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SPACE NUCLEAR POWER PLANTS—I

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Abstract—Space nuclear power plants can be configured in a number of different ways depending on the choice of primary loop transport, conversion techniques and heat addition and rejection systems. The large number of the possible configurations mandates a modular approach. A global approach to analyzing the various configurations has been developed. A generalized software, SNAPS (Space Nuclear Auxiliary Power analysis System), has emerged from the studies thus far. The first part of this project which we are presenting in this paper is this computer program SNAPS designed to simulate space nuclear power plants with different energy conversion techniques, to find optimal characteristics constrained in feasibility limitations, and to design the plant for maximum reliability and flexibility. This program is based on the flowsheeting approach in chemical engineering.

1. INTRODUCTION

Reliability, abundance and portability of energy is a key factor in developing and sustaining man's permanent presence in outer space. Space nuclear power systems in turn represent an enabling technology that must be incorporated into future space programs (Anglo and Buden, 1985).

Space nuclear power technology involves the use of the thermal energy liberated by nuclear processes. This heat is released in the spontaneous decay of isotopes (isotope systems), or in the controlled fission of heavy nuclei in a sustained neutron chain reaction (nuclear reactors). The thermal energy so liberated can be used to generate electricity. A generic space nuclear power system consists of the energy source (isotope system or nuclear reactor), the primary heat transport system, an energy conversion-technique and a radiator for heat rejection. There are two general types of primary heat transport systems—pumped-loop and heat pipe. Pumped-loop heat transport systems include the liquid working fluid loop, the liquid–vapor working fluid loop and the gaseous working fluid loop. The possible energy conversion techniques can be divided into two general classes: static and dynamic. A static energy conversion system, such as thermoelectric or a thermionic device uses thermophysical principles that require no moving mechanical parts to convert heat into electricity. A dynamic conversion system, on the other hand, uses the heat engine principle to provide the mechanical work necessary to generate electricity in a turbo-alternator assembly. Dynamic conversion systems can be further subdivided into rotating (Brayton and Rankine cycles) or reciprocating (Stirling cycle) devices.

The key factors which are important to space application of a nuclear power plant include power and efficiency, mass and volume, reliability, safety and flexibility.

Stringent spacecraft mass and volume restrictions force nuclear power system designers to develop systems with the best power-to-mass ratio possible. Isotope systems are best suited for lower power (below 10 kWe), while nuclear reactor systems are more suitable for MW power sources. The key advantage offered by space reactors is that of high power at an attractive power-to-mass ratio. Since nuclear reactors can be considered as a tremendous source of energy, the factor which drive mass and volume reductions are thermal transport from reactor to conversion system, the power conversion system (PCS), and the radiator, and not the nuclear reactor.

Long duration space missions impose very strict reliability requirements. Further, more continuous advancements in materials technology introduce uncertainties in operating parameters, which call for higher flexibility in design. The primary thermal transport system, power conversion technique and radiator also play an important role in the reliability and flexibility issues.

Since 1961, the U.S. has launched a number of NASA and military space systems which derived all or part of their power requirements from nuclear energy sources. The current research program which is underway, is the SP-100 program. This program involves assessment of a large matrix of various combinations of reactors and power converters that could form a reactor electric system. However, the program is facing the problem of over ambitious

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goals of power requirements constrained by the overall mass. There is no clear-cut choice between dynamic and static conversion processes; each application brings different considerations of power, mass, volume, reliability, safety etc. For space nuclear power systems, the choices of heat source and power conversion methods are highly interdependent. A global analysis which accounts for future advancements in materials technology, and considers combinations of different thermal transport and power conversion techniques is essential.

This paper is the first in a series which will deal with development of such a global approach for designing an overall optimal space nuclear power system with maximum power output, reliability and flexibility, and minimum mass. The first part of the project, described here, is a computer program to simulate a space power plant with any of the possible combinations of thermal transport and power conversion systems.

The computer program SNAPS (Space Nuclear Auxiliary Power analysis System) is based on the popular concept of flowsheeting commonly used for simulations, optimization and analysis of chemical engineering plants. Although there are a number of computer codes which can be separately used to simulate different conversion techniques for space nuclear power plants (Marshall, 1986; Moyers, 1985; Wetch, 1988), SNAPS provides a unified global approach for simulation, optimization and analysis of possible space nuclear power systems.

2. A UNIFIED APPROACH

As stated earlier, the primary thermal transport systems, the energy conversion techniques and radiator design play an important role in space nuclear plant analysis, since these govern the mass and volume reductions.

The primary thermal transport system in a space nuclear power system carries thermal energy from the nuclear reactor to the power conversion loop. The energy conversion techniques operate between the primary heat transport system and the radiator. The two candidates for static power conversion are thermoelectrics and thermionics. Thermoelectrics use the same principle as the thermocouple, whereas thermionics operate at a much higher temperature and are based on the concept of electron transfer from cathode to anode. The thermionic converters offer a somewhat higher efficiency than the thermoelectric converters. The dynamic conversion techniques work on the concept of the heat engine and their performance can be directly assessed in terms of the Carnot efficiency.

A unified approach to all the conversion techniques described above is based on the Carnot cycle principle. Unlike dynamic cycles (heat engine principle), thermionic converters and thermoelectric converters do not involve conversion of mechanical work into electrical work and the electrical energy is generated directly. However, the thermionic and thermoelectric converters also obey the second law of thermodynamics, and hence can be considered as heat engines with electrons as the "working fluid". This unified approach is useful in identifying global components or equipment in the possible energy conversion techniques and is the basis of SNAPS (described in the next section). In addition, SNAPS also has a modular structure. The modularity will allow different combinations of heat addition, rejection and work generation stages. Improving energy efficiency by regeneration, interstage heating and cooling to obtain modified cycle performance can also be analyzed using SNAPS.

The basic unit modules needed to build an energy conversion system along with the primary transport system are heat exchangers, the thermionic converters, the thermoelectric converters, radiators, heat pipes, compressors and turbines and pumps.

3. SNAPS—A MODULAR APPROACH FOR ANALYSIS OF SPACE NUCLEAR POWER PLANTS

Flowsheeting is a widely accepted technique for carrying out design and cost estimation studies for chemical process plants. Flowsheeting may be defined as the use of computer aids to perform steady-state heat and mass balancing, sizing and costing calculations for a chemical process (Westerberg *et al.*, 1979). An extension of the flowsheeting approach of chemical process simulators is used in the development of SNAPS in our work. SNAPS differs from the conventional chemical process simulators in the stream matrix concept, the final objective or results, and unit operation modules.

3.1. Stream matrix and point concept

In chemical processes material balance is very important since several unit operations like distillation, flash, absorption, mixing, splitting etc. results in changes in material stream composition and flowrates. Space nuclear plants are different from chemical processes in that most of the time, the stream compositions or flowrates remain the same throughout the plant. This calls for major changes in the stream matrix. The common material stream vector format containing stream properties with the component flows and total flowrate is wasteful in this context, since an entire stream vector is needed to account for differences in temperature or pressure. SNAPS uses a unique concept of points identified by short property vector where only properties like vapor fraction, enthalpy, density etc. associated with each stream are stored. The stream vector contains the molar flowrates only. SPAD (Hugh *et al.*, 1981), the chemical process simulator is based on this concept. SNAPS has been built using the executive from the SPAD simulator. In SNAPS, the points are associated with each material, and information stream (with no mass). Two types of information streams are available: the heat stream and power stream. Although the novel concept of point was introduced in SPAD, it is more appropriate for space nuclear power plants where mostly point properties change in any of the unit modules while stream flowrates and compositions remain constant throughout.

3.2. *Final objective*

The objective of SNAPS is to evaluate the key factors necessary to design a feasible, reliable, and optimal space nuclear power plant. As stated earlier the potentially important factors are power, efficiency, mass, reliability and flexibility.

Power is the measure of work done. In dynamic conversion techniques the mechanical work results in electric power, while static converters produce electric power directly without any mechanical work. Overall power and efficiency is calculated by adding all the power streams in the plant at the end of the calculation. Mass and volume constraints drive almost every aspect of a spacecraft design, since spacecraft is useless if it is too heavy or too large to be launched. The need of lighter equipment for space nuclear power plant is hence of utmost importance. In SNAPS, there is a provision to add mass correlations for each equipment and the SNAPS executive will be able to predict the approximate mass of the space nuclear power system under consideration, using the additive property of mass. Calculation of reliability and defining a proper reliability index will also be introduced in SNAPS in future, since reliability is one of the important considerations. A measure of flexibility of the system under uncertainty will also be defined and its calculation will be implemented in SNAPS.

3.3. *Unit operations*

SNAPS has a number of new unit operations which are not found in any of the chemical process simulators. Figure 1 shows all the unit modules available in SNAPS and the connectivity of each unit in terms of streams and points. The unit modules essentially provide energy balance around each unit. The mathematical equations for the above unit operations can be found elsewhere (Diwekar, 1991). Since, as a first step, SNAPS will be used for preliminary design and optimization, simplified steady-state models are provided for the unit operations. As the need arises, the rigor of the model will be increased and a simultaneous approach will also be employed.

4. RESULTS AND DISCUSSION

The current version of SNAPS is used to simulate the different space nuclear power plants configuration proposed in the literature. The first example uses the Brayton cycle from the SP-100 evaluation report (Anderson *et al.*, 1983). The Brayton cycle working fluid is a mixture of He and Xe, with Li being used for primary thermal transport. An equivalent block diagram with SNAPS unit modules is generated based on the availability of data. The block diagram and point summary along with input data and specifications are shown in Fig. 2a. It can be seen from Fig. 2a that the reactor and the coolant loop are simulated using a heat exchanger with heat absorption and the electromagnetic pump is omitted because the design data are not reported.

The overall flowsheet uses only three unit modules (HEX, CMP, ZTA) from SNAPS. The modularity of the system made this possible. The converged results from SNAPS are shown in Fig. 3a. Although the Rockwell report states that this cycle exceeds the currently applicable technology limitations, we selected it to demonstrate the capabilities of SNAPS. Closer correspondence to the reported results was the aim of this exercise. One aspect of SNAPS is to simplify the process of performing the parametric studies, Fig. 3b shows the effect of different parameters like heat added, initial temperature of heat exchanger 1, maximum temperature of the cycle, radiator area and gas flowrate etc. These parametric studies combined with optimization can provide design trade-off. For example, the power goes through a minimum value if the energy added is increased and this minimum depends on what initial temperature heat exchanger 1 is operating at. Similarly, it can be seen that the power increases asymptotically with an increase in radiator area.

Figure 2b represents the SNAPS block diagram for another possible configuration of space nuclear power generation. The heat exchanger supplies heat to the thermoelectric generator with 1000 thermoelectric converters operating in series, which generates power and rejects the residual heat to the radiator. The input data and results of this problem are shown in Table 1, where the material properties are obtained from El-Wakil (1982). This example demonstrates the use of SNAPS for simulating the operation of

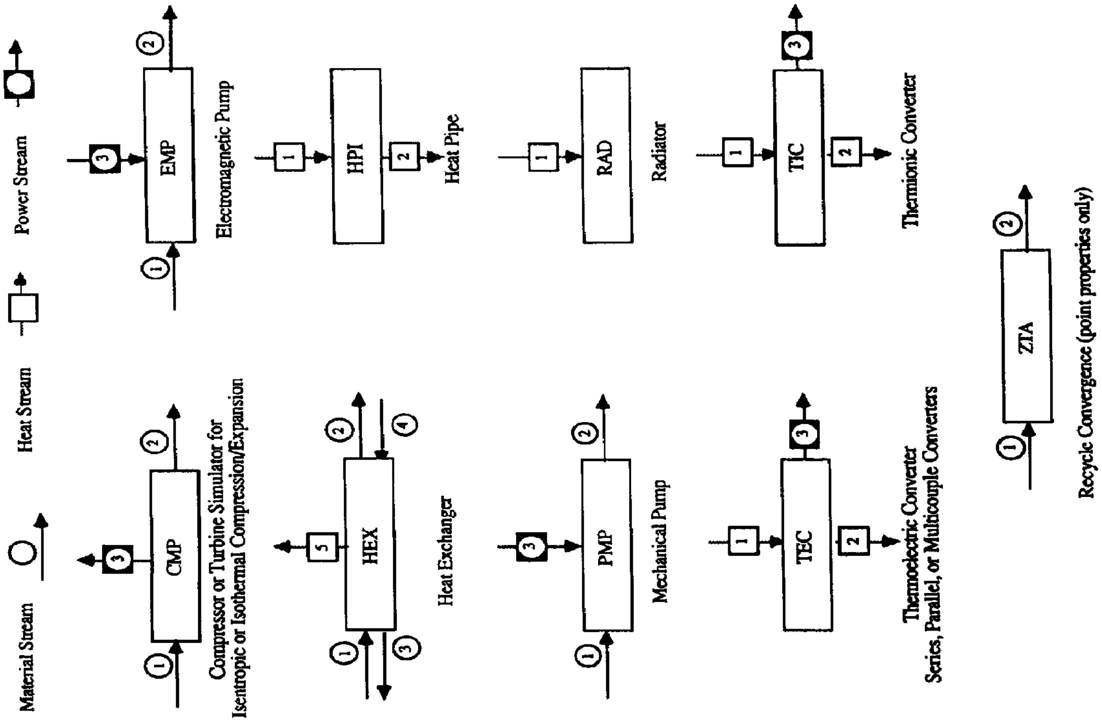


Fig. 1. SNAPS—unit modules and connectivity.

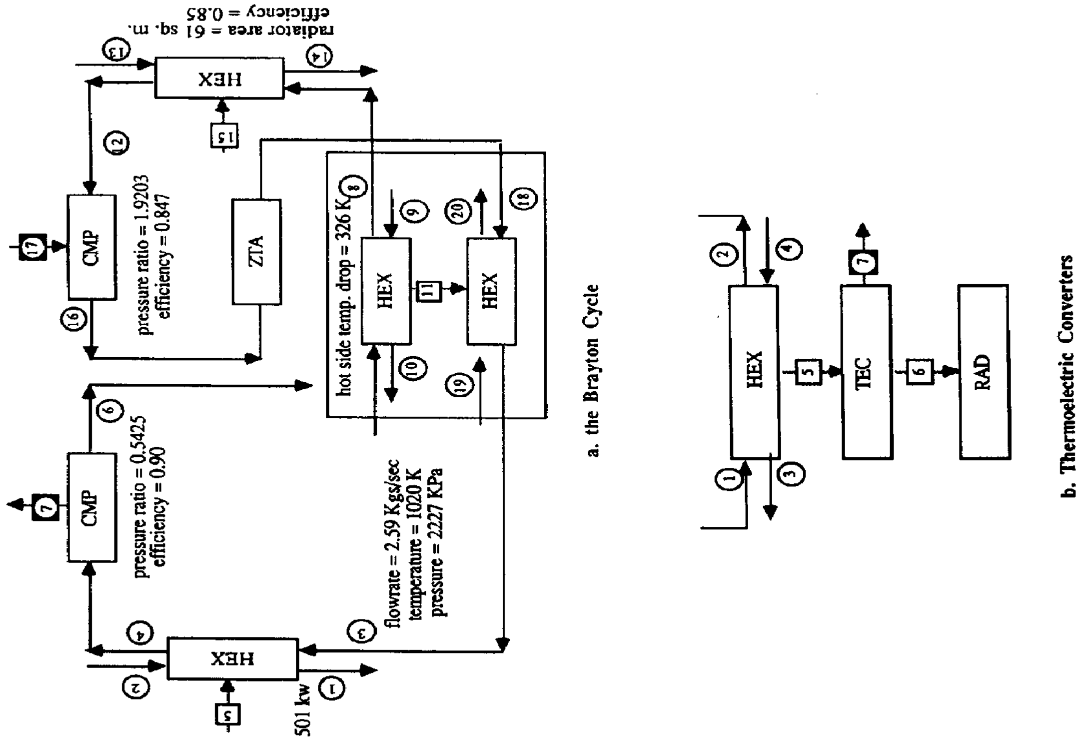
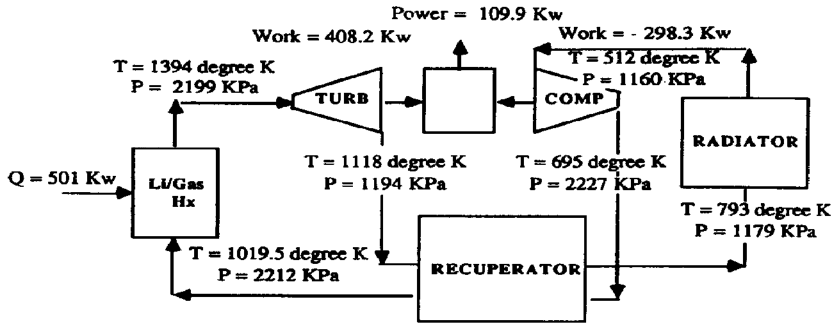
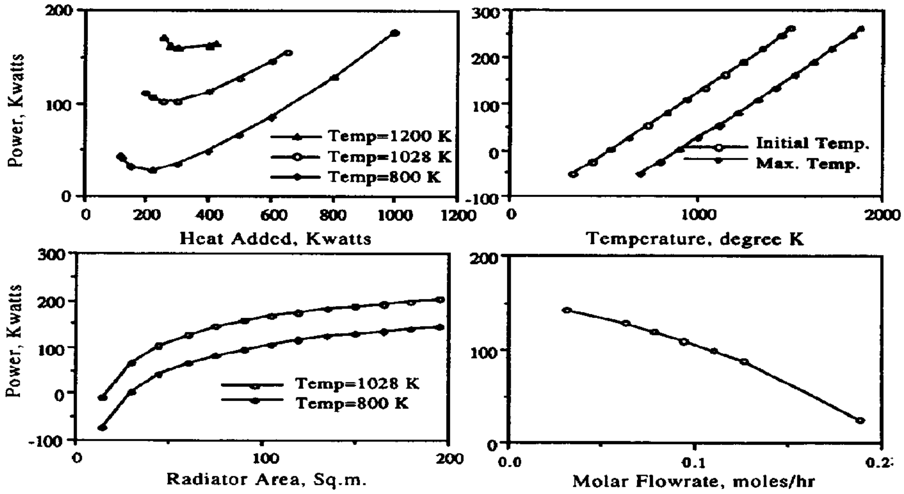


Fig. 2. Brayton cycle.



a. Base Case



b. Parametric Studies

Fig. 3. Parametric study.

a thermoelectric converter similar to that used in SNAP-10A (El-Wakil, 1982).

The above two examples show that the modular nature of SNAPS allows one to simulate any possible space nuclear power plant configuration. Implementation of mass correlations and formulation of reliability and flexibility indices along with the optimization capability will be a part of the next version of SNAPS.

5. CONCLUSIONS

This paper presents a new approach to analyzing space nuclear power plants. A modular computer

Table 1. Input data and results for Problem 2 (Fig. 2b)

Input data		Results	
Heat exchanger		Heat exchanger	
Hot side liquid	NaK		
Liquid flow	6.15 gpm	Heat duty	8.748 kW
Entering temperature	745 K		
Thermoelectric converters		Thermoelectric converters	
Thermoelectric material: n-type	SnTe–PbTe	Figure of merit	0.00159
Thermoelectric material: p-type	AgSbTe2–Ge–Te	Resistance ratio	1.45
Number of TECs	1000 in series	Current	10 amp
Load resistance (individual)	0.0045 Ω	Power	0.451 kW
$(l/A)_n$	104.9 m^{-1}		
$(l/A)_p$	46 m^{-1}		
Radiator		Radiator	
Heat rejected	8.297 kW	Area	1.845 m^2
		Average temperature	400 K

environment (SNAPS) based on the flowsheeting approach in chemical engineering is developed. SNAPS is a flexible package which aids in analyzing space nuclear power plants with any possible combination of the primary thermal transport and the energy conversion techniques. A global approach to design is possible because of this versatility of SNAPS. In the future, SNAPS will also contain an optimization tool. This general-purpose tool will then allow the user to design an optimal, flexible, and reliable nuclear power plant for space applications. The first part of the program which generates the overall energy balance of the plant is tested extensively using the data from a number of space nuclear power plants reported in the literature.

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