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DESIGN CHANGES IN SNAP-8 FOR REDUCED REACTOR OPERATING TEMPERATURES

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Lewis Research Center
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TECHNICAL PAPER proposed for presentation at
Fifth Intersociety Energy Conversion Engineering Conference
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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

The SNAP-8 mercury Rankine system is a nuclear-electric power conversion system designed to explore the principles and technologies required for electric power production in space using liquid metals as working fluids. The current system is designed to produce a net electrical output of 35 kWe. A number of system changes are presently being considered by NASA as a result of endurance testing of the two most recent zirconium hydride (ZrH) reactors. The design changes and the resulting performance is discussed.

Introduction

The SNAP-8 program is now entering a new phase, viz., preparation for the Combined System Test of the power conversion system in combination with the reactor. As a consequence of the test of the two most recent ZrH reactors some adjustment in the design of the power conversion system is being evaluated as a means of reducing reactor operating temperature and thereby perhaps extending reactor life. Furthermore, space station and space base concepts currently under study by NASA contractors desire electrical power levels of 50 to 100 kWe with 5- to 10-year life.

This paper will present the results of performance studies that have established a new SNAP-8 system operating point at reduced reactor discharge temperature, and describe the hardware modifications associated with these changes.

Power Conversion System

The power conversion system (PCS) for SNAP-8 consists of four loops (Fig. 1). Thermal power from the reactor is transferred to the boiler via the reactor coolant, a eutectic mixture of sodium and potassium (NaK-78) that is driven by a NaK pump in the primary loop. The mercury loop consists of the boiler, turbine-alternator assembly, condenser, and the boiler-feed pump. Waste heat is removed in a second pump-driven NaK loop, the heat-rejection loop. The fourth loop contains an organic fluid which lubricates the bearings of the mercury-loop rotating components and provides coolant for the alternator, motors, and electrical controls. There is also an auxiliary loop which couples the two NaK loops during startup in order to provide a thermal load for the nuclear reactor prior to startup of the mercury loop. The steady-state design operating condition for a SNAP-8 flight system in the present state of development is also shown in Fig. 1. A detailed description of the power conversion system components is reported in Ref. 1.

PCS Performance

The SNAP-8 mercury-Rankine system is further along in its development than any other dynamic power system. Every major component of the system has successfully operated for at least 10,000 hours, and the complete power conversion system was tested for 7320 hours without replacement of any of its components.

The SNAP-8 Power Conversion System (PCS) was tested in breadboard arrangement to determine its performance over a large range of simulated reactor discharge temperatures and turbine back pressures. Figure 2 illustrates the system performance when the turbine discharge pressure is held constant at the design level of 14 psia and the boiler NaK inlet temperature is lowered. At a 1200° F nominal NaK inlet temperature the system net electrical output drops from 37 kWe at the nominal reactor conditions of 1300° F outlet temperature and 535 kWt reactor power to 24 kWe. At 1100° F the net electrical output drops to zero. The effect of reducing turbine back pressure on system power while holding turbine design inlet conditions is shown in Fig. 3. At approximately 8 psia turbine back pressure, the gain in system electrical output for a proportional reduction in back pressure begins to diminish. This effect is caused by choking in the turbine fourth-stage passage areas due to the volume flow increase resulting from the lower turbine back pressure. The combination of lowering the reactor temperature to 1200° F and operating the turbine at a back pressure of 8 psia with the present SNAP-8 hardware resulted in a measured system net electrical output of 30 kWe as shown in Fig. 2. The electrical parasitic power consumption for the pump motor assemblies and control system is 21 kWe.

New PCS Arrangement

The basic arrangement of the current PCS has recently been modified to include an intermediate heat exchanger (IHX) as shown schematically in Fig. 4. In this heat exchanger, NaK that is heated in the reactor transfers its heat to a second stream of NaK, and heat from this second stream of NaK boils mercury for operation of the mercury-Rankine loop. Because the NaK in this intermediate loop does not pass through the reactor, it does not become radioactive. The principal reasons for adding this heat exchanger are as follows:

(1) Because the NaK-NaK intermediate heat exchanger is smaller than the mercury boiler, the size and thus weight of reactor shielding is thereby reduced.

(2) The increased isolation of the reactor provided by this heat exchanger diminishes the probability that radioactive material will be widely distributed throughout the power conversion system.

(3) The design of the reactor primary loop and reactor shield are then almost independent of the type of power conversion system using the reactor.

These advantages are obtained at the expense of both increased complexity for the system and performance penalties resulting from both the temperature drop in the heat exchanger and the amount of power required for operation of the electromagnetic pump used in the reactor primary loop.

Reduced Reactor Operating Temperatures

A 100° F or more reduction in the reactor discharge temperature would ease the operation stresses in the fuel element cladding and extend the operating lifetime of the Zirconium Hydride Reactor. For a fixed mercury-Rankine heat rejection temperature the energy available for power conversion decreases when the upper cycle temperature is reduced. This loss in available energy can be restored by reducing the rejection temperature at the expense of larger radiator areas. PCS performance studies were made for a reactor discharge temperature range of 1300° to 1100° F and for turbine discharge pressures ranging from 14 psia down to 2 psia. The ground rules used for this study were as follows:

(1) Design for a minimum net electrical power level of 50 kWe.

(2) Do not exceed the 600 kW thermal rating of the ZrH reactor.

(3) Minimize the changes to those components that have been qualified and operated for over 10,000 hours.

(4) Maximize the performance-life characteristics of the electrical generating system.

The reactor energy-temperature characteristics used in these studies are shown in Fig. 5. The information in Fig. 5 is used for defining trends since actual reactor life is dependent on core changes that will result from present corrective action programs. Figure 6 combines the above reactor life characteristics with the available energy from the mercury-Rankine loop at turbine discharge pressures of 8 and 4 psia. An optimum operating point occurs at approximately 1175° F (reactor discharge temperature) with substantial drop-off at the 1100° and 1300° F conditions. Below 1175° F the available energy from the mercury-Rankine loop decreases at a faster rate than the gain in reactor life. Above 1175° F the reactor life decreases faster

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than the gain in available energy from the mercury-Rankine loop. Operation at 1175° F maximizes the performance-life characteristics of the electrical generating system.

The optimum operating point for the electrical generating system does not change markedly for the two turbine back pressures, 8 and 4 psia, plotted in Fig. 6.

New System State Point

A decision to derate the current 1300° F power conversion system to 1200° F has been made by the NASA-Lewis Research Center. The IHX requires that the reactor be operated at 1220° F. The expected reactor discharge temperature variation at 1220° F is in the order of ±12° F. Allowing 3° F for heat loss in the piping system between the reactor and boiler and allowing 20° F across the IHX establishes the minimum boiler NaK inlet temperature at 1185° F. Assuming a 35° F minimum pinch point (temperature difference between the bulk NaK and Hg at the boiling interface) and a 35 psia boiler pressure drop allows the turbine inlet pressure to be set at 145 psia. The turbine inlet temperature is 1150° F as a result of a 35° F terminal temperature difference between boiler NaK inlet temperature and boiler mercury vapor discharge temperature. In order to obtain larger system output powers, the turbine vapor flow was increased to utilize the full 600 kWt thermal rating of the reactor.

Tests on the current condenser indicate that it can be used at 8 psia. At inlet pressures of 6 psia and lower choking occurs causing increased pressure losses through the condenser. Optimization studies on the mercury jet pump indicate that the mercury-pump motor assembly suction limit can be reduced to below 4 psia. In an attempt to minimize component changes the turbine discharge pressure for the new state point was conservatively set at 8 psia. The new state point conditions for a nominal reactor temperature at discharge of 1220° F is summarized in Table I.

The changes shown in Table I to the current turbine state point conditions allows a substantial improvement in the specific speed ($NQ^{1/2}/H^{3/4}$) of the turbine. Figure 7 compares the performance of most of the mercury turbines built in this country against turbine specific speed averaged on a stage basis. The maximum efficiencies obtainable are characterized by the three-dimensional (impulse-reaction) curve (Ref. 2). Since the current SNAP-8 turbines have been designed based on two-dimensional flow (pure impulse) a maximum two-dimensional efficiency curve is shown. The large mercury turbines designed by General Electric during the late 20's and 30's approached 75 percent turbine efficiency for a specific speed range of 48 to 70. These turbines fell short of the maximum efficiency possible for three-dimensional designs since they were designed to operate with saturated mercury vapor at the inlet, and as a result operated with large amounts of moisture in the later stages. By comparison, SNAP-8 utilizes 200° F of superheat and operates with less moisture per stage. The SNAP-2 turbines, along with the present SNAP-8 turbine, performed between 57 and 62 percent efficiency for a specific speed range of 34 to 42. The maximum efficiency for this specific speed range is 66 to 70 percent. The lower performance of these turbines is attributed to the influence of the interstage labyrinths and the relatively large wheel tip clearance to blade height ratios, moisture, and the Reynolds number effect when dealing with smaller size turbines.

The specific speed for the modified turbine has increased markedly as a result of the higher volume flows and reduced head across the turbine. The average per stage specific speed is 56 for the modified design as compared to 36 for the current design. The maximum turbine efficiency at this specific speed is 74 percent. Correcting the parameters that caused the original departure of 10.5 points for the new conditions results in an overall correction of 7.5 points. These are listed in Fig. 7. A new turbine efficiency of 66.5 percent might be possible without making any modifications to the present labyrinth and wheel tip clearances, and the criterion of two-dimensional flow. Using the 66.5 percent turbine efficiency value, the state point conditions set down in Table I, and 24 kWe of electrical parasitic power yields a net electrical output of 54 kWe. Table II shows the performance comparison of the electrical generating system for the current and proposed systems. The net electrical output power can be increased by 4.65 kWe for systems that do not use the IHX.

Reducing the turbine back pressure from 14 to 8 psia will cause an increase in radiator area. Table III summarizes the important radiator characteristics of the 1220° F SNAP-8 system operating at the reduced back pressure. The overall system characteristics for the IHX systems using ac EM pumps in the reactor primary loop are compared against the current system in Table IV.

Of significant importance is the comparison of the parameter kWe-hr/lb for the two systems shown. The 1220° F system with the IHX can produce 27.3 kWe-hr/lb as compared to 12.5 kWe-hr/lb for the current system.

Hardware Changes for the 1200° F System

The following component changes are required to operate at the reduced reactor temperature and reduced turbine back pressure conditions.

Turbine

Only the Turbine Assembly portion of the Four-Stage Turbine Alternator Assembly must be modified. This is made possible since the turbine assembly, and the alternator assembly are of modular design that are bolted together. No significant changes in the first two-stage rotor blade heights are expected, however the nozzle areas will increase allowing full admission as compared to 38 and 49 percent admission on the current design. These changes will improve the aerodynamic design of the turbine and eliminate the thermal temperature gradients associated with partial admission designs. The new third-stage rotor blade height will be similar to the present fourth-stage blade height. The basic modification to the turbine is in the fourth stage that requires a blade height increase from 0.631 to 1.39 inches. The long endurance hours achieved on the bearing system and the alternator will not be invalidated by the redesign of the turbine assembly. Structural technology developed on the previous turbine assembly, operating clearances, and materials used previously will again be used in the redesign.

Boiler

The increased volume flow through the boiler that results from lower systems pressures will require additional boiler tubes. The design of the boiler will be the same, Bare Refractory Double Containment, as will the plug and coil insert, tube size, materials, etc. The overall tube length will be slightly shorter (22 vs. 25 ft).

Mercury Pump

The primary stage of the mercury pump motor assembly, the jet pump, will be optimized in order to reduce the suction pressure limit to below 4 psia. Jet pumps tests at Lewis (Ref. 3) indicate the change to be within known technology. No changes are required in the motor, the bearing system, or the centrifugal impeller design presently being used. The change to the jet pump is considered to be minor.

Conclusions

Reducing the SNAP-8 system temperature from 1300° to 1200° F will allow substantial gains in reactor operating life (using the calculated reactor life-temperature characteristics shown in Fig. 5) and substantially improve the kWe-hr/lb parameter. In addition, substantial improvements in the prime mover efficiency result from the improved specific speed range that occurs at reduced turbine back pressure and increased volume flow through the turbine. An intermediate performance improvement from 37 to 54 kWe is possible for the Combined System Test by modifying the boiler and turbine assembly and by optimizing the jet pump on the mercury pump motor assembly. New hardware is required for the Reactor Primary Loop with the Intermediate Heat Exchanger (IHX) approach. The major new components in the Reactor Primary Loop are the Intermediate Heat Fxchanger and the electromagnetic pumps.

References

1. Thur, G. M., "SNAP-8 Power Conversion System Assessment," Intersociety Energy Conversion Engineering Conference, Vol. 1, IEEE, New York, 1968, pp. 329-337.

2. Baljé, O. E., "Axial Cascade Technology and Application to Flow Path Designs. Part I - Axial Cascade Technology," Journal of Engineering for Power, Vol. 90, No. 4, Oct. 1968, pp. 309-328.

3. Sanger, N. L., "Noncavitating and Cavitating Performance of Several Low Area Three Ratio Water Jet Pumps Having Throat Lengths of 3.54 Diameters," TN D-5095, 1969, NASA, Cleveland, Ohio.

TABLE I. - NEW TURBINE STATE POINT CONDITIONS

State point	Current	1220° F system
Inlet temperature, °F	1250	1150
Inlet pressure, psia	245	145
Exhaust pressure, psia	14	8
Vapor flow, lb/hr	11,850	13,685
Speed, rpm	12,000	12,000

TABLE II. - NET ELECTRICAL OUTPUT

	Current 1300° F system	1220° F system
Reactor discharge temperature, °F	1300	1220
Boiler NaK inlet temperature, °F	1300	1200
Reactor thermal power, kWt	535	600
Turbine discharge pressure, psia	14	8
Turbine specific speed (average/stage	36	56
Turbine efficiency, percent	57	66.5
Alternator gross output, kWe	58	78
Electrical parasitics, kWe	21	24
Net electrical power, kWe	37	[a]54

[a]Turbine efficiency could be as low as 63.5 percent and still achieve 50 kW.

TABLE III. - RADIATOR CHARACTERISTICS

	Current 1300° F system	1220° F system
Heat rejected in HRL radiator, kWt	445	512
Radiator inlet/discharge temperature, °F	636/457	586/416
Radiator areas, ft²		
Heat rejection loop (NaK)	1216	1725
Lube/coolant (4P3E)	480	480
Total radiator area	1696	2205
Radiator weights, lb (Dual fin with structure and armor) reliability = 0.99		
Heat rejection loop radiator	2170	3200
Lube/coolant radiator	720	720
Total weight	2890	3920

TABLE IV. - SYSTEM CHARACTERISTICS

	37 kWe current system	54 kWe modified system
Reactor power, kWt	535	600
Nominal reactor temperature, °F	1300	1220
Reactor life, hr	27,000	39,000
System weights, lb[a]		
PCS components[b] and frame	15,000	13,500
Fifth loop	N/A	2170
Radiator and supports	2890	3920
Nuclear system and shields[c]	61,900	57,700
Total weight, lb	79,790	77,290
kWe-hr/lb	12.5	27.3
Cycle efficiency, percent	6.9	9.0

[a]Estimated system weights.
[b]Includes weight for redundant PCS.
[c]NASA five-layer shield design for reference ZRH reactor. Gallery outboard of reactor. Side dose: 30R/6 months at 200'; Crew direction: 1R/6 months at 200', 2600R/6 months outboard of gallery (away from crew).

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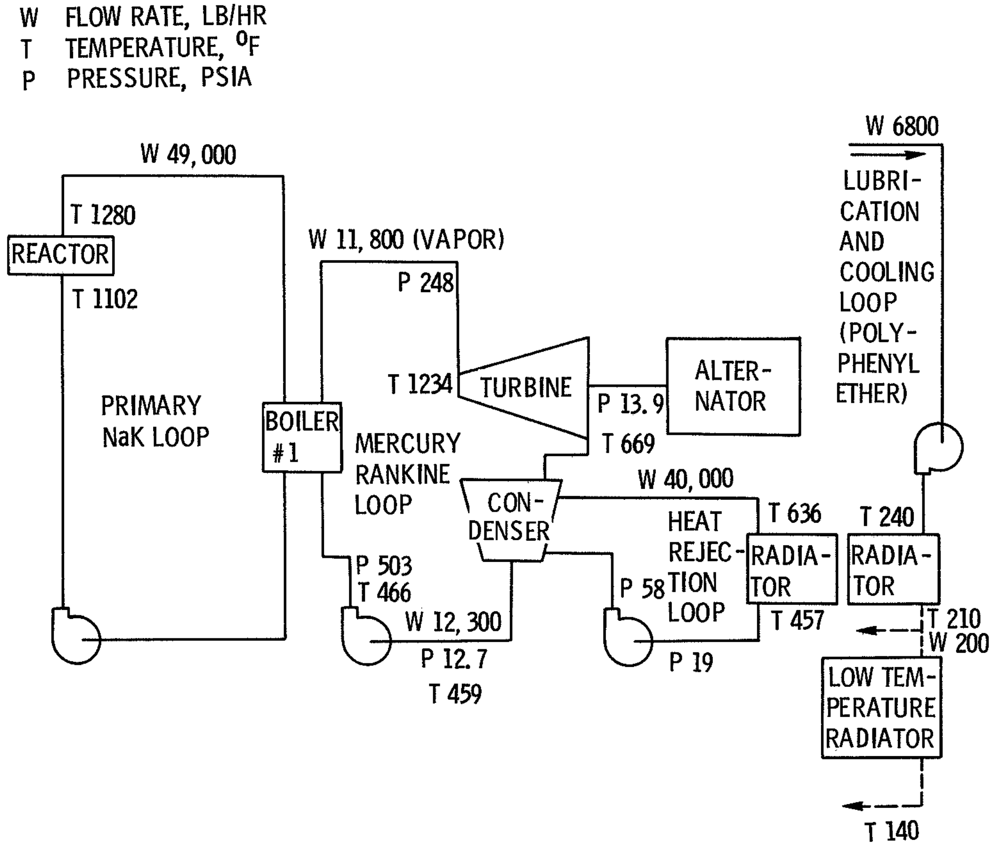

Figure 1. - System arrangement and operating conditions.

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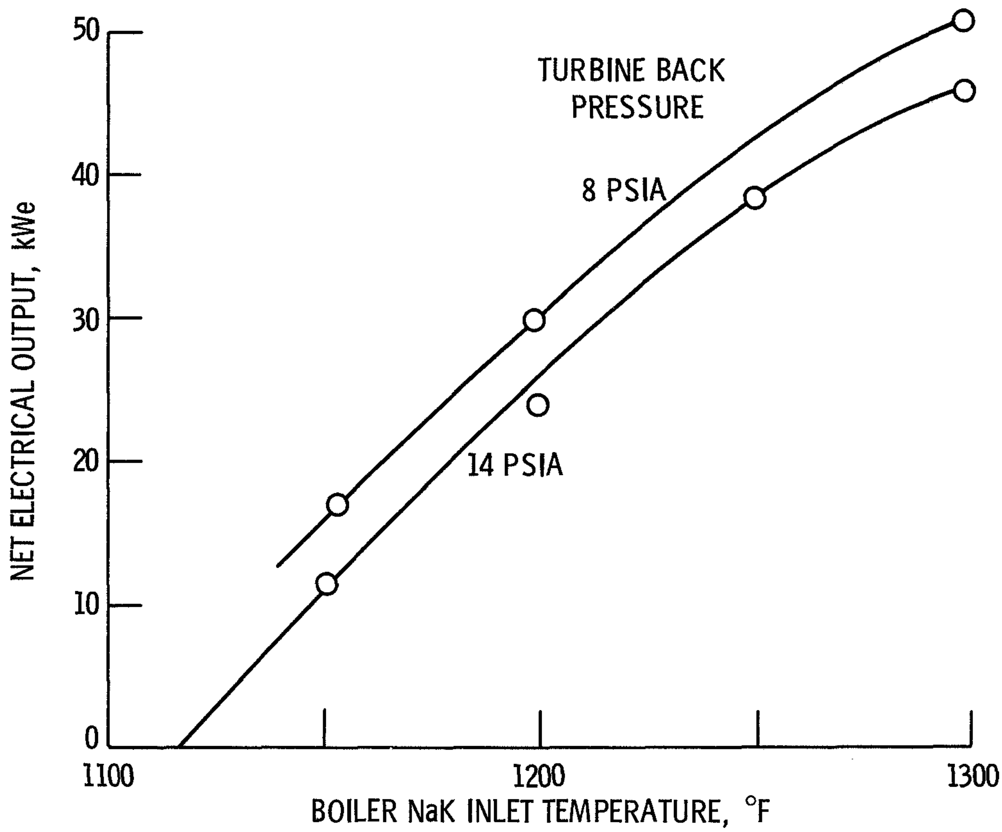

Figure 2. - Current system performance at reduced boiler inlet temperatures.

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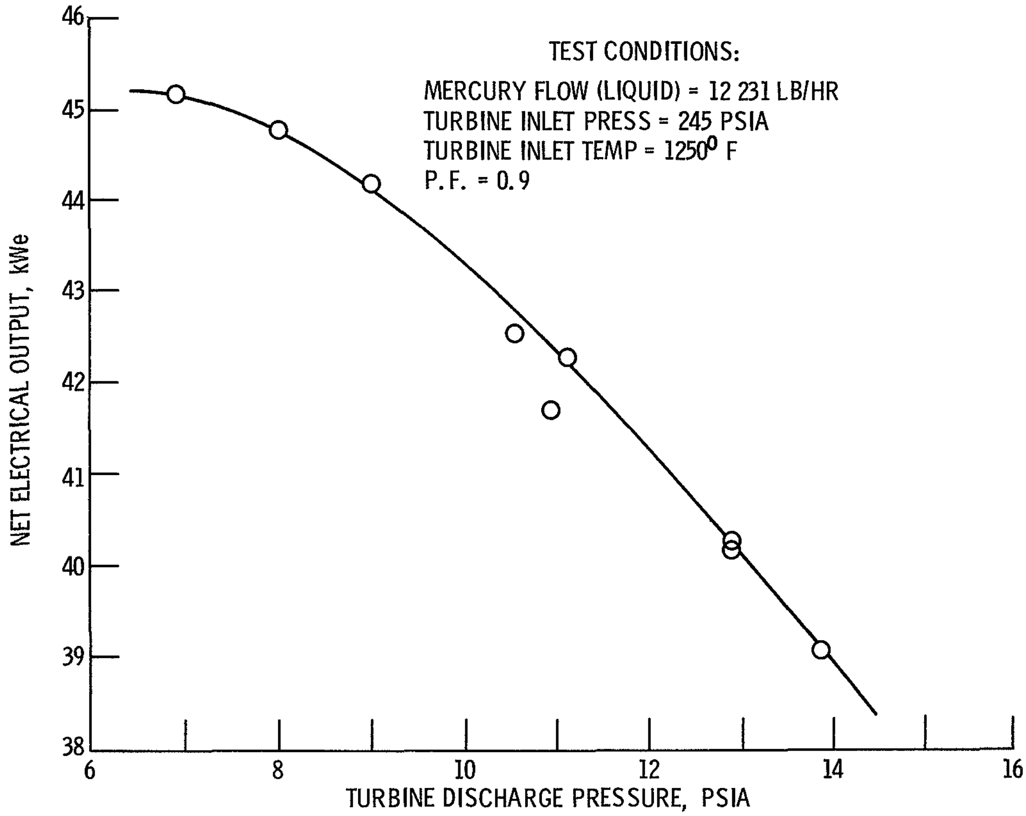

Figure 3. - Net electrical output versus turbine discharge pressure.

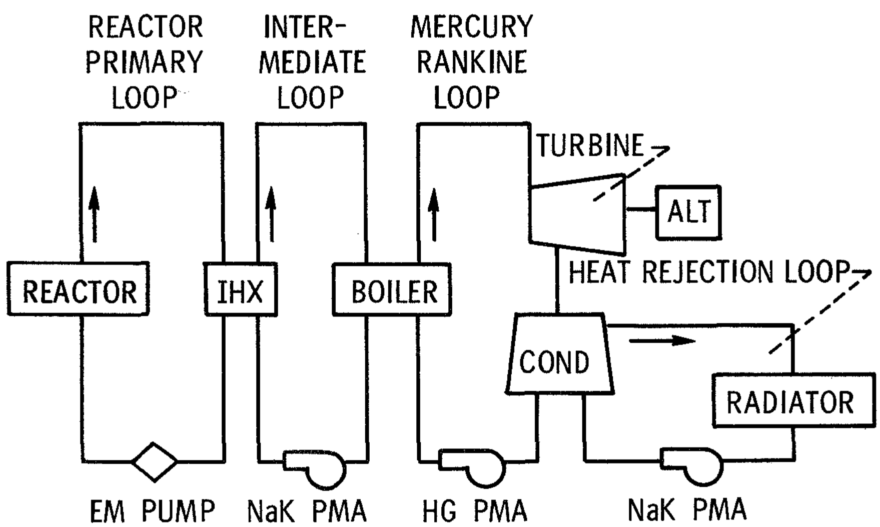

Figure 4. - SNAP-8 system.

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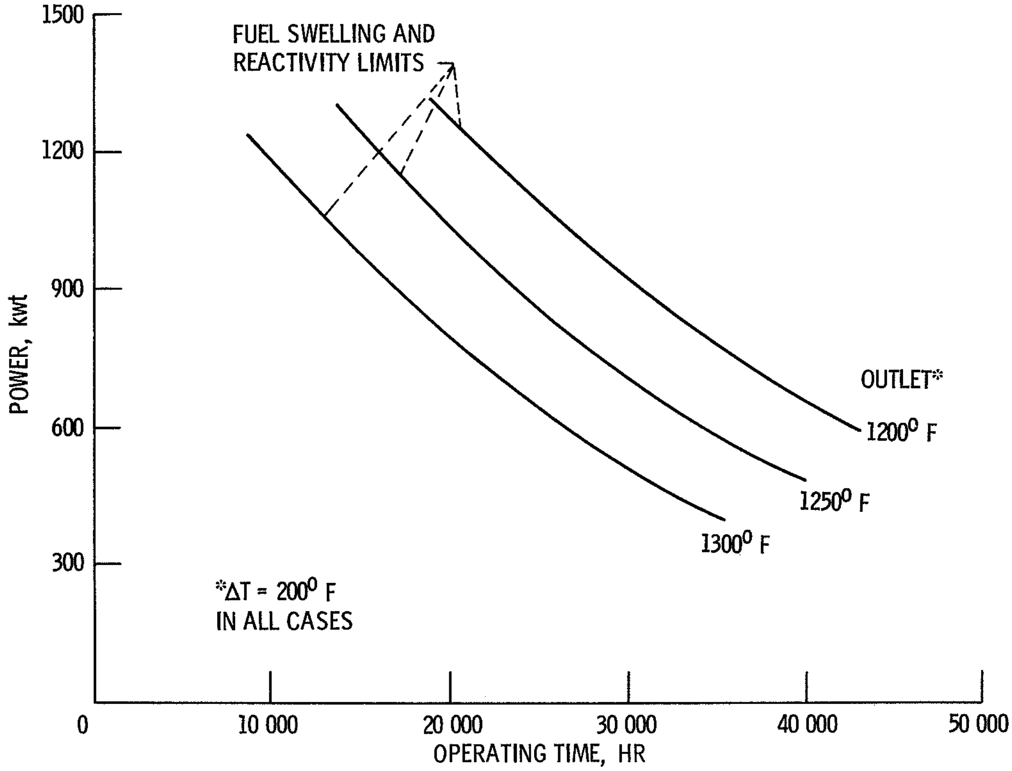

Figure 5. - Performance map - reference ZrH reactor.

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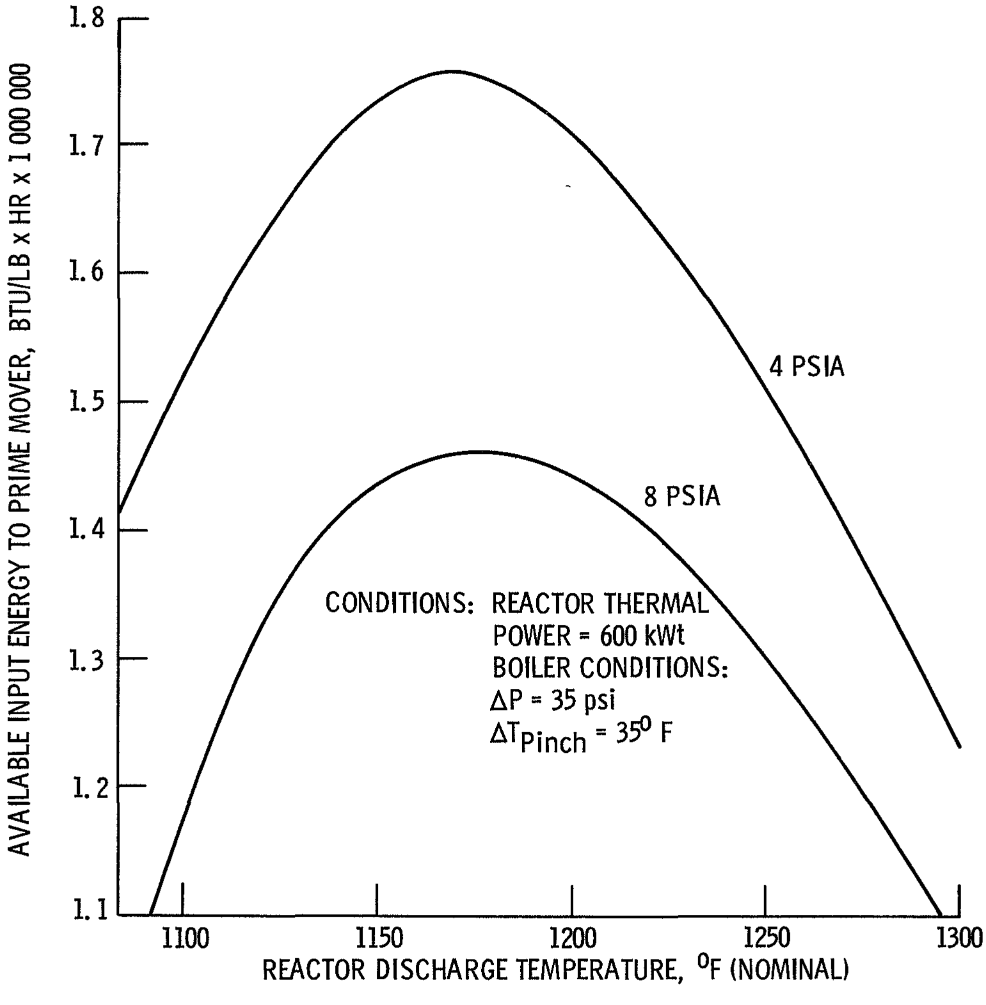

Figure 6. - Optimum available energy.

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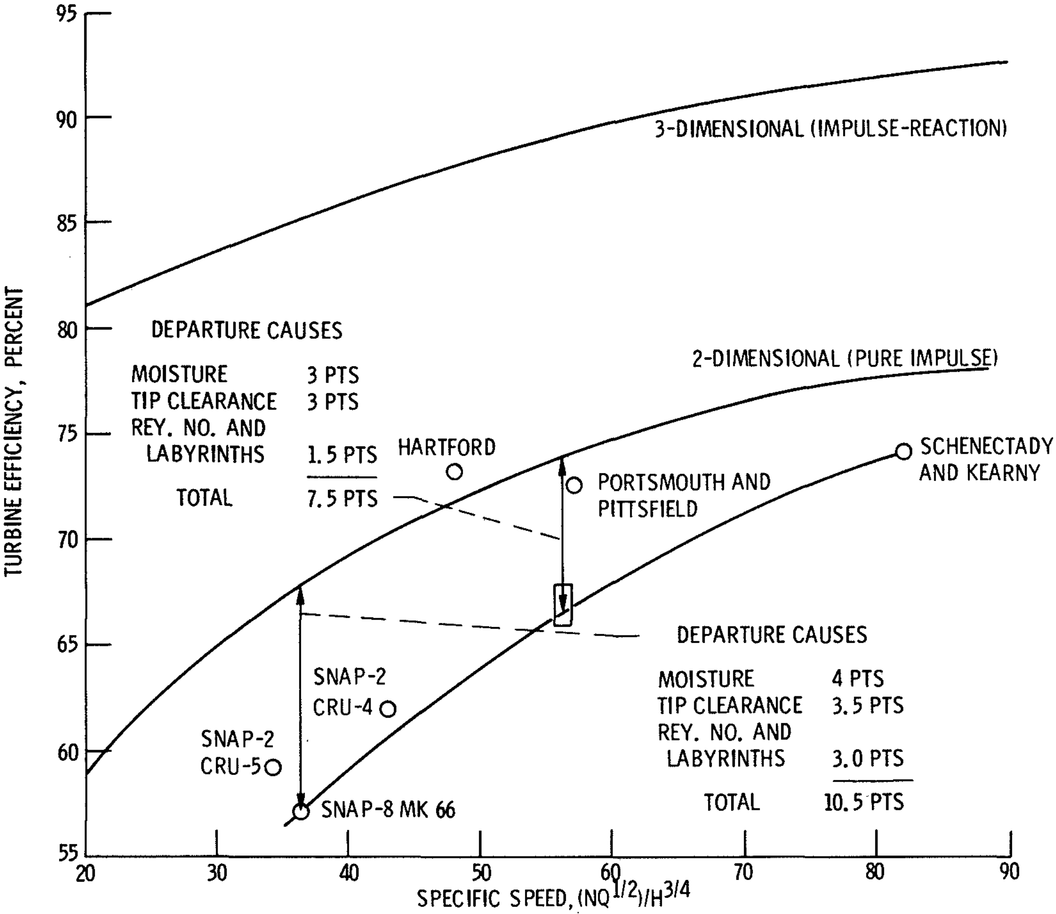

Figure 7. - Turbine specific speed versus turbine efficiency.