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TECHNICAL BRIEFS, PART 4, SNAP 8

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SNAP (SYSTEMS FOR NUCLEAR AUXILIARY POWER)

TECHNICAL BRIEFS, PART 4, SNAP 8

(Title Unclassified)

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Frontispiece: SNAP 8 Nuclear System

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I. TECHNICAL DESCRIPTION AND DEVELOPMENT OBJECTIVES

"The SNAP-8 Electric Power Generation System will provide power for advanced space missions, such as lunar stations or orbiting space platforms, and for interplanetary communications. In addition, SNAP-8 may provide an early electrical propulsion capability. It is also designed to provide some advanced technology which will be required for higher powered nuclear electric systems in the megawatt range."*

The SNAP 8 Electrical Generating System (EGS) utilizes a Nuclear System (NS) and a Power Conversion System (PCS). The NS consists of a uranium-zirconium hydride (U,Zr)H_x, reactor cooled by eutectic sodium-potassium alloy (NaK). The nuclear system is coupled to a power conversion system (PCS) which utilizes a mercury Rankine cycle turboalternator. The NS includes the reactor and its controls, shield, and safety devices and the PCS includes the complete mercury system, all the primary NaK system except the NS, a heat rejection system, all associated pumps and heat exchangers, and controls necessary for extended use in space.

SNAP 8 is being developed jointly by the Atomic Energy Commission (AEC) and the National Aeronautics and Space Administration (NASA). The AEC is responsible for the nuclear system (NS) and for nuclear ground testing of the complete EGS. NASA is responsible for the PCS and the spacecraft, for non-nuclear testing of the EGS, and for flight testing. The NASA schedule currently is planned for the first flight test in calendar year 1967.

This report covers on the NS of the SNAP 8 program. The NASA is currently reviewing the PSC and overall system objectives; however, these are not currently available.

A. OBJECTIVES

1. Overall System

The SNAP 8 EGS will be designed to produce a minimum of 35 kw of electrical power, as measured for the spacecraft load switch for 10,000 hr.

The EGS will be designed for initial startup in orbit upon ground command. (That is, restart capability in orbit is not a requirement.)

*Statement of President Kennedy, "Report to the Congress from the President of the United States," included in the report "United States Aeronautics and Space Activities 1962," January 28, 1963, Chapter III, p 27.

The EGS will be designed to operate unattended for 10,000 hr in a space environment. It also will be designed to withstand launch environment along with normal ground transportation and handling environments.

2. Reactor and Shield (Nuclear System)

In addition to the overall system objectives described above, the SNAP 8 NS will be designed to meet the following specific performance objectives:

- a) Power — After startup the NS will operate at a nominal constant level between 300 and 600 kw of thermal power with reactor outlet temperature of 1300°F.
- b) Life — The NS will be designed for continuous unattended full power operation of 10,000 hr in a space environment.
- c) Startup — The NS will be designed for automatic startup in space upon receipt of a ground command signal. Restart capabilities in space are not required; however, restart capability for ground test development operation will be required.
- d) Shutdown — The NS will be designed for automatic shutdown in space upon end of useful life and will be designed to disassembly upon re-entry into the earth's atmosphere.
- e) Weight — The NS, excluding the shield assembly, weight objective is 500 lb. The current reference weight objective for the shield is 1100 lb.
- f) Shielding* — The shield is currently designed to limit the total direct integrated neutron dose in an 8-ft circle located in a plane 15 ft from the bottom of the active core to 5×10^{12} nvt and to limit the total integrated direct gamma dose at the same location to 9×10^6 rads (C). It is assumed that the direct dose plus the scattered dose at the payload will be 10^{13} nvt and 10^7 rads of gammas.

B. DESCRIPTION

Figure 1 is a photograph of the SNAP 8 NS full scale model built to the reference flight design drawings. Only the top of the neutron shield is shown on this model.

*This specification is expected to change as a result of the current NASA review of the overall SNAP 8 program.

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Figure 1. SNAP 8 Reactor Model

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1. Core

The SNAP 8 reactor core contains 211 fuel elements made of Zr - 10.5 wt % U alloy hydrided to a hydrogen content of 6×10^{22} hydrogen atoms/cc of $(U-Zr)H_x$. The uranium is 93.15% enriched and the elements are clad in 10 mil wall Hastelloy-N tubing coated internally with a hydrogen permeation barrier. The active length of the fuel element is 16.5 in.

The core vessel is a 9.214 in. ID cylinder of Type 316 stainless steel. The coolant inlet nozzle is located in the side of the inlet plenum head while the outlet coolant nozzle is located in the center of the outlet plenum head. Besides the fuel elements, the core vessel contains an upper and lower grid plate to position the fuel elements and a flow baffle plate to provide proper coolant flow distribution. Internal reflector elements made of beryllium oxide (BeO) clad in stainless steel fill in the space between the hexagonal array of fuel elements and the cylindrical core vessel as shown in Figure 2.

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Figure 2. SNAP 8 Reactor Core

The reflector control mounting brackets and positioning lugs are attached to the outside of the core vessel. The core vessel is attached to the shield assembly by a Marman clamp which is opened when the reflector control assembly is jettisoned upon shutdown of the nuclear system.

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2. Reflector Control Assembly

The reflector control assembly is made in two halves so that it completely surrounds the cylindrical portion of the core vessel. Each half is composed of a stationary beryllium section, three movable beryllium drums, drive motors, gears, and necessary supporting plates and brackets. The nominal beryllium thickness is 3 in. Each drum has its own drive motor. Three of the six drums are used only for startup, and are driven in and locked in the in position by low temperature, externally commutated dc motors. The other three drums are used for the long-term active control and are driven by bidirectional high temperature stepper motors. A startup programmer and long-term controller, located in an instrument compartment which has a radiation and temperature controlled environment, are provided to achieve proper operational sequence of drum rotation. The outlet coolant temperature controls and is measured by a temperature sensor-switch. The reactor is controlled on coolant outlet temperature. No neutron detectors are used in the control system.

3. Shield Assembly

The shield assembly is designed to be a major structural component transmitting the core and reflector assembly loads through the shield vessel wall to a mounting ring located on the bottom of the shield.

The shield is composed of two parts, one a gamma shield and the other a neutron shield. The gamma shield is a 0.85-in. thick plate of tungsten (W) located directly beneath the core vessel lower plenum. The 28-in. thick neutron shield is a two-region shield. The region nearest the reactor, approximately 10 in. thick, contains 99.99% lithium⁷-hydride (Li^7H) while the region located below contains natural lithium hydride (LiH). Lithium⁷-hydride is used to reduce neutron heating of the shield by approximately a factor of 10 and thus prevent the LiH from melting.

II. BASIS FOR SELECTION OF CURRENT APPROACH

A. OVERALL REACTOR CONCEPT

The SNAP 8 reactor concept is based on the technology developed for the SNAP 2/10A reactor systems. The basic philosophy underlying most SNAP 8 design decisions is the desire to develop a reactor system with minimum changes in the SNAP 2/10A concept. There is also a continual effort to reduce the complexity of the system for reliability considerations. The achievement of a minimum size and weight system is, therefore, somewhat tempered by the desire for high reliability.

The net result is a thermal reactor operating at 1300°F outlet coolant temperature, using conventional nonrefractory construction materials and utilizing a simple control scheme.

B. FUEL, CORE AND REFLECTOR DIMENSIONS

A detailed parameter study was made early in the SNAP 8 program to determine the "trade-offs" associated with various approaches to the reactor design. The results of this study established many of the present design parameters.

The selection of the fuel rod diameter involves the conflicting aspects of heat transfer area, neutron economy and fabrication. Large fuel rods are desirable for ease of fabrication and to maximize the fuel volume fraction in the core, thus minimizing the core volume. On the other hand, small rods provide improved heat transfer which minimizes fuel temperatures, cladding temperatures, and fuel thermal stresses. The selected diameter of 0.560 in. represents a compromise which will provide adequate heat transfer area without imposing undue fabrication problems.

The fuel composition of 10 wt % uranium in zirconium hydrided to an N_H of 6.0×10^{22} hydrogen at./cc also represents a compromise between conflicting aspects. A high uranium and hydrogen content are desirable from a nuclear standpoint, but there are mechanical, reactivity lifetime, and thermal limitations to practical achievement. The relative reactivity worth of uranium decreases as additional uranium is added to the fuel and the alloy becomes difficult to fabricate at about 15 to 20 wt %. The dissociation pressure of hydrogen in the fuel matrix increases exponentially with hydrogen content and temperature. At a

given temperature, there is an upper limit to the amount of hydrogen which can be contained by the fuel element cladding.

The basic parameter studies showed that, for the selected core composition, the desired excess reactivity, and the required reactivity control capability, a minimum weight reactor should be about 9 in. in diameter and 14 in. long. Thus, the core configuration (selected about two years ago) contains 211, 0.56 in. OD fuel elements in a 9.214 in. ID core vessel. During the past two years, the fuel element cladding and core diameters have not changed, but the fuel length has increased to 16.5 in. for the present reference design. The increased active core length was necessitated due to reactivity losses after the $(U,Zr)H_x$ fuel rods were made about 6 mils smaller in diameter in order to compensate for irradiation swelling. Also, the SNAP 8 Experimental Reactor (S8ER) critical experiments indicated that the reactivity calculations were slightly low.

The reflector dimensions also originated in the basic parameter studies and have remained relatively unchanged throughout the program. The six control drums are designed to have a ± 1 in. variation in thickness to compensate for manufacturing tolerances, calculational errors, and unforeseen reactivity perturbations.

C. MATERIALS SELECTION

1. Fuel Moderator

A homogeneous mixture of $(U,Zr)H_x$ was selected as the SNAP 8 fuel material because of its excellent moderating properties due to the contained hydrogen, its fast acting, negative temperature coefficient due to homogeneously mixing the fuel into the moderator, and its established technology from the SNAP 2/10A reactor. A small (~ 0.2 wt %) amount of carbon was added to the fuel material to reduce the problem of fuel rod cracking during the hydriding process.

Other fuel materials, notably yttrium hydride, were investigated for possible use for SNAP 8. Yttrium hydride has a low dissociation pressure at SNAP 8 operating conditions, but was rejected because of its low hydrogen content ($\sim 4 \times 10^{22}$ at./cc) and higher absorption cross section which would necessitate an increase in the size and weight of the reactor. An increased development program would also have been required.

2. Hydrogen Barrier

A ceramic coating is placed on the inside of the fuel element cladding to inhibit the rate of hydrogen loss from the fuel element cladding by about a factor of 10^3 as shown in Figure 3. The SNAP 2/10A reactors use Solaramic S14-35A for this purpose and initially it was planned to use this coating for SNAP 8. During the course of the SNAP 8 development, however, it became apparent that Solaramic would not adhere to the cladding metal for 10,000 hr at the higher SNAP 8 temperatures. Therefore, a higher temperature coating (AI-8763D) was developed and used in the S8ER fuel elements. Coatings with even better temperature stability are being developed for use on subsequent SNAP 8 reactors.

3. Fuel Element Cladding

Hastelloy-N has a relatively low coefficient of thermal expansion which matches well with the fuel and ceramic coating materials. It has good strength and corrosion resistance at the temperatures of interest and is available in the form of thin-walled tubing. The ceramic coatings adhere well to chromized Hastelloy-N and fabrication is not difficult.

4. Coolant

NaK-78 was selected because of its good heat transfer characteristics, well established technology, and low (12°F) melting point to ease orbital startup.

5. Internal Reflectors

Beryllium oxide internal reflector pieces occupy the space between the hexagonal fuel element array and the circular core vessel. BeO is used in SNAP 8 instead of beryllium to eliminate the uncertainties of the high temperature compatibility of beryllium with stainless steel and Hastelloy-N. The BeO internal reflectors for the S8ER are clad in Hastelloy-N to match the thermal expansion of the fuel elements. A modification in the internal core structure of the reference design will permit the use of stainless steel as the BeO cladding material on subsequent reactors.

6. Core Vessel

The core vessel is made of 316 stainless steel because of the strength, corrosion resistance, availability, and relative ease of fabrication of that metal.

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Figure 3. Hydrogen Permeability of Typical Metals and Hydrogen Barrier Materials

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7. Reflectors

Reactor grade beryllium is used for the external reflectors because it has low weight, excellent neutron reflecting properties and adequate strength for use as a structural member.

8. Upper Grid Plate

The upper (outlet) grid plate is made of 316 stainless steel since its high coefficient of thermal expansion acts to provide an additional prompt negative power coefficient of reactivity.

9. Lower Grid Plate

The lower (inlet) grid plate is made of Hastelloy-C. This alloy has a relatively low coefficient of thermal expansion which reduces the delayed negative power coefficient and thus tends to increase reactor stability.

D. CONTROL REQUIREMENTS

An automatic startup and control system is required to bring the reactor from its subcritical (launch) configuration to full power. The system must compensate for short-term reactivity transients due to temperature, xenon and hydrogen redistribution within the fuel elements.

Active control is used throughout life to compensate for reactivity changes due to fission product poisons, fuel burnup, hydrogen loss, and load changes. Burnable poison, samarium oxide (Sm_2O_3), is used to reduce the overall reactivity swing. The magnitude and uncertainty of the reactivity losses make it impossible to use only burnable poisons without active control.

E. REFLECTOR CONTROL SYSTEM

1. Reflector Control

Small, compact reactors show a very high rate of neutron leakage (e.g., about 38% of all fission neutrons born in SNAP 8 leak from the system). It is, therefore, possible to obtain excellent reactivity control by means of varying the amount of reflector around the reactor. The present 6-drum control scheme provides about 14% $\Delta k/k$ in reactivity control. The use of control drums instead of control rods simplifies the system since there are no penetrations into the core for control rods. The length and weight of the reactor are also reduced.

2. Startup Control

For reliable orbital startup, the ultimate in simplicity is required. Since the kinetic behavior of the system is fairly well understood, and will be verified in the SNAP 8 Development System (S8DS) described below, a timed reactivity insertion technique is used. The control drums are moved in rapidly (increasing reactivity) during the initial subcritical phase of startup. The reactivity insertion rate is reduced as the reactor becomes critical and comes to temperature. The slow reactivity insertion rate and the negative temperature coefficient of reactivity limit the magnitude of the power transient which occurs during startup. The reactor startup time is ~ 3 hr.

3. Long-Term Control

Probably the simplest and most reliable form of long-term control is a "deadband" control of reactor outlet temperature. If the reactor outlet temperature exceeds the desired setpoint by more than 30°F , the reflector control drums are moved out decreasing reactivity and temperature. If the outlet temperature drops, the control drums move in to increase system reactivity. This long-term control scheme is used to control the reactor during PCS startup and load changes. It will be noted that this is a relatively simple and reliable control concept. The reactor does not require a fast-acting, load-following control system because the PCS operates continuously at rated power after startup.

F. SHIELD

1. Materials

The present SNAP 8 shield is essentially a neutron shield for unmanned spacecraft. The shield attenuates the neutron current by approximately a factor of 10^4 but attenuates the gamma radiation by a factor of only 50. Lithium hydride is used as the neutron shield material because it has a very high neutron removal cross section per unit density ($\Sigma_r/\rho = 0.15 \text{ cm}^2/\text{gm}$). The lithium hydride used in the half of the shield adjacent to the reactor is made of 99.99% Li^7 instead of natural lithium which contains 7.5% Li^6 . The use of Li^7 reduces the heat generated in the shield by a factor of 10 and thus greatly simplifies the design of the shield. If the entire shield were made of natural lithium hydride the heat generated by the (n, α) reaction in Li^6 , which has a 930 barn cross section, would cause the lithium hydride to exceed its melting point of 1270°F .

When LiH melts, it expands 15% in volume. Since LiH is a poor material for attenuating gamma rays, a 3/4 in. thick tungsten slab is placed near the reactor core to reduce the gamma dose at the payload.

2. Configuration

The neutron shield is a truncated cone which casts a shadow over the payload region to be shielded. Every effort is made to enclose all components of the system inside of the shadow cone to reduce the problem of scattered neutrons. A relatively small amount of material placed outside of the shadow cone can result in an excessive localized dose at the payload. It is obvious that the vehicle configuration has a very significant effect on the shield design. Every attempt has been made to keep the diameter of the shield as small as possible, consistent with vehicle configuration. This not only reduces weight, but permits the heat generated in the shield to be conducted to the surface and radiated to space. A large diameter shield would require supplementary cooling to prevent melting of the LiH.

III. PRESENT TECHNICAL STATUS

A. SYSTEM DESIGN

The present SNAP 8 reference design is a result of analytical studies made to determine the effect of system parameters on the overall system performance. Wherever possible, the analytical techniques have been used to calculate results obtained from experiments as a check on the validity of the analysis. As experiments are performed using the SNAP 8 system, the experimental data is compared with the calculated predictions and the calculational techniques are continually improved.

The performance characteristics of the SNAP 8 reactor core are undergoing measurement in the S8ER. Initial critical experiments were performed on the S8ER in September through November 1962 and a series of "zero" power physics experiments were performed.

The S8ER will be brought to temperature and power in mid-calendar year 1963. The experiments performed at this time will serve as a verification of calculations made to determine temperature and power coefficients of reactivity, xenon-worth, hydrogen redistribution, component temperature, reactor stability, etc. The data obtained regarding temperature and power coefficients will be of particular value since data obtained from other SNAP reactors are difficult to extrapolate to SNAP 8 conditions.

Data obtained from the S8ER will permit refinement of the calculational techniques used to predict the behavior of the S8DS. The S8DS will be the first nuclear test of the complete flight reactor and will also be the first test in which the reactor and power conversion system will be coupled together to form a complete electrical generating system. Experiments will be performed to determine the operating characteristics of both the flight reactor and the overall system.

The present startup and long-term control concept is based on the results of analog computer studies and the details will be refined as data becomes available from the experimental program.

The detailed experimental program planned for the S8DS is necessary since the simplified startup and control scheme planned for SNAP 8 requires a thorough, accurate knowledge of the behavior of the overall system.

B. COMPONENT PERFORMANCE REQUIREMENTS AND DEVELOPMENT STATUS

The performance requirements and development status of key components (fuel elements, core assembly, reflector control assembly, and shield) are discussed below.

1. Fuel Elements

The SNAP 8 fuel elements, illustrated in Figure 4, will be designed to meet the following performance requirements:

- a) Peak power density of 5.5 kwt/ft (for 600 kwt)
- b) Peak fuel cladding temperatures of approximately 1450°F and peak fuel centerline temperatures of approximately 1550°F
- c) Endurance of 10,000 hr
- d) Total hydrogen loss from the core limited to 5% in 10,000 hr
- e) Peak fuel burnup of 0.4 metal at. %
- f) Capability to withstand repeated thermal shocks and thermal cycles
- g) Capability to withstand mechanical shock, vibration and acceleration due to handling, transportation, launch and, perhaps, coolant flow
- h) Goal of 99% reliability of meeting these performance requirements.

These performance goals for the fuel element research and development programs are in excess of the 90-day life, 450 kwt power requirement for the first SNAP 8 flight test system.

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.

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Figure 4a.
SNAP 8 Fuel Element Concept

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Figure 4b.
AP 8 Fuel Element
Present Status

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Figure 4. SNAP 8 Fuel Element, Concept and Present Status

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On the average, the characteristics of these fuel elements met, or were better than, 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 0.54 cc H₂ (STP)/hr-fuel element at 1400°F isothermal compared to the maximum specified value which was 1.60 cc/hr under the same conditions.

Although the fuel elements for the S8ER should perform as desired for this specific experiment, they would probably not meet the endurance, vibration, and reliability goals previously described. The fuel element research and development programs have been directed toward improvement of anticipated shortcomings in the present state-of-the-art as represented by the S8ER design.

The decision in November 1961 to add carbon to the fuel moderator alloy, for the purpose of grain refinement, increased the hydriding process yield from approximately 30% to very nearly 100%. Approximately 0.50 wt % carbon was added to the fuel alloy for the S8ER fuel fabrication. Unfortunately, the carbon atoms combine with zirconium atoms thus reducing the number of zirconium atoms available for hydriding. This effect causes the dissociation pressure of the hydrogen inside the fuel element at operating temperatures to increase from about 15 psia to about 45 psia. This is not a significant stress problem in the S8ER since the NaK pressure outside the cladding is about 30 psia. However, because the permeation rate of hydrogen through a given ceramic barrier increases with the hydrogen pressure, it is desirable to maintain this pressure as low as possible. The research and development program investigated hydrided fuel alloys containing as low as 0.03 wt % carbon. It was found that a factor of 2 reduction of the dissociation pressure could be obtained by reducing the carbon from 0.50 to 0.15 wt %, and that the fuel containing 0.15 wt % carbon could be hydrided with no loss in production yield. The lower hydrogen pressure inside the fuel element will give the overall design a higher probability of meeting the specified 5% hydrogen loss in 10,000 hr.

The greatest development progress for the SNAP 8 fuel element has been achieved with the ceramic hydrogen permeation barrier. Preliminary success was established with development of the AI-8763-D coating for the S8ER. This coating is basically a glassy barium silicate enamel which becomes more crystalline with time and thus improves as a hydrogen barrier. A considerable amount of data has been obtained on this coating material and only the highlights are presented briefly in this report.

One cluster of five coated cladding tubes (called permeation test membranes) has been tested at 1300, 1400, and 1500°F for an accumulated time of approximately 1 yr. The average leak rate of these membranes during this period has ranged from 1×10^{-3} to 8×10^{-4} cc(STP)/cm² at 1400°F with one atmosphere of hydrogen pressure. The average hydrogen leak rate has always been well below the equivalent of the specified 5% maximum hydrogen loss in 10,000 hr. Eight fuel elements containing the AI-8763-D coating have been subjected to design shock, vibration and acceleration tests with no apparent change in the hydrogen leak rate. Twelve of the fuel elements which were used in the S8ER critical experiments were rechecked to see if handling and transportation had increased the leak rate. They showed no increase in hydrogen leak rates. The limitations of the coating used in the S8ER are:

- a) its low softening point, near 1500°F, and
- b) its possible inability to withstand thermal cycling and shocks.

The latter has not been definitely proven although some elements have shown increases in leak rate as a function of thermal cycling.

These two potential shortcomings of the AI-8763-D coating appear to have been solved with the formulation of a new coating designated SCB. This coating contains oxides of barium, silicon, titanium, and aluminum; crystallization can be controlled to a stable state during the application of the coating to the Hastelloy-N cladding tube. Two cladding membranes containing this barrier were tested at 1500°F for over 2500 hr before an equipment failure terminated the test. During this period the permeation rate was in the satisfactory range of 2.0×10^{-3} to 3.0×10^{-3} cc/hr-cm² at 1500°F with one atmosphere of hydrogen pressure. Another membrane was tested at 1900°F for 400 hr without failure to demonstrate the margin of thermal stability of the new coating. An additional 800 hr testing time has been accumulated on this same membrane at 1500°F. The permeation rates were very satisfactory, 5×10^{-3} cc(STP)/hr-cm² at 1900°F and 7×10^{-4} cc(STP)/hr-cm² at 1500°F with one atmosphere of hydrogen pressure. In summary, all the data obtained on this new coating to date have been encouraging although additional data on completed developmental fuel elements containing this coating are still necessary before a complete evaluation can be made.

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Another area of fuel element development is the process for 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. The research and development program has subsequently established a new configuration which is as good as the S8ER design for hydrogen retention and is electron-beam welded to the cladding tube for positive mechanical retention. Finally, confirmation of the irradiation stability of the fuel is needed.

When the SNAP 8 program was initiated, two fuel irradiation capsules were tested to determine the fuel swelling and fission gas released at SNAP 8 conditions of temperature and burnup. These capsules indicated that the fuel would swell a significant, but not excessive, amount (i. e., approximately 7 mils maximum on the diameter). In order to more accurately determine the amount of fuel swelling to be expected and to evaluate the variables involved (i. e., temperature, N_H , uranium content, carbon content, total burnup, and burnup rate), the irradiation program was expanded in FY 1963. This program will supplement data obtained from the two initial capsules, NAA-53-1 and NAA-53-2, each of which contained two subsize fuel elements with noncarbon modified fuel. The irradiation program will extend over several years because of the long time required to build, irradiate, and evaluate many of these experiments.

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 will be subjected to environmental testing for complete evaluation. The results of these tests will be used to establish the S8DS-1 fuel element design. The reliability goal for the fuel elements will be demonstrated in fiscal years 1966 and 1967 along with the fabrication of flight system fuel elements.

2. Core Assembly

The reactor core vessel is designed to contain the primary NaK coolant at pressures up to 50 psia for 10,000 hr and to limit creep to approximately 0.1%, thus preventing interference with the Be reflector control assembly. It is further

designed to separate from the shield assembly when the reflector control assembly is ejected.

The flow baffle plate is designed to increase the coolant flowrate through the center of the core and thereby reduce the peak fuel and cladding temperatures. Hydraulic experiments have verified the validity of this approach.

The upper and lower grid plates are designed to properly position the fuel elements and internal reflectors. In conjunction with the coolant, the grid plates provide damping of the fuel elements during the launch vibrations.

The use of NaK at temperatures above 1200°F may lead to mass transfer problems in the primary coolant loop. This potential problem is under study by NASA. Corrosion and subsequent weakening of the core vessel and fuel element cladding does not currently appear to be a problem; however, analysis of this area is not yet complete.

3. Reflector - Controls

The reflector control system contains all the moving parts, electro-mechanical components, and electronic components used in the SNAP 8 reactor. These components must, in general, operate for 10,000 hr at high temperatures, in a high radiation field, and in the vacuum of space. The development problems and status of these components are discussed below.

Many components in reactor systems must move upon command after being held together with no relative motion between rubbing surfaces for considerable periods of time at temperatures around 1000°F. Under certain conditions present in reactor systems, intermolecular attraction can cause such parts to weld together because of their direct contact. Two materials brought together within their intermolecular attraction range will experience this binding. In terrestrial atmospheres, these bonds are normally very weak because oxide films keep molecules of touching surfaces far enough apart; but, with the absence of oxides, very strong bonds can develop. In space, the lack of available oxygen to form oxide films and to "reheal" them if they are damaged presents the problem commonly referred to as self-welding.

A study of the materials that have shown considerable promise in preventing self-welding are oxides, metallic salts and graphites. All these materials form very weak bonds with metals in which they are in contact; therefore,

little force is required to break the bond. The stability of these materials confirms their successful usability based on laboratory tests under environmental temperatures and simulated space vacuum.

Much of the self-welding theory also applies to the behavior of bearings, such as the control drum bearings which must operate at temperatures around 1000°F. Low shear strength contacts must be formed between mating surfaces if a low coefficient of friction is to be realized. In conventional ground mechanisms, petroleum products are most frequently utilized to provide this low shear film at metallic interfaces. Unfortunately, vacuum oil will evaporate and, even though hermetical systems were devised, the oil degradation from neutron irradiation would prohibit its use.

Extensive testing led to potential solutions in the use of complex dry film lubricants and impregnated graphites. These have operated satisfactorily with suitable coefficient of friction for over 3,000 hr at system temperature and simulated space vacuum. Additional studies are now in progress which strongly point the direction for obtaining long-time stability and known friction behavior.

Actuators have been developed (Figure 5) which approach the requirements of 10,000 hr operation at 1000°F in a radiation field of 10^{19} nvt in a hard vacuum. Insulation systems have been developed and tested at temperature and vacuum in radiation fields. Several of the operating units have been undergoing life tests and are now still successfully operating after periods ranging from 7 months at 1040°F and 10^{-6} mm Hg to others which have successfully passed 1 year at 840°F and 10^{-6} mm Hg.

Two "direct drive" actuator concepts are being developed to eliminate the gear train required with the present actuator design. The present wire harnesses are made of stainless steel clad copper wire with the glass insulation sheathed with braided stainless steel. The braided sheathing provides physical as well as radio-interference protection. This harness will withstand the required temperatures, but will not withstand humidity typical of vehicle launch sites. Humidity-resistant insulation materials are being investigated.

The reactor control system measures coolant outlet temperature and rotates a control drum in or out if the temperature gets too cold or too hot. For this purpose a temperature switch is used. Two types of temperature switches have been developed for this requirement. One is a mechanical switch

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a.

SNAP 8 Control Drum Actuator Concept

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b.

SNAP 2/10A Actuator
(Operating successfully after 7 months
at 1040°F and 10^{-6} mm Hg)

Figure 5. SNAP 8 Control Drum Actuator, Concept and Present Status

which is activated by the differential rate of thermal expansion of two metals (Figure 6a). Devices of this type have been made and subjected to shock and vibration tests and temperature-vacuum stability tests. A second switch system which has been developed utilizes a platinum resistance element temperature sensor (Figure 6b) and a magnetic amplifier relay switch. Sensors and switches combined by the systems have been subjected to extensive development tests. Further development of the temperature switch is required to meet the SNAP 8 accuracy requirements.

The controller is the component which analyzes and reacts to the coolant outlet temperature. This unit receives discrete input signals from the temperature sensor switches placed in the reactor coolant piping. The switches indicate whether the coolant outlet temperature is within predetermined temperature limits (1270 to 1330°F). Whenever the temperature falls outside of these limits, the controller applies power impulses to the control drum actuators. This causes the control drums to move in the proper direction to change the coolant temperature back into the desired range. Since the inputs and the outputs of the controller are in discrete steps, the controller is a digital device.

The environmental requirements of the controller are not as stringent as those of components mounted in the immediate vicinity of the reactor, but development is required, nevertheless. A controller fulfilling the required performance has been completely designed and built using transistorized logic. It follows the philosophy of the SNAP 10A controller which is now in the final stages of a qualification test program and has been irradiated to 5×10^{13} nvt without undue degradation. Other approaches actively under development include magnetic logic systems, thermionic integrated micromodule systems, electro-mechanical systems, and combinations of these systems. These advanced concepts exhibit characteristics which should produce systems tolerant to high nuclear radiation even to the range of 10^{15} to 10^{18} nvt.

The requirement of a reliable reactor shutdown system after useful system life is closely related to the reliable operation requirement. The reactor shutdown system must operate after remaining dormant during the lifetime and must operate with very limited onboard internal energy. The current concept is based upon the ejection of the beryllium reflectors by springs which can be triggered by one of three devices. The feasibility of all three devices has been

Figure 6a.
Temperature Switch Based
on Differential Thermal
Expansion

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Figure 6b.
Temperature Switch Based
on Electrical Resistance

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Figure 6. Temperature Switch Based on Differential Thermal Expansion
or on Electrical Resistance

- #### 4. Shield

There is interest at the present time in significantly reducing the fast neutron dose at the payload below 10^{13} nvt. To further reduce the scattering component of the dose at the payload and thus achieve a dose of less than 10^{12} nvt would probably require that the NaK lines and, perhaps, the electrical cables be embedded in the surface of the shield or passed through the shield.

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Further testing, including thermal cycling, is in progress. The casting of the two-region test shield has revealed certain potential improvements which are being incorporated into the casting procedure of subsequent shields. Of particular importance are limitations on the radial temperature gradients incurred during the casting process in order to control thermal stresses in the shield casing.

The next SNAP 8 shield scheduled to be cast is the SNAP 8 Developmental Reactor Mockups (S8DRM-1) shield. This shield vessel is shown in Figure 7.

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Figure 7. Shield Vessel for S8DRM-1

IV. PROGRAM LOGIC AND SCHEDULE

A. GENERAL APPROACH

As pointed out above, much of the technology required for SNAP 8 either has been or is being developed under the SNAP 10A and 2 programs. Therefore, the major emphasis in the SNAP 8 development plan is placed on (1) extending the SNAP 10A and 2 technology to meet the SNAP 8 component requirements of a higher power level (a factor of 10 higher) and higher temperature (100 to 300°F higher), and (2) the reactor system development and testing required on the SNAP 8 design.

The current development plan and schedule is illustrated in Figures 8 and 9 and is described below. This schedule leads to delivery of the SNAP 8 reactor for flight test in November 1967, approximately 1 year behind the current NASA schedule for flight testing in calendar year 1967.

B. PROGRAM ORGANIZATION

SNAP 8 is being developed jointly by AEC and NASA. The general division of responsibility is as follows: Aerojet General Corporation, under contract to NASA, is responsible for development of the power conversion system and for design integration of the power conversion system and reactor into a powerplant; Atomics International, under contract to AEC, is responsible for development of the reactor and for the nuclear testing of the powerplant required prior to flight. A second NASA contractor is expected to be selected to design the spacecraft for final testing.

The specific responsibilities of the AEC contractor, Atomics International, are set forth in NASA's original request for quotation (RFQ) on SNAP 8, dated October 30, 1959. This RFQ says that, as part of the reactor development program, the AEC and/or its contractor will:

- 1) Specify system design requirements necessary to ensure nuclear safety
- 2) Provide guidance to the system design on the basis of: (a) experience from other SNAP programs and (b) influence on reactor design and operation.

*THE CIRCLES INDICATE REACTOR DELIVERY DATES TO SANTA SUSANA FOR TEST SYSTEMS OR TO NASA FOR DELIVERY SYSTEMS

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Figure 8. SNAP 8 Development Plan*

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SNAP 8 DEVELOPMENT SCHEDULE

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- 3) Select and design the system used in starting and shutting down the reactor loop in orbit
- 4) Design all reactor shielding and evaluate the effect of radiator design on reactor and shield configuration and weight
- 5) Keep NASA fully informed of the design, performance, and operation of the reactor
- 6) Provide the nuclear test facilities used in the SNAP 8 program
- 7) Direct and operate the nuclear system tests with assistance from the NASA PCS contractor
- 8) Review and approve the test program and test equipment to assure the safety of the complete nuclear system.

C. REACTOR SYSTEM DEVELOPMENT PLAN

The present SNAP 8 reactor development program is geared to the delivery of the first flight reactor (FR-3) to NASA in November 1967. To deliver a reactor which meets the user's requirements, the following development program is planned.

- 1) The S8ER is essentially a proof test of the SNAP 8 reactor core without power conversion. The S8DS design will not be completed until the S8ER has demonstrated 60 days accumulated operation at 450 kw. The S8ER is illustrated in Figures 10 through 14.
- 2) The S8DRM-1 is a nonnuclear prototype composed of flight type hardware allowed by the existing state-of-the-art. Its primary purpose is to prove that the mechanical systems proposed are indeed feasible for the environments anticipated. Failures which occur during testing will result in changes in flight hardware design. It is truly a developmental system. The S8DS design will not be completed until bench tests and initial thermal tests have been performed on S8DRM-1 systems. A wooden model of S8DRM-1 is shown in Figure 1.

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a. S8ER Concept

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b. SNAP 8 Reactor

Figure 10. SNAP 8 Experimental Reactor, Concept and Status

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Figure 11
S8ER Critical Assembly

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Figure 12
S8ER Reactor and Shutdown Shield

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Figure 13. S8ER Schematic Diagram

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a. Concept

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b. Facility

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Figure 14. S8ER Test Facility, Concept and Structure

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- 3) The S8DS is a developmental nuclear test of the flight reactor system. It will be the first SNAP 8 reactor coupled to a power conversion system (PCS). The test facility for the S8DS is shown in Figure 15.
- 4) The flight test reactor design will not be firmly established until the S8DS reactor has demonstrated 30 days accumulated operation at power. From a standard flight test reactor design, the following eight reactors will be fabricated for tests and delivery:
 - a) DRM-2: This is a non-nuclear flight reactor to be used for environmental proof testing of the mechanical and structural systems.
 - b) FS: This is a complete flight reactor which is to be coupled to the prototype PCS for ground proof testing of the entire electrical generating system (EGS) in flight configuration. The test facility for FS is shown in Figure 16.
 - c) FRM-1: The FRM-1 is a flight test reactor with dummy fuel elements to be delivered to NASA for integration and non-nuclear environmental testing of the EGS.
 - d) FR-1 and FR-2: These systems are live reactors to be delivered to NASA for a nuclear ground test of the spacecraft, probably at Plum Brook, Ohio. The control systems will be modified as testing procedures demand.
 - e) FR-3, FR-4, and FR-5: These are live reactors delivered to the flight test, probably at the Atlantic Missile Range.
- 5) In addition to the systems noted above, NASA requires three simple, non-working mockups for their overall development program. PRM-1 will be a wooden mockup based upon the DRM-1 design and incorporating modifications resulting from subsequent research. The extent of these modifications will depend upon the delivery date established by NASA. PRM-2 and PRM-3 are mass mockups for mechanical and structural tests of the PCS system.

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a. Concept

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b. Facility

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Figure 15. S8DS Test Facility, Concept and Structure

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a. Concept

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b. Current Status

Figure 16. S8FS Test Facility, Concept and Current Status

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An important aspect of the SNAP 8 reactor development program is that most of the program is based on fairly well known technology. The key areas requiring further development to achieve 10,000 hr endurance are the fuel elements and the electromechanical components in the reflector control system. The development plan for fuel elements and other reactor components is outlined below.

D. FUEL DEVELOPMENT PLAN

The fuel element development program target dates are determined from the fuel element fabrication schedule. The target dates are determined from several ground rules:

- 1) The composition and process for fabricating enriched uranium fuel rods must be established one year before a delivery date. The lead time on the normal uranium fuel rods is reduced to six months.
- 2) The final mechanical design, as well as established assembly processes, must be fixed ten months in advance of a scheduled delivery of enriched uranium elements and six months in advance for normal uranium elements.
- 3) A transition period for training of production personnel and for qualifying the production processes must be planned.
- 4) A design change or process modification cannot be incorporated into the production program until it has been proven to be equal to or superior than the current reference design or process.

The reactor system development schedule dictates two key target dates for the fuel research and development: (1) December 1, 1963, for the S8DS fuel element design, and (2) August 1, 1965, for the fuel element design for S8FS, S8DRM-2, and S8FR deliveries. These dates allow three months for the pilot production run to train production personnel and qualify the production process prior to start of assembly of enriched elements.

The plan and schedule of the R & D program leading to the design and process selection for the S8DS-1 fuel elements are shown on Figure 17. Although each task is shown separately, a continuous cross flow of information is maintained to focus the development toward a common goal. During the early stages of coating development, information on melting temperatures, adherence, and coefficient of expansion is made available for preliminary design of possible

X SELECTION OF SINGLE ITEM FOR ADDITIONAL DEVELOPMENT FROM SEVERAL UNDER CONSIDERATION

SV ESTABLISH PRELIMINARY PRODUCTION PROCESS AND RELEASE PRELIMINARY SPECIFICATION

SV ESTABLISH FINAL PRODUCTION PROCESS AND RELEASE SPECIFICATION

DV PRELIMINARY DRAWING RELEASE

DV FINAL PRODUCTION DRAWING RELEASE

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Figure 17. SNAP 8 Fuel Element Research and Development Schedule for S8DS-1 Fuel Elements

closures. In turn, components fabricated to the early design are submitted to determine if new coating processes and compositions are compatible with the design. The welding development also uses preliminary coating and closure development data to assure compatibility of the final design. A cross flow of testing data from components and fuel elements is also maintained to assure validity in the data and help isolate variables.

A backup program that is not shown on this chart is superimposed in most areas and lags the primary development by approximately 6 months to one year. This backup development also serves as the advanced development required for the next fuel development target date of August 1, 1965, for the flight test reactors.

After the preliminary designs and process are established, approximately 100 developmental elements will be fabricated for evaluation. From this group approximately 25 elements will be used for performance testing to measure the status of the overall design toward meeting the performance goals.

E. COMPONENT DEVELOPMENT PLAN

The component development plan covers a fairly wide range of problem areas. Many environmental stresses will be imposed upon the reactor and its control components not only during space flight but also during acceptance testing, transportation, prelaunch assembly, and checkout and launch. These environmental stresses include ambient temperature fluctuations, ambient humidity cycles, vibration and shock due to transportation, erection on the launch pad, the shock imposed by sudden vacuum during launch and the ultra-high vacuum and high temperature of operation during space flight. These problems are solved in a step-by-step development program in the following way. The most difficult stresses and the simplest to evaluate are first included in a test program. In this way, maximum economy of testing is incorporated. The high temperature test work is usually the first step in the evaluation of the system of parts. These tests are followed by tests of combined environments such as high temperature and vacuum evaluation, and radiation effects combined with high temperature and vacuum effects. In addition to developing reactor components, there is a continuous need to advance the state-of-the-art in the test equipment available in order to accurately simulate and measure the required test environments.

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Initial testing is conducted on the parts, the subassemblies and the entire components in a step-by-step fashion so that the variables are kept to a minimum in each phase of development. This assures a reasonable reliability when the component is developed and delivered to the system for a complete system testing. Reliability is emphasized in all developmental design and testing programs.

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V. RELIABILITY CONSIDERATIONS

In the design and development of the SNAP 8 EGS, primary emphasis is to be placed first on reliability, second on performance, and third on weight.

A. RELIABILITY OBJECTIVES AND TENTATIVE APPORTIONMENT

The SNAP 8 EGS is to be designed with a reliability of 80% for achieving orbital startup, 10,000 hr operation, and successful shutdown. This reliability goal includes the system nonpuncture probability due to meteoroids. Table I gives a tentative apportionment of the reliability of the NS and PCS and the non-puncture probability of each system.

TABLE I
TENTATIVE RELIABILITY APPORTIONMENT
BETWEEN NS AND PCS

System	Nonfailure Probability (%)	Nonpuncture Probability (%)	Total Reliability (%)
NS	92.6	99.9	92.6
PCS	88.1	97.9	86.4
EGS	81.7	98	80

The reliability apportionments must remain tentative or preliminary until the program reaches final design so that development information may be properly factored into the overall system reliability.

It does not appear economically feasible to perform enough tests to demonstrate this high reliability with a high confidence level. However, certain critical components can be tested to demonstrate a high reliability with a reasonable confidence level in conjunction with the development and qualification testing programs.

Some examples of reliability consideration in the SNAP 8 reactor design are given below.

B. FUEL ELEMENT REDUNDANCY

The SNAP 8 NS is designed to achieve 10,000 hr of operation at 600 kw even if the hydrogen barrier fails on up to six fuel elements. In other words, six

redundant fuel elements are included in the SNAP 8 core. Figure 18 is a graph of single fuel element reliability vs fuel element cluster reliability for 211 fuel

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Figure 18. Core Reliability vs Fuel Element Reliability for Different Values of Fuel Element Redundancy

elements. From this curve it is obvious that redundant fuel elements improve system reliability. For instance, with a 99% reliable fuel element and no redundant fuel elements, the 211 fuel elements have an overall reliability of 10% while with six redundant elements, the reliability of the cluster is greater than 99%.

C. ACTUATOR REDUNDANCY

Each Be reflector drum has its own drive motor. The loss of any motor will not prevent proper operation of the other motors. Hence, although the loss of reactivity available in that drum lost from the system is lost, complete mission failure is not encountered. For example, if an actuator fails after 1 week, the reactor should still operate satisfactorily for several months.

D. METEOROID PUNCTURE

As previously mentioned under the reliability objectives, nonpuncture probability is included as a part of the overall system reliability. This phase of reliability can be increased by the addition of armor protection to the vulnerable area. However, this increases system weight. Figure 19 shows the weight penalty to increase the meteorite nonpuncture probability of the neutron shield vessel above 95%. A lower limit of 95% is dictated by the minimum vessel thickness for ease of fabrication. Figure 19 shows that a 99.9% nonpuncture probability can be achieved by the addition of approximately 125 lb.

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Figure 19. Weight Penalty to Increase
Meteorite Nonpuncture Probability of
Neutron Shield Vessel Above 90%

VI. SYSTEM GROWTH CAPABILITY

A. GROWTH WITH CURRENT REACTOR

The SNAP 8 reactor may be coupled with various power conversion systems besides the current NASA system, such as a thermoelectric system, or multiple SNAP 2 power conversion units. These systems could effectively cover the power range from 15 to 60 kw with the present reactor design and could be extended to higher power by uprating the reactor design.

It is possible, and in some cases highly desirable, to have multiple power conversion systems coupled to the same reactor. This can result in an increased system reliability at partial power. Figure 20 shows a schematic of eight SNAP 2 CRU's connected in parallel with the SNAP 8 reactor. Such a system has a power output in excess of 30 kwe and weighs about 4500 lb. A weight breakdown for this system is given in Table II. The reliability vs percent power output is shown in Figure 21 as a function of the number of power conversion units employed. As can be seen, there can be a significant increase in reliability at partial power output at the expense of decreased reliability at 100% power output. This situation might be highly desirable, for example, for a manned space station where the maintaining of some power is a more stringent requirement than maintaining full power.

B. UPRATING OF REACTOR PERFORMANCE

The performance characteristics of the SNAP 8 reactor can be uprated by three general methods: increasing reactor outlet temperature while holding power constant; increasing power level while holding the outlet temperature constant; and increasing both power and outlet temperature. The first two of these techniques will be discussed in some detail.

1. Increases in Reactor Outlet Temperature

Increases in system operating temperatures can be used to increase the thermal efficiency of the system or to decrease the radiator size. The degree of improvement which can be achieved by this technique is limited by the properties of materials used in the system. Since SNAP 8 does not use refractory metals or a ceramic fuel material, gross increases in reactor operating temperatures are not attainable. With relatively minor changes in the existing

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Figure 20. SNAP 8 Reactor Coupled to Eight S2 Power Conversion Systems to Produce 30 kwe

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TABLE II
 SNAP 8 REACTOR PLUS MULTIPLE SNAP 2 CRU's
 (8 CRU's-30-kwe output)

	No. Required	Weight/Unit (lb)	Weight (lb)
Reactor	1	530	530
Shield	1	600	600
NaK heat exchanger	8	20	160
Mercury boiler	8	35	280
CRU	8	45	360
Mercury-organic or NaK cond.	8	32	256
Radiator (135 ft ² ea., 1080 ft ² total)	8	130	1038
Mercury inventory	8	16	128
Structure	1	300	300
Orbital startup system	8	38	300
Pumps	8	31	250
Piping	1	170	170
Parasitic load control	8	16	128
Total			4500 lb

reactor design, a 100°F increase in the operating temperature appears to be attainable. Additional increases in temperature would require significant design changes.

Some of the problem areas associated with the operation of the existing SNAP 8 reactor at an outlet temperature of 1400°F and an inlet temperature of 1200°F are:

- a) The internal fuel element hydrogen pressure would be approximately doubled. Hydrogen loss rates (and associated reactivity loss) would be doubled and the creep strength of the existing cladding becomes marginal.
- b) Irradiation damage swelling of the fuel may be doubled due to the increased temperature. This will necessitate a smaller fuel rod diameter to prevent the rod from "growing" against the cladding. Some additional irradiation data will be available in late 1963, but the most valid data will come from a capsule which is due out of pile in mid 1965.

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Figure 21. Reliability Effect of Multiple Power Conversion Systems

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- c) The reactivity losses associated with the increased temperature and items a and b above will make it necessary to increase the core length by about two inches and the reflector thickness by about one inch if a 10,000 hr life is to be attained.
- d) The ability of the ceramic coating to withstand the increased temperature must be verified. The information presently available indicates that this would not be a problem.
- e) The beryllium reflector and control drum bearings would operate about 100°F hotter than in the present design. The problems associated with self-welding in space and oxidation during ground testing would require investigation.
- f) The margin between the operating temperature and burst temperature of the fuel would be reduced. Reactivity insertion rates would have to be reduced (longer startup time) in order to assure safe operation, particularly during ground testing.

While there are many problems associated with increasing the reactor operating temperatures, a 100°F increase appears possible with some design modifications.

2. Increases in Reactor Power

The reactor power can be increased holding the inlet and outlet temperatures constant above the existing 600 kwt design point. The problems associated with a 50% increase in power to 900 kwt are very similar to those outlined above for operation with a 1400°F outlet temperature. An additional problem area which would require investigation is the effect of increased neutron and gamma heating in the shield and control system components adjacent to the core. Some redesign effort would probably be required in these areas.

Increasing the reactor power by 100% or more (to 1.2 mwt or greater) would require a significant redesign of the system. The fuel rod diameter would be made smaller and the N_H reduced in order to prevent an excessive internal hydrogen pressure. The core and reflector dimensions would be increased to provide adequate reactivity control. The higher flux level might indicate the use of CD rather than samarium as a burnable poison. The nuclear heating of the shield might be sufficient to require supplemental cooling.

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A comparison of the existing SNAP 8 design (600 kwt) with the type of design required to achieve a power level of 1.2 Mwt is given below:

TABLE III
1.2 Mwt REACTOR DESIGN SUMMARY

	600 kwt	1.2 Mwt
Fuel rod diameter, in.	0.560	0.40
Active fuel length, in.	16.5	18.0
Core vessel diameter, in.	9.5	10.5
N_H , atoms $\times 10^{22}$	6.0	5.8
Wt % uranium	10.5	11.0
Be reflector thickness, in.	3.0	4.5
Burnable poison	Sm_2O_3	CdO
Burnable poison worth, % $\Delta k/k$	2.7	5.0

It is apparent that upgrading the SNAP 8 reactor to the megawatt power range would involve a sizable redesign and development effort. Such a redesign appears within the limits of SNAP 8 technology and would have a high probability of success.

APPENDIX A HISTORY OF TECHNICAL DECISIONS

August 1959	Initial performance requirements jointly established by AI, AEC, and NASA: 30/60 kwe 500 kwt 1350°F NaK outlet temperature 10,000 hours life.
October 1959	NASA issued RFQ for SNAP 8 PCS
May 1960	Aerojet General Corporation initiated PCS development under contract to NASA.
May 1960	NaK outlet temperature requirement reduced to 1300°F.
July 1960	Electrical power requirement increased to 35/70 kwe and reactor thermal power requirement increased to 600 kwt.
September 1960	Decision to test an experimental reactor (S8ER) in the S2ER test facility.
January 1961	Preliminary design of SNAP 8 reactor established all materials and dimensions in the core.
September 1961	Selected S8ER fuel element design: 0.56 in. OD, 0.010-in. thick Hastelloy-N cladding 14.0 in. active length 10 wt % U, $N_H = 6.0 \times 10^{22}$
October 1961	Select six control drum configuration (like S8ER) for flight reactor.
November 1961	Decision to add about 0.5 wt % carbon to the fuel-moderator material to prevent cracking during hydriding.
December 1961	Select cast LiH shield for flight reactor.

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January 1962	Shield criteria specified as: <ul style="list-style-type: none">a) 8-ft diameter payload 15 ft from reactorb) direct dose from reactor to payload to be 5×10^{12} nvt and 9×10^6 rads of gammas.
February 1962	Decision to use Li^7H in shield.
February 1962	Decision to make two region shield (Li^7H and $\text{Li}^{\text{Na}} + \text{H}$)
March 1962	Changed flight reactor fuel element design <ul style="list-style-type: none">a) length - 15.5 in.b) diametral gas gap ~ 4 mils
March 1962	Decision to place flight-type shield in S8DS.
April 1962	Incorporated "burn-off" lip on top head of flight core design.
May 1962	Selected anodized coating for Be in S8ER.
June 1962	NASA abandoned Atlas-Centaur for SNAP 8 launch vehicle; design for Titan III or Saturn C-1
August 1962	Selected six-drum scram for S8DS.
September 1962	Increased flight reactor fuel element design <ul style="list-style-type: none">a) length - 16.0 in.b) diametral gas gap - 7 mils
November 1962	Initiated redesign of shield for 600 kwe level instead of 300 kwt
November 1962	Selected 1-piece fuel element closure design for reference design.
December 1962	Selected electron beam welding of fuel element closure for reference design.
December 1962	Selected unitized loading scheme for S8ER.
January 1963	Revised flight reactor fuel reference design. <ul style="list-style-type: none">a) length - 16.5 in.b) diametral gas gap - 8 milsc) uranium content - 10.5 wt %
January 1963	Decision to use neutron source in flight reactor reference design.

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APPENDIX B SNAP 8 NUCLEAR SYSTEM DESIGN DATA

TABLE IV
SNAP 8 NUCLEAR SYSTEM DESIGN DATA

Operating Conditions		Reactor Design	
Reactor Thermal Power, kwt	300-600	Fuel Elements	
Net Electrical Power, kwe	30-60	Number	211
Operating Life, hr	10,000	Fuel diameter, in.	0.528
NaK Outlet Temperature, °F	1300	Cladding diameter, OD, in.	0.560
NaK Inlet Temperature, °F	1100	Cladding thickness, in.	0.010
Operating Pressure, psia	40	Fuel alloy, wt % U in Zr	10.5
Maximum Fuel Temperature, °F	1580	Degree of hydriding, N_H (10^{22} a/cc)	6.0
Maximum Cladding Temperature, °F	1480	Cladding material	Hastelloy-N
Shield Parameters		Active fuel length, in.	16.5
Material		Internal Reflectors	
Neutron shield	LiH	Composition	BeO
Gamma shield	W	Cladding material	347 SS
Neutron Shield Cladding		Cladding thickness, in.	0.018
Material	347 SS	Inlet Plenum Grid Plate	
Maximum Dose at Payload		Material	Hastelloy-C
Fast neutrons		Thickness, in.	7/16
Scattered, nvt	5×10^{12}	Core Vessel	
Direct, nvt	5×10^{12}	Internal diameter, in.	9.214
Gammas		Length, in.	22.4
Scattered, rad (C)	1×10^6	Thickness, in.	0.105
Direct, rad (C)	9×10^6	Material	316 SS
		Reflector Control Elements	
		Number	6
		Material	Be
		Nominal thickness, in.	3
		Outlet Plenum Grid Plates	
		Material	316 SS
		Thickness, in.	7/16

TABLE V
NUCLEAR PARAMETERS

Reactivity Lifetime		
Xenon, % $\Delta k/k$	-0.9	
Samarium (prepoisoned to $-2.7\% \frac{\Delta k}{k}$), % $\Delta k/k$	+1.8	
Burnup and fission products, % $\Delta k/k$	-1.3	
Cold to power, % $\Delta k/k$	-1.7	
Hydrogen redistribution, % $\Delta k/k$	-0.5	
Hydrogen loss and contingency, % $\Delta k/k$	-3.5	
Cold, clean excess reactivity, % $\Delta k/k$	+6.1	
Reflector worth	23	
Total drum worth, % $\Delta k/k$	14.0	
Individual drum worth, % $\Delta k/k$	2.45	
Positive shim worth, % $\Delta k/k$	2.5	
Negative shim worth, % $\Delta k/k$	-3.0	
Temperature Coefficients	Temp, °F	$\beta/^\circ\text{F}$
Spectrum	1330	$\sim 0^*$
Axial expansion	1330	0.052
Upper grid plate	1300	0.029
Both grid plates	(1200)	0.042
Reflector, prompt	1000	0.06
Reflector, total	940	0.11
Total isothermal, $\beta/^\circ\text{F}$	-0.2	
Power defect, % $\Delta k/k$	-1.93%	
B_{eff}	0.0077	
Mean prompt lifetime, sec	6.7×10^{-6}	
B_{eff}/ℓ , sec^{-1}	1150	
Median fission energy, ev	0.20	
Average thermal flux, $\text{n/cm}^2\text{-sec}$	5×10^{12}	

*There is some experimental evidence to indicate that this partial coefficient could be as large as $-0.1 \beta/^\circ\text{F}$ at 1330°F .

TABLE VI
THERMAL PARAMETERS

Fuel Elements	
Number	211
Pitch/Diameter	1.015
Fuel rod diameter, in.	0.528
Fuel rod length (active), in.	16.50
Maximum fuel temperature, °F	1470 (ideal)-1580 (worst)
Fuel element diameter, in.	0.560
Maximum ceramic temperature, °F	1350 (ideal)-1480 (worst)
Maximum heat flux from fuel element to coolant, Btu/hr-ft ²	88,000
Maximum power density in core, kw/liter	27
Maximum Temperatures of Reactor Components	
Reflector Ejector Spring, °F	1150
Ground Command Shutdown Actuator, °F	820
End of Life Shutdown Actuator, °F	1280
Re-entry Heat Sensing Band, °F	800
Control Drum Bearing, °F	1035
SLO-SYN Stepper Motor, °F	1065 Rotor 955 Stator
Drum Drive Gears, °F	1280
Lithium Hydride in Shield, °F	890
Tungsten in Shield, °F	1150
Shield Insulation Material, °F	1150
Reflector, °F	1185

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TABLE VII

SNAP 8 NUCLEAR SYSTEM WEIGHT SUMMARY

Nuclear System			1633.5
Core Assembly		296.9	
Head Assy., outlet plenum	6.0		
Upper grid plate	6.7		
Large internal reflectors	7.6		
Small internal reflectors	1.5		
Fuel elements	201.0		
NaK in core vessel	13.6		
Basic vessel	33.8		
Lower grid plate	6.2		
Lower grid plate supports	0.5		
Baffle plates	1.1		
Reflector brackets	1.1		
Lower ring	1.8		
NaK pipe and NaK	14.0		
Temperature sensor switch	2.0		
Reflector Assembly		224.1	
Control motors	15.0		
Startup motors	9.0		
Reflector adjust brackets	1.2		
G. C. shutdown actuator	1.0		
Upper drum support assembly	15.0		
Reflector external fixed	42.9		
Reflector drums	110.8		
End-of-life shutdown actuator	1.8		
Safety circuits	5.0		
Drum release actuators	3.6		
Lower drum support assembly	12.0		
Reflector support structure	1.2		
Reflector ejection springs	4.0		
Drum position servos	0.5		
Shield Assembly		1045.3	
Marmen ring	2.0		
Reactor support structure	7.4		
Gamma shield	33.6		
Destruct charge	11.0		
Upper head	51.1		
Thermal insulation	8.9		
Upper ring	27.5		
Upper and middle diaphragm	57.3		
Shell	72.5		
Cables	10.0		
Multiple connectors	5.0		
Neutron shield	681.0		
Fill Pipe	2.1		
Lower ring	13.1		
Lower diaphragm	34.9		
Mounting ring	28.0		
Instrument Compartment	17.0	17.0	

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APPENDIX C

GROUND TEST PROBLEMS

The ground testing of the flight reactor system presents various problems which will not be encountered in space. One of these is the requirement to shut down and restart the reactor which has been designed for a single irreversible shutdown in orbital operation. A design for accomplishing this requirement with the minimum number of changes to the flight components has been completed and is being readied for developmental testing.

The ground test conditions of impure inert gas or partial vacuum (i. e., a slightly oxidizing atmosphere) cause material problems. Bearing materials which have exhibited high potential for long time space application, for example graphite, degrade rapidly in the presence of oxygen. This has necessitated the development of special bearings to meet ground test conditions. Figure 22a shows the results of the material degradation in an oxidation test at 1450°F. Figure 22a shows the excellent condition of the present special bearing after an exposure three times as long under similar conditions.

The rapid oxidation of beryllium at reactor operating temperature is another problem limited to ground test conditions. Extensive investigation and development has resulted in a surface coating which will provide the oxidation resistance required. Figure 23 shows the condition of the beryllium with and without the protective coating under similar oxidizing conditions.

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a. Graphite Bearing

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7568-5527

b. Carbide Bearing

Figure 22. Graphite and Carbide Bearings at 1450°F in Impure Nitrogen

a. Protected Be

7568-55101

b. Unprotected Be

7568-55102

Figure 23. Protected and Unprotected Be Under Oxidizing Conditions

APPENDIX D

AVAILABILITY OF MATERIALS, FABRICATION TECHNOLOGY, ETC.

1. FUEL ELEMENTS

The materials for the SNAP 8 fuel elements can be obtained from commercial vendors using established processes that meet the AI materials specifications. The Hastelloy-N bar stock used for end components is ordered six months before it is needed, while the Hastelloy-N material used for tubing is ordered one year in advance to allow vendor time for forming the thin-walled tubing. Advanced planning and ordering is also required for the enriched uranium. The other materials for the fuel alloy and ceramic coating are stocked by several commercial vendors and only require a nominal procurement time.

The fabrication and assembly of fuel elements requires trained personnel using established processes. The ability to perform and control these processes was demonstrated with the fabrication and delivery of the 211 fuel elements for the S8ER. No additional changes in the production processes or techniques will be made until new or modified processes have been thoroughly tried and proven. The general operations used to fabricate a fuel element are discussed briefly in the following paragraphs.

A closed end-cladding subassembly is made by tungsten-inert-gas (TIG) welding a premachined top cap to a section of Hastelloy-N tubing. It should be noted that all the Hastelloy-N components can be machined on standard equipment using standard shop techniques. Next, an 0.0005 in. layer of chromium is chemically applied to all the surfaces, the subassembly is outgassed and straightened, and the ceramic coating is applied to the inside cladding surface and fired. A chromium layer is also applied to the premachined ceramic seal cup before the coating is applied.

The fuel alloy is made by arc melting the zirconium uranium-carbon compacts into billets and extruding the billets to 0.60 in. rods. The fuel rods are then hydrided and machined to the final dimensions. The fuel can be handled through all the operations using standard procedures, that is, no remote handling or elaborate storage containers are required.

The final fuel element assembly is made by inserting the fuel and the coated seal cup into the cladding tube subassembly, forming the glass-to-glass seal,

and TIG welding the premachined end plug to the cladding tube. In addition to a final detailed inspection and hydrogen permeation test, the components and sub-assemblies are inspected throughout each stage of fabrication to assure a high quality product.

2. CORE

The manufacture of the core vessel has been a vexing fabrication problem but not a significant development problem. The problem has been due to the thin cylindrical wall and the internal and external brackets which must be welded to the vessel. This process frequently results in out-of-round vessels. In order to improve the core vessel manufacturing yields, an attempt is now being made to machine the vessels out of forged billets.

The other manufacturing problem in the core assembly is the BeO internal reflectors. Difficulty was encountered in the manufacturing of the SNAP 8 Experimental Reactor (S8ER) internal reflectors. The design has since been modified to increase the cladding thickness resulting in better tolerances.

In general the development status of the core assembly is in excellent shape with the major efforts being directed towards improving the yield of the fabrication process.

3. REFLECTOR-CONTROLS

In the course of developing the reflector control system for SNAP 2, 8, and 10A, fabrication experience has been obtained which indicates that the reference design can be made with the present knowledge and materials. A review of the areas requiring the most scrutiny is described above under Bearings and Self-Welding.

The reflector material being used, beryllium, has been investigated for all steps through which it must go to finally reach its ultimate function of neutron reflection in space. It has been studied as a reflector as well as a structural member since the present design concept is based on the reflectors acting without reinforcement. The handling and manufacturing of beryllium is now a fairly common process which is well-known in the industry. Probably the most difficult phase of beryllium technology is solving of the beryllium oxidation problem during ground testing.

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The manufacture and assembly of the SNAP 8 Experimental Reactor (S8ER) confirmed the fabricability of the reflector-control system for the flight system is being confirmed with fabrication of the SNAP 8 Developmental Reactor Mockup (S8DRM-1).

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APPENDIX E
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