THE SNAP 2 CONCEPT*

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ABSTRACT

The objectives of the SNAP 2 program are to develop, test, and qualify a 3 Kwe nuclear auxiliary power unit for space utilization prior to 1964. The overall SNAP 2 development effort is directed toward these general objectives: minimum weight, maximum reliability, operational safety, producibility, mission environment compatibility, and minimum payload design restrictions. The results of preliminary design studies which evaluated the "state-of-the-art" of reactor and power conversion technology, as well as projected space vehicle and mission requirements, have established the following specific development objectives for SNAP 2: 3 Kwe net output, one-year unattended automatic operation, system weight less than 750 lb, and cycle heat rejection area less than 110 ft^2. In order to meet these objectives, the SNAP 2 reactor employs a homogeneous fuel moderator of zirconium hydride containing 10 wt % U^{235}. For minimum weight the reactor is reflected by beryllium and controlled by variations of the effective reflector thickness. The SNAP 2 system employs a mercury Rankine cycle for power conversion.

I. SNAP 2 CONCEPT

The basic objective of the SNAP program is to develop a nuclear auxiliary power source concept for space application which can be used over a broad power range. The first turboelectric system chosen for development in this power range is SNAP 2. SNAP 2 will provide 3 Kwe continuously for one year with a shielded system weight of about 1000 pounds. It will be flight tested in 1963 and will be available for operational use in the time period beyond 1964.

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A. HISTORY

The need for long lived, auxiliary, power sources for space grew out of Air Force studies in the early 1950's. The weight, power, and endurance requirements clearly indicated the need for nuclear heat sources. As a result, a series of reports on a nuclear heat source for project "feedback" were issued in February of 1954.[1,2] In October 1955, the current SNAP concept was selected and formed the basis for NAA-SR-1500, "A Proposed Nuclear Auxiliary Power Plant, 0.5 - 10 Kw Net Electrical Capacity." A joint AEC-Air Force study contract was let in May of 1956. In January 1957, a feasibility report[3] was issued which outlined essentially the reactor type and power conversion cycle which is now under development and has reached the stage of engineering demonstration. The AEC, through the Aircraft Reactor's Missile Projects Branch of the Division of Reactor Development, awarded the system development contract to Atomics International in April 1957. A power conversion subsystem development subcontract was awarded to Thompson Ramo Wooldridge near the end of that year.

B. POWER CONVERSION CONSIDERATIONS

In choosing a space nuclear auxiliary power unit concept there are two predominant considerations that dictate the concept selection. They are:

1) The system must be of minimum weight because of the cost and complexity of delivering the plant and its payload package into an earth orbit or an outer space trajectory.

2) The system must operate with the low temperature of the thermodynamic conversion cycle maintained by radiative heat rejection only. The second consideration implies a large or heavy heat rejection radiator which is inconsistent with the first consideration. In order to minimize the radiator area and weight, it can be shown, as a result of balancing Carnot efficiency against the T^4 law of radiation, that a minimum area space radiator results when the radiating temperature is 3/4 of the cycle high temperature. This yields an optimum Carnot efficiency of 25%. This consideration forms the basis for evaluating the source temperature and conversion cycle requirements. If one assumes a Rankine cycle with a mechanical conversion efficiency of 40% and the optimum Carnot efficiency of 25%, which

leads to an overall efficiency of 10%, the conversion system radiator area can be determined as a function of cycle hot temperature. This result is shown in Figure 1 with the applicable region of various Rankine cycle working fluids. These regions are defined by consideration of the boiling fluid saturation pressure. Another point of definition is the radiator temperature for a condensation pressure of 5 psia which should allow boiler feed pump operation without cavitation. Radiator weight can be estimated from Figure 1 by using a specific weight of about one-half to one pound per square foot.

C. REACTOR CONSIDERATIONS

The temperature dependence of reactor weight must also be considered in choosing a reactor heat source and power conversion system combination. In general, the lightest high temperature reactor is desired. Reactor size is predominantly determined by the moderator material. The common moderators in order of increasing reactor size are H_2O, Be, BeO, D_2O, and C. Reactor size is temperature dependent because,

1) the moderator density is a function of temperature and,
2) the fuel and moderator material are temperature limited by their physical properties and materials compatibility problems.

An approximate evaluation of reactor weight for various moderators can be estimated from the survey of Safonov.[4] The approximate temperature dependence of these reactors can be computed by adjusting the reactor diameter to be inversely proportional to the density of the core material at temperature.[5] Figure 2 shows the weight of bare spheres having a critical mass of 5 kg of U^{235}. These results are qualitative and should not be considered exact. Water moderation gives the lightest, room temperature reactor but the pressure necessary to suppress boiling and maintain the water density at temperatures above 600 - 700°F make the pressure vessel incompatible with the light weight requirement. Beryllium can be used at temperatures below about 1500°F but it leads to a reactor weight in excess of 500 pounds. A material which can provide the same hydrogen density as cold water and thus the same reactor size at elevated temperature without high pressure is zirconium hydride. At temperatures beyond about 1200°F, the hydrogen density must be decreased with a resultant reactor weight increase in order to maintain the zirconium hydride dissociation pressure constant. In order to use zirconium hydride at elevated temperature the dissociation must be eliminated by containing the material in a cladding that is impervious to hydrogen. It can be seen then from Figure 2 that in the temperature range of 600 - 2000°F, a zirconium hydride moderated reactor is the lightest. Even though a solid U^{235} sphere can lead to similar reactor weights below about 1100°F, fast reactors were eliminated from the selection because the critical mass of a useful reactor would result in a uranium cost of the order of one million dollars. For low power, nonrecoverable space systems, which will be used in quantity in the future, the uranium cost alone for a fast reactor could exceed the cost of delivery into space when the launch costs fall below $1000 per pound.

D. SNAP CONCEPT SELECTION

Of the major system components, the radiator, cycle selection, and reactor concept selection are influenced by the absolute temperature. The power conversion package weight is relatively insensitive to temperature. The boiler weight is primarily a function of the available temperature difference between the cycle boiling temperature and the reactor heat source temperature. This consideration again emphasizes the desire for a high temperature heat source. Even though the popular selection criterion for high power systems is specific weight or pounds per kw, a low power system must be selected primarily on minimum weight in order to allow wide application within current boost vehicle limitations. Inspection of Figures 1 and 2 therefore reveals the following conclusions:

1) Of the possible combinations considered, the zirconium hydride reactor with a mercury Rankine cycle yields the lightest weight system.
2) The water moderated reactor steam cycle combination is definitely eliminated because of the extreme radiator size and weight.
3) The beryllium moderated reactor rubidium cycle combination is eliminated for low power systems because the decrease in radiator weight is far less than the accompanying reactor weight increase. At high powers where the radiator weight is predominant, the rubidium and other alkali metal cycles

are very attractive. However, because of the specialized usage of high power systems (> 100 Kwe) the fast reactor appears to be a better reactor heat source.

Gas cycles have not been considered in this selection because:

1) At a given reactor heat source temperature the radiator area requirement for a gas cycle is very much larger, which is both a weight and awkwardness disadvantage.
2) At a given radiator area the reactor heat source temperature requirement is considerably higher.

These disadvantages arise from the small fraction of Carnot that is recoverable by a gas cycle without resorting to the weight and complexity of reheat and intercooler gas heat exchangers. The limitations imposed by the maximum reactor heat source temperature is particularly significant when the system lifetime objectives are evaluated with respect to the existing state-of-the-art of high temperature reactors and materials. The bulk of the existing long lived reactor and materials experience lies below 1200°F. Therefore, in practice, the development time and cost must also be seriously considered in the selection of a reactor concept and its peak temperature limitation.

E. SNAP 2 DESIGN POINT

A detailed design optimization of the SNAP 2 system for 3 Kwe has resulted in the following design point selection:

Reactor outlet temperature	1200°F
Reactor coolant ΔT	200°F
Reactor power	50 kwt
Hg boiling temperature	900°F
Hg boiling pressure	100 psia
Hg superheat temperature	1150°F
Hg condensing pressure	6 psia
Hg condensing temperature	600°F
Hg subcooled temperature	450°F
Net electrical output	3 kwe

Net system efficiency	6%
Radiator area	110 ft^2

A schematic of the SNAP 2 cycle is shown in Figure 3.

F. SNAP 2 DESIGN CRITERIA

A useful space system must be designed and developed on the basis of many requirements beyond minimum weight. The most important of these are:

1) one-year unattended automatic operation
2) operation in the space environment of vacuum and micro-meteorites
3) remote startup in orbit
4) re-entry burnup and fission product dispersal of systems operating below about 600 miles orbital altitude
5) capability of withstanding the severe shocks, vibrations, gravity, pressure, and temperature transients during vehicle launch
6) capability of operating without subjecting the vehicle to excessive disturbing torques
7) design and installation to permit efficient low weight shadow shielding of payloads
8) packaging and installation to permit prelaunch startup and

   checkout with maximum safety and minimum vehicle and facility risk
9) packaging and installing to provide for vehicle structural and flight stability
10) designed for low cost quantity production with maximum reliability
11) designed for minimum interference and interaction with basic booster and payload subsystems.

The extent to which these practical considerations influence the design of the system and its components will be evident in the subsequent papers which discuss the design features of the major system components and their configurations. For example, safety and shielding which were not stressed in the concept selection have become major design criteria during the translation from concept to practical system.

SUMMARY

In summary, the SNAP 2 system has the following specific objectives: 3 Kwe net output, one-year unattended automatic operation, system weight less than 750 lb, and cycle heat rejection area less than 110 ft^2. In order to meet these objectives, the SNAP 2 reactor employs a homogeneous fuel moderator of zirconium hydride containing 10 wt % U^{235}. The core is composed of a bundle of fuel moderator elements which are contained within a 9-in. diameter core vessel. For minimum weight the reactor is reflected by beryllium and controlled by variations of the effective reflector thickness. The reflector is outside the core vessel and completely separable from the core for safe reactor shutdown and handling. The reactor power output of 50 kwt is removed by a primary coolant loop of NaK 78, which enters the core at 1000°F and exits at 1200°F. The SNAP 2 system employs a mercury Rankine cycle for power conversion. The cycle working fluid is boiled at 900°F and 100 psia, superheated to 1150°F, expanded through a 2-stage axial flow turbine, and condensed at 600°F and 6 psia in a combination condenser-radiator which is a portion of the vehicle skin and which rejects the cycle waste heat to space by radiation. All of the moving parts of the power conversion system are contained within a hermetic housing and mounted on one common shaft which is supported by mercury lubricated bearings.

During the past 5 yr, the SNAP 2 development program has progressed from concept selection through engineering demonstration of all of the major system components.

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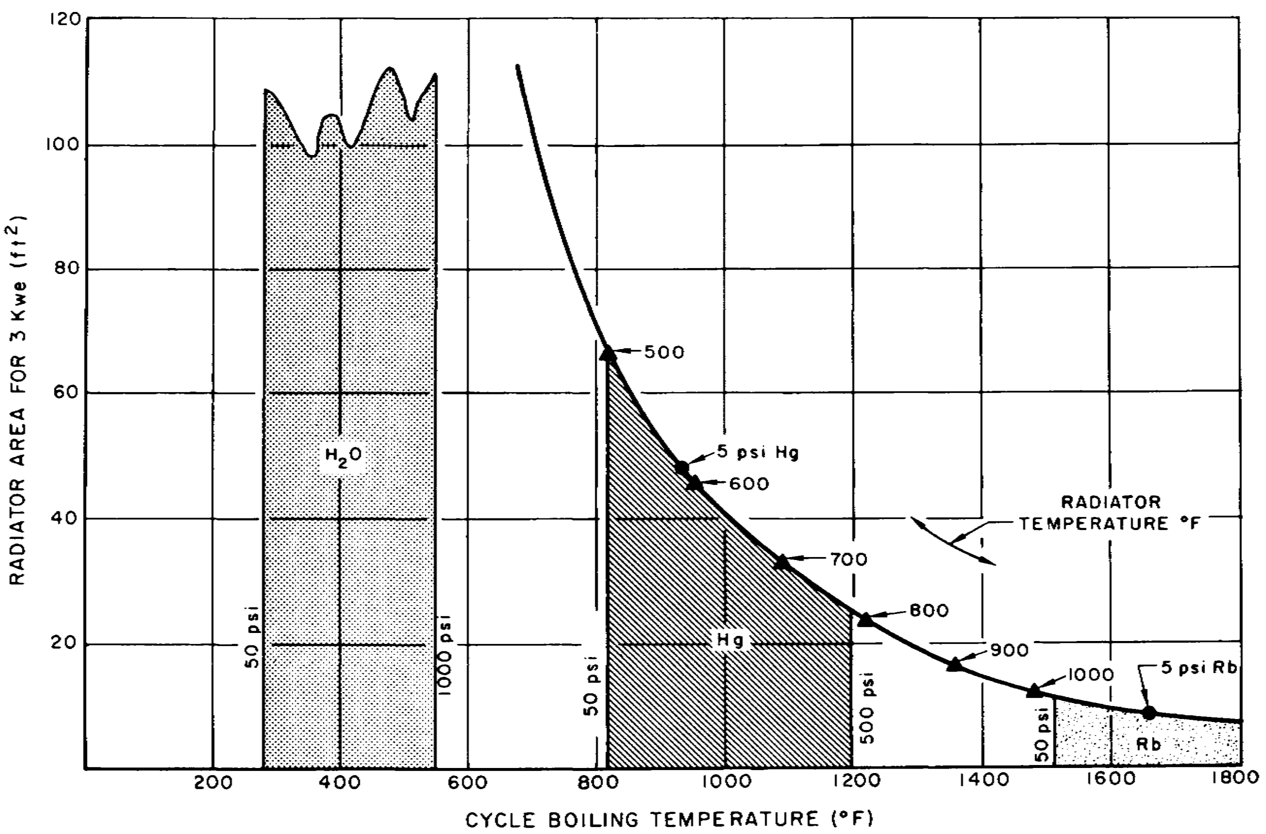

Fig. 1. Radiator Area vs Boiling Temperature Rankine Cycle (η_c = 25% η_o = 10%)

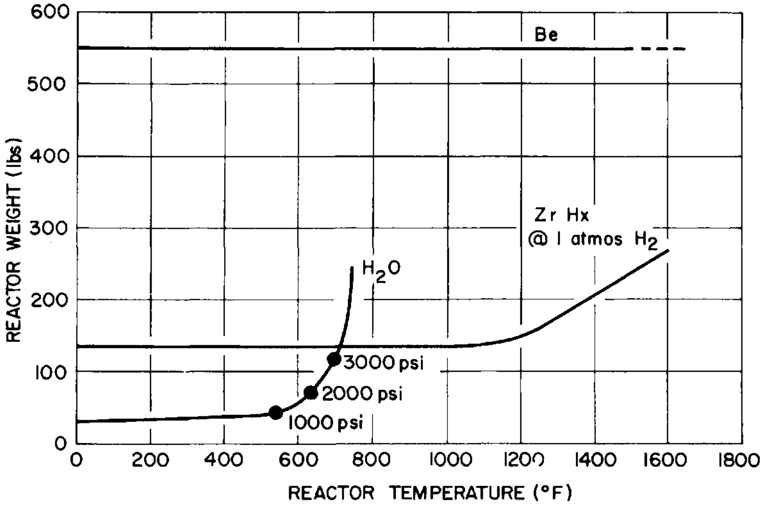

Fig. 2. Reactor Weight vs Temperature Bare Spheres (U^{235} Critical Mass = 5 kg)

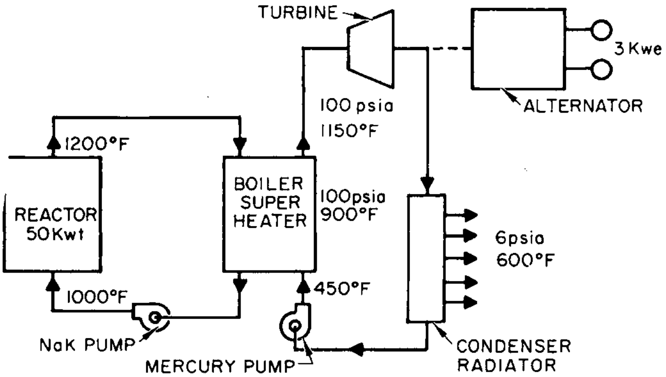

Fig. 3. SNAP 2 Schematic