IDAHO NATIONAL ENGINEERING & ENVIRONMENTAL LABORATORY

INEEL/CON-2000-01020
PREPRINT

Innovative Approaches to Development and Ground Testing of Advanced Bimodal Space Power and Propulsion Systems

T. Hill
C. Noble
J. Martinell
S. Borowski

July 16, 2000 – July 19, 2000

36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference

B E C H T E L   B W X T   I D A H O ,   L L C

INNOVATIVE APPROACHES TO DEVELOPMENT AND GROUND TESTING OF ADVANCED BIMODAL SPACE POWER AND PROPULSION SYSTEMS

T. J. Hill, PE, Consulting Engineer, C. Noble, Project Manager ,and J. Martinell, Project Manager
Idaho National Engineering and Environmental Laboratory, Idaho Falls, ID

Dr. S. K. Borowski, Member AIAA
NASA Glenn Research Center, Cleveland, OH

ABSTRACT

The last major development effort for nuclear power and propulsion systems ended in 1993. Currently, there is not an initiative at either the National Aeronautical and Space Administration (NASA) or the U.S. Department of Energy (DOE) that requires the development of new nuclear power and propulsion systems. Studies continue to show nuclear technology as a strong technical candidate to lead the way toward human exploration of adjacent planets or provide power for deep space missions, particularly a 15,000 lbf bimodal nuclear system with 115 kW power capability. The development of nuclear technology for space applications would require technology development in some areas and a major flight qualification program. The last major ground test facility considered for nuclear propulsion qualification was the U.S. Air Force/DOE Space Nuclear Thermal Propulsion Project. Seven years have passed since that effort, and the questions remain the same, how to qualify nuclear power and propulsion systems for future space flight. It can be reasonably assumed that much of the nuclear testing required to qualify a nuclear system for space application will be performed at DOE facilities as demonstrated by the Nuclear Rocket Engine Reactor Experiment (NERVA) and Space Nuclear Thermal Propulsion (SNTP) programs. The nuclear infrastructure to support testing in this country is aging and getting smaller, though facilities still exist to support many of the technology development needs. By renewing efforts, an innovative approach to qualifying these systems through the use of existing facilities either in the U.S. (DOE's Advance Test Reactor, High Flux Irradiation Facility and the Contained Test Facility) or overseas should be possible

INTRODUCTION

Fifty years ago, the concept of routinely placing humans and equipment into earth orbit and performing a host of now routine functions such as frequent piloted missions, International Space Station, Global Positioning System, and modern communications, was for dreamers. Today, NASA considers new science missions that will push the space frontier back even further. Next generation missions, such as Mars Outpost/Lunar Applications, Human Exploration Missions, Deep Space, Outer Planet Science and Deep Space "Interstellar Precursor", must meet the challenges of exploring and operating in even more distant locations and in more hostile environments. For example, a piloted Mars mission would require movement of equipment, personnel, and supplies from the surface of the Earth, through low Earth orbit, and on to Mars. Space transfer vehicles traveling between Earth orbit and Mars orbit require safe, reliable, high performance propulsion systems in order to reduce the trip times as much as possible.

The combined requirements of high performance and low-mass necessitate consideration of advanced propulsion concepts such as nuclear propulsion. Nuclear propulsion offers the potential for significantly greater performance and reduced vehicle mass compared to the current propulsion systems. Although it will require additional engineering effort to update existing propulsion concepts with recent technological advances and include power generation capability, the resulting propulsion system will greatly enhance the nation's capability to travel to Mars and beyond.

Nuclear reactor technology is mature and there has been a wide variety of nuclear reactors designed over the past 50 years for many terrestrial applications and for some applications in space. The design and construction of a typical nuclear plant is a complex and time consuming process, but the basic theory on which it operates is fairly simple. In simplistic terms, a nuclear reactor can be viewed as consisting of three major subsystems: (1) the reactor core with its nuclear fuel, (2) a fluid that that flows through the reactor to remove the heat being generated by the nuclear reactions in the core, and (3) a control system that allows a reactor operator to maintain a balance between nuclear reactions in the core and the coolant temperature flow so that the reactor will operate at the desired temperature. (See Figure 1)

NASA studies have shown high-performance propulsion to be enabling for some missions that are being considered. High-performance propulsion would also substantially enhance other missions by reducing cost or risk. In a nuclear thermal propulsion (NTP) system, the primary coolant hydrogen is pumped from a tank into a nuclear reactor core where it is heated. After leaving the reactor, the heated hydrogen is then expanded through a convergent-divergent nozzle creating thrust. In this case, the hydrogen serves the dual purpose of reactor fuel coolant and rocket propellant. This means that the hydrogen does not recirculate but completely exits the system through the rocket nozzle. The exit temperature of the hydrogen at the rocket nozzle is controlled by the rate at which hydrogen is pumped from the tank into the core and by the rate at which nuclear reactions are occurring in the core. The NERVA program[1] conducted by DOE from the 1960s until the early 1970s demonstrated that the basic design for a nuclear rocket was sound. The significant technical accomplishment of the NERVA program beyond demonstrating the feasibility of a nuclear rocket was to establish a baseline for nuclear fuel performance, high-temperature materials development, and the use of hydrogen as a reactor core coolant. Even though the NERVA program developed an NTP engine almost to flight status, a number of technical and political issues remain to be addressed. The key technical issues are again surface testing, updating the reactor design with high-temperature materials and advanced fuels that would significantly improve engine performance, and integration of the reactor, reactor controls, shielding, and propellant into the overall flight vehicle. Specific areas that will most likely require additional attention in order to attain the required performance and reliability are:

FUELS TECHNOLOGY

Fuel development is required in order for fuels to operate at higher temperatures and for longer times than are available for existing systems, and to achieve the higher specific impulses and velocity changes required for these space missions. In addition, cyclic operation of the fuel will also be required because a number of restarts will be needed for orbit capture and departure, and trajectory corrections.

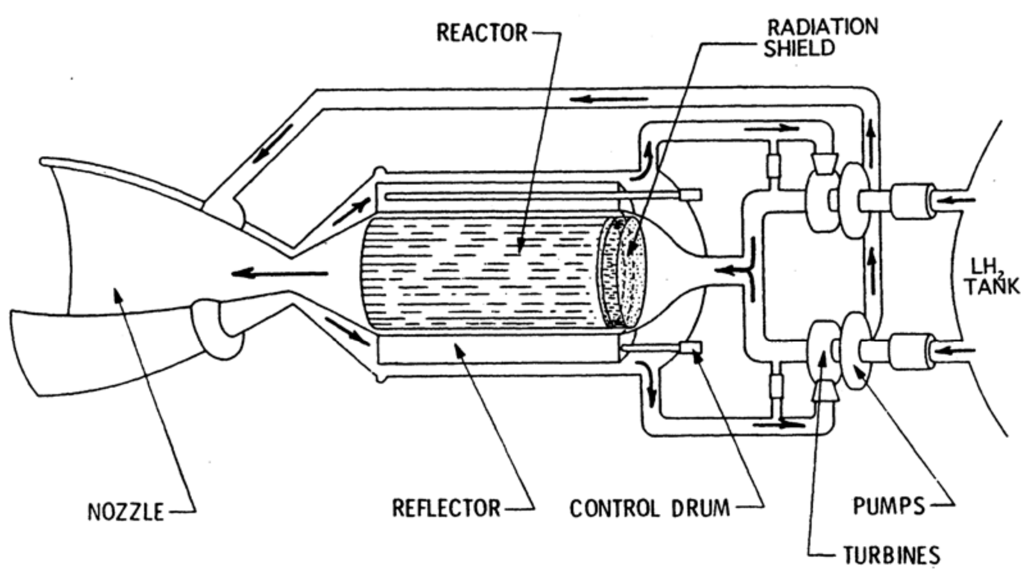

Fig. 1 Schematic of NTP

MATERIALS TECHNOLOGY

Materials need to be developed for higher operating temperatures and for longer duration of operation.

INSTRUMENTATION AND CONTROL (I & C) SUBSYSTEM TECHNOLOGIES

Higher temperatures expected in advanced reactor designs and radiation levels from space dictate the need to develop high-temperature, irradiation-hardened thermometry devices, neutron detectors, and electronic devices. Safety requirements and the introduction of moderating coolants require the need to control the reactor over several orders of power levels that dictate the need to develop neutronic algorithms and maintain criticality control over a range of adverse conditions.

PROPELLANT FEED SUBSYSTEM TECHNOLOGIES

The tanks, pumps, and feed lines required to supply propellant for these NTP systems will need to be developed. For engines in the 15,000 lbf class, existing turbo pumps developed by NASA may be adequate. It is important to note that the hydrogen serves the dual purpose of reactor fuel and test assembly coolant and rocket propellant. This means that the hydrogen does not re-circulate but completely exits the system through the rocket nozzle. The exit temperature of the hydrogen at the rocket nozzle is controlled by the rate at which hydrogen is pumped from the tank into the reactor core and by the rate at which nuclear reactions are occurring in the core. The sizing of a test assembly, hydrogen supply system must both simulate propellant and possibly cool equipment downstream of the core exit.

TESTING AND VERIFICATION

A key element of any nuclear propulsion development effort is the testing program. The testing program will ensure that the integrated system can be operated safely and will satisfy mission requirements. The complete testing effort would most likely be accomplished with a combination of component and subsystem tests performed both on the earth surface and in space. The components, subsystems, and systems to be developed for space nuclear propulsion applications will need to be thoroughly evaluated by analytical and experimental demonstration means to ensure that design requirements are met. In order to establish safety margins, an integrated engine test will be required. Integrated engine testing over the entire performance range of the propulsion system will guarantee the greatest possibility of success for space flight qualification.

In addition, experimental feasibility verification will be required for some of the advanced technologies, such as fuel performance, that would be considered in any well-designed testing program. NTP technology and systems development will require new facilities for fuel element development and qualification, reactor demonstration, and engine system demonstration and qualification. Existing facilities will be required for basic fuels and materials development, and various nuclear and nonnuclear component development using hot, flowing hydrogen as the working fluid.

Key parts of the testing program will need to be identified in an NTP development effort early so that facilities needs will be identified, existing facilities and infrastructure will be preserved, and designs and development schedules for new facilities will be made early in the NTP program. An early emphasis on testing is necessary because this will be a major driver of schedule driver for the overall program.

The major facility needs for a ground demonstration facility of either a bi-modal or nuclear propulsion system of a NERVA type are defined below and shown in Figure 2 as developed by the SNTP program. Largely the power, temperature, and time of reactor operation will determine the sizing of these various systems below.

- Test control center
- Data acquisition and control system
- Coolant management system
- Engine test system
- Effluent treatment system
- Post test handling and examination system
- Nuclear storage, assembly, and waste management systems

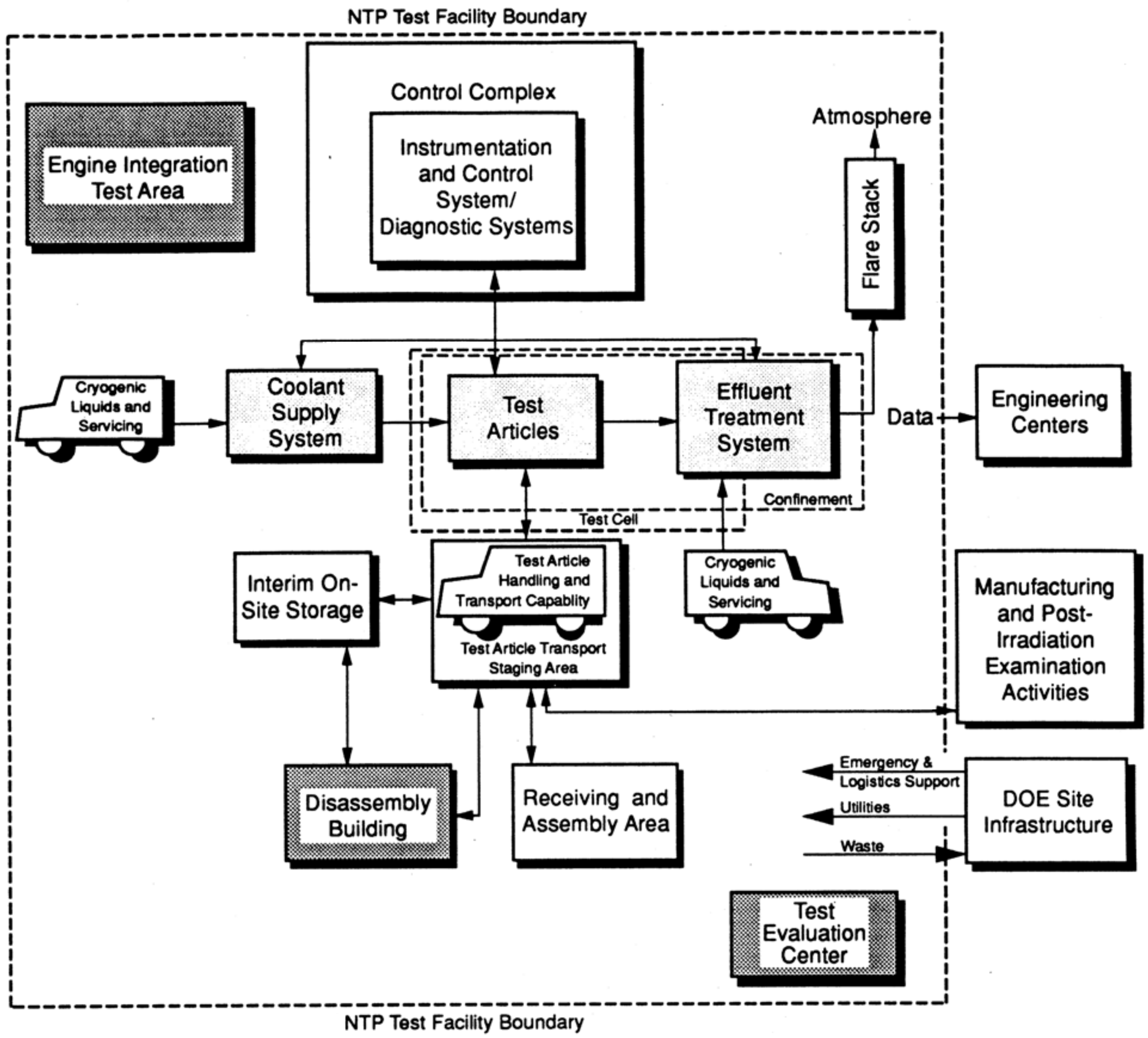

Fig. 2 Components of a Ground Test Facility

Test Control Center

The test control center provides an environment for operational personnel to achieve a safe startup of the reactor, perform the test according to the test plan, and safely shut down the reactor after the test completion. Also the operations people will be trained to recognize abnormal events and safely shut down the system.

Data Acquisition System

The data acquisition system will provide the information required to safely operate the system and the instrumentation to collect and store specified data so that technical personnel can determine and verify the performance of test articles.

Coolant Management System

The coolant management system (pipes and valves) would supply the coolant gases to various locations at the test facility in appropriate quantities to support test and operational activities. Auxiliary equipment required by the coolant distribution system would include vaporizers to maintain pressure on the bulk liquid hydrogen storage vessels during transfer operations; facility pumps and vaporizers to enable filling the high pressure ambient temperature hydrogen storage vessels; filters at the fill stations and test cell to maintain fluid cleanliness; instruments to monitor conditions in the storage vessels and distribution systems; and mixers to deliver variable temperature hydrogen to the test cell. For bimodal testing, the test cell would provide the capability to transfer excess heat to the environment, perhaps using the coolant management system for the heat dump.

Test Articles

A test cell would be required to accommodate the major reactor components and have sufficient penetrations to provide fluids, power, and data acquisition necessary for reactor operations. The test cell must also be capable of handling and storing irradiated materials.

Effluent Treatment System

The effluent treatment system (see Figure 3) would be designed to accomplish the following five objectives: (1) ensure that radioactive material entering the effluent treatment system remains in a subcritical geometry; (2) cool the test article effluent to temperatures acceptable for normal engineering materials used in gas treatment systems; (3) remove particulates and debris for the effluent stream; (4) remove halogens, noble gases and vapor phase contaminates from the effluent system; and (5) flare the resulting hydrogen to the atmosphere.

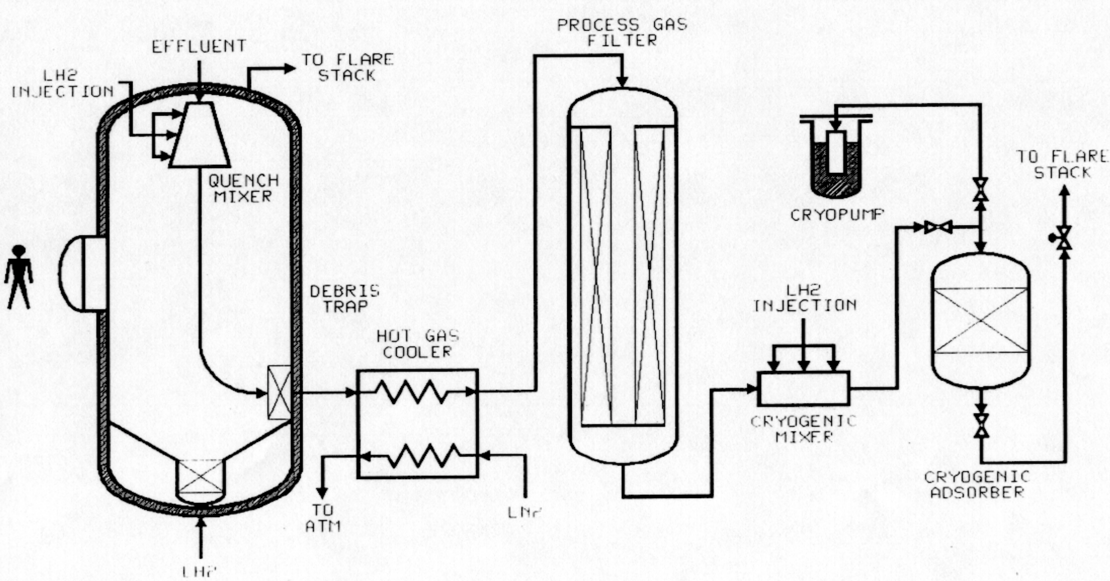

Fig. 3 Effluent Treatment System

The major subsystems of the effluent treatment system are: (1 debris trap to collect failed fuel elements and to divert coolant flow; (2) heat removal system to remove the heat from the coolant stream; (3) particulate filters to remove any particles that may become entrained in the coolant stream; (4) cryogenic mixers and absorbers to remove the halogens and the noble gases from the coolant stream; (5) and flare the remaining coolant to prevent hydrogen accumulation in the vicinity of the test cell.

Post Test Handling and Examination System

A disassembly facility with an integrated hot cell would be required to accommodate initial disassembly and post irradiation activities for fuel elements and reactor components. Once the initial disassembly has occurred, the detailed evaluation of components or subsystems can be performed at various existing hot cells.

Nuclear Storage, Assembly, and Waste Management Systems

An interim storage area would accommodate the handling of multiple cores, including a pretest core, a core currently used in testing, and a post-test core. Such a facility would also have the capacity to store other articles that have become contaminated during the testing process.

U.S. TEST FACILITIES

The test facilities available in the U.S. are becoming limited as the DOE continues to cleanup and close facilities used for years as part of the U.S. weapons complex. Of the remaining DOE test sites, operating steady-state test reactors are located at the Oak Ridge National Laboratory and the Idaho National Engineering and Environmental Laboratory (INEEL). While the other DOE sites have experienced long reactor operating careers, those facilities are mostly being decontaminated and decommissioned. Two facilities previously investigated at the INEEL are the Advanced Test Reactor (ATR) and the Contained Test Facility. While these two facilities are mentioned in this paper, consideration should also be given to revisiting overseas facilities and the potential for new facilities at an existing site.

Advanced Test Reactor

In the early 1990's, the ATR was evaluated for installation of an advanced hydrogen loop in which multiple-clusters of pins could be tested. The evaluation went beyond the feasibility stage and functional and operational requirements were developed to begin the detailed design. The test loop was sized for flowing hydrogen up to 45 g/sec. Today, seven years later, a relook at the feasibility study would be required to ensure operational and environmental safety of performing such tests in an existing reactor. The original test loop was estimated in the 10s of millions of dollars, but could be implemented relatively quickly permitting early fuel selection and establishing a baseline for fuel performance. The pursuit of a smaller hydrogen loop in an existing reactor would also provide confidence in the development of the effluent treatment system for larger NTP engine tests. The institutional issue of large nuclear tests could be mitigated through smaller subscale reactor loop tests.

It is expected that in the near-term a nuclear propulsion engine would be very similar to the NERVA design. However, the performance could be significantly enhanced with an improved fuel. Previous studies indicate that a testing program to verify improved performance is feasible in a 5-year time frame. The Russians have conducted tests with a high temperature ternary carbide that has the potential of producing hydrogen exhaust around 3100K or about 500K higher that that achieved in the NERVA program. One of the key technical tasks in developing a modern rocket would be the investigations and selection of a specific fuel to be used. The ATR is routinely used to analyze and determine the capabilities of nuclear fuels. The ATR higher flux levels permits the accelerated burnup testing of test fuels. Options exist to enhance the flux to near prototypic conditions for any fuel element test. The ATR was used to test the SP-100 fuel, New Production Reactor, advanced commercial fuel development, etc.

In order to study the performance of a nuclear rocket fuel the addition of a hydrogen loop. A preliminary scoping study at the INEEL determined that a hydrogen loop addition would be considered a technological challenging project. Nevertheless, the type of testing performed at ATR and the subsequent post-irradiation examination on the candidate fuel would need to be performed in order to have data to support performance verification and to establish the safety margin.

Contained Test Facility

In 1992, the U.S. Air Force (USAF) was evaluating an SNTP program to acquire and validate advanced technologies that could be used to sustain superior capabilities in the areas of space power and propulsion. The specific program objectives were to develop the technology and demonstrate the feasibility of a particle bed reactor propulsion system. Two locations for the test facilities were considered, the Contained Test Facility at the INEEL, near Idaho Falls, Idaho, and a new, undeveloped site called Saddle Mountain on the Nevada Test Site, north of Las Vegas, Nevada.

The basic facility consisted of systems and subsystems identified earlier in this paper. The effort continued through the preparation and publishing of a final environmental impact statement[2] for the project, but a Record of Decision was not issued.

The proposed USAF system was larger than those currently being considered by NASA. The system proposed for testing in the SNTP was 550 MWt system with a run time of up to 1000 seconds. Further testing was contemplated at 1000 MWt for up to 500 seconds. These proposed tests easily bound the current proposed test of a 15,000 lbf, ~330 MWt nuclear propulsion engine.

The proposed concept for testing the SNTP in the Contained Test Facility is shown in Figure 4. The testing approach used for the SNTP was to place all the nuclear components and contaminated filters and absorbers in the containment vessel at Contained Test Facility. The reactor, debris trap, filters, and absorbers all fit within the 70-ft diameter containment vessel. Adjacent control rooms, hot cells, and disassembly area are all readily available.

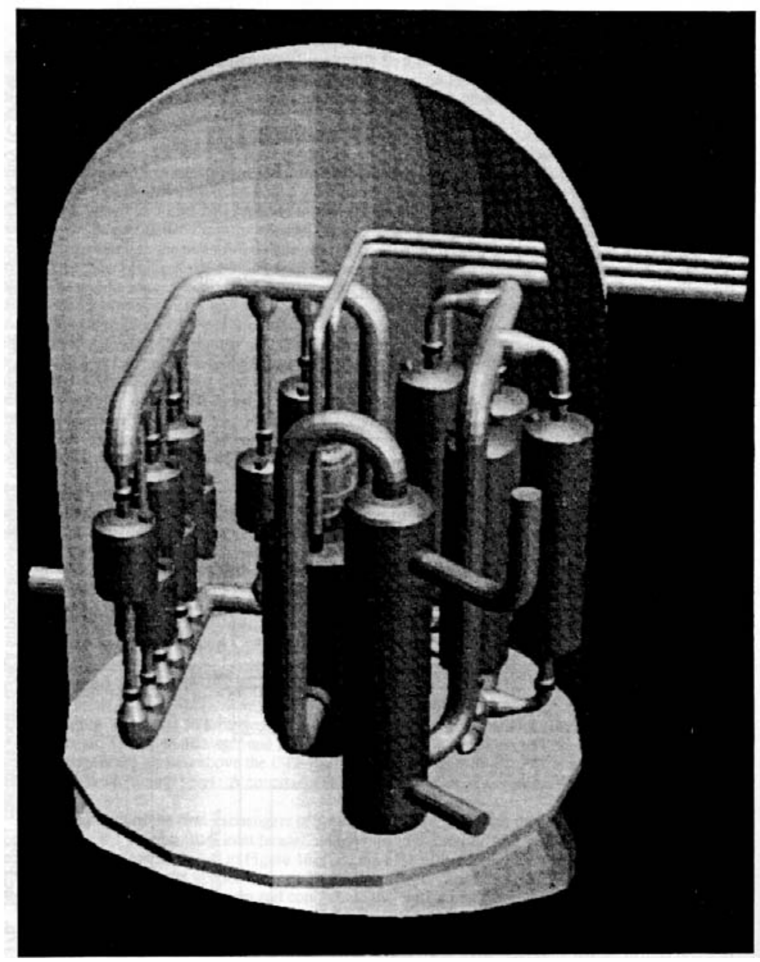

Fig. 4 Layout of ETS in CTF

In order to provide some detail on a candidate baseline system, we shall consider the testing of a small bimodal engine with the same basic design and operating parameters as described in two paper[34] by S. K. Borowski and others. Under the "propulsion mode" conditions shown in Figure 5, a small 15,000 pound thrust engine, operating at ~2900 K (5220 R), would operate at a specific impulse (Isp) pf ~940 sec and require a hydrogen flow rate of ~7.2 kilograms per second. In the "power generation mode", the reactor power would be ramped down from ~335 MWt to ~115 kWt and operated for extended periods. The energy generated would be removed by either regeneratively-cooled tie tubes as in the earlier NERVA engine design or dedicated energy extraction ducts within the fuel assemblies, and dumped via a simple heat exchanger. Operating in the neighborhood of 3000K, and capable of generating 115 kW in the bimodal power generation mode. In 1992, the Contained Test Facility was investigated as a candidate to test the a 550 MWt SNTP with an Isp of ~850 sec particle bed reactor. See Figure 6.

As a previous INEEL estimate stated[5], the cost to test an SNTP type reactor would take approximately 9 years and cost $450,000,000. This included the entire project from the environmental impact statement through testing of the first system. It did not include any disassembly because it was assumed there would be further testing on other engines. The testing assembly for the SNTP system would need to be modified to test the reactor operating for 25 minute duration in the propulsion testing mode. The system would need some minor modifications to accommodate operating for a long period in a steady state low-power generating mode (115kW).

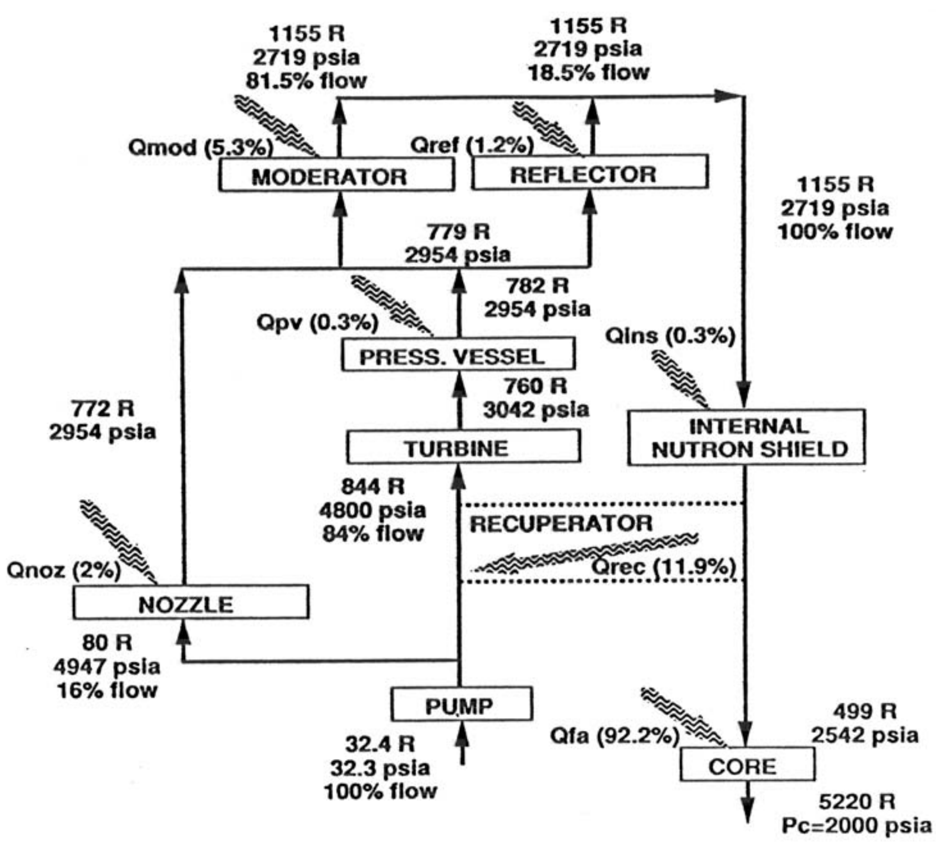

Fig. 5 Flow Schematic of Recuperated Topping Cycle for the Russian Engine

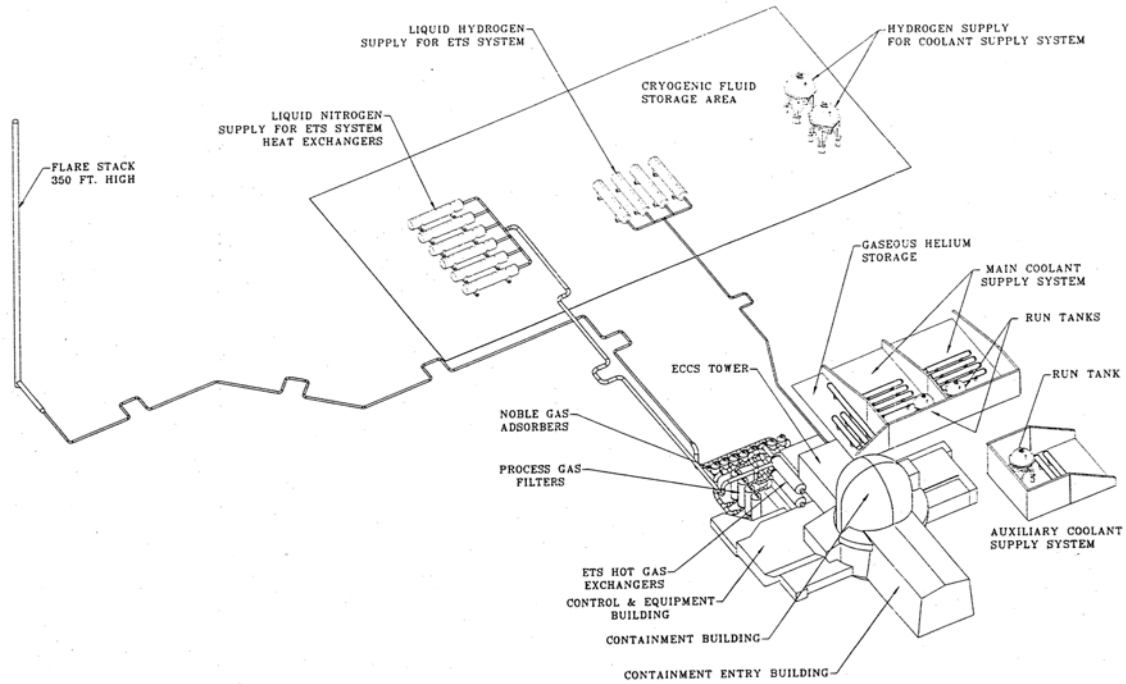

Fig. 6 Contained Test Facility

The supply system would need the capability to supply approximately 15 tons of hydrogen per engine test, plus an additional 15-20 tons for the effluent treatment system cooling requirements. A facility of this type is considered a national resource and would be available for future test programs. The designed system would be of modular construction to permit modifications for testing of these future systems. Future systems in the same power and performance class are assumed for development of the effluent treatment system.

The Contained Test Facility is in some sense a verified containment system that in the past has housed a number of nuclear experiments in the 55 MWt steady state class. For these previous experiments, it was deemed that a containment was necessary. It has not been determined that a verified containment would be required nuclear thermal propulsion testing, though the advantages of containment and the use of an effective effluent treatment system would enhance public perception. For example, the SNTP was actively considering confinement versus containment for the test at the Nevada Test Site. The containment comes into play only if there is an abnormal occurrence that breaks the primary containment system. Testing with containment is marginally more expensive if an existing containment such as the Contained Test Facility is used. The key issue revolves around the public acceptance of nuclear testing. Testing in vessel such as LOFT may set a precedence of testing with a containment. Not using a containment may delay the test program beyond what can be accepted by programmatic needs. These issues need to be resolved prior to the start of the program.

CONCLUSION

A broad range of mission activities such as system development, qualification testing, launch, and ultimate disposal of NTPs must be done in a manner that ensures the health and safety of the public, the protection of the environment, and the protection of government and private property. In particular, the testing and flight qualification program to demonstrate the technical objectives of the program have been met is the essential elements of any space nuclear program. The testing plan must be based on mission requirements and to the maximum extent practical, simulate the in-flight configuration in order to ensure the mission can be performed with acceptable risk. The testing plan must be environmentally responsible, acceptable to the public, and meet the objective of demonstrating the NTP performance. We have touched lightly on these issues for NTP testing with an effluent treatment system and discussed containment versus no containment. No specific recommendation is being made at this time. Further analysis is necessary to set precedence that will best serve long-term needs. In the section above, we have discussed a number of components of a ground test facility that would be used for nuclear engine testing. Not all the components would need to be collocated, and some are currently existing. However, the components needed for an integrated engine test need to be collocated and do not currently exist. Their design and construction will drive any nuclear propulsion testing and qualification program. The performance of an integrated engine test over its full operating envelope will provide the best assurance that the system will perform as desire in the space environment. In fact, the construction and operation of a test facility, along with startup in low Earth orbit, may well be the arena in which the acceptability of nuclear propulsion is decided.

---

[1] D. R. Koeing, “Experience Gained from the Space Nuclear Rocket Program (Rover.NERVA)”, LA-10062-H, Los Alamos National Laboratory, May 1986.

[2] Final Environmental Impact Statement, Space Nuclear Thermal Propulsion System, October 1992.

[3] S. K. Borowski, L. A. Dudzinski and M. L. McGuire, “Vehicle and Mission Design Options for Human Exploration Missions of Mars/Pheobos Using “Bimodal” NTR and LANTR Propulsion”, AIAA-99-3883, American Institute of Aeronautics and Astronautics, June 1998 and NASA/TM—1998-208834, December 1998.

[4] S. K. Borowski, , L. A. Dudzinski and M. L. McGuire, “Artificial Gravity Vehicle Design Options for NASA’s Human Mars Mission Using “Bimodal” NTR Propulsion”, AIAA-99-2545, American Institute of Aeronautics and Astronautics, June 1998.

[5] W. C. Reed, et al, “Contained Test Facility Feasibility Study for Testing Space Nuclear Thermal Propulsion Program”, Internal Report, Idaho National Engineering Laboratory, October 1992.