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TECHNOLOGICAL IMPLICATIONS OF SNAP REACTOR POWER SYSTEM DEVELOPMENT ON FUTURE SPACE NUCLEAR POWER SYSTEMS

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Abstract

Although the Space Transportation System brings a new era to United States space technology, the U.S. still lags the U.S.S.R. in total space launches per year and in the development of nuclear systems for higher electric powers in space. The power levels for future U.S. military and civilian space missions are not fully defined at this time; however, power needs can easily be projected to much higher values than required today. Nuclear reactor systems are one method of satisfying these power needs. The development of such systems must proceed on a path consistent with mission needs and schedules. This path, or technology roadmap, starts from the power system technology data base available today. Much of this data base was established during the 1960s and early 1970s, when government and industry developed space nuclear reactor systems for steady-state power and propulsion. One of the largest development programs was the Systems for Nuclear Auxiliary Power (SNAP) Program. By the early 1970s, a technology base had

evolved from this program at the system, subsystem, and component levels. There are many implications of this technology base on future reactor power systems. A review of this base highlights the need for performing a power system technology and mission overview study. Such a study is currently being performed by Rockwell's Energy Systems Group for the Department of Energy and will assess power system capabilities versus mission needs, considering development, schedule, and cost implications. The end product of the study will be a technology roadmap to guide reactor power system development.

Introduction

With the advent of the Space Shuttle, the 1980s bring a new era to United States space technology. The Space Shuttle is ultimately capable of lifting 30-metric-ton payloads into low-earth orbits (Figure 1). Not only is the shuttle a reusable launch vehicle, but a viable space experimental laboratory. Using sortie missions, experiments can be launched, carried out in the environment of space, and recovered (Figure 2). The total Space Transportation System (STS) will eventually encompass upper stages for placement of missions into higher altitude and geosynchronous equatorial orbits (Figure 3).

The 1980s, however, also pose a different perspective for the United States in its role as military and technology leader of the world. Even with the advancements in launch capability, our chief political competitor, the

U.S.S.R., has "out launched" the United States, 88 launches to 12 through the first 10 months of 1982. Of the U.S.S.R.'s 88 launches, 71 were for military purposes, compared to only three of the U.S.'s 12 launches.

On the other hand, the United States' leadership in military technology became apparent during the Lebanon war of 1982. This war focused on Western war-fighting technology and demonstrated the superiority of this technology over that supplied by the U.S.S.R. to its allies. The bottom line is that U.S.S.R. capabilities tend to exceed U.S. capabilities in quantity, but not in quality.

One technology area where the U.S.S.R. has succeeded in both quantity and quality is the development of space nuclear reactor power systems. Seventeen years ago, the U.S. launched a single space reactor power system called the SNAP-10A (Figure 4). This system, launched in a spacecraft called SNAPSHOT in 1965, was a flight qualification system developed for the Atomic Energy Commission and the Air Force by Atomics International (now a division of Rockwell's Energy Systems Group). It is interesting to note that the original Soviet space reactor power system, called "ROMASHKA," was a derivative of a very early static SNAP-10 concept (Figure 5). Since the SNAPSHOT launch in 1965, the Soviets have improved the quality of their space nuclear reactor power capabilities through a thermionic system called "TOPAZ." A derivative of the ROMASHKA and TOPAZ systems provides power for their Radar Ocean Reconnaissance Satellites (RORSATs) (Figure 6). Approximately 20 RORSATs have been

launched by the Soviets, with four launches in the first 10 months of 1982. Although the RORSAT nuclear power system is neither high powered nor long lived, the Soviet use of reactors exemplifies their belief that power requirements for space will increase over time.

For the U.S., these increasing power requirements will come from military missions (surveillance and war-fighting) and also from civilian missions (scientific and large commercial). The real power system needs for these missions can only be estimated at this time. To assess these needs, two parameters in addition to power must be evaluated. These are the duration of the power and the mass of the system providing the power. The product of the power and its duration is the energy output of the system, and both the power and energy affect the system mass. The mass in turn affects the total launch requirements for the mission. For the types of missions being discussed by military and civilian planners today, ranges on power, power duration, and power system mass can be defined and interrelated. Power requirements range over 4 decades, from 10 kWe to 100 MWe. Power duration requirements range over 6 decades, from seconds of semicontinuous power for directed energy applications to near 100,000 hours for long-lived, steady-state applications. System mass requirements range over 3 decades, from hundreds of kilograms to tens of thousands of kilograms. When plotted in a three-dimensional log-log-log coordinate system, the interrelation of these three parameters defines a "requirements" space (Figure 7). Examining this space, the difference between steady-state and semicontinuous needs becomes apparent. What does not become

apparent is the level of power system technology necessary to meet the real needs of military and civilian applications. The schedules and budgets required to develop power systems which are time-compatible with missions must be factored into a plan for development – a technology roadmap. The roadmap for power systems must begin with the complete nuclear power system technology base that exists in the United States today.

Background

The U.S. development of a steady-state space nuclear reactor power system technology base began in the early 1950s. Reactor systems were code-named with even-numbered "SNAP" designators and were initially considered with power capabilities from hundreds of watts through multi-kilowatts. The principal SNAP reactor power systems were SNAP-2, SNAP-8, SNAP-10A, SNAP-50, and the SNAP follow-on concepts (Figure 8). All the numerically designated systems were designed for a 1-year power duration, with power capabilities ranging from 0.5 kWe to 350 kWe. The follow-on system concepts were aimed at 2- to 7-year lives with power capabilities up to 75 kWe. The SNAP-2, -8, -10A, and follow-on systems were based on a thermal reactor using uranium zirconium hydride fuel. The SNAP-50 was based on a fast reactor using uranium nitride fuel.

The hardware phase of the SNAP program occurred in the 1960s and centered around the SNAP-2, -8, -10A, and -50 systems. Separate reactor and power conversion subsystem development/test was performed for the SNAP-2 and -8 systems. The SNAP-10A system included reactor development, power conversion subsystems development, and full-up system testing on the ground and in space. The SNAP-50 program included component development testing, and did not proceed through reactor or system fabrication and testing. The SNAP follow-on concepts were oriented at subsystem technology improvement, and drew their data base largely from the SNAP-2, -8, and -10A programs. The major hardware milestones in the SNAP program included the SNAP-10A ground test and flight tests in 1965 and the SNAP-8 reactor demonstration tests in the 1960s (Figure 9).

Paralleling this hardware phase was the Aerospace Nuclear Safety Program (Figure 9). Approximately \$50 million (1960s dollars) was spent in this program alone to verify the safety of nuclear reactor systems before launch, during launch, in space, and upon reentry.

Early in the 1970s, system concepting and subsystem improvement activities were underway. These activities included the design of various reactor power systems such as the 5-kWe Reactor Thermoelectric System and the 75-kWe Reactor Turboelectric System (Figure 9). At the end of this improvement phase, the uranium zirconium hydride reactor system technology base was well on its way to providing a 25-kWe system with a 5-year life. Over the range of

powers being considered at that time, specific powers of 6 to 30 W/kg were projected. These systems had longer lifetimes and specific energy capabilities of 30 to 210 W-yr/kg. The uranium nitride reactor system technology base was oriented to much higher powers, with SNAP-50 type systems offering large increases in specific power and energy.

The SNAP Program was terminated later in the 1970s. At that time, several hundred million dollars had been invested in the technology base, with over \$200 million of this investment at Atomics International.

System, Subsystem, and Component Implications

The technology base which was most completely demonstrated and supported by test resulted from the SNAP-10A and SNAP-8 programs. This base was also used in the SNAP follow-on programs. Another technology base was established by the higher power, higher temperature SNAP-50 program.

The SNAP-10A, -8, and follow-on programs considered various types of power conversion, but the reactor and shielding concepts were similar for all systems. The reactors were thermal, based on uranium zirconium hydride fuel. The hydrogen moderator was intrinsically bound in the fuel matrix. This was done to minimize fuel inventory and maximize reactor safety. Fuel composition for all reactors was generally the same, using 10 w/o (weight percent) fully

enriched uranium and 90 w/o zirconium. The fuel was hydrided to 6×10^{22} hydrogen atoms/cc or about the same hydrogen density as water. The reactors were cooled with a liquid metal eutectic, NaK-78 (78 w/o potassium). Reactor neutron shielding used lithium hydride (LiH) in a stainless steel containment vessel. Gamma shielding, when employed, used heavy metals.

The SNAP-10A system, launched on April 3, 1965, was designated Flight System 4 (Figure 10). The total spacecraft was called SNAPSHOT and included the Agena vehicle with primary and secondary payloads. The SNAPSHOT spacecraft was launched into a 1,300-km (700 nautical mile) orbit with approximately a 3,500-yr orbit life. The SNAP-10A reactor power system initially produced 580 W (electric) in orbit. SNAP-10A was designed to be actively controlled only at the beginning of its life; and after the reactor was stabilized, electric power drifted down with time. SNAP-10A performance in space tracked the performance of the ground test system (Flight System 3, see below). At the forty-third day of in-space operation, following Orbit 553, telemetry from the SNAPSHOT spacecraft was lost. It was later determined that thermal overstressing of the Agena voltage regulator caused an erroneous shutdown command to the reactor's permanent shutdown device.

The SNAP-10A system had a single NaK loop and employed silicon-germanium thermoelectric elements (Figure 11). The reactor coolant outlet temperature was 833°K (1040°F). The unshielded reactor mass per unit thermal energy was 2,650 kg/MWt-yr. The overall system had a specific power of 1.3 W/kg. Because the system was designed for a 1-year life, the specific energy was equal to the specific power.

SNAP-10A Flight System 3 was tested on the ground in vacuum for 10,000 hours at power and temperature (Figure 12). The ground test was initiated prior to Flight System 4 launch, so that flight performance could be tracked against ground performance. The ground test system operated at the same reactor outlet temperature and average radiator temperature as the flight test system. The effective higher sink temperature of the ground facility versus space resulted in lower power output from the ground test system.

Because of the concerns of launching a reactor system into space, a significant safety program supported the SNAPSHOT launch (Figure 13). This program was called the Aerospace Nuclear Safety Program and supported reactor and radioisotope system development activities. Both safety analysis and testing were performed for the SNAPSHOT launch. In the Reentry Flight Demonstration Test, a full-scale nonfueled and nonradioactive replica of the SNAP-10A reactor was launched and subjected to a suborbital flight path. This test demonstrated beryllium reflector separation from the reactor vessel and also supported theoretical modeling in areas such as aerodynamic heating and reactor disassembly.

A highlight of the safety program was a series of reactor transient tests called the SNAPTRAN experiments. These experiments were used to measure the response to rapid reactivity insertions and core water flooding. SNAPTRAN-3 was specifically conducted to characterize the SNAP-10A reactor in

the water-flooding event which could follow a launch abort (Figure 14). In this experiment, a SNAP-10A core was located in a water-filled environmental chamber. The core was surrounded by a poisoned and voided sleeve. The sleeve was pyrotechnically removed and the reactor was destructed. The expansion of the well-instrumented core was followed by three high-speed cameras, and the data collected was used to determine coefficients of reactivity versus volume expansion. Experimental data also verified that the reactivity temperature coefficient was $-0.4\%/^{\circ}\text{C}$ prior to the initiation of core expansion. The SNAPTRAN-3 experiment further demonstrated that fuel element disintegration was caused by the generation of hydrogen overpressure. The one intact fuel element from the experiment showed that this hydrogen evolution was nonuniform about the cross section of the fuel (Figure 14). A very positive outcome of the experiment was confirmation that a high fraction of the fission products were retained in the fuel element.

The SNAP-8 program was directed at a 600-kWt reactor with a 978°K (1300°F) coolant outlet temperature. The reactor was to be used with higher electric power mercury Rankine turboelectric power conversion subsystems. Two complete reactors were tested in this program — the SNAP-8 Experimental Reactor (S8ER) and the SNAP-8 Developmental Reactor (S8DR).

The S8ER was tested in an inerted containment vessel for 12,000 hours and operated for 1 year at power and temperature (Figure 15). The reactor employed nonflight-type hardware and the test did not incorporate flight-type

neutron or gamma shields. The technology of the S8ER was over a factor of 6 improved from SNAP-10A, i.e., for a given unshielded reactor mass, S8ER could deliver over six times the energy (420 kg/MWt-yr).

The SNAP-8 Developmental Reactor was ground tested for 7,000 hours at powers from 600 to 1,000 kWt (Figure 16). Testing was performed in vacuum using flight-type reactor components and a flight-type neutron shield. The actuators were bidirectional, and the reflectors incorporated a separate ground test scram mechanism. The S8DR had an unshielded reactor mass per unit energy of 450 kg/MWt-yr, a value slightly higher than the value for the S8ER.

In each SNAP-8 reactor post-test examination, fuel cladding cracks were found. Destructive examination, experimentation, and theoretical analysis confirmed that the cracks resulted from excessive fuel swelling. The fuel swelling phenomena was characterized, and this resulted in a temperature limit of 922°K (1200°F) being established for the outlet temperatures of follow-on uranium zirconium hydride reactor designs.

The SNAP-8 reactors were designed and tested for use with mercury Rankine turboelectric power conversion subsystems. The total SNAP-8 system was intended to generate 30 to 60 kWe (nominal 50 kWe) at reactor powers of 300 to 600 kWt. The mercury Rankine power conversion subsystem was being developed by Aerojet Corporation under direction of the NASA Lewis Research Center. NASA-LeRC was also investigating the gas Brayton power conversion subsystem for this application. Based on development test results for the mercury

Rankine unit, the SNAP-8 system efficiency was projected to be 10% (24% of Carnot efficiency). The total system specific power was projected in the 7 to 10 W/kg range.

The SNAP-8 technology base was then used in the design of several SNAP follow-on reactor system concepts (Figure 17). The reactor designs were based on SNAP-8 data and ranged in power from 100 to 600 kWt. The unshielded mass per unit energy of the reactors remained in the range of 400 to 450 kg/MWt-yr. The reactors and power systems were designed for longer lives, in the 2- to 7-year range. The systems incorporated various thermoelectric and turbo-electric (Brayton and Rankine) power conversion subsystems. Total system specific powers were projected at 6 to 30 W/kg, depending on the absolute power level. Total system specific energies were projected at 30 to 210 W-yr/kg.

The time frame during which the SNAP follow-on systems were being conceived was also the time frame for subsystem technology improvement activities. These activities were performed during the early 1970s and resulted in some expansion of the SNAP data base. This data base is discussed below for the reactor, shielding, primary heat transport, and power conversion and processing subsystems.

The data base for the uranium zirconium hydride reactor subsystem is based on over 41,000 total hours of reactor testing (Figure 18). During this testing, peak fuel linear power densities of 11.3 kWt/m were obtained, as were peak cladding temperatures of 1015°K (1370°F). As mentioned earlier, the testing resulted in an imposed limit of 922°K (1200°F) on the U-ZrH reactor coolant outlet temperature, with a limit of 3.3 kWt/m on average linear power density. Reflectors, reflector materials, vessel materials, coolant headers, vessel structure, high-temperature bearings, and high-temperature control actuators were also demonstrated and are part of the reactor subsystem data base. Of considerable importance is the status of control actuators. Sixty-seven actuators were tested for a total 264,000 hours. A single actuator was tested for 26,000 hours at a temperature of 880°K (1125°F). Other actuators were tested in reactor environments at temperatures of 644°K (700°F). An important implication of this actuator testing is the temperature and fast-neutron dosage capabilities of these units. Higher temperatures and dosages will require new materials and insulators, with resultant actuator development and qualification.

The shielding subsystem data base results from 13 neutron shields being tested for 19,000 hours (Figure 19). In all cases, the neutron shielding material was lithium hydride. This is the consensus material for neutron shielding because it has an extremely high macroscopic neutron removal cross section per unit density ($0.15 \text{ cm}^2/\text{gm}$). The equivalent value for water is only $0.10 \text{ cm}^2/\text{gm}$. Lithium hydride is a fabricable material, and Atomics

International cast shields up to a diameter of 1.8 m (6 ft). The major limitation on lithium hydride as a shielding material is its operating temperature. LiH melts at 959°K (1266°F), and although molten lithium hydride could be used at temperatures slightly above the melting point, it is apparent that very high-temperature reactor systems will require active shield cooling or other shielding materials. Either solution will require development.

The primary heat transport subsystem data base encompasses piping, liquid metal, electromagnetic pump, and coolant volume compensator technologies (Figure 20). In the SNAP program, 58 electromagnetic pumps were tested for 212,000 total hours, with a single pump operating successfully for 42,000 hours. These pumps operated at temperatures up to 920°K (1200°F). Volume compensators were also successfully demonstrated in the SNAP program. These components used metallic bellows to accommodate the differential volume expansion between the liquid metal coolant and the piping. The volume compensators also provided pressurization for the liquid metal coolant, while maintaining it void free. Fifty volume compensators were tested at elevated temperatures for over 100,000 total hours. The SNAP-10A ground system compensator accumulated 10,000 test hours.

The power conversion and processing subsystem data base includes technologies for thermoelectric and turboelectric power conversion (Figure 21). Although the SNAP-10A system used silicon-germanium thermoelectrics, developmental efforts were also focused on lead-telluride (PbTe) because of its

higher potential figure of merit, Z (equals material Seebeck coefficient squared divided by electrical resistivity and thermal conductivity). Lead-telluride compact tubular thermoelectric converters were designed by Westinghouse Astronuclear Laboratory and tested by both Westinghouse and Atomic International. Two hundred and twenty units were tested for 720,000 hours, with a single unit operating for 42,000 hours. A figure of merit of $0.8 \times 10^{-3} \text{K}^{-1}$ was demonstrated for these converters, i.e., an efficiency of 5% at a hot clad temperature of 858°K (1085°F) and a cold clad temperature of 537°K (507°F), the required system temperatures. The turboelectric subsystems included the mercury Rankine units for SNAP-2 and SNAP-8 which were developed by TRW and Aerojet, respectively. A mercury Rankine subsystem was tested in a full-up SNAP-2 reactor power system configuration using an electrically simulated reactor. Thirty thousand hours of test experience were demonstrated on the mercury Rankine units with a 5,000-hour single-duration test.

In reviewing the reactor power system technology data base which evolved from the SNAP program, a question that may be asked is "What does it mean today?" Over the past 10 years, no further activities were performed on these compact reactor systems. However, in support of the Radioisotope Thermoelectric Generator (RTG) programs, development activities did proceed with silicon germanium thermoelectric power conversion.

An interesting perspective can be gained by "concepting" a SNAP-type reactor power system using a SNAP-evolved U-ZrH reactor with current silicon germanium thermoelectric capabilities (Figure 22). To be consistent with currently envisioned mission requirements, a power system life of 7 years is used. As the design electrical power level of this system concept is increased, the specific power and specific energy capabilities of the system increase dramatically. Although SNAP-10A exhibited a specific power and energy of only 1.3 W/kg, a SNAP-evolved derivative system with a 100-kWe capability exhibits a specific power of 11 W/kg and specific energy of 80 W-yr/kg. Such large improvements are due to the economy of size, to increased reactor coolant temperature (from 833°K to 922°K), and to improved thermoelectric converter efficiency. This system concept would still be very large and heavy in high-power ranges. The important conclusion is the dramatic system-level effect of power on the mass of such a system.

A further perspective into this effect can be gained by looking at the same type of SNAP-evolved power system concept, but one utilizing improved thermoelectrics (Figure 23). These improved thermoelectrics have a figure of merit of $1.0 \times 10^{-3} \text{K}^{-1}$ and have been proposed as a reasonable technology improvement. The specific power achievable by such a system concept at 100 kWe is 15 W/kg. The specific energy achievable at this power is over 100 W-yr/kg.

A review and evaluation of the technology data base established by the Pratt and Whitney SNAP-50 reactor turboelectric system provides a similarly dramatic demonstration of the system-level effect of power on mass. SNAP-50 was being configured for power levels of 300 to 1000 kWe. The system employed a fast uranium nitride reactor, operating at a lithium coolant temperature of 1367°K (2000°F). The reactor was projected to have an unshielded mass per unit energy of 730 kg/MWt-yr. The projected system conversion efficiency was 14% using a potassium Rankine turboelectric power conversion subsystem. SNAP-50 was being designed for a 1-year life and was projected to have an unshielded specific power in the range of 100 to 200 W/kg.

The key conclusion from this review and evaluation of the SNAP technology data base is that an "order-of-magnitude" power system technology improvement is not required to meet the specific power and specific energy goals envisioned for future space missions. These goals are currently in the ranges of 40 to 50 W/kg and 250 to 350 W-yr/kg. Extrapolations of all types of past system technologies demonstrate that these goals seem reasonable with newer, more advanced technologies. It is only necessary to determine the level of technology advancement necessary to meet real mission needs.

Mission Considerations

Reactor power systems have always been directed at next-generation, far-term missions. In the early 1960s, reactor-powered space station concepts

were being studied (Figure 24). As power system concepts and missions evolved, the 1970s envisioned reactor-powered lunar and space stations (Figure 25). In the 1980s, the Galileo mission to explore Jupiter is being planned (Figure 26).

Today, the most important activity for the space nuclear power community is determining if any mission requires a reactor power system. As a starting point in the search for a mission, we can turn to the Soviets and note their use of reactor power for RORSAT. Surveillance is a potential mission with a potential near-term need. A possible technology for this mission had its initial demonstration on the second shuttle voyage. This technology is synthetic aperture radar, demonstrated in the Shuttle Imaging Radar (SIR-A) experiment. SIR-A was built by the Jet Propulsion Laboratory as part of the OSTA-1 (Office of Space and Terrestrial Applications) experimental package (Figure 27). SIR-A operated at an altitude of 260 km (140 nautical miles). Interesting views from SIR-A include an oil slick near Venezuela (Figure 28), oil derricks near Abu Dhabi in the Persian Gulf (Figure 29), and freeways in the Los Angeles basin (Figure 30). SIR-A required a power of only 1 kWe. It does not take much imagination to envision the capabilities of a near-term radar system having 20 or 30 kWe of power.

A radar surveillance system is only one potential mission. It does, however, illustrate one truism — mission power needs will increase with time, and power system capabilities must follow these needs. As the power

needs continue to increase, the necessity for reactor power systems will increase. Relooking at the mission "requirements" space (from Figure 7) with a time variable imposed, a possible progression of power system capabilities over time can be seen (Figure 31). This time dependence is different for steady-state and semicontinuous missions. In the late 1980s, there could be near-term missions, and only certain power system technologies may be capable of meeting near-term mission needs. In the early 1990s and mid-1990s, there could be mid-term and far-term missions. Mid-term and far-term reactor power systems will be available to meet mid-term and far-term mission needs only if proper planning is performed now. This planning is the technology roadmap which fits time-phased mission needs to realistically achievable power systems.

Technology-Mission Overview

The determination of such a technology roadmap was recommended to the Department of Energy by Rockwell International. The Energy Systems Group of Rockwell International is currently performing a technology-mission overview study to determine this roadmap for the DOE. The study uses a "bottom-up" approach to assess power system capabilities, and ties these capabilities to validated mission needs generated by the Department of Defense and the NASA (Figure 32).

An important feature of the study is a technology assessment. In the "bottom-up" study approach, reactor power system technologies are first assessed at the subsystem level. Five subsystems are defined for this assessment (Figure 33). For each subsystem, current technologies are assessed, as are the future capabilities of improved technologies for mid-term needs and advanced technologies for far-term needs. Of prime importance is the consideration of development time and development cost for each improved or advanced technology. When complete, the technology assessment provides time-compatible building blocks, i.e., subsystems whose development can be achieved in the same time frame. These building blocks are then used to generate systems whose schedular availability can be time phased by near-term, mid-term, and far-term Initial Operating Capability (IOC).

In parallel, the study implements a review of near-term, mid-term, and far-term power system capabilities with the users – the military users and the civilian users. The needs of the users are correlated with the schedular availability of the power systems. Power system requirements are iterated with the users' mission needs (Figure 34). Considerations of development cost and development schedule will then result in a preferred technology roadmap for reactor power systems (Figure 35). The technology roadmap will correlate cost to schedule and need. The generation and use of this technology roadmap will assure that space nuclear power is no longer 20 years ahead of its time (Figure 36).

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Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

SYSTEMS FOR NUCLEAR AUXILIARY POWER PROGRAM
REACTOR ELECTRIC SYSTEMS

SYSTEM	SYSTEM CONTRACTOR	ELECTRICAL POWER (kW _e)	POWER DURATION (yr)	REACTOR	REACTOR CONTRACTOR	POWER CONVERSION	POWER CONVERSION CONTRACTOR
SNAP-2	ATOMICS INTERNATIONAL	5	1	U-235 THERMAL	ATOMICS INTERNATIONAL	H ₂ O RANKINE TURBOELECTRIC	TRW
SNAP-8	AEROJET	60	1	U-235 THERMAL	ATOMICS INTERNATIONAL	H ₂ O RANKINE TURBOELECTRIC	AEROJET
SNAP-10A	ATOMICS INTERNATIONAL	0.5	1	U-235 THERMAL	ATOMICS INTERNATIONAL	SiGe THERMOELECTRIC	RCA
SNAP-50	PRATT AND WHITNEY	350	1	UN FAST	PRATT AND WHITNEY	K RANKINE TURBOELECTRIC	AIRRESEARCH
MANNED SPACE STATION SYSTEM	ATOMICS INTERNATIONAL	25	2	U-235 THERMAL	ATOMICS INTERNATIONAL	PbTe THERMOELECTRIC	WESTINGHOUSE
5 kW _e REACTOR TEST SYSTEM	ATOMICS INTERNATIONAL	5	5	U-235 THERMAL	ATOMICS INTERNATIONAL	PbTe THERMOELECTRIC	WESTINGHOUSE

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Figure 8

Figure 9

Figure 10

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SNAP-10A FLIGHT SYSTEM 4 PICTORIAL OF LAUNCHED SYSTEM

- NaK-COOLED U-ZrH_x REACTOR
- 43 kWt AT 833°K (1040°F) COOLANT TEMPERATURE
- 2650 kg/MWt-yr REACTOR
- SiGe THERMOELECTRICS ($Z = 0.4 \times 10^{-3} \text{ K}^{-1}$)
- 0.56 kWe OUTPUT FOR 1 YEAR
- 436 kg (960 lb) FLIGHT SYSTEM WEIGHT
- 1.3 W/kg SPECIFIC POWER
- 1000-hr SYSTEM FLIGHT TEST

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Figure 11

SNAP-10A FLIGHT SYSTEM 3 PRIOR TO GROUND TEST

- NaK-COOLED U-ZrH_x REACTOR
- 38 kWt AT 833°K (1040°F) COOLANT TEMPERATURE
- 3000 kg/MWt-yr REACTOR
- 0.4 kWe ELECTRICAL OUTPUT
- SiGe THERMOELECTRICS ($Z = 0.4 \times 10^{-3} \text{ K}^{-1}$)
- FLIGHT-QUALIFIED HARDWARE
- 10,000-hr GROUND TEST

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Figure 12

A SIGNIFICANT SAFETY PROGRAM SUPPORTED THE SNAPSHOT LAUNCH MAJOR ACTIVITIES PERFORMED

- ANALYSIS (REENTRY, REENTERING FUEL, PARTICLE, ...)
- REENTERING VESSEL-REFLECTOR ADHESION TESTS
- HYPERTHERMAL WIND TUNNEL TESTS (REACTOR ABLATION, FUEL BURNUP)
- FUEL PULSE HEATING EXPERIMENTS
- FISSION PRODUCT RELEASE EXPERIMENTS
- REENTRY FLIGHT DEMONSTRATION TEST (NON-RADIOACTIVE)
- SNAPTRAN-1 PROMPT NEUTRON KINETICS EXPERIMENTS
- SNAPTRAN-2 SUPERCRITICAL REACTOR DESTRUCTIVE EXCURSION
- SNAPTRAN-3 FLOODED REACTOR DESTRUCTIVE EXCURSION
- REACTOR OVERPRESSURE TESTS
- REACTOR LOX SPRAY TESTS
- REACTOR DROP AND WATER IMPACT TESTS

Figure 13

Figure 14

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SNAP-8 EXPERIMENTAL REACTOR INSTALLATION INTO TEST PIT

- NaK-COOLED U-ZrH_x REACTOR
- 600-kWt AT 978°K (1300°F)
COOLANT TEMPERATURE
- 420 kg/MWt-yr REACTOR
- GROUND TEST HARDWARE
- 12,000-hr GROUND TEST
- 1-yr AT POWER AND TEMPERATURE

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Figure 15

SNAP-8 DEVELOPMENTAL REACTOR GROUND TEST

- NaK-COOLED U-ZrH_x REACTOR
- 600-1000 kWt AT 978°K (1300°F)
COOLANT TEMPERATURE
- 450 kg/MWt-yr REACTOR
- 7000-hr REACTOR GROUND TEST
AT POWER
- FLIGHT HARDWARE TESTED
- 7 TO 10 W/kg PROJECTED TOTAL
SYSTEM SPECIFIC POWER
- 7 TO 10 W-yr/kg PROJECTED TOTAL
SYSTEM SPECIFIC ENERGY

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Figure 16

FOLLOW-ON SNAP REACTORS

100 kWt REACTOR

600 kWt REACTOR

- NaK-COOLED U-ZrH_x REACTORS
- 100 TO 600 kWt AT 922 TO 950°K (1200 TO 1250°F)
- 400 TO 450 kg/MWt-yr REACTORS
- 2 TO 5 YEAR REACTOR LIFE
- 8 TO 30 W/kg PROJECTED TOTAL SYSTEM SPECIFIC POWER
- 30 TO 210 W-yr/kg PROJECTED TOTAL SYSTEM SPECIFIC ENERGY

Figure 17

SNAP PROGRAM DATA BASE REACTOR SUBSYSTEM

NaK-COOLED U-ZrH_x REACTORS

- SIX TESTED FOR 41,250 TOTAL HOURS
- 10,000-hr SINGLE DURATION TEST
- 11.3 kWt/m PEAK LINEAR POWER DENSITY
- 1080°K (1485°F) PEAK FUEL TEMPERATURE
- 1015°K (1370°F) PEAK CLADDING TEMPERATURE

CONTROL ACTUATORS

- 87 TESTED FOR 284,000 TOTAL HOURS
- 26,000-hr SINGLE DURATION TEST
- 880°K (1125°F) PEAK TEMPERATURE
- 4.1×10^{18} n/cm² PEAK FAST NEUTRON DOSE
- 5.7×10^9 rad PEAK GAMMA DOSE

Figure 18

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SNAP PROGRAM DATA BASE SHIELDING SUBSYSTEM

LITHIUM HYDRIDE NEUTRON SHIELDS

- THIRTEEN SHIELDS TESTED FOR 19,000 TOTAL HOURS
- 10,000-hr SINGLE DURATION TEST
- 755°K (900°F) PEAK SHIELD TEMPERATURE
- 1.8-m (6-ft) DIAMETER SHIELD FABRICATED

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Figure 19

SNAP PROGRAM DATA BASE PRIMARY HEAT TRANSPORT SUBSYSTEM

ELECTROMAGNETIC LIQUID METAL PUMPS

- 58 TESTED FOR 212,000 TOTAL HOURS
- 42,000-hr SINGLE DURATION TEST
- 920°K (1200°F) PEAK TEMPERATURE
- 7.6 kg/sec (60,000 lb/hr) PEAK NaK FLOW

VOLUME COMPENSATORS

- 50 TESTED FOR 100,000 TOTAL HOURS
- 10,000-hr SINGLE DURATION TEST
- 670°K (750°F) PEAK TEMPERATURE

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Figure 20

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SNAP PROGRAM DATA BASE POWER CONVERSION AND PROCESSING SUBSYSTEM

PbTe TUBULAR THERMOELECTRIC

- 220 TESTED FOR 720,000 TOTAL HOURS
- 42,000-hr SINGLE DURATION TEST
- 1005°K (1350°F) PEAK TEMPERATURE
- $0.8 \times 10^{-3} \text{ K}^{-1}$ FIGURE OF MERIT

MERCURY RANKINE TURBOELECTRIC

- 30,000 TOTAL TEST HOURS
- 5,000-hr SINGLE DURATION TEST
- 950°K (1250°F) PEAK TEMPERATURES

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Figure 21

THE POTENTIAL USING SOME DEVELOPED SPACE POWER TECHNOLOGIES

- SNAP-EVOLVED REACTOR
- 922°K (1200°F) COOLANT TEMPERATURE
- CURRENT SiGe THERMOELECTRICS ($Z = 0.7 \times 10^{-3} \text{ K}^{-1}$)
- 7-YEAR SYSTEM LIFE

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Figure 22

Figure 23

Figure 24

Figure 25

Figure 26

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Figure 27

Figure 28

Figure 29

Figure 30

Figure 31

Figure 32

Figure 33

Figure 34

Figure 35

Figure 36