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Historical Perspectives: The Role of the NASA Lewis Research Center in the National Space Nuclear Power Programs

H.S. Bloomfield and R.J. Sovie
Lewis Research Center
Cleveland, Ohio

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HISTORICAL PERSPECTIVES: THE ROLE OF THE NASA LEWIS RESEARCH CENTER IN THE NATIONAL SPACE NUCLEAR POWER PROGRAMS

H.S. Bloomfield & R.J. Sovie
NASA Lewis Research Center

Abstract

NASA Lewis Research Center's role in space nuclear power dates back prior to the establishment of NASA by an Act of Congress in October 1958 and even before the launch of the first man-made satellite (Sputnik) in 1957. As early as 1945, as an outgrowth of turbojet propulsion research, Lewis initiated work in rocket propellants and engines and by 1949 recognized the potential of rocket powered missiles for military weapons and space missions. By the mid-1950's, Lewis researchers were conducting feasibility studies of nuclear rockets that could take a piloted vehicle to Mars and were evaluating space nuclear power systems for electric propulsion and auxiliary electric power for Lunar and interplanetary exploration. Since that time Lewis has provided leadership in research, development, and the advancement of space power and propulsion systems. From the simple solar cells and batteries used on early satellites, power-generation research at Lewis has advanced to thin-film solar cell arrays, exotic fuel cells, and components for nuclear-electric power and propulsion systems — which provide power and propulsion for missions extending from low Earth orbit to millions of miles into space. Lewis' pioneering efforts in nuclear reactor technology, shielding, high temperature materials, fluid dynamics, heat transfer, mechanical and direct energy conversion, high-energy propellants, electric propulsion and high performance rocket fuels and nozzles have led to significant technical and management roles in many national space nuclear power and propulsion programs including NEPA, ANP, Rover, NERVA, RIFT, SNAP-8, SNAP 50/SPUR, APR, Thermionics (TFE), and, most recently, SP-100.

Introduction

After opening in 1941, when it was called the Aircraft Engine Research Laboratory of the National Advisory Committee for Aeronautics (NACA), Lewis Research Center had the urgent task of improving the performance of piston aircraft engines. By the late 1940's, however, the focus of the aeronautics work had shifted to gas turbine (jet) engines for aircraft propulsion and had begun to expand into high energy rocket propellants and propulsion systems for space exploration[1]. Although there is still a significant aeronautics propulsion effort at Lewis, the early space-related propulsion technology work was instrumental in leading the nation toward new visions of what might be achieved and formed the basis for the transition from the aeronautics emphasis of NACA to the space emphasis of NASA. This transition was hastened by the Soviet launch of Sputnik in October 1957, which changed forever the nation's outlook on space.

NASA Lewis' current role and involvement in space power and propulsion is an outgrowth of it's early commitment to advanced research and development. A typical example of this commitment in the propulsion arena was the pioneering development of liquid hydrogen rocket fuel initiated at Lewis in 1949. This research provided the basis for the development of the first regeneratively cooled liquid hydrogen-liquid fluorine rocket in 1954, the development of the NERVA nuclear rocket engine and the Centaur upper stage in the 1960's, the Space Shuttle main engines in the 1970's, and the National Aerospace Plane propulsion system in the 1980's. In a similar fashion, early studies of nuclear energy propulsion and "unconventional engines", which began in the mid-1940's, revealed Lewis' eagerness to practice on the frontiers of propulsion technology.

Transition to Space Nuclear Power and Propulsion

The NACA 1957 Flight Propulsion Conference[2] held at the Lewis Flight Propulsion Laboratory in November 1957 serves as an early milepost that signalled Lewis' transition to a position of leadership in space nuclear power and propulsion technology. At that keynote conference, held only a month and a half after the Soviet Sputnik launch, Lewis researchers clearly outlined the major feasibility issues, required technological advances, and potential performance benefits of nuclear power and propulsion for a wide range of future space applications. A paper on nuclear rockets concluded that "The use of nuclear energy as a heat source in heat-transfer rockets as presently conceived does not even begin to use the ultimate potential of the fission process. New ideas and concepts are required to utilize the full potential of nuclear energy for rocket propulsion." Another equally visionary paper on satellite and space propulsion systems contained a distillation of the advanced thinking of the Laboratory — flights to the Moon and Mars, including the first detailed discussion of a Moon landing in NACA literature. The conference also highlighted Lewis interest in space nuclear electric propulsion systems, including a comparison of solar, radio-isotope, and nuclear electric power generation concepts.

Early Lewis Roles in Space Power and Propulsion Programs

In 1946 the Army Air Corps initiated the Nuclear Energy Propulsion for Aircraft (NEPA) program to evaluate the feasibility of nuclear powered aircraft of long endurance and unlimited range. In 1948, Lewis engineers were assigned to the Oak Ridge National Laboratory to provide expertise in high temperature heat transfer and advanced materials technology, and in 1949 Lewis acquired a cyclotron to support basic materials research for the NEPA program. Both nuclear aircraft and rocket propulsion were studied, and in 1951 NEPA was superseded by a joint program with the Atomic Energy Commission (AEC) called the Aircraft Nuclear Propulsion program (ANP). As part of Lewis' role in the ANP program, Congress, in 1955, authorized the construction of the Lewis Plum Brook nuclear reactor to contribute fundamental studies on the effects of radiation on materials. With the cancellation of the ANP program in 1961, the early promise of aircraft nuclear propulsion was never realized.

However, Lewis management still believed that the potential of the nuclear aircraft was sufficiently attractive to warrant further consideration. In 1964, under NASA support, Lewis initiated the Atmospheric Nuclear Transport Study to assess the technical prospects for the development of a realistic, practical, safe, and publicly acceptable subsonic nuclear aircraft[3]. This far-ranging study, which continued into the early 1970's, focussed on nuclear system safety and long-life powerplant components. Detail reactor design, shielding, and containment concept studies at Lewis and high velocity containment impact tests at Sandia National Laboratory and Holloman AFB in New Mexico established the basis for the technical feasibility of safe, subsonic nuclear transport aircraft. In addition to aircraft transport, Lewis researchers conducted technical feasibility and application studies of these reactor powerplants to air cushion vehicles.

Project Rover

Perhaps the most significant role for Lewis in a national program began in the late-1950's with the Rover nuclear rocket program. Project Rover was an outgrowth of a joint Air Force-Atomic Energy Commission (AEC) nuclear rocket program initiated in 1955 at the Los Alamos Scientific Laboratory (LASL) and Lawrence Radiation Laboratory (LRL). In 1957 LASL was selected as the single AEC laboratory for the Rover nuclear rocket program, and LRL was assigned responsibility for the Pluto nuclear ramjet program. With the establishment of NASA in 1958, Air Force responsibilities for Project Rover were transferred to the new agency in keeping with the important space role expected for nuclear rockets. As a result of earlier Lewis work on high energy propellants, hydrogen was established as the preferred propellant for nuclear rockets, and Lewis' technical expertise was required in the design and testing of the KIWI series of experimental reactors, managed jointly by the AEC and NASA. The first KIWI tested in July 1959 used gaseous hydrogen propellant, and the first use of liquid hydrogen occurred in September 1962 with the test of the KIWI B1B reactor. Lewis also provided major technical leadership for materials, nuclear fuels testing, fuel element research, and hydrogen heat transfer, with much of the nuclear fuels and materials testing conducted at the recently completed Lewis Plum Brook nuclear reactor. In September 1960, the separate nuclear and nonnuclear responsibilities of Project Rover were merged, and Harold Finger, a Lewis scientist, was named director of both the joint AEC-NASA Space Nuclear Propulsion Office (SNPO) and NASA's Nuclear Systems Division.

The Rover program, although classified because of anticipated military significance, was known to have a long-range plan that included flight testing of the rocket. In order to assess the potential problems of flight-testing nuclear systems and how these problems might be met, the SNPO initiated the Reactor in Flight (RIFT) program in 1961. The purpose of these contracted studies was to provide data on safety issues, vehicle and stage design, and cost estimates of the developmental program. Lewis' involvement in the RIFT studies included the evaluation of safety issues and advanced reactor concepts, such as gaseous cores, and of the use of tungsten as a promising material for solid core reactors, particularly it's low-neutron-absorbing 184 isotope.

As part of the Rover project, SNPO initiated research and development of a Nuclear Engine for Rocket Vehicle Applications, and the project was renamed NERVA in February 1961. This engine development program supported additional reactor test work and preliminary design of a flight engine. Lewis played a major role in the NERVA project and was responsible for directing the research and development of the entire engine system and vehicle, including controls and reactor shielding[4].

In conjunction with the mainline solid-core NERVA rocket project, NASA sponsored, both directly and through the SNPO, research on three advanced reactor propulsion concepts. These analytical and experimental research projects were initiated in the early 1960's to determine the feasibility of two potential future propulsion systems, based on gaseous core reactors[5], and of a novel solid core thermal reactor concept which could serve as a backup to the NERVA fast spectrum, carbide fuel element reactors. The gas core concepts included the open cycle unconfined plasma, coaxial flow, cavity reactor (invented by Frank Rom, a Lewis researcher) and the confined plasma, transparent partition, "light bulb" reactor. The advanced solid-core concept was based on a tungsten, water-moderated, hydrogen-cooled, thermal reactor (TWMR) which had been under study at Lewis since 1957[6].

Significant milestones in NASA Lewis-managed gas core projects included: the first cavity reactor critical experiments performed at the Los Alamos Scientific Laboratory in 1965; operation of the first uranium hexafluoride fueled cavity reactor in the U.S., by General Electric Co., at the National Reactor Testing Station (NRTS) in Idaho in 1967; and experimental demonstrations of the fluid dynamics and heat transfer of the light bulb reactor at NASA Lewis and at the United Aircraft Corp. Research Laboratory.

The Lewis TWMR project included extensive analytical and experimental projects in tungsten reactor neutronics, fuel elements, and rocket engine systems. Neutronics studies conducted by NASA Lewis and critical experiments performed by General Atomics in San Diego and General Electric Co. at NRTS in 1965-1966 verified the feasibility and performance of the reactor design. Fuel element studies at Lewis led to the development of tungsten-uranium dioxide composites capable of operating for 10 hours to 2755 K with multiple restart capability, and the fabrication of fuel element structures was demonstrated.

In 1962 Lewis engineers began to plan and design a new space simulator facility with the capability for buildup, operation, and posttest evaluation of a full-scale nuclear rocket reactor or nuclear reactor electric generating system with reactor power levels up to 15 MWt. Completed in 1969, the NASA Plum Brook Space Power Facility (SPF), located about 50 miles from Lewis, is still the largest nuclear-rated space simulator (high vacuum, deep-space thermal environment and collimated solar radiation) in the world. Although the SPF was never used for space nuclear power system testing, it's nonnuclear capabilities have been, and continue to be, fully utilized for a variety of civilian and military space and terrestrial programs.

Electric Propulsion

In parallel with the early nuclear rocket activity during the 1950's, the Lewis laboratory environment supported theoretical and hardware development of electric propulsion and space power systems for use in future space exploration missions to Mars and other planets. These advanced propulsion technology efforts led to a detail conceptual design study of a 20 MWe nuclear turboelectric (Rankine cycle) powerplant suitable for a manned space vehicle with interplanetary (Mars) capability[2,7]. The critical research areas identified in that study have served to guide space power development over the next 30 years, and the powerplant and vehicle design concepts developed are still relevant today.

In addition, the electric propulsion technology efforts also led to the invention of the electron-bombardment ion thruster by Harold Kaufman, a Lewis engineer. The operation of a mercury vapor propellant ion thruster, designed and built at Lewis, was space proven in the successful launch and flight test of SERT I (Space Electric Rocket Test) in 1964. Further development of the ion-bombardment thruster culminated in 1970 with the successful launch of SERT II. Since that time Lewis researchers have continued development of ion thrusters for stationkeeping, orbit-raising and planetary propulsion applications.

In 1961 the Lewis Electric Propulsion Laboratory (EPL) was built to test electric thrusters, spacecraft, and related equipment at an altitude range of several hundred miles with simulated near-vacuum space environmental conditions. This unique facility consists of two large, high pumping rate, vacuum chambers which are cryogenically cooled and can simulate altitudes up to 300 miles.

SNAP-8

The first suggestions for the use of metal hydrides for solid core nuclear reactor applications came from the NEPA program in the late 1940's. By 1953, Atomics International had identified the feasibility of a uranium-zirconium hydride (UZrH), beryllium reflected, NaK-cooled thermal reactor. The AEC's Space Nuclear Auxiliary Power (SNAP) program began in 1955 with the design of a 3-kWe SNAP-2 space power system using a UZrH/NaK reactor with a 1200 °F (920 K) reactor outlet temperature, coupled to a Rankine cycle turbogenerator.

Initiated in 1960 and supported jointly by the NASA and the AEC, the SNAP-8 development used SNAP-2 reactor technology with a 1300 °F (977 K) reactor outlet temperature, and a mercury Rankine cycle power converter to provide 30 to 60 kWe electric output to meet NASA's need for higher power levels.

From a program management and organizational standpoint, the NASA SNAP-8 program was a highly integrated team, which included NASA as the system sponsor and development manager for the ion and arc-jet propulsion system payload. NASA Lewis served as technical director for all system development, including the mercury ion engine. The Jet Propulsion Laboratory (JPL) provided the mission requirements. And the AEC provided reactor development advice to NASA[4].

Significant advances in reactor and Rankine cycle turboelectric system technology, hardware development, and component life were achieved in the SNAP-8 program. In particular, all power conversion components achieved over 10,000 hours of endurance testing, with the boiler reaching 15,000 hours, and a complete power conversion system test achieved 7320 hours. However, technology problems of corrosion and surface contamination in the SNAP-8 mercury boiler along with an unexpected 80 percent fuel element clad cracking problem, caused major program delays. The urgency of the flight test was lost and as a result SNAP-8 never flew in space.

SNAP 50/SPUR

Although Lewis only played a minor role in the initial formation and technical development of the SNAP 50/SPUR program, it was a major contributor of technology. SNAP 50/SPUR was established under a tri-agency agreement between the AEC, NASA and the Air Force in 1962. The AEC was responsible for the overall coordination of a prototype demonstration and flight test. The Air Force was responsible for establishing the mission requirement, project integration, and flight testing. NASA maintained cognizance of the program, and Lewis contributed it's technical expertise gained from it's past experience in the NEPA and ANP programs.

The SNAP 50/SPUR program was conceived to provide from 300 kWe to 1 MWe of power for an electric propulsion vehicle and was originally based on a high temperature (1370 K), fast spectrum, lithium cooled, refractory metal alloy reactor coupled to a potassium Rankine power conversion system. In 1965, major changes occurred in program objectives, and in 1967 funding was substantially reduced. The program was redirected to a technology effort and transferred from Pratt and Whitney's Connecticut Advanced Nuclear Engineering Lab (CANEL) to Lawrence Radiation Laboratory (LRL) in Livermore, California. Further funding cuts occurred, and the program was terminated in 1968[8].

Advanced Power Reactor

Although the SNAP 50/SPUR program was losing support, NASA Lewis maintained a strong interest in this advanced reactor technology and initiated an Advanced Power Reactor (APR) program in the mid-1960's. This significant development effort, which continued into the mid-1970's, was supported by major Lewis technology projects in nuclear and power conversion materials and components.

The APR program was aimed at future NASA missions requiring reactor power systems with power levels above 300 kWe and 50,000 hour operating lifetimes. Two principal reactor types were evaluated: a fast spectrum, high temperature, liquid metal reactor, which could use potassium Rankine, Brayton, or out-of-pile thermionic energy conversion, and an in-pile thermionic reactor. Because these reactors and conversion systems operated at temperatures higher than SNAP-8's 1300 °F (977 K), projects were initiated to develop the technologies required. In many instances these advanced technologies were extensions of previous Lewis projects begun in the mid-1960's in support of the SNAP-50/SPUR program.

Significant high temperature space power materials efforts carried out at Lewis included investigation of refractory metal alloys, nuclear fuels and their cladding, and electrical materials[9]. Much of this advanced technology development is still relevant to current space power programs. For example, high strength refractory alloy development work focused on the more ductile alloys of niobium, tantalum, and molybdenum, and resulted in the development and characterization of: Nb-1Zr, PWC-11 (Nb-1Zr-0.1C), T-111 (Ta-8W-2Hf), ASTAR-811C (Ta-8W-1Re-1Hf-0.025C), and TZM (Mo-0.5Ti-0.08Zr-0.03C).

The Lewis program in nuclear fuels and cladding focused on high temperature capability and compatibility with alkali metal coolants. Extensive in-pile high temperature (1263 K) testing of T-111 clad UN fuel pins was conducted in the NASA Plum Brook reactor and at the Oak Ridge National Laboratory, and fuel-clad-coolant compatibility was tested up to 2670 K. The Lewis program in electrical materials was aimed at high temperature performance verification of alternators, motors, EM pumps, conductors, and electrical insulation.

Parallel programs to develop the technologies for advanced Brayton and Rankine cycle thermal-to-electric conversion for space applications were also initiated at Lewis in the mid-1960's. These programs, which ranged from fundamental research through state-of-the-art operating hardware, generated a substantial body of technology, including appreciable test time on components, subsystems, and for Brayton cycles, included long-term endurance testing of a space prototype engine system.

The Brayton cycle program addressed the critical issues of the applicability of well-known principles of terrestrial airbreathing fuel-burning gas turbines to space systems of much lower power level, higher performance, and longer life. This program demonstrated key components and a space prototype, 10-kWe Brayton powerplant that had a measured efficiency of 29 percent at an 1150 K turbine inlet temperature, that withstood 100 deep thermal cycles, and that operated unattended for over 38,000 hours[10].

The Rankine cycle program extended the existing low temperature known technologies for water, organics, and mercury working fluids to potassium with a capability for 1450 K turbine inlet temperatures. The program resulted in component performance demonstrations of the principal components of an 1100 K turbine inlet temperature system: boiler, turbine, generator, condenser and pumps[11].

Thermionic Space Power

Lewis pursued a vigorous basic research and technology program in thermionic and MHD energy conversion[10]. In 1964, Lewis entered the AEC's space thermionic reactor program, which had begun at Los Alamos in 1959. The Lewis contribution to the program included in-house, university, and industry efforts focused on cesium diode thermionic fuel elements. Lewis-sponsored work at General Atomics on in-core thermionic converters produced the longest operating, stable performance thermionic device ever tested, the LC-9 (Lewis Converter-9)[12].

With the termination of the space reactor power program in 1973, all nuclear-related technology efforts at Lewis came to a halt. However, many of the space power energy conversion technologies found application as ground power and transportation options in civilian and military terrestrial programs. An interesting example of this shift in application includes the Lewis managed NASA Thermionic Conversion for Applied Research and Technology (TEC-ART) program[13]. Original program emphasis on thermionic topping of coal-fired central power stations was aimed at converters with 1400 K emitters, low-work-function collectors, requisite plasma enhancement, and stainless steel/ superalloy materials. However, in an interesting back-to-space twist, in 1975 the NASA TEC-ART program was broadened to include high temperature out-of-core nuclear thermionic power systems for future space applications.

SP-100 Program

In 1979, low-level efforts were initiated by the DoE and NASA in space reactor and power conversion technology, respectively. By 1981, a need for nuclear reactor power in space was identified by NASA and DoD, and a tri-agency group (NASA-DoE-DoD) was chartered by the DoD's Air Force Systems Command and NASA's Office of Aeronautics and Space Technology (OAST) Interdependency Working Group. The task set before the group was to draft a detailed plan for a reactor space power system program to start in 1983. The effort was to be conducted jointly by NASA and DoE, on the basis of a signed agreement, and was to provide sufficient data for a decision in FY 85-86 whether to proceed with a ground demonstration system.

The proposed program plan constituted a departure from previous joint NASA-DoE policy. Previously, DoE was solely responsible for funding reactor subsystem technology, and NASA for the appropriate power conversion technology. However, for this Space Nuclear Power Project, to be named SP-100, NASA agreed to support of the reactor technology development in addition to the conversion technology. By early-1982, disagreements about the responsibilities and management of the proposed tri-agency program led NASA to sign a bilateral Memorandum of Agreement with DoD's Defense Advanced Research Projects Agency (DARPA). However, a mutually acceptable tri-agency agreement was concluded by late 1982, and the SP-100 program was officially underway.

The role of NASA Lewis in the early stages of the SP-100 program included major roles in program definition and cost estimation, and system technology assessment and selection. The SP-100 system downselection process resulted in the selection of a pin-type fast reactor with uranium nitride fuel, niobium-alloy clad, and lithium coolant. The baseline reference power conversion system selected was conductively coupled, SiGe multicouple thermoelectric conversion, and the SP-100 growth power conversion system selected was a free-piston Stirling cycle capable of producing up to five times the electric output of the baseline system. After system concept downselection, Lewis responsibilities included contractor review and assessment and space subsystem technology support in refractory metal alloy and thermoelectric materials testing, thermal management, and space environment interactions. Additionally, under NASA funding through the Civilian Space Technology Initiative (CSTI), Lewis has played a major role in development of the growth SP-100 Stirling cycle power conversion system and identifying and developing advanced thermal management and power conditioning technologies.

With the prospect of the Space Exploration Initiative (SEI) becoming a reality, Lewis has begun to take on additional responsibilities in the requirements and technology definition of SP-100 based nuclear electric propulsion and planet surface power-generation systems.

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