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AEC Research and Development Report

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ABSTRACT

An unmanned SNAP 8 reference design and a manned SNAP 8 reference concept are described in detail. Performance characteristics of each at the reference design point of 600 kwt, 1300°F outlet coolant temperature are given showing how high reliability for 10,000 hours of operation is attained. Off-design performance operation as it affects reliability and operating life is also discussed. Curves to estimate shield weights for each design are presented as a function of payload separation distance, payload diameter, neutron and gamma doses, dose rate, and reactor power level.

The SNAP 8 nuclear system application potential is given, along with a summary of the development status.

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Frontispiece: SNAP 8 Reactor and Shield

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I. INTRODUCTION

Manned orbital space stations, lunar bases, manned and unmanned space probes, and earth satellites will require electric power in the 10- to 100-kwe power range. The primary source of this power is expected to be nuclear energy because of the small size, light weight, and low cost of nuclear power sources as compared to solar or chemical power sources. The SNAP 8 nuclear system is being designed to produce 600 kw or, depending upon the power conversion system (PCS), 15 to 60 kwe. The thermal power of the SNAP 8 nuclear system can be extended to cover the entire electrical power range up to 100 kwe without significant design changes.

This report summarizes the design and operating characteristics of the SNAP 8 nuclear systems. It is intended for use in preliminary

design studies of spacecraft requiring 10 to 100 kwe. The reference unmanned (see Frontispiece) and a conceptual shadow-shielded man-rated SNAP 8 nuclear systems are described in detail. A conceptual 4π shielded man-rated SNAP 8 design study is now in progress and will be reported subsequently. Figure 1 shows the typical configurations of the three basic designs. The use of a nuclear power system imposes some restrictions on the spacecraft design. For example, it is shown in the report that the shield weight can vary from a few hundred pounds to several thousand pounds depending on the payload design dose requirement and the dose plane separation distance and dimensions.

The major performance objectives are the same for each reference design. These are: 600 kw of thermal power, 1300°F NaK coolant outlet temperature, 10,000 hours endurance,

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Figure 1. SNAP 8 Reactor and Shield Configurations

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orbital startup and automatic control, high reliability, and low weight. Orbital restart is provided in the manned system.

The SNAP 8 nuclear system is comprised of four major assemblies. These are: core assembly, reflector assembly, shield assembly, and control and instrumentation assembly. The core assembly contains 211 fuel elements, of 0.56 in. OD, positioned in a 316 stainless-steel core vessel by an upper grid plate and a lower grid plate.

Located outside the core vessel is a beryllium neutron reflector assembly approximately three inches thick. The reactor is controlled by rotating reflector control drums which control the amount of leakage flux from the core. The control drums are positioned by control drum actuators which receive a signal from a controller sensing the reactor outlet coolant temperature. The shield assembly protects the payload area from the neutrons and gamma rays which are generated in the core and scattered by the reflector assembly. Each major assembly, for both the unmanned and manned reference design, is described in more detail in the body of the report.

The SNAP 8 nuclear system is being developed by Atomics International (AI) under contract to the Atomic Energy Commission

(AEC). Development programs relating to various power conversion systems suitable for use with the SNAP 8 nuclear system are currently in progress. These include:

a) A 35-kwe, 3-loop mercury-rankine system, currently being developed by the National Aeronautics and Space Administration (NASA);

b) A radiator-converter thermoelectric module, similar to the SNAP 10A module, under development by the AEC;

c) A compact thermoelectric power conversion module, development of which is planned by the AEC as an outgrowth of the SNAP 10A program;

d) The multiple installation of 3.5- to 5-kwe combined rotating units (CRU's) of the mercury-rankine cycle being developed by the AEC under the Mercury-Rankine Improvement Program (formerly SNAP 2); and

e) The multiple installation of larger CRU's of the mercury-rankine cycle planned by the AEC as an outgrowth of the SNAP 2 program.

The use of the SNAP 8 nuclear system with the above power conversion systems will provide a family of reliable space powerplants in the 10- to 100-kwe power range.

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II. UNMANNED SYSTEM, SNAP 8 REFERENCE DESIGN

In this section of the report, the design and performance characteristics of the SNAP 8 unmanned reference nuclear system are described. In general, the performance characteristics are quite similar to those of the manned system though the design differs quite markedly in the reflector assembly and shield assembly.

A. DESIGN DESCRIPTION

1. Core Assembly

The core assembly consists of a core vessel, grid plates, baffle plate, internal reflectors, and fuel elements as shown in Figure 2. Attached to the outside of the core vessel are supports which hold and position the reflector assembly.

The core vessel is a right circular cylinder of 316 SS which has a side inlet NaK coolant nozzle at the bottom and an outlet nozzle in the center of the top head. The grid plates, which position the fuel elements and internal reflectors, are fastened to the core vessel. The baffle plate is also attached to the core vessel. The baffle plate, combined with the grid plates, provides the proper coolant flow distribution to minimize the average fuel element maximum temperature.

The SNAP 8 core contains 211 0.56-in. - diameter fuel elements located in a triangular array on a 0.57-in. centerline spacing. The fuel-moderator material is Zr - 10.5 wt% U alloy hydrided to a hydrogen content (N_H) of about 6×10^{22} hydrogen atoms/cc of $(U-Zr)H_x$. The uranium is approximately 93% enriched U^{235} . The fuel elements are clad in 10-mil-thick Hastelloy-N.

Internal beryllium oxide (BeO) reflectors clad in 316 SS are used to fill the space between

the hexagonal array of fuel elements and the wall of the cylindrical core vessel.

2. Reflector Assembly

The core vessel is surrounded by an annulus of beryllium nominally 3-1/8 in. thick and approximately 17-3/4 in. long. This neutron reflector contains six movable semicylindrical sections or drums (see Frontispiece).

Reactor control is accomplished by rotation of the drums toward or away from the core to increase or decrease the fraction of leakage neutrons reflected back into the core. During ground checkout, assembly, and launch, the reactor control drums are locked in the least reactive position by squib-actuated drum lock-out pins.

Three of the six drums are "startup drums" and are driven in by springs and locked at the full-in position. The other three drums, driven by stepping actuators, are "long-term control drums" and are stepped inward fairly rapidly to a predetermined degree of subcriticality. At this point, the stepping rate is reduced by a signal to the controller from a position-sensing limit switch on one control-drum shaft or from a timer in the startup programmer. The control drums continue to rotate inward until the NaK temperature reaches approximately 1300°F, about four hours after initiation of startup. The closing of the high-temperature switch in the temperature deadband circuit switches the automatic control system to the long-term control mode after a suitable delay.

Before nuclear system startup, the temperature of the NaK coolant, which freezes at +12°F, should be kept above about 50°F to prevent oxide precipitation and possible plugging of small flow passages in the system. At about one hour after startup of the nuclear system

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a. Core Vessel With Lower Grid Plate Installed

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b. Core Partially Loaded With Dummy Fuel Elements

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c. Core With All Dummy Fuel Elements Assembled

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d. Core Vessel Assembly With Upper Grid Plate in Place

Figure 2. SNAP 8 DRM-1 Core Assembly

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has been initiated, the nuclear heat is sufficient to keep the NaK coolant from dropping below 50°F.

The reflector assembly is divided axially into two halves. Each half is attached to special hinges at the reflector bottom support structure, and when brought into position, the reflector halves contact and preload the two sets of ejection springs. The reflector halves are held together by a reflector retainer during operation and by a reflector unlocking actuator (pinpuller) during launch. Irreversible shut-down is accomplished by actuating the retainer, which results in spring ejection of the entire beryllium reflector from the core.

3. Control and Instrumentation Assembly

The control and instrumentation assembly consists of a temperature sensor, a power supply, a controller, a programmer, and a relay box. A block diagram of the system is shown in Figure 3.

Basically the power supply receives 28 volts d-c power from the spacecraft or power conversion system and regulates it for use in the controller and programmer. In addition, the power supply contains an approximately 1500-watt-sec storage device which is used to irreversibly shut down the reactor at the end of useful life.

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Figure 3. Simplified Control System Block Diagram

The controller receives its input from the temperature sensor and causes the correct control-drum motion to maintain the outlet coolant temperature between 1280 and 1330°F.

The programmer is used during reactor startup to provide proper sequencing of the various events that must occur, such as ejecting the environmental cover, unlocking the reflector drums, etc. After performing its useful function, the programmer turns itself off.

The relay box receives various command signals and activates power relays accordingly.

All components are designed to operate in an ambient temperature environment not exceeding 150°F. In addition, all components except the startup programmer are designed to operate with total integrated neutron and gamma exposures of 10^{13} nvt and 10^7 rads (C), respectively. The startup programmer is designed to operate with total integrated dose two orders of magnitude less, as its operating lifetime is only 10 hours compared with the 10,000-hour operating life of the others.

External power requirements for the nuclear system are:

- 1) Startup: 550 watts of 28 ± 3.0 volts dc for 6 hours;
- 2) Lifetime: 200 watts of 28 ± 3.0 volts dc for 10,000 hours [This is a continuation of (1) above.]; and
- 3) Squib Firing: 100 amps of 28 ± 5.6 volts dc for 10 msec and 50 amps of 28 ± 5.6 volts dc for 10 msec separated by a minimum of 30 sec.

During the first few flights, power requirements for diagnostic instrumentation whenever the telemetry system is in operation are ~75 watts of 28 ± 0.28 volts dc and ~50 amperes of 115 ± 1.15 volts ac, 400 ± 4.0 cps.

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Figure 4. Shield Weight as a Function of Unmanned System Parameters

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The nuclear system will need approximately 50 telemetry channels capable of accepting 0- to 50-millivolt d-c signals with an input impedance of 10 K-ohms and about 40 telemetry channels capable of accepting 0- to 50-volt d-c signals with an input impedance of 100 K-ohms.

It is estimated that the total volume of all components will be about 2500 in.³, and about 1200 in.² of mounting surface will be required.

The power dissipated by the nuclear system instrumentation will not exceed 175 watts.

4. Shield Assembly

As the SNAP 8 nuclear system is designed to operate with various power conversion systems, at various power levels, and for various missions, no one shield can be presented as optimum for all cases. Instead, a reference shield design, representing a typical design, is presented. In addition, nomographs are given which will allow the user of a SNAP 8 nuclear system to estimate the size and weight of a shield for a wide range of parameters.

The reference shield design is based upon a shielded envelope with a 27.6-inch diameter at a plane about 7-3/4 inches above the center of the core. This diameter represents the full-out position of the control drums and, as will be shown in Section II-B-5, a control drum can fail to operate and the nuclear system still achieve 10,000 hours of full-power operation. Thus, the shield must protect the payload from scattered radiation from a drum stuck in the full-out position or the reliability advantage gained by redundant drums is defeated. It is also very important that all extraneous scatter sources be eliminated or the shield weight may be excessive. The spacecraft designer should maintain all equipment within the shield shadow cone. The reference shield considers a power level of 600 kw, a gamma dose of 10^6 rads (C)/10,000 hours and a neutron dose of 10^{11} nvt/

10,000 hours for a 20-ft-diameter payload located 40 feet from the center of the core.

The shield corresponding to the above parameters is a total of 34.3 in. thick down the centerline and has a maximum diameter of 51.5 in. The total shield weight is 1930 lb, which is broken down as follows: neutron shield (lithium hydride), 1365 lbs; gamma shield (tungsten), 115 lbs; and structural materials, 450 lbs. These values for shield weight and dimensions comprise the reference values for the parameter study.

To find the variations in shield weight and dimensions, each parameter was varied separately about the reference point, and the shield weight vs each parameter was computed directly. The curves of weight vs each parameter were then normalized to the reference value to produce a set of curves from which relative weight may be found when more than one parameter is varied at one time. In this procedure it is assumed that all of the variables are separable within the variable range of interest. A subsequent check, however, showed that separation distance and payload diameter are not mutually separable over the complete range of interest. Therefore, a family of curves of weight and shield diameter vs payload diameter was derived for several different values of reactor-payload separation distance.

As an example, consider a system with a 600-kwt SNAP 8 reactor, 40-ft payload diameter, 100-ft reactor-payload separation distance, and the same dose rates as the reference design. From Figure 4, the power level scaling factor is 1.00, the payload diameter scaling factor is 1.52, and the separation distance scaling factor is 0.43. The product of these factors and the reference weight yields an estimated weight of 1260 lb. A direct calculation yields a weight of 1270 lb.

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Figure 5. Shield Weight as a Function of Unmanned System Reactor Parameters

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The data in Figures 4, 5, and 6 should be sufficiently accurate to provide a prediction of shield weights and dimensions for preliminary surveys. However, specific designs should be checked out individually wherever possible.

5. Safety Systems

The major safety systems and components that are under development at AI and which may be used in SNAP 8 applications are discussed below.

a. Poison Sleeve and Shipping Container

Shipment and transportation of an assembled and fueled core over public domain will be required during one or more phases in the SNAP 8 factory-to-flight sequence. As the shipment will contain a potential critical mass of fissionable material in a single package, the danger of criticality exists if one considers the possibility of an accident in which the core could be surrounded with a moderating material such as water. Special procedures will be followed during the transportation phases to prevent the occurrence of criticality and thus prevent exposure of the general public to radiation as a result of such shipments. The poison sleeve and shipping container will be specifically designed to protect against the occurrence of these hazardous conditions.

A shipping container has not been designed for the SNAP 8. However, it is expected that a unit similar to the one used for the SNAP 10A shipment would be provided. The unit would consist of a metallic outer container and a hermetically sealed inner container which would be capable of protecting the shipping sleeve and reactor during shipment.

b. Drum Lockout Safety System

During the prelaunch assembly, checkout, and handling operations, the possibility exists that the control drums could be accidentally

driven or forced in, producing a possible situation where an excursion or steady-state operation could occur. To protect the reactor from such occurrences, the control drums will be locked in the least reactive position by the following devices: (1) a set of void-filler inserts which are bolted in the drum cavities; (2) a mechanical lock on each drum which requires a key for removal; and (3) drum lockout pins.

The void-filler inserts will consist of low moderating, and possibly neutron poison, material formed and shaped to fit into the space vacated when a control drum is rotated to the full-out position. The inserts prevent rotation of the control drums and also minimize potential increases in reactivity by limiting the approach of moderating or reflective material to the core. The poison inserts remain in the drum cavities until time for installation of the nose cone or skin fairing. When the inserts are removed, the drums are maintained in the least reactive position by the keylocks and the drum lockout pins. After the nose cone has been installed and all checkouts are completed, the drum keylocks can be unlocked and removed through small access holes (approximately 6 in. square) which must be provided in the vehicle nose-cone skin. The drum lockout pins are pulled as part of the startup sequence by explosive pinpullers after a successful launch trajectory or orbit has been attained.

c. Abort-Destruct Safety System

During launch or preorbital operation it is possible that an abort could produce conditions of criticality, particularly if the intact nuclear core landed in water. To protect against this possibility, a shaped destruct charge may be provided on the environmental cover which would disassemble and disperse the core components on ground command, thereby rendering

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Figure 6. Shield Thickness as a Function of Unmanned System Parameters

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the system subcritical. After a successful orbit has been attained, the destruct system is ejected with the environmental cover during the startup sequence to prevent possible interference with the mission.

However, other approaches to prevent criticality are under investigation at the present time. In addition, certain launch trajectories will not require use of a destruct charge. Hence, the need for a destruct charge will be evaluated for each mission.

d. Reflector Ejection Safety System

As the SNAP 8 nuclear system startup and power operation is accomplished entirely by the external reflector control system components, misoperation of the control system or an accident involving the reflectors could conceivably lead to inadvertent criticality or abnormal power operation following abort, or orbital operation, or upon reentry. Therefore, it is desirable to remove the entire beryllium reflector and drive system from the core in the event of abort or after completion of the normal operating cycle (10,000 hours) to irrevocably shut the nuclear system down prior to reentry into the earth's atmosphere. Furthermore, it is necessary to remove the beryllium reflectors from the nuclear system to enhance burnup of the core vessel and separation of the fuel during the final reentry phase. The above objectives will be accomplished by the reflector ejection system which will permit command or inherent ejection of the entire beryllium reflector system when necessary.

To accommodate reflector ejection, the reflector control system has been designed in two halves (divided axially) which are mounted separately on the core vessel. Each half is supported by a hinged-pivot fixture on the bottom of the core vessel. The reflector halves bear against support brackets at the top of the

core vessel and are held in place by a reentry actuator. Parting or breaking of this reentry actuator releases the reflector halves permitting the entire assembly to be ejected away from the core vessel by four preloaded springs. Reflector assembly ejection may be accomplished either by ground command to an electrically heated device which is mounted integrally with the reentry actuator, or by inherent reentry heating of the reentry actuator.

B. PERFORMANCE CHARACTERISTICS

The unmanned SNAP 8 nuclear system is conservatively designed to operate at 600 kw for 10,000 hours. It is due to this conservative design that the power level may be raised approximately 20% while still maintaining a high overall system reliability.

In this section of the report, the nuclear, thermal, shielding, environmental, and reliability characteristics of the unmanned reference SNAP 8 nuclear system are discussed.

1. Nuclear

The SNAP 8 nuclear system is designed for 10,000-hour operating time at 600 kw. These time and power requirements determine the minimum excess reactivity required for the system. Figure 7 shows the excess reactivity

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Figure 7. SNAP 8 Nuclear System Reactivity Requirements

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required as a function of operating time for various power levels. The nominal amount of reactivity and maximum amount of reactivity using a fully shimmed reflector assembly are also shown. Note that there is considerable excess reactivity above the minimum required, which is used for reliability purposes described in Section II-B-5. The excess reactivity, in turn, affects the control requirements for the reactor.

The design multiplication factor, k_{eff} , of the cold and clean SNAP 8 nuclear system is 1.066. The needed excess is determined by the total temperature defect (i.e., loss of reactivity due to increase of temperature in going to power), fission product poison buildup, fuel burnout, hydrogen loss by permeation of the barrier material, and a contingency for failure of fuel elements and reflector drum-drive assemblies.

The temperature defect is due to three main effects. The higher temperatures at power cause expansion of core and reflector components, thereby increasing leakage and decreasing reactivity. The second effect is a change in the neutron spectrum in the thermal range due to increased kinetic energy of the moderating hydrogen atoms in the core. The total defect of these two effects is calculated at about $-1.7\% \Delta k/k$.

Another effect is hydrogen migration along the axis of the fuel rods toward the colder end of the rods. The reactivity loss from this effect is expected to be about $-0.4\% \Delta k/k$.

The fission product poisons may be considered in three categories, samarium-149, xenon-135, and stable fission fragments. These three effects result in a $\Delta k/k$ of about -2.5% . Fuel burnout contributes about $-0.5\% \Delta k/k$ to reactivity loss.

The normal hydrogen loss from the fuel is expected to contribute about $-1.6\% \Delta k/k$ to the total reactivity loss. About -2.4% in reactivity is reserved to allow for failure of fuel element hydrogen barriers and reflector drum-drive assemblies.

Prepoison samarium has been added to the core to compensate partially for the reactivity losses and to reduce the rate of change of system multiplication factor. The prepoison samarium, worth about $2.5\% \Delta k/k$, burns out almost completely. The total excess requirement is thus about $9.1\% \Delta k/k$ less the $2.5\% \Delta k/k$ gain due to burnout of the prepoison samarium. The total reactivity requirement is thus $6.6\% \Delta k/k$.

Further flexibility is allowed in the design of the startup and control drums by the built-in shim capability. The removal of all shims can reduce system reactivity by as much as $-2.0\% \Delta k/k$ while addition of all shims can add as much as $3.2\% \Delta k/k$.

The required total control drum worths are dictated by the total excess reactivity and the fact that three drums (startup drums) will be driven full-in at the start. The three control drums will have a worth of approximately $2.4\% \Delta k/k$ each, or a total of about $7.1\% \Delta k/k$, sufficient to make the system subcritical with three drums in the innermost position.

Negative temperature coefficients help prevent reactor excursions by reducing the k_{eff} of the reactor as temperature increases. The SNAP temperature coefficients were calculated to be negative over the entire temperature range and these calculations have been confirmed by S8ER temperature coefficient experiments. In fact, the S8ER experiments show the temperature coefficients to become more negative at increased temperatures, thus adding to the reactor safety.

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The spectrum of neutrons causing fission is predominately thermal with about 70% of the fissions occurring in the thermal group. The median fission energy is 0.21 ev.

The prompt neutron lifetime, i. e., the mean time between the time at which a prompt neutron is born in fission and the time at which new fissions are generated, is 8.4×10^{-6} sec. The effective delayed neutron fraction in the SNAP 8 reactor is 0.0080.

The fission density distribution shows the power at the reactor center to be 1.22 times the radial average and 1.44 times the axial average.

The preceding paragraphs gave the important nuclear parameters and indicated a significant margin of excess reactivity, approximately 2.4% for contingency. However, a system can be limited by other parameters than excess reactivity. As shown on Figure 8, the operation of the reference SNAP 8 nuclear system is not limited by excess reactivity, but rather, by other design criteria.

The attainment of a design criterion should have no detrimental effect on the system per-

Figure 8. SNAP 8 Reference Nuclear System Design Criteria for 10,000-Hour Lifetime

formance, as the existing SNAP 8 nuclear system is conservatively designed to produce 600 kw for 10,000 hours. A better assessment of the reactor operating performance can be found by estimating the effects of operating the reactor beyond the design criteria until a probable operating limit is reached, as shown in Figure 9. With minor changes to the beryllium drums and hydrogen moderator concentration within the fuel, the existing system could operate at over 1 Mwt for 10,000 hours. This higher power level is the nominal predicted operating potential and, although reactivity-limited, still maintains approximately \$3.00 surplus reactivity for redundancy. The higher power levels are obtainable by decreasing the redundant reactivity which is a measure of reactor reliability.

2. Thermal

The SNAP 8 fuel configuration consists of 211 cylindrical (U-Zr) H_x fuel rods clad in seamless Hastelloy-N tubing and positioned in a close triangular array to form a compact modified hexagonal core. The system is

Figure 9. SNAP 8 Reference Nuclear System Probable Operating Limits for 10,000-Hour Lifetime

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Figure 10. SNAP 8 Nuclear System Temperature Map

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designed to generate 600 kw in a space environment for a duration of 10,000 hours and is cooled by eutectic NaK-78. Due to the relatively high H_2 partial pressure at 600-kwt operating condition (~ 3 atmospheres) and the high permeation rate of H_2 through metals at this high temperature, the internal surface of the cladding is coated with a thin ceramic coating to minimize the amount of excess reactivity required to compensate for the loss of the hydrogen moderator.

The basis of the SNAP 8 design is an extrapolation of the SNAP 10A/2 technology to a higher power level. The fuel contains 10% fully enriched uranium in zirconium. Because of the increase of hydrogen partial pressure of $(U-Zr)H_x$ with increasing temperature, SNAP 8 fuel is hydrided to an N_H of about 6.0 ($N_H = 10^{22}$ hydrogen atoms/cc fuel) compared to the SNAP 10A N_H of 6.5 (the N_H of water at 338°F is 6.0). In order to decrease the average and central fuel temperatures, the fuel rod diameter was decreased from the value of 1.25 in. used in the SNAP 10A reactor, which has 37 fuel rods, to 0.56 in. for SNAP 8. The fuel elements are clad with 10-mil-thick Hastelloy-N.

NaK-78 is used as the coolant due to its high thermal conductivity (~ 14.5 Btu/hr-ft²-°F at 1100 to 1300°F), high heat capacity (~ 0.21 Btu/lb-°F at 1100 to 1300°F), high boiling point ($\sim 2000^\circ\text{F}$ at 20 psi), and low melting point ($+12^\circ\text{F}$ at atmospheric conditions).

The various reactor components external to the reactor core are heated by neutron and gamma radiation as well as by conduction and radiation from the core vessel. These components, in turn, radiate heat to space. A temperature map of the SNAP 8 nuclear system showing surface temperatures and the

amount of heat radiated to space, assuming an unimpeded view of space, is shown in Figure 10. Internal and external temperatures of various components under the simulated space operating conditions ($\sim 10^{-6}$ Torr, 100°F sink temperature) of the SNAP 8 Developmental System (S8DS) have been calculated.*

3. Shielding

The radiation levels outside the SNAP 8 reactor are presented in Figure 11. The doses in this figure correspond to a 10,000-hour exposure to an unshielded reactor operating at a nominal power level of 600 kw. The angular distribution of the radiation leakage is approximately isotropic.

The importance of fast neutron scattering from vehicle components located outside the shield's shadow cannot be overemphasized. The extremely high values of the neutron scattering contribution from any appendages outside the shield shadow cone angle prompt the recommendation that all potential scattering sources be located behind the shadow shield. Otherwise, a severe weight penalty is inflicted by the necessity of a shield at the large surface area of the payload.

The dose rate per kw at 10 feet from a shutdown, unshielded, SNAP 8 reactor as a function of time after shutdown for various operating times is given in Figure 12. Dose rates at other points in space can be determined by applying the inverse square law.

The shield vessel thickness is determined largely by the micrometeoroid protection desired and the operating temperature of the vessel.*

4. Environmental

The nuclear system is designed with a safety factor of 1.4 to withstand shock, vibration, and

*C. E. Johnson, "SNAP 8 Quarterly Progress Report, May through July 1964," NAA-SR-9992 (SRD), September 22, 1964

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Figure 11. Nuclear Radiation Levels Outside an Unshielded SNAP 8 Reactor After 10,000-Hour Operation at 600 kw

acceleration, etc., encountered during SATURN-class vehicle launch.

The nuclear system, being designed for 10,000 hours of reliable unattended operation, is a precision assembly and is protected against adverse environments such as rain, snow, sand, dust, salt spray, and fungus growth by an environmental cover.

A detailed summary of the environments which the nuclear system can withstand without any detrimental effect is given in Appendix C.

5. Reliability

One of the prime incentives for developing nuclear electric power for space applications is the long life potentially available from nuclear power plants. Attendant with this long-life potential is a requirement for high reliability.

For unmanned applications, the power plant reliability should probably be at least as high as the payload reliability. The reliability goal of the nuclear system (the reactor and its associated shield and controls) would then be in the range of 0.95 to 0.98 for startup in space followed by 10,000 hours of unattended operation. The reliability goal for the unmanned SNAP 8 nuclear system is ~0.97.

For manned applications, the safety of the crew and great expense of each mission indicate higher reliability requirements. Current goals for manned nuclear systems are in the range of 0.99 to 0.999 for 10,000 hours of operation.

In order to demonstrate these high reliability goals with a reasonable degree of confidence, a prohibitively expensive test program would be required. For example, Figure 13 shows that to demonstrate with a 50%

Figure 12. Radiation Levels From SNAP 8 Core as a Function of Time After Shutdown

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Figure 13. Number of Tests Required to Demonstrate SNAP 8 Reliability at 50% Confidence Level

confidence level the unmanned SNAP 8 nuclear system reliability goal of 0.97, 22 systems would have to be tested for 10,000 hours each. If one of these systems should fail, an additional 33 systems would have to be tested for 10,000 hours without failure. If one assumes a conservative cost of \$5 million per system tested, the cost of such a reliability test program would be at least \$100 million and perhaps significantly more. Thus a straightforward demonstration of nuclear system reliability would be extremely expensive.

An alternate approach to achieve high reliability is therefore used. It employs the following plan:

- a) A few developmental reactor tests are conducted, culminated by one nuclear system qualification or demonstration test.
- b) A large number of developmental component tests are conducted, followed by a limited number of component qualification tests.
- c) A thorough component development program is conducted. The objective of this program is to develop and demonstrate that reactor components will operate under

more severe environmental conditions than are expected in actual use, for example, at higher temperatures.

d) The overall nuclear system is designed to achieve maximum reliability. With the low-power reactors, which are inherently simple, the design stresses simplicity. For example, the SNAP 10A reactor utilizes a static, nonmoving control system. On the other hand, the design of high-power reactors, which are of necessity more complex, stresses redundancy. For example, the SNAP 8 nuclear system employs active control but includes sufficient redundancy so that failure of an individual control-drum drive and a limited number of fuel elements will not prevent the system from achieving rated power and life.

e) Logic circuit diagrams and reliability prediction models are formulated to assist in failure mode analyses.

f) Design reviews are conducted during the conceptual, preliminary, and final design stages to review and correct potential weak areas in the system design.

The SNAP 8 design approach to reliability, for both the manned and unmanned systems, is to make maximum use of redundancy. The use of redundant components allows a lower individual component reliability goal while still achieving a high system reliability goal. In both the SNAP 8 nuclear systems, the redundant component approach is possible largely because excess reactivity is provided which permits failures and malfunctions of fuel elements and control-drum drive assemblies.

a. Available Excess Reactivity

Figure 7 was a plot of the excess reactivity needed vs reactor lifetime for various discrete power levels for the unmanned SNAP 8 nuclear system. Also shown on this figure is the nominal reactivity available, \$11.00, and

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Figure 14. SNAP 8 Nuclear System Reactivity Requirements, 1200°F Outlet Coolant Temperature

the reactivity available using maximum reflector shim capability, \$15.00. The \$4.00 difference between the nominal and maximum reactivity is available with an additional weight of 78 lb for extra contingency, to account for manufacturing tolerances (maximum <\$2.00), and to account for analytical inaccuracies (maximum <\$0.50).

In Figure 7 it was shown that the 600-kwt unmanned SNAP 8 nuclear system has sufficient reactivity at the nominal value to run approximately 17,500 hours (740 days), and with maximum shim can operate approximately 29,000 hours (1200 days).

Figure 14 is a plot similar to Figure 7 except that the nuclear system outlet coolant temperature is reduced to 1200°F and hence, lifetime at a specific power level is increased, or the reliability at a specific power level and specified lifetime is increased. Figure 15 is also a plot similar to Figure 7 but for an outlet coolant temperature of 1400°F; hence, lifetime at a specific power level is decreased or reliability at a specific power level and lifetime is decreased.

These three figures show that the unmanned SNAP 8 nuclear system has sufficient excess

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Figure 15. SNAP 8 Nuclear System Reactivity Requirements, 1400°F Outlet Coolant Temperature

reactivity to operate for 10,000 hours at various power levels, from 600 kwt at 1400°F to 1200 kwt at 1200°F. However, when the nuclear system is operated at higher power and temperature, the amount of excess reactivity available for redundant components is decreased. Figure 16 shows the nominal amount of excess reactivity available for redundancy (reliability) at the end of 10,000 hours of operation at various power levels and coolant outlet temperatures. Also shown for comparison is the maximum amount of excess reactivity available (full shim capability) at the reference outlet coolant temperature of 1300°F for various power levels. To a first order approximation, the relative reliability of operating the unmanned SNAP 8 nuclear system at off-design conditions can be determined by the amount of excess reactivity available. For instance, the reliability of the system at 600 kwt, 1300°F outlet coolant temperature is approximately equal (same excess reactivity at end of 10,000 hours) to the reliability of the system operating at 375 kwt and 1400°F outlet coolant temperature.

b. Available Redundancy

Figures 17 through 21 deal with nuclear system lifetime based upon available reactivity.

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The other operating limits provide bounds to the normal operating range, while reactivity exhaustion is a real limit to operation. For example, when the available reactivity reaches zero, the nuclear system temperature begins to drop and the end of useful power operation occurs shortly thereafter. However, if the beryllium temperature rises from its design criteria limit of 1350°F to 1355°F or even to 1375°F, no immediate cessation of operation will occur. Rather, the operating life of the system may be reduced but the amount of reduction or reliability decrease is difficult to predict.

Figure 17 plots reactor lifetime as a function of time of malfunction of one control-drum drive assembly for various power levels and an outlet coolant temperature of 1300°F. This figure conservatively assumes that only the nominal amount of reactivity (see Figure 7) is available. This figure also assumes that all six control drums are used for control and that the control system philosophy used is "fail-as-is." The system is assumed to be prepoisoned at the reference design level ($-\$3.00$, Sm_2O_3).

Figure 18 is similar to Figure 17 except that the outlet coolant temperature has been decreased to 1200°F. The assumptions used to derive Figure 17 also apply to Figure 18. Figure 19 is similar to Figure 17 except that the outlet coolant temperature has been increased by 100°F to 1400°F.

Figure 20 shows the number of fuel elements that can "fail" at various power levels as a function of reactivity lifetime for a 1300°F outlet coolant temperature. The curves in Figure 20 are based on the following assumptions:

- 1) The hydrogen density in a fuel element drops instantaneously from its initial value of about 6.0×10^{22} hydrogen atoms/cc of fuel ($N_H = 6.0$) to 3.0×10^{22} atoms/cc of

fuel. (This assumption is extremely conservative. Results of a recent investigation based upon 2.0 cm^2 of bare cladding surface area show that it takes 4000 hours to reach the beta-delta phase boundary, $N_H \sim 5.0$. Once this phase boundary is reached, the hydrogen loss rate decreases by an order of magnitude.)

- 2) The reactivity worth of the lost hydrogen is equivalent to the peak value (-15%) for any fuel element in the core.

- 3) All fuel element failures occur prior to the time designated "reactor lifetime" in Figure 20. (If one or more of the total number of fuel element failures does not occur before this time, the operating life is actually extended beyond the time shown.)

- 4) There are no control-drum drive assembly malfunctions.

Figure 20 shows that when the reactor is operating at 600 kw, 18 fuel elements may fail and the reactor still has sufficient reactivity to achieve 10,000 hours.

Figure 21 is a cross-plot of Figures 17 and 20 and shows the number of fuel elements that may fail as a function of time of control drum malfunction and the reactor will still achieve 10,000 hours of operation. From Figure 21 it can be seen that nine fuel elements and one control drum drive assembly may malfunction and the reactor still has sufficient reactivity to operate 10,000 hours at 600 kw with an outlet coolant temperature of 1300°F.

Figure 22 shows the available redundancy (reliability) of the SNAP 8 nuclear system operating at off-design conditions of power and temperature for 20,000 hours or twice the design life. These curves show that the SNAP 8 nuclear system can operate for 20,000 hours at 600 kw and 1200°F with only a small decrease

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Figure 16. Nominal Excess Reactivity Available at End of 10,000 Hours

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Figure 17. Nuclear System Reactivity Lifetime vs Time of Failure of One Control-Drum-Drive Assembly, 1300°F Outlet Coolant Temperature

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Figure 18. Nuclear System Reactivity Lifetime vs Time of Failure of One Control-Drum-Drive Assembly, 1200°F Outlet Coolant Temperature

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Figure 19. Nuclear System Reactivity Lifetime vs Time of Failure of One Control-Drum-Drive Assembly, 1400°F Outlet Coolant Temperature

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Figure 20. Nuclear System Reactivity Lifetime vs Number of Fuel Element Failures, 1300°F Outlet Coolant Temperature

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Figure 21. Fuel Element Contingency Available for 10,000-Hour Operation vs Time of Failure of One Control-Drum-Drive Assembly, 1300°F Outlet Coolant Temperature

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Figure 22. Fuel Element Contingency Available for 20,000-Hour Operation vs Time of Failure of One and Two Control-Drum-Drive Assemblies

in reliability over the design conditions. Even if two control drums malfunction, operation is possible for 20,000 hours at 300 kw and 1300°F with approximately the same reliability. An improvement in reliability is attained when operating at 300 kw and 1200°F outlet coolant temperature.

Although extending the life of the nuclear system to 20,000 hours might tend to decrease system reliability, the reduced operating temperature and/or power level should compensate for the extended life. Wear-out failure of mechanical components due to extended operation is not expected in the nuclear system, because the majority of the components are completely passive in their operation. Deterioration due to neutron flux, temperature, etc. are the most probable modes of failure. Operation at a reduced power level of 300 kw for 20,000 hours gives the same integrated flux and, hence, should not significantly decrease system reliability. Operation at the reduced temperature, 1200°F, for 20,000 hours should significantly improve component reliability over the 10,000-hour, 1300°F operation.

c. Passive Operation

The preceding section has covered the effect of control-drum-drive assembly malfunctions upon the ability of the system to achieve the desired lifetime, using the assumption that loss of active control would result in an immediate loss of electrical generating capability. This assumption is not strictly valid.

Since the SNAP 8 reactor has a negative temperature coefficient of reactivity, the time required for the system to deteriorate to the point where electrical generation ceases is directly related to the rate of change of the system reactivity. Figure 23 shows the excess reactivity of the SNAP 8 reactor as a function of time for various power levels with a 1300°F outlet coolant temperature. The temperature coefficient of reactivity for SNAP 8 is about $-0.2\text{¢}/^\circ\text{F}$ so that an uncontrolled loss of 10¢ in reactivity will result in a 50°F drop in temperature. A 50°F drop would probably result in failure of the power conversion system and would occur in about 15 days if the reactor has operated more than 200 days at 450 kw. The use of thermoelectric pumps would probably result in an apparent increase in the reactivity feedback coefficient. Therefore, a larger reactivity loss could be tolerated for the same

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Figure 23. Reactivity as a Function of Time, 1300°F Outlet Coolant Temperature, Initial Prepoison = \$3.00

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temperature drop (increased life) or the same reactivity loss would sustain a smaller temperature drop (increased efficiency).

If the SNAP 8 nuclear system were coupled to a power conversion system which required significantly less power than the present reference value of 450 to 500 kw, the time for the reactor temperature to decrease is considerably increased. If, for example, the reactor were operated at 150 kw, the control system could fail after only 25 days of operation and the system would still achieve over one year of operation. The reactor temperature would gradually increase about 50°F as the burnable poison is depleted. The temperature would start to decrease after about 250 days and would show a net loss of 50°F in about 400 days.

Also, passive operation at higher power levels is feasible if the reactor outlet coolant

temperature is reduced. For example, a comparison of Figures 7 and 14 shows that the reactivity requirements for 300 kw, 1300°F outlet coolant temperature and 450 kw, 1200°F outlet coolant temperature are nearly identical. Therefore, at low power levels and 1300°F outlet coolant temperature or at medium power levels and 1200°F outlet coolant temperature, the use of burnable poison in the core, in effect, provides a redundant backup to the control system.

d. Component Reliability Goals

The excess reactivity available for redundant components and subsystems means that less stringent reliability goals can be established for individual components. For instance, the fuel element core cluster has a reliability goal of 99%. Figure 24 shows the necessary reliability of a single fuel element which will ensure the desired reliability for a cluster of 211 fuel elements. The reliability curves are plotted as a function of the number of redundant fuel elements. If no redundancy were available, each fuel element would have to meet a reliability goal in excess of 0.9999 for cluster reliability of 0.99 to be achieved. However, with only 5 redundant elements, the single element reliability goal is reduced to 0.99, and with 10 redundant elements the requirement is reduced further to 0.96.

The same reduction in reliability goals is also true for the control-drum drive assembly. The design goal for the six-drum drive assembly is about 0.992. Figure 25 shows that without a redundant control drum, the individual drive assemblies would require a reliability of about 0.999 while with one redundant drum assembly, the individual reliability goal is reduced to about 0.975.

As previously discussed, lowering the reactor power level can also increase the system

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Figure 24. Reliability of a Cluster of 211 Fuel Elements

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reliability or for the same system reliability, decrease the component reliability necessary. Figure 22 shows that two drum-drive assemblies can be allowed to fail and 10,000 hours of operation at 300 kwT will still be attained. Referring to Figure 25 and maintaining the same six-drum-drive assembly reliability goal of 0.992, an individual drive assembly reliability goal is decreased from 0.975 to a goal of only 0.92. Conversely, with the same individual drive assembly reliability of 0.975, the overall six-drum drive assembly reliability is increased from 0.992 to 0.9997 when two individual drive assemblies are permitted to malfunction.

In addition to the redundancy approach to component design, a conservative philosophy is employed in the structural design of the SNAP 8 nuclear system. This conservative design results in a high system reliability. In general, design criteria limits are set well below the point at which damage might be expected to occur, and safety factors are applied to the expected loads. As an example, the design point allowable creep of the core vessel is 0.2%. The core vessel would not interfere with the reflectors, however, until the core vessel creep exceeded 0.9%. In addition, a safety factor of 1.4 is used to compute the design load on the vessel. Using the maximum expected range of material strength and operating loads, the design reliability of this vessel has been computed to be in excess of 0.9999. Other components in the system are designed using the same philosophy and similar safety factors.

In addition to the application of redundancy through excess reactivity, redundancy has been

provided in other potential problem areas. Figure 26 is a reliability logic diagram which has been developed to assess areas where reliability may be improved either through redundancy or increased safety factors.

As can be seen from Figure 26 essentially all of the series elements in the logic diagram have either complete redundancy or partial redundancy. With this logical approach to the problem of high reliability, the reliability of the overall nuclear system is continuously being upgraded through use of more redundancy and/or higher design margins and safety factors.

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Figure 25. Reliability of a Six-Control-Drum-Drive Assembly

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Figure 26. SNAP 8 Nuclear System Reliability Logic Diagram

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III. MANRATED SNAP 8 NUCLEAR SYSTEM

The design and performance characteristics of the shadow-shielded manrated SNAP 8 nuclear system concept are described in this section. In addition, the current 4π shield design studies are outlined. The results of these studies, not yet completed, will be reported subsequently. In general, the performance characteristics and core assembly of the manned systems are essentially the same as those of the unmanned system, while the conceptual design of the reflector assembly and shield assembly are different. Figure 27 shows a typical conceptual layout of a shadow-shielded manrated SNAP 8 nuclear system.

A. DESIGN DESCRIPTION

Each of the major assemblies comprising the reference SNAP 8 manrated nuclear system concept is described separately.

1. Core Assembly

The core assembly is composed of a 316 stainless-steel core vessel which contains 211 fuel elements in a hexagonal array supported between two grid plates. Internal beryllium-oxide reflectors clad in 316 stainless steel are located between the hexagonal fuel element array and the cylindrical core vessel.

The fuel elements are made of Zr - 10.5wt% U alloy hydrided to a hydrogen content of about 6×10^{22} hydrogen atoms/cc of $(U - Zr)H_x$. The uranium is 93% enriched. The elements are clad in 10-mil-thick Hastelloy-N tubing of a nominal 0.560-in. OD and are coated internally with a hydrogen permeation barrier. The active length of the fuel element is 16.825 in. and the overall length, neglecting the positioning end-pins, is 17.145 in.

Attached to the outside of the core vessel are brackets to support and position the reflector assembly.

2. Reflector Assembly

The core vessel is surrounded by an annulus of beryllium approximately 17-1/2 in. long which tapers from a thickness of about 2-1/2 in. at the inlet end of the core to about 4 in. at the outlet end.

Eight control drums made of beryllium are located around the core vessel. The drums are sections of truncated cones with their axes of rotation inclined at approximately 6° to the axis of the core vessel. The flat sides of the control drums are 1/4 inch from and parallel to the axes of the drums. The conical drum shape results in the varying proportions of fixed and movable reflectors shown in Figure 28, Sections BB, CC, and DD, which are cross sections taken at the top, middle, and bottom of the control drums. The control drums can be counter-balanced to eliminate torque on the drum actuator resulting from transverse acceleration of the space station; however, this is not anticipated to be necessary.

The fixed reflector consists of eight individual pieces of beryllium attached at the upper end and guided at the lower end.

The control drums are driven by stepping actuators. The actuators are mounted above the core vessel to eliminate any interference with the piping at the lower end and to place them in the most favorable position for radiation of their heat to space. The diameter of the actuators makes it necessary that they be set inward from the drum axes and that a gear train be used to connect the actuator and drum shafts. Each control drum has its own stepper motor and they operate independently as determined by the controller.

The control-drum actuator used is a bidirectional stepper motor which upon command, steps

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SCALE (in.) 5 0 5 10 15 20 25 30 35 40 45 50

NOTES:

1. REACTOR POWER - 600 kw
2. RADIATION SHADOW CONE
DIAMETER = 60 ft @ 150 ft
FROM CORE CENTER
3. RADIATION DOSE RATE = 1.5mr/hr
@ 150 ft FROM CORE CENTER

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Figure 27. SNAP 8 Manrated Nuclear System Conceptual Design

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Figure 28. SNAP 8 Manrated Reflector Assembly Cross Sections

the control drum a nominal $1/4^\circ$. The actuator is a "fail-as-is" device which maximizes nuclear system life and minimizes inadvertent shutdown. No scram circuits are provided and shutdown of the nuclear system is accomplished by driving the control drums to their least reactive (out) position.

Consideration is also being given to a control-drum drive override concept in which a control drum with a failed motor could be put into its most reactive position (fully inserted), thereby maximizing system life.

3. Control and Instrumentation Assembly

The control and instrumentation assembly consists of a temperature sensor, a controller, a programmer, and a relay box.

The unmanned reference control scheme was selected on the basis of its simplicity and inherent reliability. It senses the reactor outlet coolant temperature and maintains this temperature

between preset limits (1280 to 1330°F) by means of an on-off digital control system.

A temperature sensor (platinum resistance detector) continuously measures the reactor outlet temperature and compares it with a reference temperature. The comparison signal is amplified and routed to a bi-stable amplifier which, in turn, signals the controller to take appropriate action whenever the reactor outlet temperature is outside the preset deadband limits.

The long-term control system attempts to maximize reliability by minimizing complexity. The controller is designed to allow maximum deterioration of the electronic components from radiation and two temperature sensors (using a voting-type circuitry) are used to maximize sensor accuracy and reliability. In addition, periodic readjustment of the temperature reference point is possible. Additional pairs of temperature sensors and reference point circuitry are provided which can be switched into the control system in the event of failure of the assembly being used. The controller is of modular construction with test points brought out for ease of maintenance and trouble shooting. On-board maintenance of modules is not anticipated and they would be replaced with spare modules or a spare controller in the event of malfunctions. The controller output switches power through the relay box to the control drum actuators.

In addition to the long-term control, a startup control mode is provided to minimize startup time. Using the reactor outlet temperature control and a preprogrammed control drum insertion rate, startup can be automatically accomplished in less than 4 hours. Nuclear instrumentation is provided so that an operator can restart the plant, if desired, after a shutdown in approximately 2 hours using semi-automatic

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control. A simplified block diagram of the nuclear system long-term control system is shown in Figure 29.

Although no scram circuits are provided, automatic setback may be provided to protect the nuclear power plant against unforeseen incidents. If automatic setback circuits are employed, a bypass switch will be provided so that all setback circuits may be bypassed during critical phases of the mission. Also, automatic setback, if provided, would occur only as long as the variable causing setback remains outside the specified limits and coincidence circuitry would be used to minimize false setbacks.

The external power requirements for the nuclear system are:

a) Startup: 600 watts of 28 ± 3.0 volts dc for 4 hours;

b) Lifetime: 200 watts of 28 ± 3.0 volts dc for 10,000 hours [this is a continuation of (a) above]; and

c) Squib Firing: 100 amps of 28 ± 5.6 volts dc for 10 msec and 50 amps of 28 ± 5.6 volts dc for 10 msec separated by a minimum of 30 sec.

It is estimated that the total volume of all instrumentation components located in the manned environment will be less than 2500 in.³ and that the total power dissipated will be less than 175 watts.

4. Shield Assembly

An important part of any manned nuclear system is the radiation shield. The shield must be light weight and long lasting, and must provide adequate protection for the crew from both neutron and gamma radiation emitting from the nuclear system. Since the shield weight is a large fraction of the total system weight, the most efficient shield materials and the optimum configuration must be used.

The manned SNAP 8 shield design concept consists of two sections, each having a two-region shield, separated by a primary heat

*ADDITIONAL UNITS AS REQUIRED TO PROVIDE ADEQUATE RELIABILITY

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Figure 29. Simplified Control System Block Diagram, SNAP 8 Manned Nuclear System

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exchanger gallery. This gallery will contain the primary loop pump(s) and the primary-to-secondary heat exchanger; e. g. , a NaK-to-NaK heat exchanger or a NaK-Hg boiler depending upon the power conversion system being used. The gallery height will range from 6 to 24 inches or larger depending upon the type and size of power conversion system being used.

The overall shield assembly must provide sufficient reduction in dose to the spacecraft to protect the astronauts while the first section; i. e. , that section close to the reactor, must provide sufficient protection to prevent activation of fluid in the secondary loop, whether it is mercury, NaK, or some other fluid.

Each section of the shield design concept contains two regions, a depleted uranium gamma shield, and a lithium hydride neutron shield. As the gamma shield is particularly heavy it appears advantageous to place as much of this shield as possible in the first section of the shield. However, as the gamma shield itself produces gammas, not all the gamma shielding can be located in the first section but the ratio of core-generated gammas to shield-generated gammas must be optimized.

In order to eliminate all neutron scatter sources, the primary and secondary piping and all electrical cabling are routed through the shield rather than around the shield.

A typical shield assembly which has a 24-in. gallery weighs about 5135 lb. It shields a 60-ft-diam. payload located 150 ft from the core center to a dose rate of 1.5 mrem/hr when the reactor is operating at its rated power of 600 kw. Shield weights for other system parameters can be approximated by referring to Figure 30. For example, consider the case with a payload diameter of 80 ft., a 200-ft separation, a dose of 1.0 mrem/hr, a reactor power level of 600 kw, and a gallery height of 12 in. From Figure 30 the following scaling factors can be obtained:

Parameter	Scaling Factor
Power level	1.00
Gallery height	0.85
Payload diameter	1.4
Payload separation	0.7
Dose rate	1.05

Hence the approximate shield weight would be:

$$\begin{aligned}\text{Shield weight} &\approx 5135 (1.00)(0.85)(1.4) \\ &\quad (0.7)(1.05) \\ &\approx 4480 \text{ lb.}\end{aligned}$$

Figure 31 shows the effect of changes in reactor design parameters on shield weight. It is interesting to note that in reducing the reactor envelope from the reference unmanned design of 27.5 in. to the base case for the manned concept of 19.0 in., there is an overall shield weight savings of greater than 30%.

From Figure 32, the approximate shield thickness can be obtained by performing the same calculation with shield thickness a function of the system parameters.

Although the shadow-shield design is used in the reference manned concept, an investigation of a 4π shield design is currently being made. The final results of this study will be reported at a later date. Preliminary results indicate, however, that a 4π shield is practical from the reactor standpoint. The main disadvantages of a 4π shield are increased system weight and increased reflector assembly and shield assembly temperatures, while the main advantage is that radiation levels are decreased throughout the entire solid angle, thus providing more flexibility for rendezvous and space-station satellite experiments. Active cooling of the inside of the shield cavity with the 1100°F primary NaK loop is being investigated and may satisfactorily reduce the reflector assembly temperatures. Changing the reflector material to BeO to minimize the cooling required is also being investigated. A previously suspected

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Figure 30. Shield Weight as a Function of Manned System Parameters

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Figure 31. Shield Weight as a Function of Manned System Reactor Design

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Figure 32. Shield Thickness as a Function of Manned System Parameters

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penalty of reduced control drum worth due to neutron reflection from a 4π shield appears to be negligible on the basis of preliminary results from recent critical experiments. Continuing critical experiments will verify this conclusion. Other major items under investigation are the use of poison-backed control drums, the use of nickel for the stationary reflector, and means of further reducing the reactor assembly envelope to minimize the nuclear system weight. Once a 4π -shield concept is selected, this concept will be integrated with the shadow shield concept, and a unified design concept applicable to either shadow or 4π shielding will be formulated. The weight and performance penalties of this unified concept will then be assessed. It is anticipated that there will be essentially no performance penalties and only a rather minor weight penalty.

In addition to the current investigation on the use of 4π shields, preliminary investigations are also being made on the use of other shielding material, particularly gamma shielding material. Serious consideration is being given to the use of tungsten in place of depleted uranium. They are quite similar in their attenuation properties and each has a secondary gamma associated with it. However, tungsten is compatible with LiH (solid or liquid) and, hence, has the advantage of being able to be cast integrally with the neutron shield material. Experimental castings have been made successfully using an aggregate of tungsten and casting it in LiH. The advantages of this type of construction are that it is much easier to support the gamma shield and final assembly of the nuclear system is easier. Also, this type of construction lends itself readily to design of a multiregion shield or a uniformly dispersed gamma shield in neutron shield, if an advantage for either concept can be demonstrated.

Lead oxide is also being considered as a gamma shield material. Its primary advantage over tungsten or depleted uranium is the lack of a secondary gamma.

B. PERFORMANCE CHARACTERISTICS

The reference manned SNAP 8 nuclear system is conservatively designed to operate at 600 kw for 10,000 hours. It is due to this conservative design that the predicted reliability of the manned nuclear system will exceed 0.99.

The nuclear, thermal, shielding, environmental, and reliability characteristics of the manned reference SNAP 8 nuclear system are discussed in the following sections.

1. Nuclear

The SNAP 8 nuclear system is designed for 10,000 hours of operation at 600 kw. This time and power requirement determines the minimum excess reactivity required for the system. However, considerable excess reactivity over and above the minimum requirement is provided for reliability purposes as described in Section III-B-5. The excess reactivity, in turn, affects the control requirement of the reactor. In order to decrease the amount of controllable reactivity, the manned nuclear system is prepoisoned to the same value as the unmanned system; i.e., $\sim \$3.00$.

The initial cold, clean, excess reactivity of the manned nuclear system is approximately \$8.25. In addition, the system has about \$3.00 worth of prepoisoning added to the fuel element hydrogen barrier in the form of Sm_2O_3 . The reactivity requirements of the manned nuclear system are identical to the reference unmanned system requirements. Table 1 summarizes these requirements.

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TABLE 1
REACTIVITY REQUIREMENTS FOR
MANRATED SNAP 8 NUCLEAR SYSTEM
(600-kwt, 10,000-hr operation)

Cause	Reactivity (% $\Delta k/k$)
Xenon (from fission)	-0.9
Samarium (from fission)	-0.9
Other fission products	-0.7
Prepoison burnout (samarium)	+2.5
Fuel burnup	-0.5
Hydrogen loss	-1.6
Hydrogen redistribution	-0.4
Temperature and power defect	-1.7
Total	-4.2
Cold, clean, excess reactivity	+6.6 (\$8.25)
Reactivity available for contingency	+2.4 (\$3.00)

Because of the tapered-drum design, the manrated nuclear system does not have as large a range of shim adjustment as does the unmanned reference design. This decrease in flexibility is relatively unimportant. Critical experiments will be performed to guarantee as a minimum the excess reactivity shown in Table 1.

The other nuclear characteristics of the manrated SNAP 8 reactor are identical to those of the reference unmanned reactor. In Section II-B-1, the conservatism of the unmanned system is discussed briefly and this discussion is equally applicable to the manrated SNAP 8 nuclear system.

2. Thermal

The reference manrated SNAP 8 fuel configuration is identical to that of the unmanned system; i.e., 211 cylindrical $(U-Zr)H_x$ fuel elements clad in 0.560-in. seamless Hastelloy-N tubing and positioned in a 0.570-in. triangular

array. The system is designed to generate 600 kwt in a space environment for a duration of 10,000 hours. NaK-78, a eutectic of sodium and potassium, is used as the reactor coolant to transfer the thermal heat generated in the reactor to the power conversion system.

The various reactor components external to the reactor core are heated by neutron and gamma radiation as well as by conduction and radiation from the core vessel. These components, in turn, radiate heat to space. As the components external to the reference manned system are in the same approximate location as in the reference unmanned system, the component temperatures are approximately the same. However, as the control drums are considerably smaller in diameter, they will have a slightly cooler temperature. Figure 33 shows the effect of reducing the control drum radius from 4-1/2 to 2-3/4 in.

The heat radiated from the major assemblies of the reference manrated SNAP 8 nuclear system is quite similar to the unmanned system heat losses (see Figure 10).

Figure 33. Maximum Beryllium Operating
Temperatures

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Although the reference manrated nuclear system employs a shadow shield design, 4π shielding of the manrated reactor design has been briefly investigated. If 4π shielding is required for a particular spacecraft design or mission, either the reflector assembly must be actively cooled or a "cold wall" must be provided in the reactor cavity. Either scheme will maintain the Be reflector temperature below its design limit of 1350 to 1400°F.

3. Shielding

The radiation levels outside the reference manrated SNAP 8 reactor shadow shield cone are identical to those of the unmanned system (see Figure 11). In the manrated SNAP 8 nuclear system it is mandatory that there be no scatter sources and all components and structure must be hidden by the shield.

In Section III-4, a typical manrated shield design is selected as the reference design with the realization, of course, that the shield for each manned application will be designed for that specific application. The shields can be designed to shield the neutron and gamma dose to any practical value. The split shield design concept provides shielding for the primary NaK loop containing approximately 345 curies of Na^{24} and 120 curies of K^{42} ; provides sufficient shielding to protect the payload area from any fission products which could be in the primary coolant system as a result of small pinhole leaks in the fuel element cladding; and also provides shielding for any activation of corrosion products in the primary coolant loop.

Although the reference manrated SNAP 8 shield employs the shadow shield principle, a 4π shield can be used, if required, for a particular mission. Naturally the weight of the shield assembly is significantly increased. Use of 4π shielding may require active cooling of the shield to prevent melting of the lithium hydride.

4. Environmental

The manrated SNAP 8 nuclear system is designed with a safety factor of 1.4 to withstand shock, vibration, and acceleration encountered during a SATURN-class vehicle launch.

The nuclear system, being designed for 10,000 hours of reliable, essentially unattended, operation with limited maintainability, is a precision assembly and must be protected against natural adverse environments such as rain, sand, snow, dust, salt spray, fungus growth, etc. This protection is provided by an environmental cover on the nuclear system.

A detailed summary of the environments which the nuclear system can withstand without any detrimental effect is given in Appendix C.

5. Reliability

One of the prime incentives for developing nuclear electric power for space applications is the long life potentially available from nuclear power plants. Attendant with this long life potential is a requirement for high reliability. The approach taken to achieve high reliability for the manrated SNAP 8 nuclear system is the same approach used in the unmanned system as described in Section II-B-5.

The reliability goal for the reference manrated SNAP 8 nuclear system will be between 0.99 and 0.999 while that of the unmanned system is approximately 97%. Hence, the failure rate of the manrated nuclear system must be decreased by a factor of 3 to 30 over the unmanned system.

Some of this increase in reliability can be accomplished by additional redundancy while some increase can be attained through maintainability. A large fraction of the nuclear system, though, because of the radioactivity associated with it, is not maintainable. The electronic controls are about the only items of the

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$$\left(R_{\text{REACTOR OPERATION}} \right) = \left(R_{\text{TEMPERATURE SENSORS}} \right) \times \left(R_{\text{TEMPERATURE SWITCHES}} \right) \times \left(R_{\text{CONTROLLERS (CONTROL \& MEMORY)}} \right) \times \left(R_{\text{CONTROLLERS (STEPPERS \& SWITCHES)}} \right) \times \left(R_{\text{CONTROL DRIVE ASSEMBLY}} \right) \times \left(R_{\text{FUEL ELEMENTS}} \right) \times \left(R_{\text{REACTOR STRUCTURE}} \right)$$

Figure 34. Nuclear System Reliability Model

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nuclear system which are readily maintainable. However, these have a failure rate apportionment of only 0.00388 for the unmanned system compared with a total unmanned system failure rate apportionment of 0.0315. Hence, even assuming a factor of ten increase in the reliability of the electronic control components due to maintainability, the overall nuclear system reliability goal would only be raised from 0.9685 to 0.9720. Essentially, the rest of the reference manrated nuclear system is unmaintainable due to the inherent high radiation. (If 4π shielding were required, certain other portions of the nuclear system might be maintainable a few days after shutdown.)

Figure 34 shows that the reliability of the reactor is the product of the reliability of the components of the reactor. This figure also graphically displays how redundancy and maintenance can be used to enhance reliability. The items outside the maintenance envelope are the temperature sensors, the control drive assemblies, the fuel elements and the structure and NaK containment. Of these items only the structure and NaK containment are not redundant. The high reliability goal needed for these items is attained by use of high design margins, providing thorough quality control, and applying conservative meteoroid protection criteria.

Additional redundancy is provided in the manrated SNAP 8 nuclear system by increasing the number of control drums from six to eight and providing sufficient excess reactivity to permit two control-drum-drive assemblies to malfunction. However, as both the overall control-drum-drive-assembly reliability and core-assembly reliability are dependent upon the number of redundant drums and redundant fuel elements, respectively, which in turn are dependent upon the total excess reactivity available, the individual element (single control-

drum-drive assembly or single fuel element) reliability must be selected based upon maximizing the reactor-assembly (core and reflector assemblies) reliability. Figure 35 shows this interaction. For a single fuel element reliability of 0.99 and a single control-drum-drive assembly reliability of 0.95, the combined core - control-assembly reliability should be in excess of 0.999.

Figure 36 shows how the reliability of the temperature sensors can be improved by use of redundant sensors. It is currently planned to use three pairs of sensors as is done in the SNAP 8 Developmental System (S8DS) test. Hence, with a single sensor reliability of only 0.9, the sensor system reliability should be greater than 0.99999.

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Figure 35. Fuel Element and Control Drum Reliability Relationship

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Previously the discussion has considered reliability as essentially a go - no-go criterion. However, for manned application, the ability to operate at reduced power and/or to recover from a malfunction by performing maintenance also adds to the reliability of a system. Therefore, a small discussion on maintenance is appropriate in this section.

As previously mentioned, the electronic controls, which are located in the human environment, are fully maintainable. Although the remainder of the nuclear system, located in a high radiation field, appears at first glance to

be unmaintainable, further investigation is warranted. For instance, a control-drum override system might be incorporated to free a "sticky" control drum after which it could conceivably operate properly. Though this is not maintenance in the sense of replacing or repairing components, it is maintenance in the sense that further operation of the control drum may be possible, or at least the control drum might be placed in its most reactive position thereby maximizing nuclear system life. This type of "maintenance" is continually being investigated to assist in achieving the highest possible reliability.

Figure 36. Temperature Sensor Reliability

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IV. DEVELOPMENT STATUS

The unmanned reference SNAP 8 nuclear system in its present status represents a good deal of realism. In addition to results from the SNAP 2 and SNAP 10A programs, it reflects results from S8ER operation, S8DRM-1 testing, about four years of intensive fuel development, a wide range of system analyses, and extensive component development.

The overall plan for the development of the SNAP 8 nuclear system calls for three nuclear tests and two nonnuclear environmental tests prior to delivery of a system for flight. These five tests include performance and environmental testing plus 43,000 hours of endurance testing. In addition, in the fuel and component development programs the equivalent of at least three additional nuclear systems will be tested for 10,000 hours. Thus, the program includes a total of over 73,000 equivalent nuclear system hours of operation.

The nuclear system tests are sequenced as follows. Early tests (the S8ER nuclear tests and the S8DRM-1 nonnuclear environmental tests) are intended to provide basic reactor and system performance data. These tests are now in progress. A second nuclear test halfway through the development program (S8DS) is intended to provide development information on automatic startup and control with the reactor coupled to a power conversion system, and to demonstrate 10,000 hours of endurance. These preceding tests are all based upon the reference unmanned SNAP 8 nuclear system.

The two final tests (the S8DRM-2 nonnuclear and the S8FS nuclear test) are intended to qualify the SNAP 8 nuclear system for flight.

A. SNAP 8 EXPERIMENTAL REACTOR (S8ER)

The SNAP 8 Experimental Reactor (S8ER) has been built and placed on test, Figure 37, without a power conversion system, to demonstrate reactor operation at rated power and temperature, and to measure reactor performance characteristics early in the development of the SNAP 8 nuclear system. The S8ER first went critical in September 1962. A series of dry critical tests were performed to predict the reactor performance. These tests were followed by a series of water immersion experiments performed as a part of the continuing flight safety program. The results of both test series compared favorably with the analytical predictions.

The reactor was then installed in the test facility, Figure 38. A series of power experiments, then conducted, demonstrated stable reactor operation over a wide range of power levels. Figure 39 shows that during over 500 days of nuclear operation, the S8ER operated one year in the power range of 400 to 600 kw with 1300° F coolant outlet temperature and operated continuously for over 5000 hours, thus establishing what is believed to be the longest continuous power run of a reactor in the United States. The test program was successfully concluded on April 15, 1965, and the S8ER was shut down for post-mortem examination.

B. SNAP 8 DEVELOPMENTAL REACTOR MOCKUP (S8DRM-1)

The SNAP 8 Developmental Reactor Mockup (S8DRM-1) is an unmanned reference flight design nuclear system except that dummy fuel elements are used. This test system was designed

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Figure 37. SNAP 8 Experimental Reactor Control Room

and built early in the development program to assure component compatibility in the nuclear system. The S8DRM-1 is currently under test, Figure 40. Figure 41 shows the S8DRM-1 test program.

To date, the assembly test, the startup reliability test, the low-level vibration and shock survey test, and the qualification level vibration and shock test have been completed. The assembly test demonstrated that the reflector assembly could be removed for shipping purposes and reassembled at a later date within $\pm 2\%$ worth of reactivity. Hence, a critical experiment at the launch site does not appear necessary.

The startup reliability test demonstrated ten successful simulated reactor startups.

The low level vibration and shock survey was conducted early in the S8DRM-1 test program in order to assist in the design of the S8DS. The test was conducted to determine amplification factors and to redesign the S8DS, if necessary, to minimize these factors. As a result of this test, the reflector support brackets and the drum bearing brackets were redesigned. In addition, the flight safety system for the unmanned reference flight design was determined to be inadequate and is being completely redesigned. The qualification level test verified that these design changes were necessary.

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Figure 38. Installation of SNAP 8 Experimental Reactor (S8ER) for Power Tests

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Figure 39. SNAP 8 Experimental Reactor Performance

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Figure 40. SNAP 8 Developmental Reactor Mockup (S8DRM-1)

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TEST SEQUENCE

S8DRM-1 ASSEMBLY PRIOR TO LOW-LEVEL VIBRATION AND SHOCK SURVEY TEST

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Figure 41. SNAP 8 Nuclear System Environmental Test Program

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C. SNAP 8 DEVELOPMENTAL SYSTEM (S8DS)

The SNAP 8 Developmental System (S8DS) is to be the first test of the unmanned SNAP 8 nuclear system with a power conversion system. The primary objectives of this test are to demonstrate 10,000 hours of power operation, to develop automatic startup and control techniques, and to demonstrate 20 successful automatic startups.

Currently, the S8DS design has been completed and fabrication of components started. The S8DS differs slightly from the unmanned reference flight design in that the safety system has been changed to permit recoverable scram and the reflector assembly has been slightly altered to allow remote removal and replacement of it. Figure 42 shows an artist's concept of the S8DS in its test facility.

D. FUEL ELEMENTS

The performance requirements of the SNAP 8 fuel elements, illustrated in Figures 43 and 44 are:

- 1) Peak power density of 5.5 kwt/ft (for 600 kwt);
- 2) Peak fuel cladding temperatures of approximately 1480°F and peak fuel center-line temperatures of approximately 1580°F;
- 3) Endurance of 10,000 hr;
- 4) Total hydrogen loss from the core limited to 5% in 10,000 hr;
- 5) Peak fuel burnup of 0.4 metal at. %;
- 6) Capability to withstand repeated thermal shocks and thermal cycles;

7) Capability to withstand mechanical shock, vibration, and acceleration due to handling, transportation, launch, and, perhaps, coolant flow; and

8) Goal of 99% reliability in meeting these performance requirements.

The first successful approach to these goals was established with the fabrication and delivery of 211 fuel elements for the S8ER. Many problems were overcome in making the transition from single element fabrication to a repetitive production basis. In addition, a detailed quality assurance procedure was established to control the entire fuel element fabrication.

In general, the characteristics of these fuel elements met or exceeded the specified requirements for the S8ER. This was particularly true of the characteristics of hydrogen retention. The average permeability rate for the 211 fuel elements was one-third of the maximum specified value.

Significant progress in development of the SNAP 8 fuel element has been achieved with respect to the ceramic hydrogen permeation barrier. Preliminary success was established with development of a coating for the S8ER fuel element. Endurance tests on this coating have shown mixed results with some failures in early tests, and the most recent tests are still operating successfully after more than 10,000 hours. Fuel elements containing this coating have also withstood the shock, vibration, and acceleration requirements for the SNAP 8 flight system, and operation of the S8ER core has been successful.

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Figure 42. SNAP 8 Developmental System (S8DS)

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Figure 43. SNAP 8 Fuel Element Concept

A new coating has now been developed which appears to be significantly superior to the one used in the S8ER fuel elements with respect to both endurance at high temperatures and thermal shock. Many tests, including irradiations, have been conducted on this coating with no failures to date. This coating has been adopted for the S8DS fuel elements. Early S8DS developmental fuel elements have shown improved thermal stability over the earlier S8ER elements.

Another area of fuel element development is the design and assembly of the final glass-to-glass seal to form a continuous hydrogen barrier inside the fuel element. The seal design used in the S8ER fuel elements was adequate for hydrogen retention but did not have the positive mechanical retention desired for additional support during shock and vibration. From the research and development program a new configuration

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Figure 44. SNAP 8 Fuel Element Assembly

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has subsequently been established which has shown superior performance to the S8ER design for hydrogen retention. The new closure is electron-beam welded to the cladding tube for positive mechanical retention.

Finally, confirmation of the irradiation stability of the fuel element is needed. A thorough irradiation program is being conducted to obtain the required data necessary before the flight system design is finalized.

In summary, a considerable amount of additional technology has been established since the state-of-the-art used on the S8ER fuel elements. The present plans are to apply this knowledge in the design of an advanced fuel element, and to fabricate a large number of developmental elements according to this design. These elements are being subjected to environmental testing for complete evaluation. The results of these tests will be used to evaluate the S8DS fuel element performance and to guide the design of advanced fuel elements.

E. COMPONENTS

1. Control-Drive Assembly Components

The control-drive assembly for the SNAP 8 nuclear system utilizes a temperature sensor to measure the reactor NaK outlet coolant temperature to determine if it lies between the preset limits. This temperature signal is routed to an electronic temperature switch, where, if it is outside the preset limits, the switch signals the controller. The controller, in turn, determines which control drum to move and its direction, then signals the appropriate actuator. The actuator rotates the control drum through a set of gears which provide the proper control-drum step size. Each of the major control

Figure 45. SNAP 8 Platinum Resistance Temperature Detector

drive assembly components is described in the following paragraphs.

a. Temperature Sensor Assembly

The temperature sensor assembly consists of a temperature sensor and electronic switch. The temperature sensor provides an analog voltage signal to the electronic temperature switch which is proportional to the reactor NaK outlet coolant temperature. The sensor in conjunction with the switch establishes the limits of the reactor deadband and commands the controller to drive the control drums whenever the temperature is outside this deadband.

The reference temperature sensor assembly uses a platinum resistance temperature detector (RTD), as shown in Figure 45, as one leg of a three-wire Sieman's bridge. As the temperature moves through the setpoint, an off-null signal from the bridge is delivered to the control windings of a high-gain magnetic amplifier

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in the electronic switch. This, in turn, controls a bi-stable stage which switches when outside the deadband, signaling the controller to take appropriate action.

Drift testing for stability of RTD's at 1300°F has passed the 5500-hour mark with less than a 2°F temperature setpoint shift as shown in Figure 46. The test data shown has been plotted with the zero adjusted to show the drift after 1000 hours. Test data has shown that 1000 hours is a sufficient time to establish a stable drift characteristic. The only detectors accepted are those which exhibit a drift trend toward increasing resistance, and at a rate less than 0.016 ohm/1000 hr after 1000 hours. (In reference to Figure 46, it should be noted that an increase of RTD resistance causes an equivalent downward shift of temperature setpoint.)

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Figure 46. Resistance Temperature Detector Drift Data
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Two evaluation breadboard temperature switches have been built and tested. One of these units is shown in Figure 47. Testing and operation of these switches to date has been very satisfactory. A circuit diagram and details of operation of the switch have been previously reported.*

*C. E. Johnson, "SNAP 8 Quarterly Progress Report, August through October 1964," NAA-SR-10492 (SRD), p 109-111 (December 23, 1964)

b. Controller

The controller provides properly sequenced outputs to the control-drum actuators which in turn control the reactivity of the reactor. The direction, rate, and order of control-drum rotation is controlled by the state of the input signals to the controller.

The basic design of the controller utilizes magnetic core-transistor logic which permits a reduction of greater than 50% in semiconductor devices as compared to an all-transistor approach. Packaging design of the individual modules has been completed. Each module is encapsulated in an 0.6- by 0.6-in. cup. The design of the packaged assembly has also been completed. The assembly package includes the electronic temperature switch previously described.

The basic design concept of the controller has been successfully demonstrated by a bread-board model constructed from "off-the-shelf" core-transistor logic modules. An extensive irradiation program has been conducted culminating in the selection of transistors which exhibit the best irradiation tolerance. Controller circuits have been built and successfully operated after being irradiated to 2×10^{14} nvt. Irradiation hardened controller modules have been designed and fabricated. Figure 48 shows the components in various stages of fabrication.

A complete flight controller utilizing irradiation hardened core-transistor logic (CTL) modules is being assembled for testing. A test circuit, performing all the functions of a flight controller, containing an oscillator, a shift driver, seven CTL's, and two relay drivers has been built. This test circuit, undergoing life testing, has completed over 2500 hours of continuous operation.

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Figure 47. Electronic Switch Breadboard Model

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Figure 48. Core Transistor Logic Module

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Figure 49. S8DRM-1 Control-Drum Actuator

c. Actuators*

The control drum actuators must rotate and accurately position the reactor control drums in response to signals from the controller. The reactor output is controlled by the position of the control drums. Two basic actuator designs being developed are the 1.8° step actuator (unmanned design) and the 0.5° step actuator (manned design). Both actuators use a gear reduction to obtain the required torque and step accuracy.

The SNAP 8 actuator development is an extension of the earlier actuator development work

performed for the SNAP 10A system. The first actuator in the SNAP 8 development series, the S8DRM-1 (Figure 49), was built and tested successfully. Tests consisted of performance, thermal cycling, shock, vibration, acceleration, and a limited life test. After approximately 1700 hours of life testing at 1000°F and 10^{-6} Torr, the actuators were disassembled for a complete inspection. This inspection revealed the desirability of several minor design changes to improve the structural and mechanical integrity of the actuators.

*S. Giles and A. A. Marcus, "SNAP 8 Control-Drum Actuators," NAA-SR-9645, December 15, 1964

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Figure 50. S8DS 1.8°-Step Actuator, Exploded View

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Figure 51. 1.8°-Step Actuator

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Figure 52. 0.5°-Step Actuator

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The S8DS 1.8° step actuator incorporates these minor design changes. Figure 50 shows an exploded view of the actuator and Figure 51 shows a fabricated actuator without the mounting bracket. These actuators are currently undergoing a test program which includes performance evaluation, temperature and vacuum, shock, acceleration, vibration, irradiation (in a high temperature and vacuum environment as well), and endurance testing up to 10,000 hours. To date, the performance of the actuators has exceeded the design requirements and some have successfully passed vibration and shock testing.

The 0.5° step actuator (Figure 52) is an advanced design which utilizes the same materials, process techniques for insulation, conductors, and bearings, as the 1.8° step actuator. The device is essentially a reluctance stepper which takes a 0.5° step per pulse. Because of its better torque-to-volume ratio, the 0.5° step actuator is especially suited to the small shield envelope desired in the manrated SNAP 8 system.

Four 0.5° step actuators have been fabricated. One unit has been temperature cycled from 70 to 1000° F in a 10^{-6} Torr vacuum at a rate of 10° F/min. Performance was very satisfactory and no detectable dimensional changes were found upon disassembly. Another unit passed a shock and vibration test successfully. Endurance testing of the other units at 1000° F and in a vacuum of approximately 10^{-7} Torr for over 1200 hours has been successful.

d. Bearings and Gears

Bearings are required to support and position the rotating shafts of various reactor components (drums, actuators, etc.). Gears are required

to transmit the actuator torque to the reflector control drums.

The two main requirements of the bearings are accurate positioning of the shaft and low friction. The friction must remain low even after long dwell periods in a space vacuum. The optimum bearing mating material combination was selected after extensive investigation and evaluation.*† Similar programs,*† have led to the selection of dry-film lubricants for use with other material combinations where structural requirements dictate the use of non-optimum combinations, such as on secondary bearing surfaces.

The SNAP 8 DRM-1 control drum bearings, which are typical of the bearings used in the nuclear system, are shown disassembled in Figure 53. The bearing shafts are Inconel-X plated with Al_2O_3 . The ball is made of Inconel-X with a compressed carbon graphite bushing insert. The outer surface of the ball is plated with Al_2O_3 and coated with MoS_2 , a dry-film lubricant. The ball socket is also of Inconel-X coated with Al_2O_3 on the race surface. The primary bearing surface is Al_2O_3 (shaft) against carbon graphite (bushing). The secondary bearing surface, Al_2O_3 coated with MoS_2 (ball) against Al_2O_3 (socket), allows for control drum misalignment due to differential thermal expansion.

Bearings of this configuration have been successfully tested through shock, vibration, acceleration, thermal cycles, and endurance testing for over 4500 hours at 1100° F and in vacuums harder than 10^{-6} Torr.

In both the manned and unmanned control drive assemblies, the actuator driving torque

*L. G. Kellogg, "SNAP Reactor Materials Development, Self-Weld Studies," NAA-SR-9643 (CRD), June 1, 1964.

†L. G. Kellogg, "SNAP Reactor Materials Development, Ultrahigh Vacuum Friction Studies," NAA-SR-9644 (CRD), June 8, 1964.

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Figure 53. S8DRM-1 Control-Drum Bearings

is transmitted to the control drum by a single set of spur gears. The gears provide a mechanical advantage to the actuator output. They also reduce the holding torque which the actuator brake must apply to hold the control drum position during space flight maneuvers.

In a space environment, metal surfaces become "super clean" and the contact of two such metal surfaces at high temperature and loading results in selfwelding or adhesion. To prevent selfwelding, a dry-film lubricant is applied on the gear teeth. Gear endurance tests are in progress (over 3500 hours) at 10^{-7} to 10^{-8} Torr, 1150°F , and a 40-psi nominal load. In addition, gears have passed all the mechanical environments of shock, vibration, and acceleration successfully.

e. Cable Harness

No discussion of the control drive assembly would be complete without a description of the cable harness which is used to transmit the electrical signals from the payload components to the reactor components. The type of cable harness used to connect the payload components is essentially off-the-shelf, low-temperature wiring. The cable harness used in the vicinity of the reactor differs in that it must withstand high temperature and high irradiation as well as the vacuum of space.

The high-temperature cable material selected is a stainless-steel-clad copper wire with a silicone-sized type-S glass fiber insulation. The reference flight system will utilize an all-welded cable harness.

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The cabling has completed temperature and vacuum, shock, and vibration testing successfully and has withstood irradiation in a high temperature-high vacuum environment successfully with essentially no deterioration of the insulation.

2. Shield

Men and electronic devices must be protected from the radiation environment of the SNAP 8 reactor. This is accomplished by shielding. For ground applications, lead and concrete are normally used; however, for space applications, shielding materials are chosen to achieve maximum protection with minimum weight; i. e., mainly on the basis of high removal cross section per unit density.

For unmanned applications, the major shield requirement is neutron attenuation to protect the electronic components. For manned applications, however, both the neutrons and gammas must be highly attenuated. The primary objective in either application is to accomplish the required shielding with minimum weight. One material for effective neutron attenuation which meets this requirement and, hence, is used extensively in shields for space applications, is lithium hydride (LiH).*

The practicability of fabricating large shield assemblies, up to 1000 lb, by casting the lithium hydride material directly in a shield casing

has been demonstrated. A method of stabilizing the LiH to control and orient internal cracking has been developed and demonstrated. Typical unmanned shields have been cast with both single and double regions of LiH. These assemblies have successfully withstood thermal cycling, shock, and vibration testing.

Shields for manned applications require an effective gamma attenuator as well as a neutron attenuator. Various high density materials, such as alloys of depleted uranium and tungsten and lead oxide, are being evaluated for this application. The feasibility of placing tungsten aggregate at selected locations within a cast LiH shield has been successfully demonstrated on a laboratory scale. A test mockup of a manned shield, with the NaK coolant pipes routed within the LiH and with a tungsten aggregate gamma shield integrally cast in the LiH, has been designed and is being fabricated. The placement of the NaK pipes within the shield is required to minimize the scattering of neutrons to the payload area.

An analytical method has been developed for optimizing the dimensions of the gamma shielding of a laminated shield configuration. (Up to 80% by weight of the shielding materials may be required for gamma shielding.) This technique permits an analytically rigorous evaluation of various gamma shield materials for a manned shield design.

*F. H. Welch, et al., "Lithium Hydride Technology I. Properties of Lithium Hydride and Corrosion Studies," NAA-SR-9400 (CRD), May 8, 1964

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V. SUMMARY

The SNAP 8 nuclear system can be adapted for either manned or unmanned application. The two designs use the same basic components and differ only in reflector assembly and shield assembly configuration. The operating characteristics of each design are essentially the same. The reliability goal of the manned system, however, is higher: >99% for the manned system compared to ~97% for the unmanned system.

The reactor assembly (core and reflector assemblies) for each application has a design weight objective of 600 lb. The reference unmanned system shield weighs 1930 lb while a typical manned shadow shield concept weighs 5135 lb.

Optimization of the SNAP 8 nuclear system for manned application is in progress. A conceptual design of a shadow-shielded manned system, as described in the report, shows a significant weight advantage (30% decrease in shield weight using the manned reactor) and no performance penalty. A similar study using a 4π -shielded manned system has just started.

Preliminary indications show that though the 4π -shielded system is heavier, the concept is practical. The results of the 4π -shield study now in progress and the shadow-shield study described in this report will be combined to provide a unified design which can be used with either a 4π shield or a shadow shield. Any weight or performance penalties of the unified design will be assessed; however, no significant penalties are anticipated.

The SNAP 8 nuclear system is based upon extensive component, fuel element, and system development programs. Successful long-term power operation (1 year above 400 kw with a 1300°F NaK outlet temperature) has been demonstrated by the S8ER; while the S8DRM-1 has demonstrated the ability of the basic design to withstand a simulated launch environment. The results of these reactor tests, in addition to numerous component and fuel element tests, provide high confidence that the SNAP 8 reactor can operate reliably at 600 kw, 1300°F for at least 1 year. Further development should extend this reliable operating life to approximately 5 years.

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APPENDIX A NUCLEAR SYSTEM DESIGN SUMMARY

1. REFERENCE UNMANNED SNAP 8*

Reactor Design		Nuclear Parameters	
Fuel Elements		Average thermal neutron flux <1 ev, n/cm ² -sec	3 x 10 ¹²
Number	211	Median fission energy, ev	0.21
Fuel alloy, wt % U in Zr	10.5	Mean prompt neutron lifetime, μ -sec	8.4
Uranium enrichment, at. % U ²³⁵	93.15	Uranium loading, kg U ²³⁵	7.65
Degree of hydriding, N _H , 10 ²² a/cm ³	6.05	Hydrogen reactivity worth, % Δ k/k	0.50
Fuel rod diameter, in.	0.530	per % Δ H/H	
Active fuel length, in.	16.825	Volume fractions in core	
Fuel element length, in.	17.145	Fuel	0.782
Cladding material	Hast-N	Cladding	0.061
Cladding ID, in.	0.540	NaK	0.123
Cladding thickness, in.	0.010	Ceramic	0.013
Ceramic barrier material	SCB	Void	0.021
Ceramic barrier thickness, in.	0.002	Radial peak to average power	1.22
Diametral hydrogen gap, in.	0.006	Axial peak to average power	1.44
Source		Average power density, watts/cc	36.6
Type	Po-Be	Reliability Goals, %	
Strength, curies	0.1	Overall	96.85
Location	top head of vessel	Core assembly	98.96
Internal Reflectors		Reflector assembly	98.50
Composition	BeO	Shield assembly	99.97
Cladding material	316 SS	Safety assembly	99.44
Cladding thickness, in.	0.030	Cumulative Probability of Success	
Inlet Plenum Grid Plate		Through launch	99.74
Material	Hast-C	Through startup	98.87
Thickness, in.	0.650	Through 10,000 hours	97.23
Diameter, in.	9.186	Complete mission	96.85
Number of coolant holes	372	Nonpuncture probability	99.9
Diameter of coolant holes, in.	0.156	Control System Parameters	
Pitch of coolant holes, in.	0.570	Single control drum worth, % Δ k/k	2.4
Outlet Plenum Grid Plate		Full-in drum position, degrees	0
Material	316 SS	Full-out drum position, degrees	154
Thickness, in.	0.850	Drum movement per step, degrees	0.26
Number of coolant holes	372	Maximum drum rotation rates, degrees/sec	
Diameter of coolant holes, in.	0.156	Startup drums (simultaneous motion)	0.086
Pitch of coolant holes, in.	0.570	Control drums	0.053
Coolant		Maximum differential drum worth, ϵ /degree (nominal shim)	5.2
Material	NaK-78	Kinetic Parameters	
Melting point, °F	12	Number of delayed neutron groups	6
Core Vessel		Decay constants, sec ⁻¹	
Material	316 SS	λ_1	0.0124
Internal diameter, in.	9.214	λ_2	0.0305
Thickness, in.	0.105	λ_3	0.111
Length, in.	26.24	λ_4	0.301
Distance between grid plates, in.	17.224	λ_5	1.13
Reflector Control Elements		λ_6	3.0
Material	Be	Effective delayed neutron fraction	0.0080
Number of startup drums	3	Group delayed fractions	
Number of long-term control drums	3	α_1	0.0329
Total number of drums	6	α_2	0.2194
Radius of curvature of drums, in.	4.5	α_3	0.1960
Nominal thickness of drums, in.	3.125	α_4	0.3947
Shimming capability, in.	+1.5, -1.0	α_5	0.1150
Envelope, drums full out, in.	27.6	α_6	0.0419
Overall length, in.	18.5	Transport delay times (@ 35 kwe), sec	
Drum length, in.	15.375	Nuclear system to boiler	1.0
Reactor Parameters		Boiler	6.8
Design Operating Conditions		Boiler to nuclear system	4.5
Reactor thermal power, kwt	600	Nuclear system	1.7
Net electrical power, kwe	35 (@ 470 kwt)	Typical Shield Parameters	
Coolant inlet temperature, °F	1100	Instrumented Payload Dimensions	
Coolant outlet temperature, °F	1300	Diameter, ft	20
Coolant flow rate, lb/sec	13.6	Axial distance from reactor core center, ft	40
Operating pressure, psia	45	Shield Materials	
Core pressure drop, psi	4.8 (@ 600 kwt)	Cladding	347 SS
Maximum hot spot fuel temperature, °F	1520	Gamma	W
Maximum hot spot cladding temperature, °F	1430	Neutron	LiH
Operating lifetime, hr	10,000	Shield Dimensions	
Peak heat flux, Btu/hr-ft ²	~100,000	Overall shield length, in.	34.3
NS pressure drop, psi	<8 (@ 600 kwt)	Neutron shield thickness, in.	33.3
Reactivity Requirements, % Δ k		Gamma shield thickness, in.	1.0
Xenon	-0.9	Maximum diameter of conical shield, in.	51.5
Samarium	-0.9	Minimum diameter of conical shield, in.	39.2
Burnable poison (Sm ₂ O ₃)	+2.5	Radiation Levels Due to Reactor Sources	
Fission product poisons	-0.7	Fast neutron dose at payload, nvt	1 x 10 ¹¹
U ²³⁵ burnup	-0.5	Gamma dose at payload, rads (C)	1 x 10 ⁶
Temperature and power	-1.7	Shield Assembly Weight	
Hydrogen redistribution	-0.4	Neutron shield, lb	1365
Hydrogen loss	-1.6	Gamma shield, lb	115
Contingency	-2.4	Shield vessel and structure, lb	450
Cold, clean excess reactivity	+6.6	Total shield assembly weight without armor, lb	1930
Total control drum worth	13.1		
Shutdown margin	6.5		
Temperature Coefficients, ϵ /°F (at design power level)			
Spectrum	-0.01		
Axial expansion	-0.048		
Upper grid plate	-0.026		
Lower grid plate	-0.019		
Reflector (prompt, lower plenum)	-0.04		
Reflector (prompt, upper plenum)	-0.04		
Total isothermal (@ 1200° F)	-0.20		
Total isothermal (@ room temperature)	-0.15		

*This summary updated in each SNAP 8 Quarterly Progress Report

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APPENDIX A
(CONTINUED)

2. REFERENCE MANRATED SNAP 8

Reactor Design			
Fuel Elements			
Number	211	Burnable poison (Sm_2O_3)	+2.5
Fuel alloy, wt % U in Zr	10.5	Fission product poisons	-0.7
Uranium enrichment, at. % U^{235}	93.15	U^{235} burnup	-0.5
Degree of hydriding, NH , 10^{22} a/cm ³	6.05	Temperature and power	-1.7
Fuel rod diameter, in.	0.530	Hydrogen redistribution	-0.4
Active fuel length, in.	16.825	Hydrogen loss	-1.6
Fuel element length, in.	17.145	Contingency	-2.4
Cladding material	Hast-N	Cold, clean excess reactivity	+6.6
Cladding ID, in.	0.540	Total control drum worth	13.1
Cladding thickness, in.	0.010	Shutdown margin	6.5
Ceramic barrier material	SCB	Temperature Coefficients, $^{\circ}\text{F}$ (at design power level)	
Ceramic barrier thickness, in.	0.002	Total isothermal (at 1200 $^{\circ}\text{F}$)	-0.20
Diametral hydrogen gap, in.	0.006	Total isothermal (at room temperature)	-0.15
Internal Reflectors		Nuclear Parameters	
Composition	BeO	Average neutron flux <1 ev, n/cm ² -sec	3×10^{12}
Cladding material	316 SS	Median fission energy, ev	0.21
Cladding thickness, in.	0.030	Mean prompt neutron lifetime, μ -sec	8.4
Inlet Plenum Grid Plate		Uranium loading, kg U^{235}	7.65
Material	Hast-C	Hydrogen reactivity worth, % Δk /per % $\Delta \text{H}/\text{H}$	0.50
Thickness, in.	0.650	Volume fractions in core	
Diameter, in.	9.186	Fuel	0.782
Number of coolant holes	372	Cladding	0.061
Diameter of coolant holes, in.	0.156	NaK	0.123
Pitch of coolant holes, in.	0.570	Ceramic	0.013
Outlet Plenum Grid Plate		Void	0.021
Material	316 SS	Radial peak to average power	1.22
Thickness, in.	0.850	Axial peak to average power	1.44
Number of coolant holes	372	Average power density, watts/cc	36.6
Diameter of coolant holes, in.	0.156	Reliability Goal, %	>99
Pitch of coolant holes, in.	0.570	Typical Shadow Shield Parameters	
Coolant		Payload Dimensions	
Material	NaK-78	Diameter, ft	60
Melting point, $^{\circ}\text{F}$	12	Axial distance from reactor core center, ft	150
Core Vessel		Shield Materials	
Material	316 SS	Cladding and structure	347 SS
Internal diameter, in.	9.214	Gamma	Depleted U
Thickness, in.	0.105	Neutron	LiH
Distance between grid plates, in.	17.224	Shield Dimensions	
Reflector Control Elements		Top half	
Material	Be	Gamma shield thickness, in.	3.5
Number of drums	8	Neutron shield thickness, in.	20
Nominal thickness of drums, in.	3.125	Gallery thickness, in.	24
Reactor Parameters		Bottom half	
Design Operating Conditions		Gamma shield thickness, in.	2.5
Reactor thermal power, kwt	600	Neutron shield thickness, in.	19
Coolant inlet temperature, $^{\circ}\text{F}$	1100	Large diameter, in.	47
Coolant outlet temperature, $^{\circ}\text{F}$	1300	Radiation Dose (RBE of 10 for neutrons), mrem/hr	
Coolant flow rate, lb/sec	13.6		1.5
Operating pressure, psia	45	Shield Weight	
Core pressure drop, psi	<4.8 (at 600 kwt)	Top half	
Maximum hot spot fuel temperature, $^{\circ}\text{F}$	1520	Gamma shield, lb	440
Maximum hot spot cladding temperature, $^{\circ}\text{F}$	1430	Neutron shield + structure, lb	615
Operating lifetime, hr	>10,000	Bottom half	
Peak heat flux, Btu/hr-ft ²	-100,000	Gamma shield, lb	2760
Reactivity Requirements, % Δk		Neutron shield + structure, lb	1320
Xenon	-0.9	Total	5135
Samarium	-0.9		

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APPENDIX B
NUCLEAR SYSTEM WEIGHT SUMMARY

1. REFERENCE UNMANNED SNAP 8*

<u>Item</u> [†]	<u>wt-lb</u>
Fuel elements	194
Core vessel and structure	77
Reflector and reflector structure	172 [§]
Control drum drive mechanisms	62
NaK piping	10
NaK	29
Wiring and sensors	20
Miscellaneous and contingency	<u>36</u>
Total	600 lb

* These weights are updated in each SNAP 8 Quarterly Progress Report.

† For more detailed breakdown see the latest SNAP 8 Quarterly Progress Report.

§ Additional 78 lb if fully shimmed.

2. REFERENCE MANRATED SNAP 8

<u>Item</u>	<u>wt-lb</u>
Fuel elements	194
Core vessel and structure	80
Reflector and reflector structure	165
Control drum drive mechanisms	90
NaK piping	10
NaK	28
Wiring and sensors	20
Miscellaneous and contingency	<u>13</u>
Total	600 lb

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APPENDIX C
NUCLEAR SYSTEM ENVIRONMENTAL CRITERIA*
MANNED OR UNMANNED SYSTEM

Environment	Ground Handling and Prelaunch*	Launch†	Orbit§															
1. Pressure	External pressures: sea level to 50,000 ft with maximum change ±1.25 psi/min.	External static pressure envelope as a function of time. (To be determined)	External pressure: 10 ⁻¹² mm Hg															
2. Temperature	+50 to +160°F	-	-															
3. Humidity	a. Protected during shipment and storage (RH < 70%)* b. During vehicle integration: 6 hr at 65% RH and 106 °F; 6 hr of decreasing temperature to 91 °F and increasing RH to 100%; 8 hr of decreasing temperature to 81 °F with release of 4.4 grains H ₂ O/ft ³ ; 4 hr of increasing temperature to 106 °F and decreasing RH to 50%	-	-															
4. Rain	a. Protected during shipment and storage b. During vehicle integration: Anticipated precipitation <table><tr><td>Rate (in. /hr)</td><td>Amount (in.)</td><td>Time</td></tr><tr><td>0.6</td><td>7.1</td><td>12 hr</td></tr><tr><td>6</td><td>0.5</td><td>5 min</td></tr><tr><td>12</td><td>0.2</td><td>1 min</td></tr><tr><td>0.34</td><td>4.0</td><td>12 hr</td></tr></table>	Rate (in. /hr)	Amount (in.)	Time	0.6	7.1	12 hr	6	0.5	5 min	12	0.2	1 min	0.34	4.0	12 hr	-	-
Rate (in. /hr)	Amount (in.)	Time																
0.6	7.1	12 hr																
6	0.5	5 min																
12	0.2	1 min																
0.34	4.0	12 hr																
5. Sand and dust	a. Protected during shipment and storage b. Applicable components tested with 140-mesh silica flour for 3 hr at 77 °F and RH < 30%; sand and dust density, 0.1 to 0.25 grams/ft ³ , with air velocity = 2500 ± 500 ft/min	-	-															
6. Salt spray	a. Protected during shipment and storage b. Applicable components tested to demonstrate ability to withstand exposure to salt spray for 6 wk as experienced at coastal regions of continental U.S.A.	-	-															
7. Fungus	Applicable components tested per MIL-E-52720(ASG), Fungus Resistance Tests, Procedure 1.	-	-															
8. Shock	Drop of 18 in. measured at either a corner or a surface, onto a concrete surface.	System Three shocks of 18 g's in each of 3 mutually perpendicular axes (18 total) of one of the following pulses: a. Triangular pulse 10 msec b. Half-sine pulse 8 msec c. Rectangular pulse 5 msec Component: Three shocks of 35 g's in each of 3 mutually perpendicular axes (18 total) of one of the following pulses: a. Triangular pulse 10 msec b. Half-sine pulse 8 msec c. Rectangular pulse 5 msec	Nonoperating††: capable of withstanding 3-g shocks on each of 3 mutually perpendicular axes at one of the following wave forms: a. Triangular pulse 10 msec b. Half-sine wave pulse 8 msec c. Rectangular pulse 5 msec Operating: withstand 3-g peak, half-sine wave pulse of one msec at mounting interface															

*These criteria are updated in each SNAP 8 Quarterly Progress Report.

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APPENDIX C (CONTINUED)

Environment	Ground Handling and Prelaunch*	Launch†	Orbit§
9. Vibration	Sweep applied to transportation container on 3(30-min log) mutually perpendicular axes: 2 to 5 cps at 1 in. double amplitude; 5 to 27.5 cps at 2-g peak; 27.5 to 43.5 cps at 0.0517 in. double amplitude; 43.5 to 500 cps at 5-g peak; then a 5-min dwell at each resonant frequency noted at above amplitude	<p>System</p> <p>Sweep from 5 to 16 cps at 0.368 in. double amplitude and 16 to 2000 cps at 5-g peak on each of 3 mutually perpendicular axes; then 5-min dwell at each major resonant frequency at the above amplitude</p> <p>Component</p> <p>16 to 100 cps at 6-g peak; 100 to 180 cps at 0.0118 in. double amplitude; 180 to 2000 cps at 19-g peak; then dwell at 1/2 above amplitude for 5 min at each major resonant frequency</p> <p>Random Vibration - Components</p> <p>A random vibration sweep test over a frequency interval of 20 to 2000 cps for 5 min in each of 3 mutually perpendicular axes according to the following schedule:</p> <p>20 to 200 cps at +2 db/oct 200 to 700 cps at 0.64 g²/cps 700 to 900 cps at -17.5 db/oct 900 to 2000 cps at 0.15 g²/cps</p>	Capable of withstanding vibrations of 0.25-g peak over a frequency of 5 to 2000 cps for 5 min at the NS mounting interface
10. Wind	Withstand steady-state wind force of 54 mph with wedge-shaped gusts of 75 mph	-	-
11. Storage life	Two years (except source)	-	-
12. Radio frequency generation and interference	-	Designed and tested to MIL-STD-826 (USAF) dated 20 January 1964	Designed and tested to MIL-STD-826 (USAF) dated 20 January 1964
13. Acoustic noise	-	Total integrated sound pressure level of 148 db, Re 0.0002 microbar over a specific frequency spectrum	-
14. Acceleration	-	Longitudinal axis: +7 g for 5 min, -3 g for 5 min; lateral and normal axes: ±4.5 g for 5 min	Operating: +1 g along axis of symmetry and ±1/4 g radially including rotational effects Nonoperating:†† +3-1/2 g along longitudinal axis in combination with ±1 g on any lateral axis for a period of time less than 5 min
15. Magnetic fields	-	-	To be determined
16. Gravitational fields	-	-	To be determined
17. External radiation	-	-	To be determined

*Environment to which the nuclear system may be subjected without any detrimental effects during shipment from Atomics International up to the time of encapsulation in the launch vehicle nose cone

†Environment to which the nuclear system may be subjected without any detrimental effects after exposure to the ground handling and prelaunch environment up to the time of separation from the launch vehicle

§Environment to which the nuclear system may be subjected without any detrimental effects after exposure to the launch environment

**RH = Relative humidity

††Nonoperating: Defined as prohibiting operation of the reflector-control system; i. e., control drums are held stationary

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APPENDIX D
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