testing is shown in Figure 6. Supporting this test program were engineering analyses, component testing and materials characterizations. Not counting the earlier MHW-RTG program and heat source development activities, the GPHS-RTGs were completed within seven years of the signing of the letter contract and in time for the originally planned launches [Bennett et al. 1986].

Currently the two GPHS-RTGs on Galileo and the one GPHS-RTG on Ulysses are performing very well and from projections all mission power requirements should be met. In large measure this success can be attributed to the phased approach of the program which allowed early identification of problems.

F-1 ROCKET ENGINE

The F-1 rocket engine, which is shown in Figure 7, used RP-1 and liquid oxygen to provide 6.8 MN thrust. Five of these engines made up the first stage of the Saturn V launch vehicle used in the Apollo missions to the Moon. Figure 8 is a montage of scenes from the Apollo 11 mission to the Moon, including a view of the launch of the 110-m-tall Saturn V launch vehicle from the Kennedy Space Center (KSC). The F-1 engine had its origins in an Air Force program dating back to 1955. The F-1 was transferred to NASA in 1958. The first full-scale F-1 mockup was unveiled in 1960 and a full-sized thrust chamber assembly prototype was tested in 1961 [Bilstein 1980].

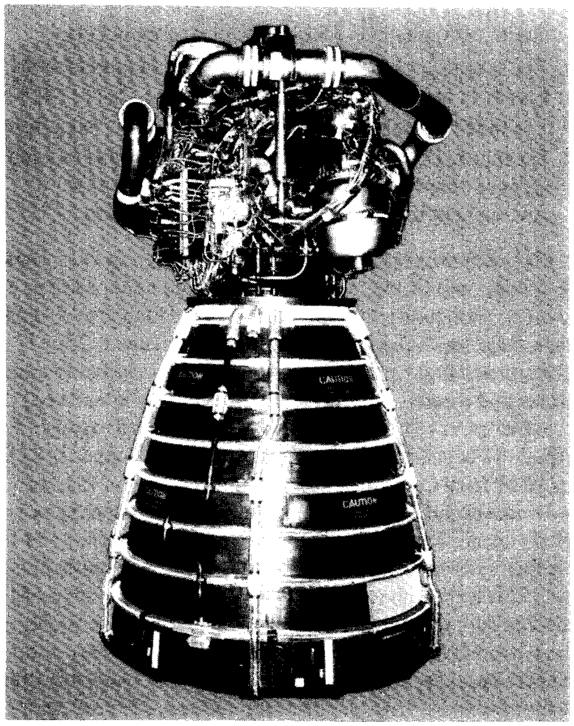


Fig. 9. Photograph of the Space Shuttle Main Engine (SSME) Which is the Highest Performance Reusable Production Rocket Engine in the World

Because the F-1 was to be man-rated simplicity, proven components, and reliability were built in. In a sense the F-1 had its heritage in the H-1 engine which in turn owed some of its heritage to the Thor, Jupiter and Atlas programs. Bilstein (1980) concludes that "Although the F-1 had its roots in early Air Force studies, it was a 'newer' engine than the H-1. Troubles with the F-1, however, were primarily a function of proportions, not innovations. Both engines used the same liquid oxygen and RP-1 propellants, but size and performance characteristics made the F-1 fundamentally different. The H-1 experienced R&D problems as it was uprated in thrust. Taking proven H-1 components, such as the injector, and scaling them up to F-1 requirements turned out to be not only difficult but basically impossible. The job necessitated a fresh approach. Reworking the engine and the injector to cope with combustion instability entailed an R&D effort of notable scope, embracing scientific and technical specialists from MSFC [Marshall Space Flight Center] and other NASA centers, the contractor, other government agencies, private industry, and universities."

Bilstein (1980) notes that "The minute, exacting requirements of engine development were such that these seemingly insignificant changes required some 18 months to prove out, and the flight-rated model of the F-1 injector did not receive MSFC's imprimatur until January 1965." Bilstein (1980) quotes Hugh Dryden, then NASA's Deputy Administrator as writing that "Such development problems are the common experience of every engine development with which I am familiar and are nothing to be concerned about so long as one makes sure that the developing agency is taking a multipronged approach to obtaining a solution." However, the

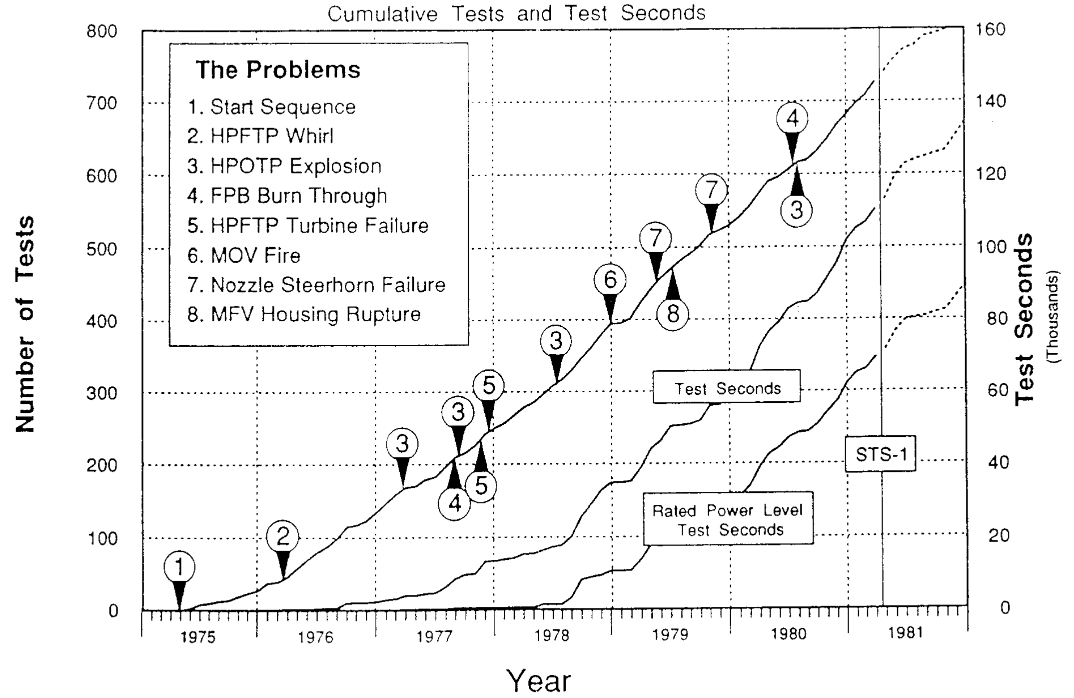
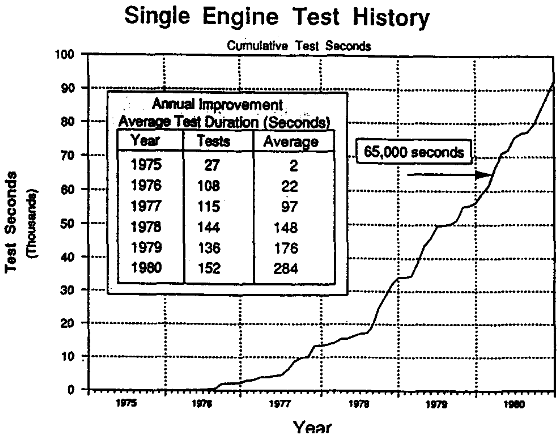


Fig. 10. Engine Test History for the SSMEs up to the Time of the First Space Shuttle Launch (12 April 1981)



Annual Improvement
Average Test Duration (Seconds)

Year	Tests	Average
1975	27	2
1976	108	22
1977	115	97
1978	144	148
1979	136	176
1980	152	284

Fig. 11. Single Engine Test History on the Space Shuttle Main Engine Prior to the First Space Shuttle Launch on 12 April 1981

Fig. 12. Photograph of a Space Shuttle Launch Showing the Two Solid Rocket Motors and the Three Space Shuttle Main Engines

turbopump "absorbed more design effort and time for fabrication than any other component of the engine;" in fact 11 failures occurred in the turbopump development program [Bilstein 1980].

Bilstein (1980) quotes Leonard C. Bostwick, a veteran MSFC engine manager, as saying that there are four distinct "problem phases" over the five- to seven-year development period of a liquid rocket engine:

- The first problem phase occurs because of the inability to totally extrapolate and build on existing knowledge
- The second problem phase occurs when the propulsion system is mated to the vehicle or stage
- The third problem phase occurs at the start of manufacture
- The fourth set of problems occurs during the actual missions because "there was no way to duplicate the actual environment in which the vehicle had to perform"

Engine acceptance testing involved subjecting each engine to a minimum of two tests demonstrating engine starting and shutdown reliability. Acceptance tests were limited to no more than three times the rated duration for the engine. The preliminary flight rating tests consisted of a calibration test series and a safety limit test series [Rocketdyne undated].

As Bilstein (1980) notes "Before the epochal voyage of Apollo 11 began on 16 July 1969, five Saturn V launch vehicles lifted off from Cape Kennedy: one in 1967; two in 1968; and two more in early 1969. Despite the thousands of metric tons of cryogenic materials already consumed in research and in the hundreds upon hundreds of tests already accomplished, the pace of research involving the F-1 only seemed to quicken in the concluding months before Apollo 11 began its flight. Dozens of additional tests of the complete engine were run at Huntsville and at Edwards, as contractors and NASA engineers determinedly verified the maturity and reliability of the mammoth rocket engine."

SPACE SHUTTLE MAIN ENGINE (SSME)

The Space Shuttle Main Engine (SSME), which is shown in Figure 9, is a high chamber pressure (>20.6 MPa) rocket engine that burns liquid oxygen and liquid hydrogen to produce a rated thrust of 2.1 MN (vacuum) with a specific impulse greater than 4430 m/s. The letter contract to develop the SSME was signed on 5 April 1972 and the first flight occurred in 12 April 1981 [Biggs undated].

The SSME went through several design iterations as the Space Shuttle requirements evolved. One of the significant early development tasks was completion of the Integrated Subsystem Test Bed (ISTB) which allowed engine-type testing. Funding constraints often led to testing components in the ISTB or in actual engines; also, it has been noted that the engines provided the most realistic environment [Biggs undated]. Even so, a number of component problems had to be overcome:

- High pressure fuel turbopump subsynchronous whirl
- High pressure oxidizer turbopump explosions
- High pressure fuel turbopump turbine blade failures
- Main oxidizer valve fire
- Main fuel valve fracture
- Nozzle feed line failures
- Fuel preburner burnthrough

At the time of the first flight, the SSME test program had accumulated 110,253 seconds during 726 tests (see Figure 10).

One engine accumulated 65,000 seconds of test time (see Figure 11) [Biggs undated]. A typical shuttle launch is shown in Figure 12. The SSMEs have demonstrated that they represent the highest performance, reusable production rocket engines in existence.

CONCLUDING REMARKS

The programs described in this paper successfully achieved their goals (although NERVA was not flown). Each of these programs operated under funding and schedular constraints showing that it is possible to do things "faster" (≤ 10 years) and "cheaper." Each of these programs had a heritage in earlier programs but that did not prevent the occurrence of new problems.

A key contributor to the successes of these programs was having two or more ground test systems which enabled early checkout of the system and the components. In many cases the design, component testing and ground system testing were almost in parallel ("concurrent engineering"); nevertheless the preflight testing more than paid off in uncovering problems. Williams (1981) has written that "After steps to ensure good design and reliable parts, NASA verifies the hardware through a series of system tests that fall into two categories: performance and environmental tests.

"The performance tests are generally done at all levels of assembly—from subassemblies through components and subsystems. These tests verify that the hardware performs as expected, in all operations, and that it 'plays together' well in the sense of being properly interfaced and integrated. These tests exercise the software as well as the hardware and ultimately embrace ground support operations as well as flight systems.

"The environmental tests ensure that the craft can withstand the anticipated launch, flight, and reentry and landing conditions. Tests are normally conducted at levels based on measured or anticipated flight loads including an appropriate safety factor."

Williams (1981) has also noted that "Emphasis on testing the highest level of assembly—the whole spacecraft—has always been a NASA priority. This is the all-up system level, consisting of the spacecraft and all flight hardware in place including instruments . . . It is quite common to discover a number of anomalous conditions during the pre- and post-test functional checks, and these conditions are not necessarily related to the actual environmental exposure. Some are caused simply by unexpected interface problems, others by workmanship errors introduced during integration. The uncovering of those flaws alone justifies the value of total system verification." NASA has recognized that these tests can be done on either a prototype, which never flies, or a "protoflight" model, which does fly [Williams 1981].

In his concluding remarks on proof testing Petroski (1992) has observed that "Unfortunately, with the development of sophisticated theories and the advent of complex computer models in engineering, not only the proof test but also its ceremonial role have become largely things of the past or of other cultures. The belief in advanced theory and endless numbers can be so great among theorists and so impressive or intimidating to nontechnical participants in large projects that the possibility of failure is dismissed as being in the realm of the hypothetical or incredible . . . The proof test, no matter how low-tech or quaint, is still among the surest of ways to catch errors that can escape even our most sophisticated applications of logic and theory."

Perhaps the best advice for anyone contemplating the qualification of a new space nuclear system is to consider the following definition of the scientific method [Caws 1972]:

"Such a definition would recommend for the solution of any scientific problem, first, an immersion in observed fact; second, the accurate definition of universal categories for the description of the regular features of what is observed; third, the inductive generalization of simple universal laws expressing such regularities; fourth, the entertainment of explanatory hypotheses; fifth, the detailed comparison of the consequences of the hypotheses with the inductive generalizations, rejecting the consequences of the hypotheses in favor of the inductive generalizations in cases of conflict; sixth, the axiomatic organization of the hypotheses which survive this test and the demonstration of the rest of the theory as following from them."

Certainly following an organized, logical approach overcomes the often-encountered problem that "there's never enough time to do the job right but there's always enough time to do it over." As Richard P. Feynman observed, "For a successful technology, reality must take precedence over public relations, for nature cannot be fooled" [Feynman 1986].

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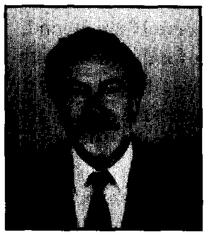

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