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AEC RESEARCH AND DEVELOPMENT REPORT

SUMMARY OF THE MPRE DESIGN AND DEVELOPMENT PROGRAM

(Title Unclassified)

A. P. Fraas

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Reactor Division

SUMMARY OF THE MPRE DESIGN AND DEVELOPMENT PROGRAM

A. P. Fraas

JUNE 1967

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee
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SUMMARY OF THE MPRE DESIGN AND DEVELOPMENT PROGRAM

A. P. Fraas

Abstract

A comprehensive summary of the MPRE program is presented, and the reactor and system are described in some detail. The bases for devising and selecting the concept are summarized, together with its development potential. The problems confronted are outlined, and the design and test program undertaken to solve them is discussed along with the principal results of the tests. Numerous references are included to relate statements in the text to the appended list of 96 reports and papers published in the course of the MPRE program. The principal accomplishments are cited, and the status of the test work as the program was halted at the end of FY 1966 is presented, together with a summary of the remaining problems to be solved if the program were reactivated.

INTRODUCTION

Studies of power plants for the production of electrical power in space vehicles were initiated at the Oak Ridge National Laboratory late in 1958 as part of the advanced design work sponsored by the ANP program. The principal interest was in plants in the 20 to several hundred kilowatt range with a minimum service life of 10,000 hr. Analyses indicated that a fission-reactor–turbine-generator Rankine-cycle power plant utilizing potassium as the working fluid was the most promising for development for operational use in the latter 1960's [1,3].* Further studies led to the conclusion that the high reliability required could be obtained only with the simplest possible system, that is, a single-loop system in which the potassium is boiled in the reactor core and the vapor flows directly to the turbine [2,3].

*Numbers in brackets refer to "Program Literature..." listed on pp. 93–100.

[redacted]

Analytical studies indicated that a specific weight of about 25 lb/kw(e) could be obtained with a stainless steel system and that this would be adequate to meet the requirements of most space missions. The more demanding requirements could be met by using a refractory metal at around 2000°F. Since the cost and time required to construct stainless steel systems are only 20 to 30% of the corresponding values for refractory metal systems, it appeared best to try first to develop a stainless steel system.

The two most vital questions associated with the feasibility of such a power plant were considered to be whether stainless steel is compatible with boiling potassium and whether the heat transfer characteristics of boiling potassium under forced convection would be adequate to remove the heat from a reasonably small core [3]. Experiments directed toward each of these two problems were initiated as part of the ANP program in the summer of 1959. The results from preliminary experiments on stainless steel-potassium compatibility and boiling-potassium heat-transfer were sufficiently encouraging that, when ORNL work on the ANP program was terminated at the end of fiscal year 1961, a new program expressly for investigating the feasibility of a boiling-potassium reactor was initiated. While the most promising application for this reactor appeared to be for power plants designed to produce electricity in space, it could also be used for other mobile power plant applications and possibly for central stations [57,58].

By the latter part of FY 1964, favorable results of the feasibility investigation led to the decision to proceed with a program to carry out a reactor experiment designed primarily to investigate the feasibility of operating a boiling-potassium reactor, with particular reference to stability and control characteristics. Since the boiling flow stability in such a reactor is very much dependent on the flow characteristics in the rest of the system, the condenser and other components were to be as similar to the units required for a flight system as could be arranged conveniently. A design power output of 1 Mw(t), or about 140 kw(e), was chosen, in part because it seemed well suited to the needs of many important space missions, and in part because it was intermediate between

the power levels of the SNAP-8 and SNAP-50 reactors. Because of this intermediate output, and partly because it was viewed as having important terrestrial applications, it was called the Medium-Power Reactor Experiment, or MPRE.

A small but intensive design and development program was carried out in FY 1964, 1965, and 1966. Both the reactor and the test facility were designed, and a series of component and system test rigs were designed, built, and operated to check and validate the design work. Of more than 40 major problems envisioned early in the program, acceptable solutions for all but two were demonstrated by the end of FY 1966. These two were the control of free-liquid surfaces under zero-gravity conditions and the demonstration of a reliable potassium-vapor turbine-generator unit. (Until FY 1966 the AEC had directed ORNL to leave these two problems to other programs.)

This report summarizes the design and development work carried out in the course of the MPRE program up to its abrupt termination at the end of FY 1966. A brief summary of the principal accomplishments in the MPRE program is presented in the following section. The reports and technical society papers covering the details of this work are listed as references at the end of this report. To facilitate use of this list, it was divided into categories, with the items in each category arranged in the order in which the work was carried out rather than the date of publication.

SUMMARY OF ACCOMPLISHMENTS IN THE MPRE PROGRAM

The major accomplishments in the MPRE program include the following:

1. The compatibility of stainless steel with boiling potassium was demonstrated in over 160,000 hr of component and system tests, including 9000 hr of testing of reduced-scale mockups of the MPRE system [55]. One of these system mockups was operated for 2500 hr with no interruptions except those caused by troubles with the electrical system used to heat the boiler [78].

2. Sufficient data on the heat transfer and burnout limitations for boiling potassium were obtained to validate the boiling-potassium reactor concept [32,44,45,94].

3. Calculations and critical experiments showed that boiling-potassium reactors can be proportioned to give both a good power distribution and good nuclear stability and control characteristics [17,24].

4. Good boiling-flow stability and good flow distribution were demonstrated in electrically heated core mockups [44,72].

5. Explosive boiling of potassium was found to be a major problem if nucleation sites were not deliberately introduced, and nucleation rings were developed to give a satisfactory solution to the problem of initiating and maintaining smooth nucleate boiling of potassium [44,95].

6. A light-weight tapered-tube direct-condensing radiator designed for space operation was developed and shown to give a uniform flow distribution with good flow stability [16,68].

7. A potassium-lubricated tungsten carbide bearing was operated in a bearing test rig for 4000 hr with 350 starts and stops under load with no loss in performance or detectable surface damage [59].

8. The world's first potassium-vapor turbine was operated, and over 4000 hr of operating experience was accumulated with potassium-vapor turbines running on potassium-lubricated bearings [59]. After one 2500-hr test, all parts of a free-turbine-driven feed pump were in good condition, with no sign of erosion of either the turbine buckets or the pump impeller, which had been operating under fairly heavy cavitation in accordance with design conditions [96].

9. The performance of typical jet pumps in the cavitating regime was established [60] (no data were available previously in the literature), and the pump characteristics required for zero-gravity operation of a Rankine cycle system were demonstrated [61].

10. Four full-scale MPRE fuel elements were operated in-pile at design power and temperature for a total of over 30,000 hr with no sign of difficulty. Two were removed for inspection after 2800 and 10,000 hr, respectively, and found to be in excellent condition [94,95]. The test is continuing on the other two as of December 1966 [96]. One of these

has operated 14,000 hr, which, allowing for a load factor of 60%, is equivalent to three years of normal service [14,15].

11. A new single-loop Rankine cycle system was devised in which the only electronic control equipment is that required to couple the reactor to the generator output and that required to regulate the generator voltage [70,73]. Studies that included analog simulation and system tests showed excellent stability and control characteristics [71-74].

12. It was shown that if proper allowances are made for fuel-coolant compatibility and fuel burnup considerations, there is little difference in size between boiling-potassium- and liquid-potassium-cooled reactors designed for a given power output and a life of 15,000 hr or more. Further, because of fuel compatibility and burnup considerations, it appears that potassium-cooled reactors are likely to be smaller than lithium-cooled reactors.

13. Studies showed that the single-loop Rankine-cycle system may be scaled readily to meet the range of requirements from 30 kw(e) to 5 Mw(e) and that it yields attractive power plants not only for refractory metal but also for stainless steel systems [16,17,89].

14. Basic heat transfer, thermodynamic, and structural considerations indicate that a series of refractory metal one-, two-, and three-loop systems designed according to a common set of design precepts for a 2000°F reactor outlet temperature will have radiator sizes and power plant weights (except for shielding) in the ratios of 1, 1.5, and 2 [16]. The performance superiority of the single-loop system is so pronounced that a stainless steel single-loop system designed for 1540°F is lighter and gives a smaller radiator than the corresponding refractory metal three-loop system designed for 2000°F [16].

15. The results of studies based on reliability data from 3×10^9 hr of component operation of well-developed equipment indicated that a single-loop system may be developed to give a probability of around 0.90 of operating 10,000 hr without a mechanical failure [16]. Application of the same data led to corresponding values for the two-loop and three-loop systems of about 0.8 and 0.6, respectively [16].

16. The probability of a failure in the control system depends on the number and complexity of the basic control functions required for

normal operation. The complexity of the electronic equipment required to carry out these control functions, as well as related diagnostic and safety functions, increases much more rapidly than linearly with the number of loops in the system. When standard Department of Defense specifications for the reliability of high-quality electronic components were applied to circuits typical of those that would be required to carry out the control functions for normal operation, it was found that even through the extensive use of derated equipment and redundancy, both in the components and the circuits, the reliability of the electronic equipment required for controlling a single-loop system would give a probability of the order of 0.90 of surviving 10,000 hr of unattended operation [16]. The corresponding values for multiloop systems with once-through boilers were much lower — well below 0.50 [16].

17. A parametric survey of the effects on shield weight of the geometry of the reactor and related equipment indicated that provisions for controls, fission-product-gas accumulation, and a vapor separator—expansion tank assembly in the boiling-potassium reactor designs resulted in an increase in shield weight over that for a simple core of about 25% for the reactor power output range 500 kw(t) to 25 Mw(t) [30]. The corresponding increase in shield weight for a liquid-cooled reactor with an intermediate heat exchanger (boiler) buried in the shield ranged from 50 to 100% [30].

18. A parametric survey of the effects of neutron and gamma scattering from a cylindrical radiator concentric with the reactor and shield showed that the shield weight penalty could be kept small, and thus this configuration could be used to give an attractive, compact launch package [30].

19. Analyses of fuel element operating experience showed that a single-loop boiling-potassium reactor system could be designed so that fission products from a fuel element leak would not contaminate the reactor coolant circuit outside the shield to the point where it would endanger the crew [15-17,24,30]. (Extensive experience with both boiling-water and gas-cooled reactors in large nuclear central stations supports this conclusion.) Further, the probability of the crew receiving a serious radiation dose as a consequence of a reactor accident appears to

be lower for a single-loop boiling reactor system than for a liquid-cooled reactor system [16,30].

20. The MPRE system was designed to include special provisions to make possible startup and operation under zero-gravity conditions [16,95]. A test program to determine the adequacy of these features was worked out [13], bench tests of the key components (i.e., vapor separator, expansion tank, boiler, and condenser) were built and operated satisfactorily [47,95], and a vapor separator—expansion tank was shown to perform fairly well in zero-gravity tests in the KC-135 airplane at Wright Field [96].

21. A 37%-scale electrically heated mockup of the MPRE was operated for over 3600 hr with a potassium-vapor turbine-driven feed pump [72,78].

22. Design and fabrication of a full-scale electrically heated mockup of the MPRE were about two-thirds completed [94,95].

DESCRIPTION OF THE POWER PLANT

The MPRE was designed as a reactor experiment intended to investigate the feasibility of a boiling-potassium reactor system that was conceived as a major simplification of the multiloop systems commonly employed in concepts of nuclear reactors for space power plants. The primary cooling system of the liquid-cooled reactor, with its electric-motor-driven pump, expansion tank, boiler, and instrumentation and control equipment, was replaced by a single reactor assembly with an integral vapor separator and expansion tank [10].

This simplified circuit, shown schematically in Fig. 1, is possible because potassium is the alkali metal least inclined to become radioactive, and it was found possible to so proportion a fast reactor that not only would the activation of natural potassium be low and that of the separated isotope very low, but the potassium would have little effect on the reactivity [24,30]. As a consequence of these two features, activity of the potassium in the system outside the shield would be acceptable [15,17,24,30], and any irregularities that might be associated with boiling flow through the reactor would not lead to appreciable variations in the nuclear power output. The system was also simplified through the

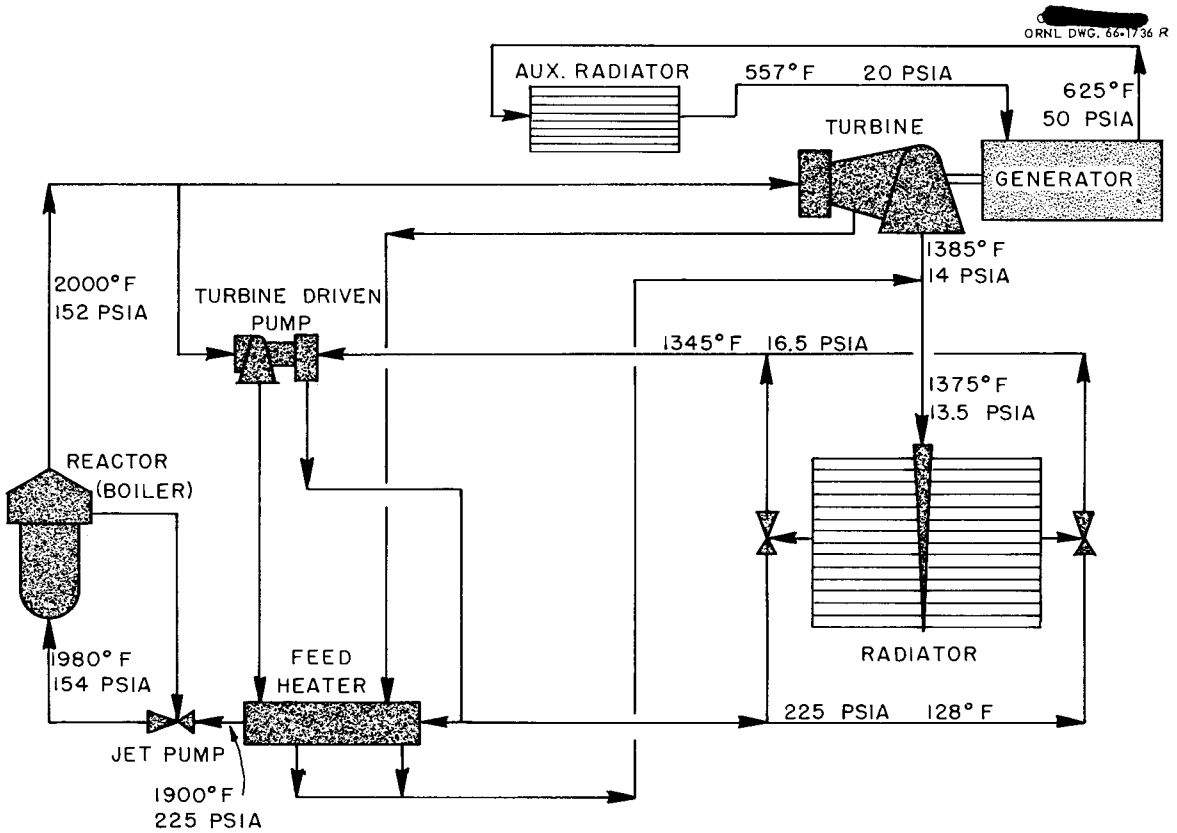

Fig. 1. Schematic Diagram of a Boiling Potassium Single-Loop Refractory-Metal System with a Boiling Reactor, Jet Pumps to Recirculate Liquid Through the Reactor, and a Direct-Condensing Radiator. If built of stainless steel the temperatures would be reduced about 400°F.

use of a direct-condensing radiator, so there would be no need for a set of NaK circuits to remove heat from shell-and-tube condensers and transport it to the radiator. An important factor in making this possible was the development of a new concept for space radiators that greatly reduced both the area vulnerable to meteoroids and the consequent weight of armor required to give a very low probability of meteoroid damage to the radiator [16,62,68].

Reactor

A vertical section through the center line of the MPRE is shown in Fig. 2. The reactor core consists of a bundle of fuel rods consisting of fully enriched UO_2 pellets contained in type 316 stainless steel capsules having an outside diameter of 0.500 in. (shown in Fig. 3) [15].

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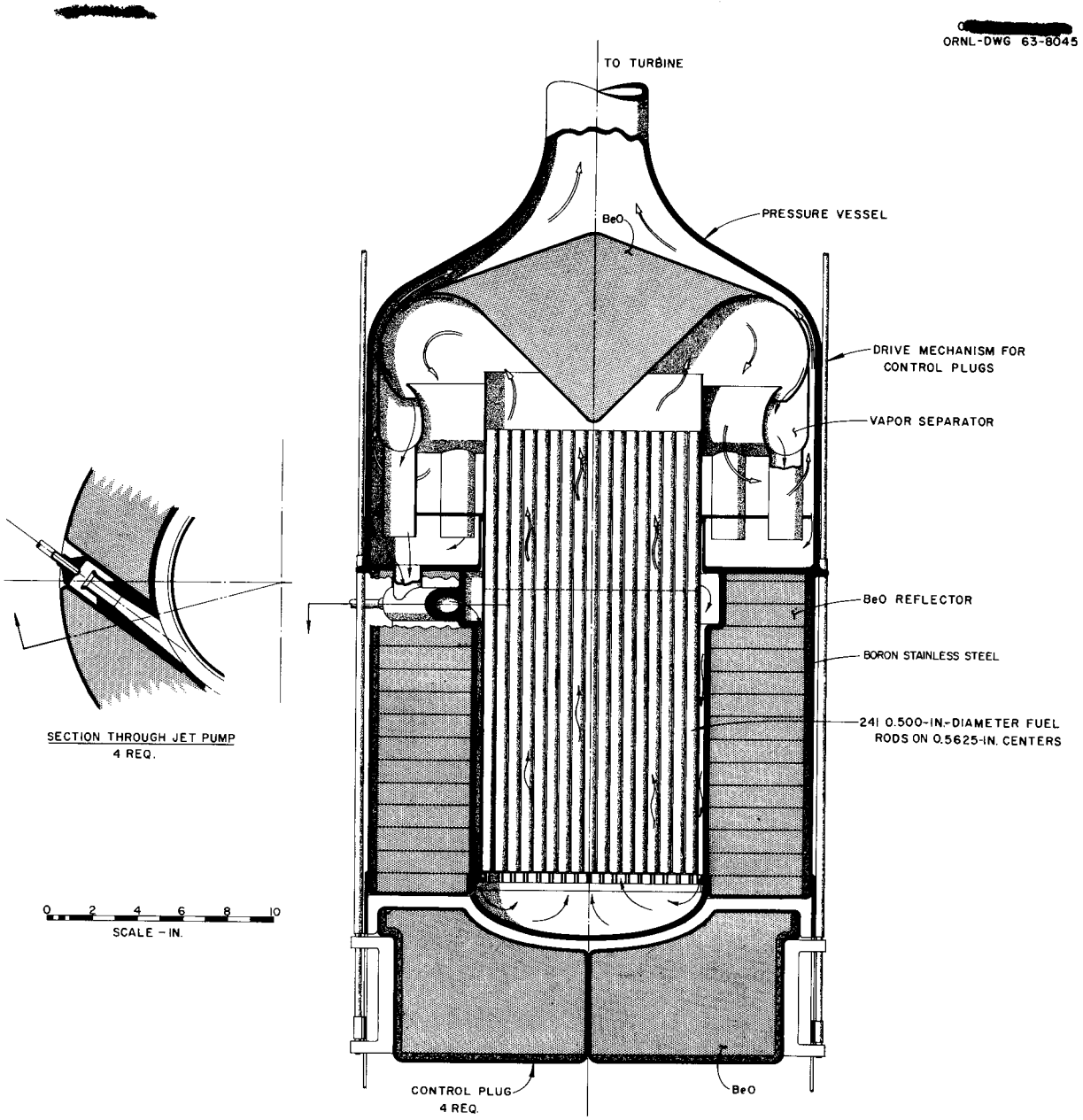

Fig. 2. Cross Section Through the MPRE Reactor Assembly.

The fuel rods are arranged in an equilateral triangular pattern, with a center-line spacing of 0.5625 in., so the coolant-passage volume fraction in the active lattice is 0.283. The core is surrounded by a beryllium oxide reflector that is 3.25 in. thick on the side and 5.00 in. thick on the bottom [24]. It is fabricated of a series of disks approximately 1.2 in. thick. A 3.0-in.-long stack of BeO pellets above the UO_2 in each

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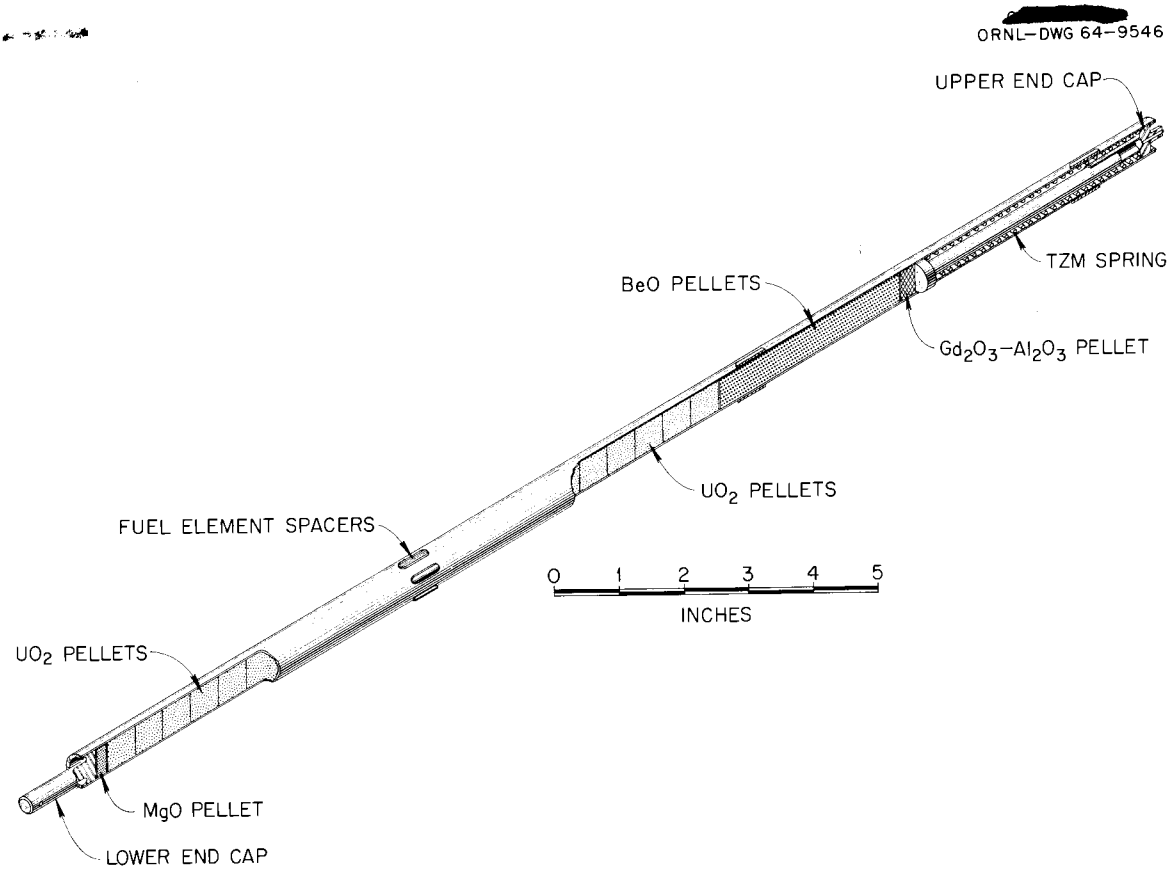

Fig. 3. The MPRE Fuel Element.

fuel rod serves as a portion of the top reflector. An additional 4.3 in. of void space above the BeO pellets provides a reservoir for fission-gas accumulation and contains a piston and molybdenum spring to restrain axial movement of the BeO and UO_2 pellets [15]. The lower BeO reflector is divided into four independent quadrants that may be moved axially to adjust reactivity and together are worth 5% in $\delta k/k$ [24,25].

Above the core is a vapor separator designed to give a vapor exit quality of about 99% [47]. Immediately below it is the expansion tank. The type 304 stainless steel pressure vessel encloses the entire vapor-separator region but passes between the core and the reflector, where its thickness is 0.25 in. [19]. Thus the side reflector, the movable bottom reflector, and all parts of the control drive mechanism are outside the potassium circuit.

In order to avoid excessive coolant flow bypass around the core perimeter, the core is surrounded by a thin stainless steel flow baffle

that conforms in shape to the fuel-rod array. The baffle also performs two additional functions: first, it provides a constraint on radial movement of the fuel rods, and second, it defines a small annular coolant passage between the baffle and the core vessel to return coolant from the vapor separator to the core inlet. This flow also removes the heat generated by radiation in the vessel and the inner portion of the side reflector.

Surrounding the entire reflector is a thin neutron-absorbing layer in the form of a 1/4-in.-thick layer of 0.1% boron steel. This layer reduces activation of components such as the control rod guides and supports; the reduction in activation would not only reduce the capture gamma problem in tungsten gamma shielding but also activation of components outside the layer and thus reduces the shielding requirements and cask weights if removal and replacement of the control plugs should be desired [24]. In addition, the boron layer isolates the reactor from its environment so that no accidental addition of reflecting material can increase the reactivity. In fact, addition of water between the boron layer and the reactor shield causes a small loss of reactivity [24].

The BeO blocks in the side reflector incorporate twelve 1-in.-diam holes centered on a circle coaxial with the core. Installation of BeO rods in any or all these holes provides a reactivity adjustment that can be made after installation of the reactor in the facility, but prior to its operation, in order to minimize the excess reactivity available from control plug insertion. In this way it should be possible to limit the maximum available reactivity in the hot, clean reactor to about 0.5% [24].

The fluid flow path through the reactor can be traced in the vertical section shown in Fig. 2. Liquid potassium enters the core at the bottom, rises between the 0.5-in.-diam fuel elements, emerges from the core at a vapor quality of about 20%, and enters the vapor separator, where the liquid is skimmed off and discharged to the expansion tank directly beneath the vapor separator. The vapor passes radially outward at the bottom of the vapor separator and then upward around the outer perimeter and out the vapor exit pipe at the top. The liquid potassium from the boiler feed pump enters a set of four jet pumps operating in parallel

beneath the expansion tank. These draw liquid from the expansion tank and discharge it so that it returns to the core inlet [70].

The principal geometric and performance data for the MPRE are presented in Table 1.

Potassium Systems

A schematic diagram showing the potassium system of a refractory-metal version of the MPRE is presented above as Fig. 1. Potassium vapor from the reactor is expanded through the main turbine to generate electricity and then is condensed in the radiator [70]. A small side stream of vapor is permitted to expand through a free-turbine-driven feed pump that returns the condensate to the boiler (reactor core). A high heat transfer coefficient in the reactor is assured by using a recirculating boiler in which the liquid removed from the vapor separator is recirculated through the core by means of jet pumps driven by the boiler feed supply (the latest General Electric Company boiling-water reactor designs employ this system). Jet pumps driven by a portion of the feed-pump discharge flow are also installed near the condenser outlet manifolds to facilitate removal of condensate from the condenser under zero-gravity conditions [70]. A regenerative feed heater serves to reduce the size of the radiator, increase the cycle efficiency, and minimize thermal stresses in the boiler recirculation system [Ref. 83, pp. 6–14].

The centrifugal feed pump of Fig. 1 is not an integral part of the turbine-generator unit; it is driven by a free turbine. This arrangement has the advantage that it separates the development problems and has made it possible to proceed with tests on the MPRE system without a turbine-generator unit. A turbine-generator can be simulated by an orifice and heat exchanger with essentially the same flow characteristics [70,90].

Separation of the pump from the turbine-generator unit has a number of additional advantages. It simplifies the design of the bearing and shaft system for the turbine and generator units and eliminates what could be an awkward temperature distribution and thermal distortion problem. Most important, however, it greatly eases the problem of matching

[redacted]

Table 1. MPRE Design Parameters

Reactor operating conditions	
Thermal power, Mw	1
Coolant	Potassium (boiling)
Inlet temperature, °F	1530
Outlet temperature, °F	1540
Inlet pressure, psia	30
Outlet pressure, psia	29
Reactor geometry	
Fuel element arrangement	Equilateral triangular pitch
Moderator	None in core
Diameter (equivalent), in.	9.17
Distance across corners, in.	9.50
Length, in.	11.625
Active core volume	
ft^3	0.444
liters	12.58
Core free-flow area, ft^2	0.130
Side-reflector thickness, in.	3.0
Fluid flow data	
Core flow passage equivalent diameter, in.	0.198
Vapor flow at outlet	
lb/hr	4000
lb/sec	1.111
Liquid flow at outlet, lb/sec	4.444
Total liquid flow entering core	
lb/sec	5.555
ft^3/sec	0.137
Total flow leaving core, ft^3/sec	19.7
Vapor quality leaving core, %	20
Core exit vapor density, lb/ft^3	0.058
Core inlet liquid density, lb/ft^3	40.7
Core exit velocity, ft/sec	152
Core exit dynamic head, psi	0.144
Core inlet velocity, ft/sec	1.05
Core inlet dynamic head, psi	0.0048
Core circuit pressure drop, psi	1.0
Heat transfer data	
Power density (core average), w/cm^3	79.5
Heat transfer surface area, ft^2	30.55
Heat flux, Btu/hr·ft^2	
Average	111,700
Maximum	146,000
Fuel element cladding temperature, °F	
Average	1555
Maximum (hot spot)	1580
Fuel central temperature, °F	
Average	2400
Maximum	2700

[redacted]

[redacted]

Table 1 (continued)

Fuel element	
Configuration	Rods
Fuel form	UO_2 pellets in metal capsules
Number of fuel elements	241
Overall length, in.	19.875
Fueled length, in.	11.625
Fuel enrichment, %	93
Cladding material	Type 316 stainless steel
Cladding thickness, in.	0.020
Fuel element outside diameter, in.	0.50
Center-line spacing, in.	0.5625
Burnup at end of life, % of uranium atoms	0.76
Core composition, volume fraction	
Stainless steel	0.11006
UO_2	0.59598
Void inside fuel elements	0.01052
Coolant flow passages	0.28344
Control elements	
Reactivity control method	Four movable BeO plugs (quadrants of the bottom reflector)
Control plug motion	Vertical displacement parallel to axis of reactor; total travel 8 in.
Vertical height of control plugs, in.	8.5
Sheath material	Type 304 stainless steel
Combined worth of control plugs, % $\delta k/k$	~5.0
Pressure vessel	
Material	Type 304 stainless steel
Shell outside diameter, in.	10.5
Wall thickness, in.	0.25
Overall length (with expansion tank and vapor separator), in.	34
Physics	
Mass of UO_2, kg	78.0
Mass of ^{235}U, kg	63.8
Effective delayed neutron fraction	0.0075
Median energy for fission, kev	840
Prompt-neutron lifetime, sec	3.2×10^{-7}
Reactivity worth of control plugs	0.05
Isothermal temperature coefficient of reactivity, $(1/k)\cdot(dk/dt)$, $°C^{-1}$	-1.6×10^{-5}
Fuel reactivity coefficient $(\Delta k/k)/(\Delta m/m)$	0.545
Loss in k, fuel burnup for 1 Mwyr	0.0040
Reactivity effect of potassium filling coolant passages (relative to normal operating condition)	0.0014

[redacted]

[redacted]

Table 1 (continued)

Physics (continued)	
Maximum excess k from control plug insertion	
Full power	0.006
Cold, clean	0.020
Neutron flux at outer surfaces of core, neutrons/cm^2.sec	
Fast (E = 0.9–10 Mev)	0.41×10^{14}
Thermal (E = 0–1 ev)	3.4×10^{11}
Radiator	
Power to be dissipated	
kw	860
Btu/hr	2.93×10^6
Ideal dissipation at 1500°F to 500°F sink, Btu/hr·ft^2	8560
Emissivity of treated surface	0.92
Fin efficiency	0.86
Reflector efficiency	0.87
Area required, ft^2	435
Radiator diameter, ft	10
Radiator height, ft	15
Tube length, ft	7.0
Vapor temperature, °R	1500
Vapor density, lb/ft^3	0.0035
Latent heat of vaporization, Btu/lb	887
Vapor quality, %	91.7
Potassium flow rate, lb/sec	1.0
Vapor volume flow rate, ft^3/sec	262
Vapor velocity at tube inlet, ft/sec	400
Vapor flow passage area at tube inlets, ft^2	0.655
Number of tubes	96
Tube inlet flow passage area per tube, ft^2	0.0068
Tube inlet inside diameter, in.	1.1
Liquid density at tube outlet, lb/ft^3	44.0
Tube outlet liquid flow rate, ft^3/sec	0.0228
Tube outlet inside diameter, in.	0.30
Tube outlet area (per tube), ft^2	0.0049
Tube outlet area (total), ft^2	0.060
Tube outlet velocity, ft/sec (for liquid)	0.38
Fin span, in.	3.2

[redacted]

the characteristics of the various components of the system, a necessity if good overall performance, stability, and control characteristics are to be obtained [70].

The generator would be cooled and lubricated by a liquid-potassium circuit coupled to the main potassium system by a pressure-balance line. The liquid potassium would be circulated by a small low-pressure-rise centrifugal pump impeller mounted on the generator shaft.

Control Concept

The layout of Fig. 1 was devised in an effort to simplify the system and to minimize the number of components, including the amount of instrumentation and control equipment required [16]. Reducing the number of components to the bare essentials makes it necessary to tailor each component so that it fits well into the system [70]. One of the innovations in the MPRE is that, unlike conventional steam turbine systems, no throttle valve is employed. Instead, the system is intended to operate in a manner much like that of a closed-cycle gas-turbine system, with the vapor velocities through the turbine piping and other elements of the system held substantially constant over a wide range of boiler (reactor core) outputs while the system pressure varies essentially in direct proportion to the load [70]. The nearly constant vapor velocities aid greatly in the control of free-liquid surfaces under zero-gravity conditions; for example, a uniformly high vapor velocity in the condenser acts to sweep the condensate film on the tube walls toward the tube outlets irrespective of load. The inherent characteristics of the system over a range of loads are indicated in Fig. 4. Note that the boiler pressure is directly proportional to the heat input to the boiler [72]. Note, too, that the speed of the free-turbine pump unit increases gradually with boiler output, and one of the problems is to adjust the slope of this curve so that it yields a feed-pump pressure rise that fits the system requirements.

It is implicit in the above discussion that the power input to the boiler, and hence the weight flow of vapor through the turbine, be controlled to maintain the speed of the turbine-generator unit constant

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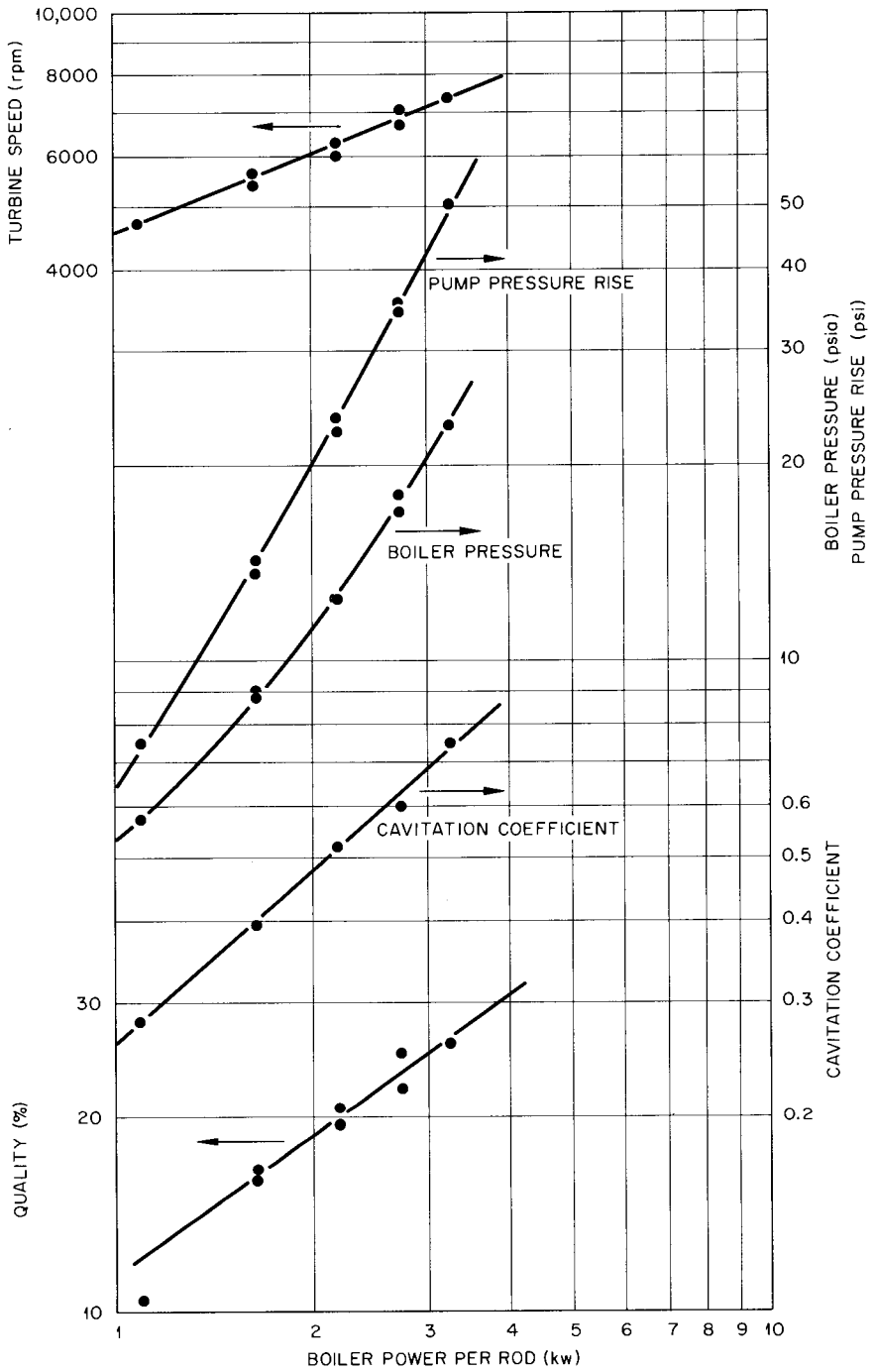

Fig. 4. Typical System Performance Characteristics Obtained with an Electrically Heated 91-Rod Potassium-Boiler System Giving 37% of the Thermal Output of the MPRE.

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irrespective of the electrical load. If the fluid system is stable under steady-state conditions throughout the operating range – and there is substantial experience with electrically heated test rigs to indicate that it is [72] – the question then becomes one of the effects on the potassium-vapor system of deviations in turbine-generator speed from the desired values [70]. The overall pressure ratio across the turbine is roughly ten times the critical pressure ratio. Turbine design studies favor the use of five-stage impulse turbines, and hence the vapor flow through the turbine behaves essentially as though it were passing through a critical-pressure-drop orifice, and the turbine rotor speed has virtually no effect on the vapor flow rate (see Fig. 5). The speed of the turbine-generator unit should be held constant to maintain the voltage and frequency; however, if something were to prevent this, the turbine speed could vary over a wide range and yet have essentially no effect on the flow through the reactor.

The quality of the mixture leaving the turbine changes, of course, with the amount of work removed from the vapor. For either a stalled rotor or a complete runaway condition, the turbine acts as a throttling

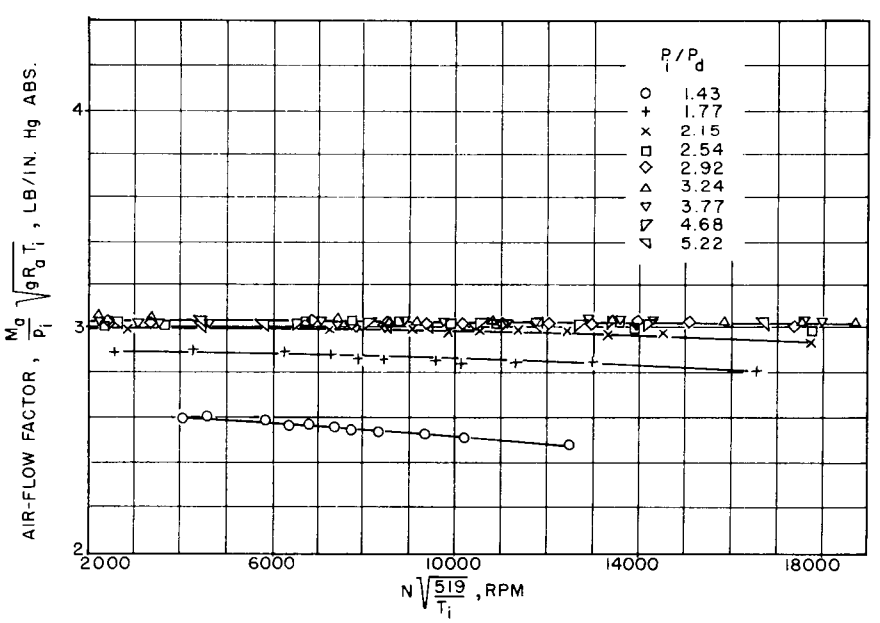

Fig. 5. Effects of Turbine Speed on the Gas Flow Rate with a Constant Pressure Ratio Across a Typical Turbine. (From NACA ACR No. E5C30)

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orifice; no work is removed from the vapor, so it enters the condenser at a temperature of about 1280°F, that is, superheated about 200°F. Even for such an extreme condition, the superheat is only about 5% of the latent heat of vaporization and has little effect on condenser performance. In practice, the extent of the turbine-speed variation should be very much less – perhaps 10% [73] – and hence the change in vapor quality would probably never be sufficient to produce superheating in the vapor mixture at the condenser inlet. Thus, so far as the potassium system is concerned, changes in turbine-generator speed and load have virtually no effect on system pressures and flow rates, except insofar as the automatic control equipment is designed to respond to changes in the generator output frequency or voltage and actuate the control plugs to change the thermal power output of the reactor [70,73].

The system liquid inventory distribution is inherently stable when the components are properly matched [70,72]. The turbine-pump speed is controlled by properly sizing an orifice in the vapor inlet line so that the pump discharge pressure tends to exceed the pressure required to return condensate through the boiler recirculation jet pump and into the boiler [72]. Under this condition, the pump scavenges liquid from the condenser until there are so many bubbles in the condensate line leaving the condenser that the line pressure drop increases. With this change, the cavitation suppression head obtained by subcooling as a consequence of normal heat losses is not sufficient to suppress cavitation in the radiator-scavenging jet pump. This unit then cavitates to a greater degree, and its discharge head drops. This, in turn, causes the centrifugal feed pump to cavitate and thus decrease its discharge head and flow. A stable dynamic equilibrium is quickly reached with the pump output reduced sufficiently by cavitation so that the discharge flow rate just matches the system requirements [72]. Operation under this condition is characterized by small rapid fluctuations in the pump discharge pressure (several cycles per second) with the average pump pressure rise less than that which would be produced at this pump speed were the pump not in cavitation [70,72].

Launch Package

The many different requirements and boundary conditions that must be met in designing a power plant launch package were studied, and several layouts were prepared in an effort to determine how best to meet the often conflicting requirements (Ref. 85, pp. 1–12). The most promising of these layouts is the 10-ft-diam package shown in Fig. 6. Although the configuration of Fig. 6 was worked out for the 140-kw(e) MPRE, as shown in Fig. 7 the basic arrangement and structure are well suited to other sizes of plant [16].

The layout of Fig. 6 differs markedly from the launch configurations that have been proposed for SNAP-2, -8, -10, and -50. In the latter, the reactor is placed at the top of the nose cone, and the radiator lies within the slender shadow cone of a minimal shadow disk shield. Such a system configuration serves to reduce the shield weight at the expense of major structural problems, with their attendant weight penalties. It also gives a high center of gravity for the launch package, and this may pose dynamic stability problems in the launch vehicle. It appears to be advantageous to make use of a radiator and system configuration such as that of Fig. 6 and avoid difficulty with fast-neutron scattering from the radiator by employing shielding around the sides of the reactor, especially since such shielding is desirable for launch, maintenance, and other reasons [30]. Note that the shield of Fig. 6 was designed for an unmanned vehicle. It is much thicker over the top of the reactor to provide a shadow cone for the payload, which would be located in the nose cone above the power plant. As discussed in a later section, the shielding for a manned vehicle would be similar to that in Fig. 6, but thicker.

The radiator layout shown in Fig. 6 was evolved in searching for a structure well suited to stowage in a launch vehicle and yet designed to be readily fabricated to give a high degree of vacuum tightness [67], sufficient sturdiness to withstand launch loads and vibration, sufficient protection from meteoroids to keep the probability of a puncture below 1% per year [16], and a fluid passage arrangement that would give good control of the free-liquid surfaces for prelaunch checkouts, low-power operation throughout the launch, and proper operation under zero-gravity

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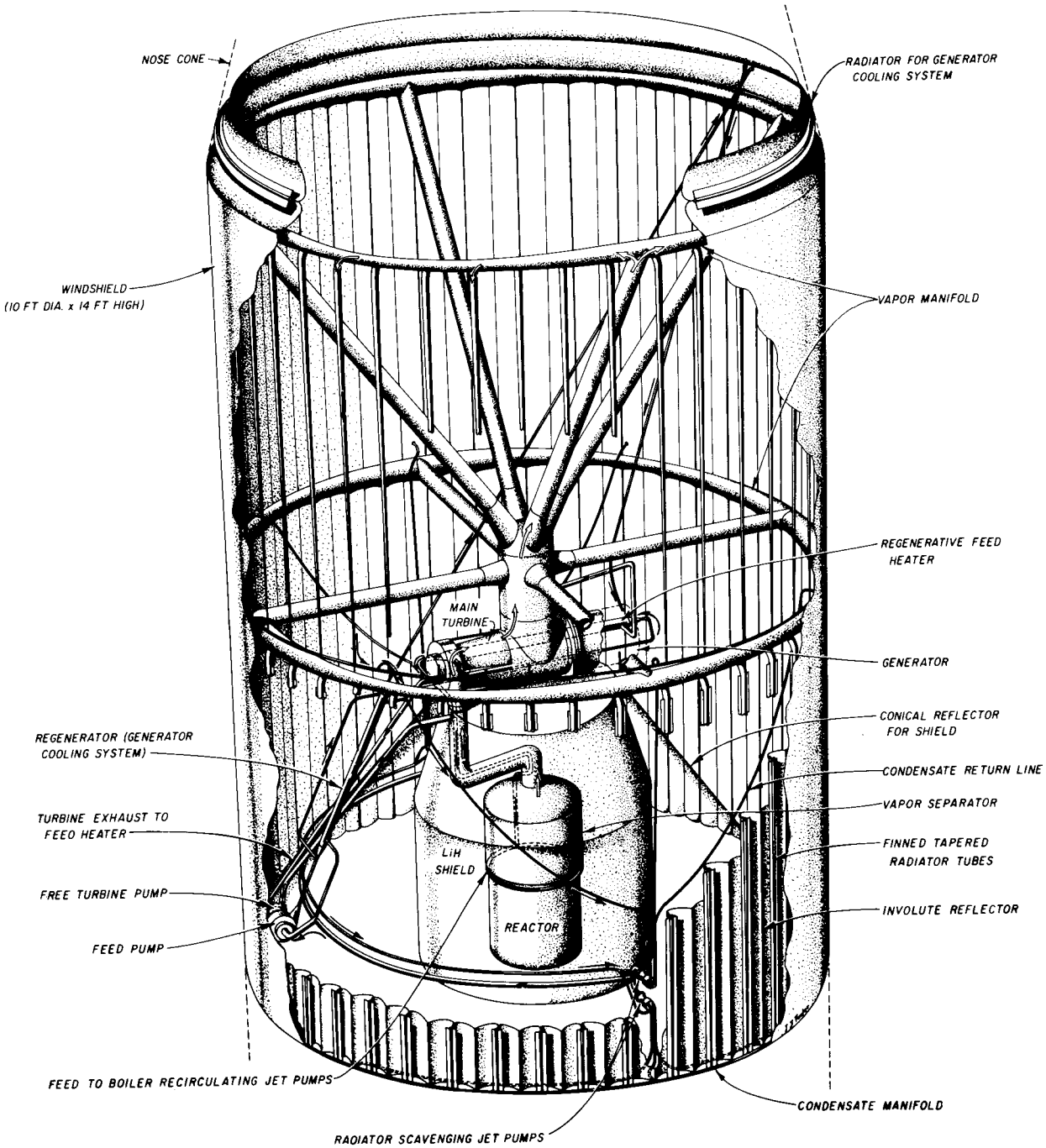

Fig. 6. Typical Power Plant Launch Package.

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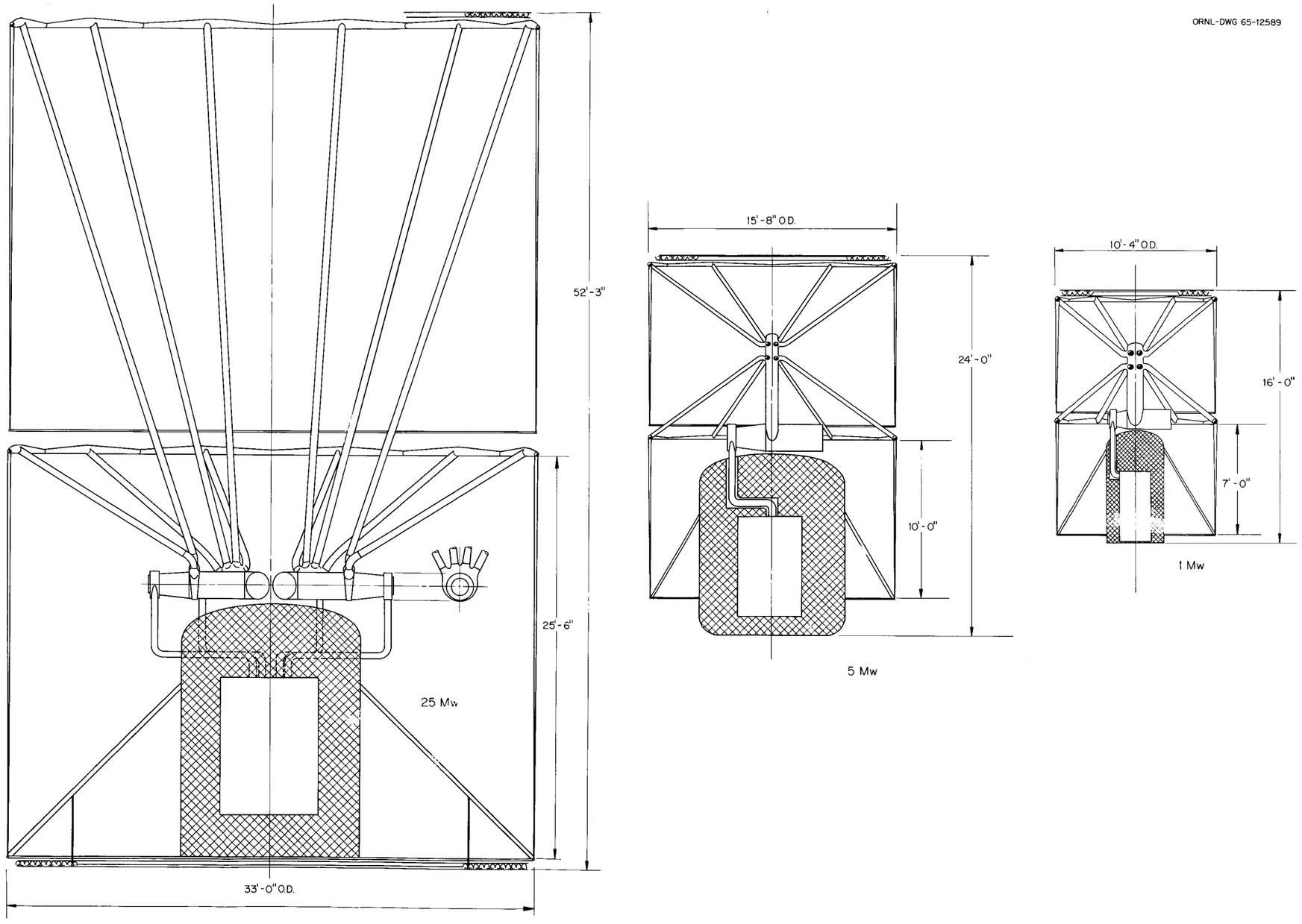

Fig. 7. Launch Package Layouts for Three Typical Plants Based on the Single Loop of Fig. 1.

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conditions throughout the full power range [9]. The thermal radiation surfaces consist of 7-ft-long finned tapered tubes arranged around the perimeter of a 10-ft-diam cylinder with the tube axes parallel to the axis of the vehicle [68]. Two cylindrical banks, each 7 ft high, form a 15-ft-high 10-ft-diam assembly. To minimize the area vulnerable to meteoroid penetration, a properly curved aluminum reflector is used in back of each tube, as shown in Fig. 8, so that the rear surfaces of the tubes and fins also emit thermal radiation to space [62,63]. Analyses and tests have indicated that the reflector will be about 85% effective [69]. This arrangement makes it possible to get close to the maximum heat output from a given size of launch package envelope without excessive fin weights [16]. (For any given fin efficiency, the fin weight per unit of surface area varies as the square of the fin height.) Further, the rear sides of the radiator tubes require no armor, since the reflector on the opposite side of the radiator would act as a bumper to disperse any meteoroid particles that penetrated it [64].

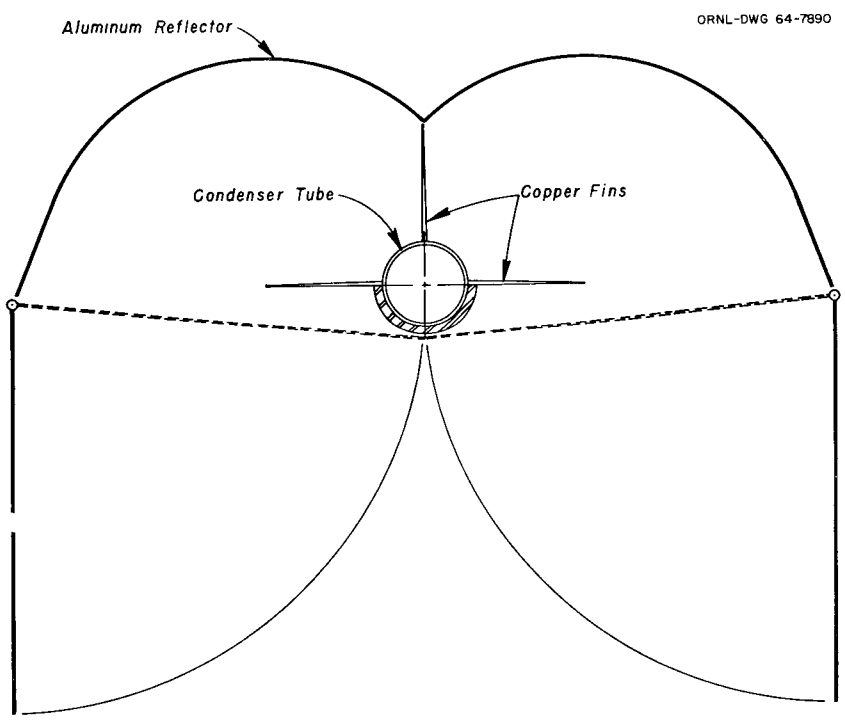

Fig. 8. Section Through a Finned Tube Fitted with Aluminum Reflector and Shutters for Installation in Cylindrical Drum-Shaped Radiators Such as Those of Figs. 6 and 7.

The tube, fin, and reflector structure by itself is unsuitable both aerodynamiclly and structurally for launching. However, if the aluminum shutters of Fig. 8 are closed to form a good aerodynamic envelope around the outer perimeter of the tubes and the spaces between the envelope, the tubes, and the aluminum reflector are filled with polyurethane foam, the resulting structure will be quite strong and stiff, since all the components will be bonded together by the polyurethane. The internal damping in the polyurethane foam should be effective in restricting the amplitude of any resonant vibrations. Such a structure could be launched at ambient temperature, and, after starting the reactor dry in orbit and increasing the power to about 15 kw(th), the radiator temperature would stabilize at about 400°F, and the polyurethane foam would be vaporized off to the high vacuum surrounding the vehicle and leave no residue [16]. The shutters shown in Fig. 8 could then be opened and the power plant operated [16,68,69].

The weight and inertial loads of the turbine-generator unit and related equipment would be carried radially outward through the 0.050-in.-thick radial vapor pipes to the manifold rings. This would distribute the load fairly well to the tubes, shutters, and aluminum reflector around the perimeter. A sheet aluminum band about 6 in. high would be mounted around the perimeter at the midplane to couple the upper and lower tube banks together structurally and thus accommodate the aerodynamic and acceleration loads. The plastic cement employed to bond the aluminum band to the radiator would vaporize on heating and allow the band to spring free of the radiator.

Layout for the MPRE

The reference design for a launch package shown in Fig. 6 was used as the point of departure in arriving at a system layout for the boiling-potassium reactor experiment [8,12]. To facilitate maintenance it seemed best to enclose the reactor in a heavy concrete shield and to spread the components out to make them readily accessible. Figure 9 shows the configuration chosen. In this layout the bulk of the liquid system lies within a foot or so of a mean horizontal plane, and thus zero-gravity

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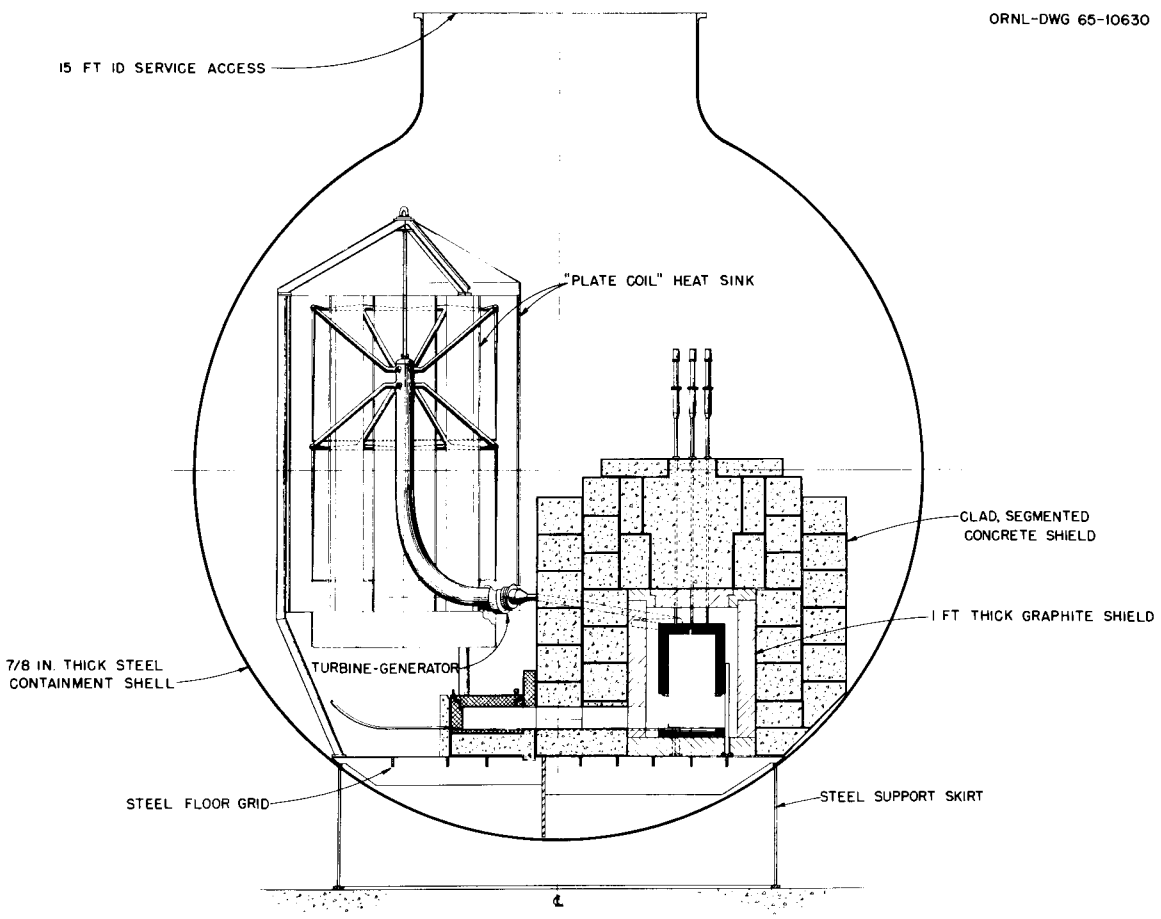

Fig. 9. Facility Configuration Chosen for the MPRE.

conditions are well simulated for a ground test. In keeping with reactor safeguards practice, the assembly is enclosed within a 50-ft-diam spherical containment shell [8,12], which was designed to withstand internal pressures ranging from a vacuum of 10^{-2} torr to 35 psig.

CONCEPT SELECTION

The selection of the boiling-potassium reactor concept on which the MPRE is based began with a survey of both space-mission requirements and the performance characteristics of the various candidate electric power supply systems [1,3]. The system choice was narrowed first to reactor–turbine-generator plants, then to a potassium Rankine cycle, and then to

[redacted]

a single-loop system. The characteristics of the materials of construction were reviewed, and a stainless steel system with UO_2 fuel elements was chosen as having adequate performance for the earlier space missions and involving the lowest development costs. The more difficult mission requirements of the future could be met by a later shift to a refractory metal in place of stainless steel. These phases of the selection process are discussed below.

Power Plant Requirements

The requirements for electrical power supplies for the principal space-vehicle missions were surveyed in 1958 and subsequently reviewed at intervals, particularly in 1965 [14]. Table 2 summarizes the ranges of values for the power output, specific weight, and operating life required for the power plant for the principal missions requiring 25 kw or more electric power [14]. In virtually all cases the power plant life desired was found to be at least 10,000 hr and, in most cases, 20,000 hr or more. The load factor for plants of over 100 kw(e) appears to be

Table 2. Space Missions Requiring More Than 25 kw of Electric Power

	Electric Power Required (kw)	Maximum Power Plant Specific Weight [lb/kw(e)]	Desired Life (years)
Unmanned			
Satellites (TV, reconnaisance, etc.)	50 to 300	30 to 100	1 to 5
Interplanetary probes	25 to 1000	Less than 40	1 to 7
Manned			
Satellite	30 to 300	Less than 200	1 to 3
Lunar base	30 to 300	Less than 200	1 to 5
Manned Mars vehicle (electrical propulsion)	1000 to 5000	Less than 20	2

about 60%. In all cases the power plant should operate unattended or nearly so – certainly without an operator continuously on duty – and the reliability should be over 90%. These requirements will be exceedingly difficult to meet; for example, none of the Army Package Power Reactor plants has been operated with less than a 25-man crew in four shifts of about six men each in spite of strenuous efforts to reduce the crew size in the arctic and antarctic plants. Further, even with these crews the longest uninterrupted period of operation in ten plant years of experience has been 3390 hr, and this was achieved only recently.*

Characteristics of Systems Under Development

The characteristics of the principal long-lived electric power sources that have been under development for spacecraft are summarized in Table 3. The bulk of the requirements to date have been met by solar cell and isotope power sources, which are well suited to small spacecraft. However, the output of a solar cell array falls off with the distance from the sun, the specific weight goes up rapidly for outputs above 50 kw (because of conductor and structural weights), and the arrays become so large and unwieldly that such factors as atmospheric drag and solar pressure become important considerations. In the larger sizes the isotope power sources present major hazards problems – there would be enough activity in a ^{238}Pu source for a 5-kw(e) thermoelectric plant to contaminate the atmosphere of the entire earth to above the standard laboratory tolerance level. A clue to the lack of a strong drive by NASA and DOD for large nuclear electric power sources is also given by Table 3; except for the potassium-vapor Rankine cycle, none of the nuclear reactor systems show strong advantages relative to solar cells from the standpoints of size, weight, and cost.

Nuclear plants based on thermionic cells are not included in Table 3 because the state of the art is not yet sufficient to make a good estimate of the probable performance. Not only is the output limited by severe materials problems stemming from the extremely high temperatures

*Nucleonics Week, p. 5, October 13, 1966.

Table 3. Estimated Performance of Typical Long-Lived Electric Power Sources

Source	Electrical Output (kw)	Approximate Size of Equivalent Cylinder (ft)		Specific Weight (lb/kw)		Manufacturing Cost ($/kw)
		Diameter	Height	Unmanned	Manned[a]	
						$\times 10^5$
Solar cells (thin film)	50	70	70	50	50	5
Isotope, thermoelectric[b]	2.5	4	10	800	1200	160[c]
Isotope, Brayton cycle[b]	5	22	10	300	800	40[c]
SNAP-10A	0.5	3	10.5	2000		80
SNAP-8	30	22	20	250	750	5[c]
Brayton cycle[d]	150	22	40	90	180	2[c]
SNAP-50 (CANEL)	300	10	40	30	80	1.0[c]
MPRE (stainless steel)	150	10	15	30	110	0.15[c]
Advanced MPRE (niobium)	367	10	17	20	60	0.5

[a]Based on separation distances of 10 to 20 ft for the isotope installations and 150 ft for the reactor installations.

[b]Estimates derived from design studies presented in Atomics International Report AI-65-221, Vol. 1, Dec. 9, 1965 and General Electric Company Report GE-65SD4508-1A, Jan. 24, 1966.

[c]Based on ORNL cost experience in dollars per pound of hardware, together with standard AEC costs for isotopes and fissionable material. (No recovery of isotopes or fissionable material assumed.)

[d]Data from Study of Nuclear Brayton Cycle Power System, Report NASA CR-54397, GE-65SD4251, General Electric Co., Aug. 5, 1965.

within the cells, but integration of the cells into a full-scale plant imposes an additional set of boundary conditions that can be met only by making compromises that degrade the performance of the assembly relative to that implied by the performance of a single cell [20]. Further, while at first thought it has appeared that the redundancy possible by coupling the cells in a series-parallel array would yield the high reliability obtainable with solar cells, the diode cooling requirement makes it necessary to introduce a major failure mode not present in solar cell arrays [20]. This comes about because proper cooling of the diodes requires a short heat-conduction path to a liquid-metal coolant, and this also gives a short electrical-conduction path. The electrical resistivity of the best ceramic insulators falls off rapidly above about 500°C, so shorting to ground, arcing, and a major melt-type failure are not only possible but likely [20].

Choice of Thermodynamic Cycle

While there have been some changes in the situation during the past eight years, the initial survey in 1958 led to a set of conclusions consistent with the picture outlined above; namely, that the most promising way to meet the requirements of the more difficult space missions is with a nuclear reactor coupled to a thermodynamic cycle employing a turbine-generator [3]. Initially, the Brayton cycle appeared to be the most attractive, since the system would be free of the problems of controlling free-liquid surfaces under zero-gravity conditions, but the large and heavy radiators inherently required for Brayton cycles led to extension of the study both to a new cycle [4] intermediate between the Brayton and the Rankine and to Rankine cycles [3]. In all, three thermodynamic cycles and ten working fluids (air, helium, hydrogen, $AlCl_3$, lithium, sodium, potassium, rubidium, mercury, and water [4,5] were investigated, and the relative sizes and weights of the major components were estimated [3]. The most significant figure of merit was found to be the radiator specific weight. Figure 10, taken from the study of Ref. 3, shows the radiator specific weights for all ten cases investigated as a function of the radiator operating temperature for a typical set of conditions

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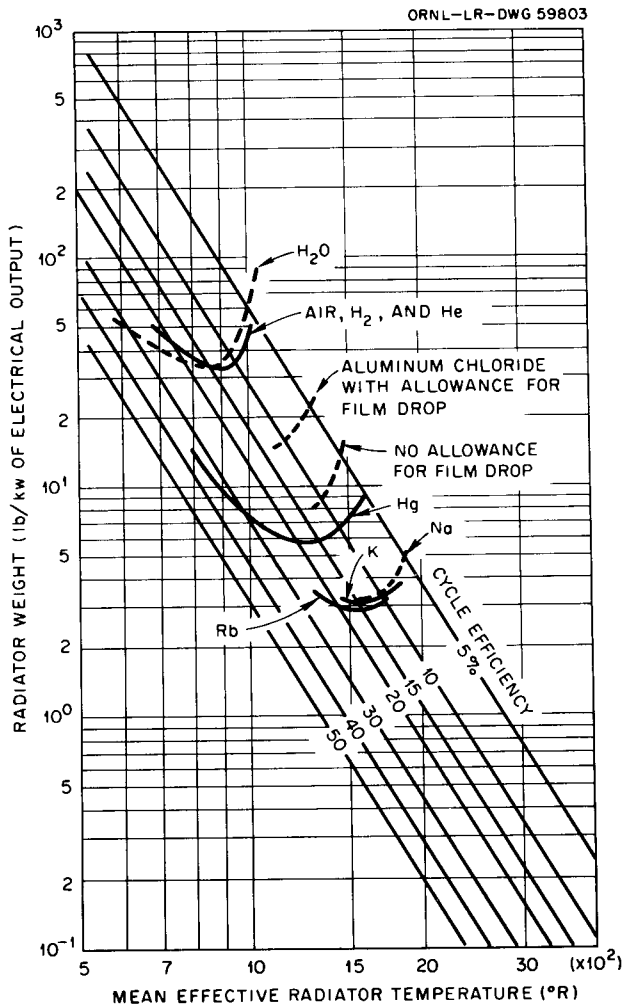

Fig. 10. Radiator Specific Weight as a Function of Radiator Operating Temperature for a Typical Set of Turbine Inlet Temperatures.

that fixed the turbine inlet temperature. Note that as the radiator operating temperature is increased, the specific weight at first falls off and then increases rapidly. The diagonal lines for constant values of the cycle efficiency help to understand this behavior; the cycle efficiency decreases with an increase in radiator temperature and thus offsets the gain in heat rejection rate per unit of surface area. These curves indicate that only the alkali-metal working fluids give promise of meeting the specific weight requirements outlined in Table 2. [A later study of Brayton cycles using argon and neon gave results consistent with the early work (see Ref. 83, p. 129).] While not shown in Fig. 10, the

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same study showed that the low vapor densities of both lithium and sodium led to large and heavy manifolds and turbines, and thus the field was narrowed to potassium and rubidium [3]. The far lower cost and ready availability of potassium make it more attractive than rubidium. The same reasoning applied to cesium, which was also considered, although no calculations were made because its characteristics are nearly the same as those of rubidium.

Comparison of One-, Two-, and Three-Loop Systems

The reactor, turbine, and radiator can be coupled in a variety of one-, two-, or three-loop systems, and each has its own advantages and disadvantages. If neutron activation of the coolant in the reactor can be kept low — as it can be with helium, water, or potassium (particularly the separated isotope ^{39}K) but cannot be with mercury, sodium, rubidium, or cesium — it is possible to make use of a single-loop system with the reactor serving as the boiler. This eliminates the weight, volume, expense, and complication associated with the pump, expansion tank, heat exchanger, instrumentation, and controls for the primary circuit. The effects of these extra components on reliability appeared to be particularly important. Data accumulated in 1959 on the reliability of turbine-generators in central stations [2], and in 1963 on other components [7], supported this view. When the relative merits of one-, two-, and three-loop systems became a crucial issue in the fall of 1965, a comprehensive study was carried out and reported [16].

System Size and Weight

The relative sizes and weights of the components for one-, two-, and three-loop systems were compared on the basis of a common set of design conditions using basic thermodynamic, heat-transfer, and fluid-flow relations [16,56]. Some results are summarized in Table 4 for four of the seven systems analyzed. (Schematic diagrams for these systems are shown in Figs. 1, 11, and 12.) As indicated in Table 4, the resulting radiator sizes and power plant weights are approximately in the ratios of 1, 1.5, and 2 for the one-, two-, and three-loop systems, respectively.

[redacted]

Table 4. Size and Weight of Each of a Series of Typical 376-kw(e) Power Plants [16]

	Boiling Reactor, Direct Condenser		Liquid-Cooled Reactor	
			Direct Condenser	Indirect Condenser
Number of loops	1	1	2	3
Structural material	Stainless steel	Niobium	Niobium	Niobium
Reactor outlet temperature, °F	1540	2000	2000	2000
Reactor thermal output, Mw	2.2	2.2	2.4	2.55
Radiator height (for a 10-ft diameter), ft	35.8	17.8	27.1	38.3
Power plant weight (excluding shield), lb	5725	4200	6920	8660

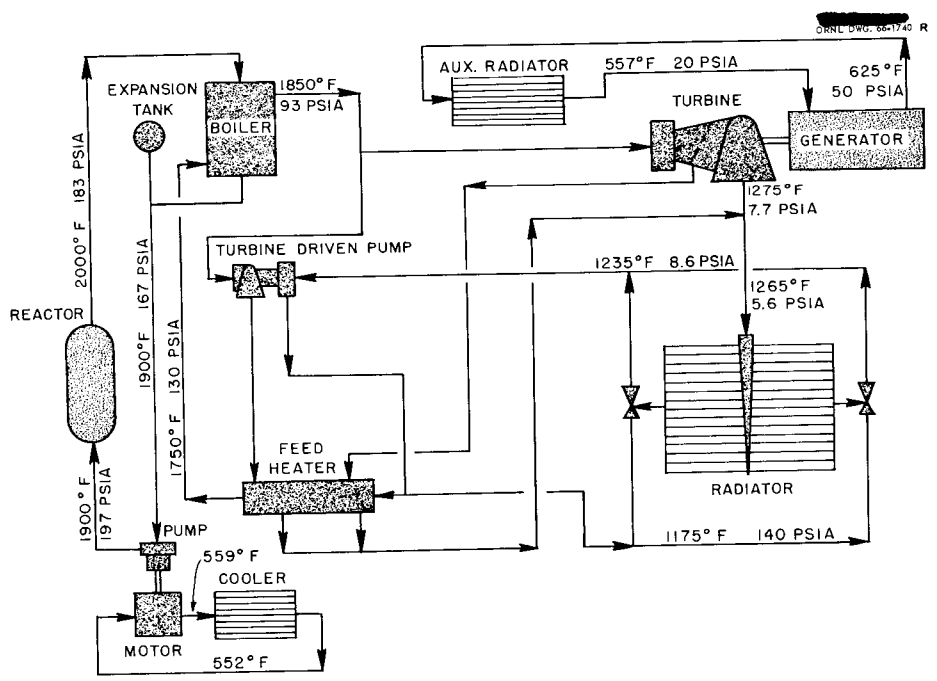

Fig. 11. Two-Loop System with a Liquid-Cooled Reactor Loop Heating the Boiler of a Refractory-Metal Rankine-Cycle Loop Containing a Direct-Condensing Radiator.

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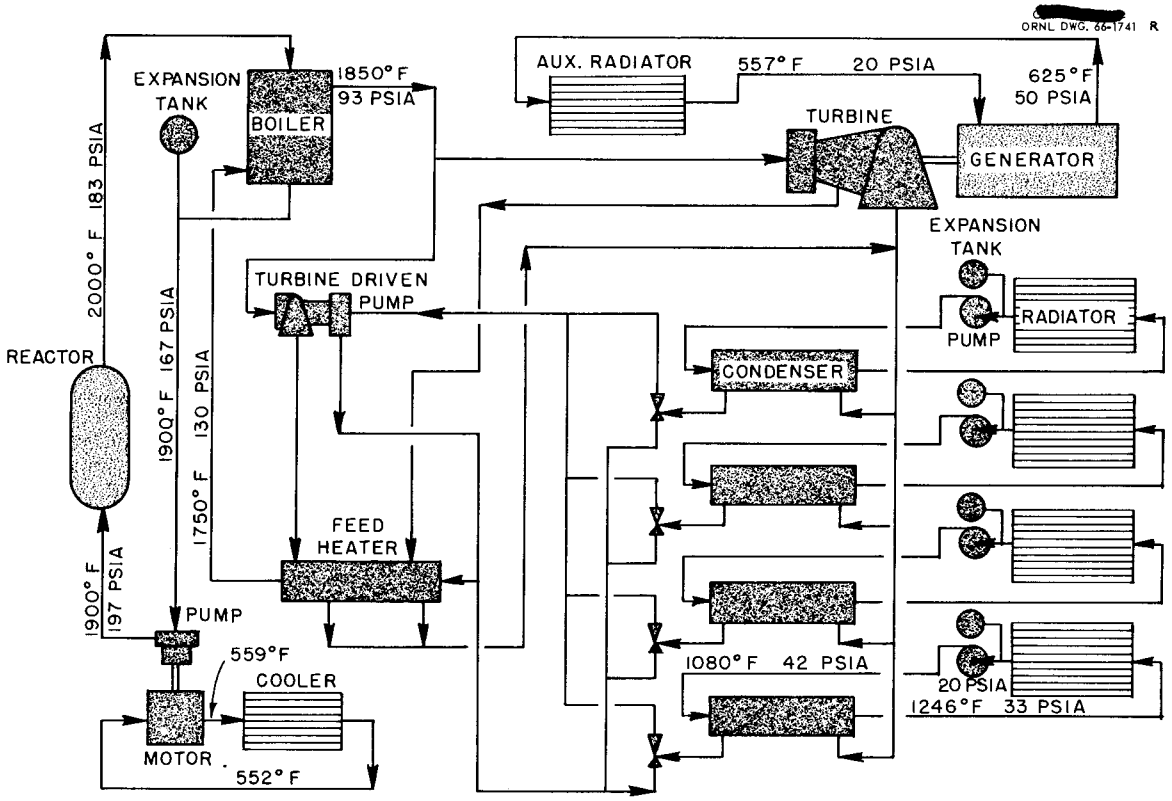

Fig. 12. Three-Loop System with a Liquid-Cooled Reactor Loop Heating the Boiler of a Refractory-Metal Rankine-Cycle Loop Coupled to a Set of Parallel Indirect Radiator Loops.

This relation was found to hold for the power range from about 300 kw(e) to 5 Mw(e) [16,17]. (See Table 5 for data on the single-loop systems.) Note also that for a single-loop system built of stainless steel for operation at 1540°F, the radiator size and power plant weight were lower than for a three-loop refractory metal system designed to operate at 2000°F. Since the size of the launch vehicle required to put a power plant in orbit is determined primarily by the size of the radiator and the system weight, it is evident that a single-loop stainless steel system gives a more attractive launch package than a three-loop refractory metal system. Extension of the studies to variations of the basic systems showed that numerous compromises could be made to favor one problem area or another but that the situation was still consistent with the implications of Table 4 [16].

[redacted]

Table 5. Sizes and Weights of a Series of Single-Loop Boiling-Potassium Reactor Systems Based on the MPRE Concept

Reactor outlet temperature, °F	1,540	1,540	2,000	2,000	2,000
Net electrical output, kw	140	367	367	1,000	5,000
Reactor thermal output, Mw	1	2.2	2.20	6.0	30.0
Reactor core diameter, in.	9.6	12.1	12.1	16.9	28.9
Reactor weight, lb	750	1,170	1,170	2,360	7,630
Radiator height, ft	15.7	35.8	17.8	30.2	73
Radiator diameter, ft	10.0	10.0	10.0	16.0	33.0
Radiator weight without armor, lb	930	1,855	1,164	3,170	15,800
Meteoroid armor weight, lb[a]	450	690	530	2,020	14,200
Total system weight, lb[b]	2,870	5,725	4,200	11,180	55,850

[a]Armor designed to give 0.1% probability of a meteoroid penetration in 10,000 hr.

[b]Not including shield weight.

Shielding

A comparison of shield weights for different types of power plant is difficult, partly because shield design requirements differ widely from one mission to another, partly because of the many variables, and partly because of the inherent complexity of shield design techniques. In an effort to clarify the situation, a fairly comprehensive study of shielding requirements, design techniques, and the effects of design parameters on shield weight was carried out and reported [30]. A brief summary of that work is presented here.

Shielding Requirements. Radiation damage to materials such as elastomers and transistors makes it necessary to employ shielding even in unmanned probes. The permissible dose levels for different materials vary substantially, not only with the type of material but also with the manner in which a given material is employed in a particular installation. For example, a given transistor may be 100 times more sensitive to fast neutrons in one type of electronic circuit than in another that would

depend on a different electronic characteristic. In general, it appears necessary to provide sufficient shielding to keep the total fast-neutron radiation dose to electronic equipment to about 10^4 rep [30]. This corresponds to around 1 rep/hr (or 10 rem/hr) for a 10,000-hr mission and proportionately less for longer missions. The output of sensitive elements of certain instruments, such as photovoltaic cells, may be affected by "background noise" unless the radiation dose level is reduced even further by such devices as the use of local shielding [30].

For manned missions the shield should be designed to keep the total dose to the crew below around 100 rem or a rate below 10 mrem/hr [30]. This is about a factor of 1000 lower than the allowable dose to the electronic equipment in unmanned vehicles. Further, to provide for rendezvous, extravehicular activity, and maintenance work on the power plant and vehicle, some shielding must be provided over the sides and rear of the reactor. The side shielding need not be as thick as the shadow shield for the crew because the periods of exposure would be quite short — hours rather than thousands of hours. A review of the probable activities and their duration indicated that the radiation dose to the side of the reactor could be about 1000 times as great as the design dose to the crew compartment [30]. Further, it should not be difficult to dispose sufficient equipment, supplies, and propellant between the reactor and the crew to attenuate the radiation by a factor of about 10. Thus, if the dose inside the crew compartment were kept to around 1.0 mrem/hr, the design dose just outside the equipment and supplies used as a shadow shield would be about 10 mrem/hr and the dose at the same distance to the side would be about 10 rem/hr [30].

Effects of Design on Shield Weight. In comparing one-, two-, and three-loop systems from the shielding standpoint, it was found that there is very little difference in the reactor core diameter between a boiling-potassium reactor and either a liquid-potassium- or liquid-lithium-cooled reactor [17], and hence the shield weights should be very nearly the same [30]. The effects on shield weight of including space within the shield for such items as controls, fission-product-gas accumulation, a vapor separator, and a heat exchanger were investigated for the series of representative cases shown in Fig. 13 [30]. These include the simple ideal

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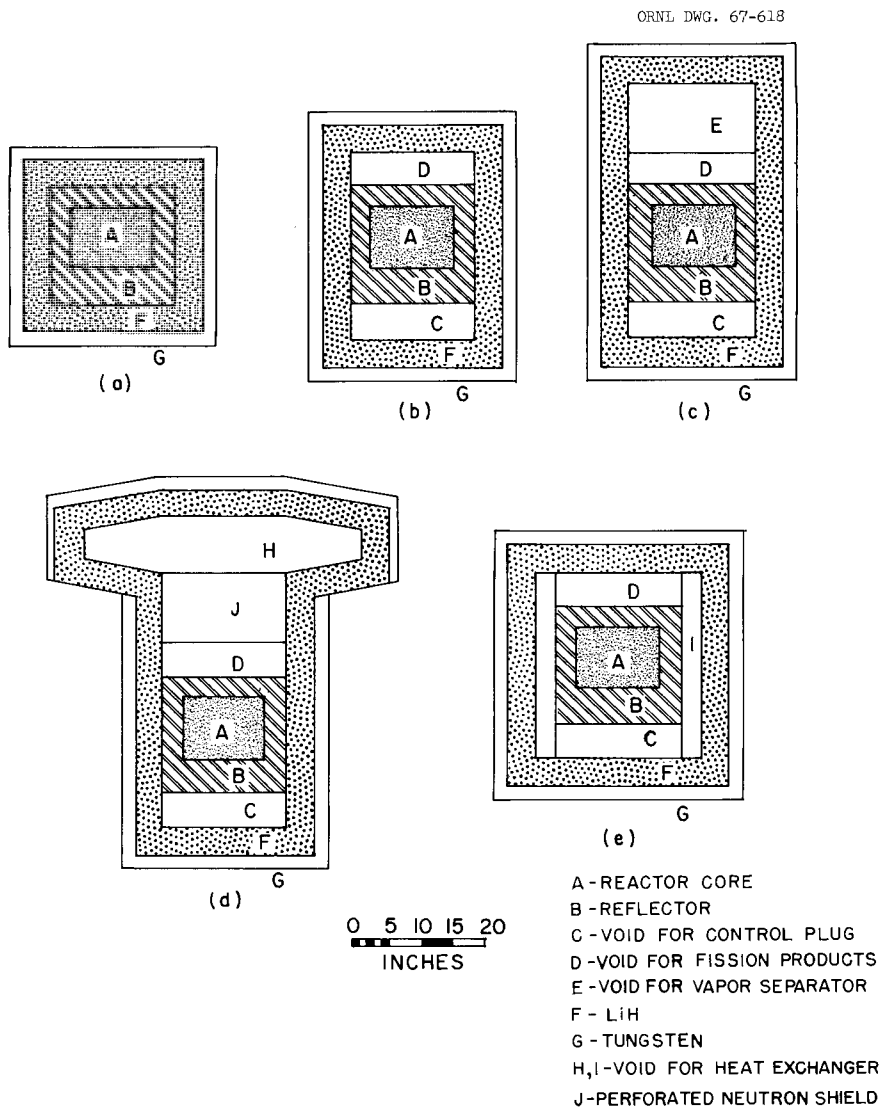

Fig. 13. Sections Through a Series of Representative Reactor and Shield Configurations.

arrangement of Fig. 13a, which consists of just the reactor core and reflector, and the arrangement of Fig. 13b, which has a void space at the lower end for operation of the control plugs (e.g., movement of the end reflectors in the MPRE) and a void space at the top to provide for fission-product-gas accumulation. Figure 13c is representative of the MPRE in that it is similar to Fig. 13b, but in addition includes a void space corresponding to the vapor separator and expansion tank. The bulk of the shielding calculations of the study were made for this configuration.

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Figure 13d represents a reactor closely coupled to an intermediate heat exchanger mounted inside the shield. Figure 13e represents a reactor closely coupled to an annular heat exchanger. In each case the heat exchanger was intended to serve as the boiler for the power-conversion system.

The effects of design power output on the shield weight for the five configurations of Fig. 13 are shown in Fig. 14 for a typical set of design conditions for a manned vehicle. Note that providing space for the controls, fission-product-gas accumulation, the vapor separator, and the expansion tank increased the shield weight by about 25% over that for an ideal unencumbered reactor core. The corresponding increase in shield weight associated with the heat exchanger for a liquid-cooled reactor would be 50 to 100%, depending on the power output and geometry.

Figure 15 shows the effects of both the degree of asymmetry in the shield and the reactor-crew separation distance for a boiling-potassium

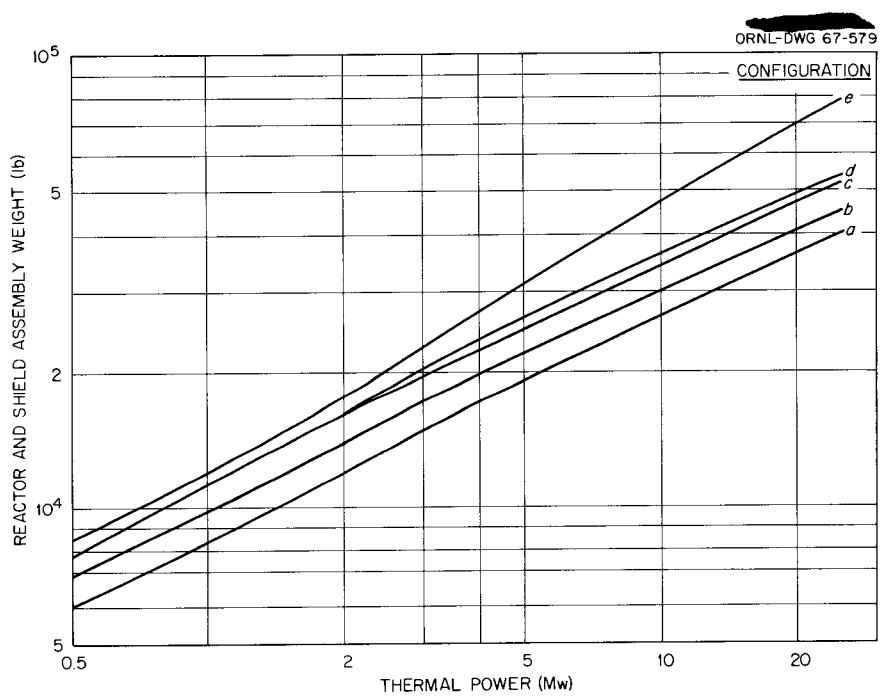

Fig. 14. Effects of Power on Reactor and Shield Assembly Weights for the Five Typical Configurations Shown in Fig. 13 with Allowances for Controls, Fission-Product-Gas Accumulation, Vapor Separation, and Heat Exchangers. Reactor-crew separation distance, 150 ft; crew dose, 10 mrem/hr; lateral dose, 10 rem/hr.

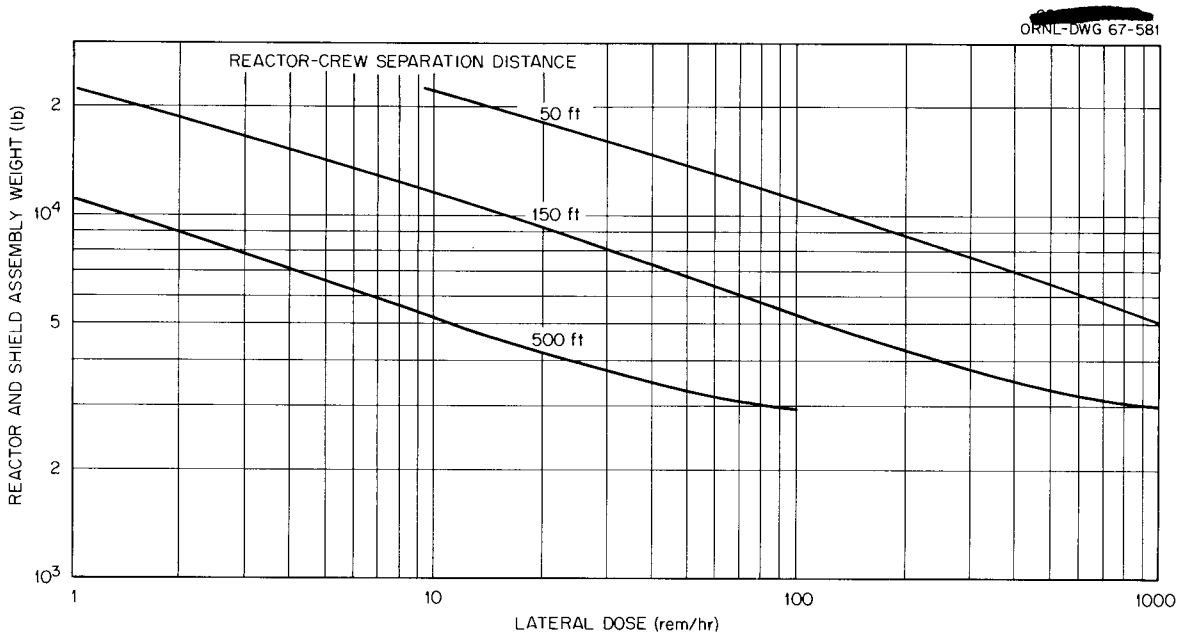

Fig. 15. Effects of Lateral Dose Rate on the Reactor-Shield Assembly Weight for a 2-Mw(t) MPRE-Type Reactor with Reactor-Crew Separation Distances of 50, 150, and 500 ft, a Dose to the Crew of 10 mrem/hr, and No Allowance for Scattering from the Radiator.

reactor similar to the MPRE for a typical set of conditions. Note the large shield weight saving possible through the use of a highly asymmetric shield. It should be mentioned that vehicle design considerations appear to favor a reactor-crew separation distance of 150 ft or more. A similar set of curves for an unmanned vehicle is shown in Fig. 16.

Effects of Radiation Scattering from the Radiator. As mentioned in an earlier section, most layouts for nuclear reactor space power plants other than those prepared at ORNL placed the reactor at the tip of the nose cone and thus imposed severe structural weight and other penalties in order to avoid problems with gamma and neutron scattering from the radiator. Early in the ORNL effort, preliminary estimates indicated that the use of a radiator and shield configuration similar to that of Fig. 6 should effect sufficient savings in structural weight to more than offset the weight of the shielding required on the sides of the reactor. Figure 17 shows the results of a recent detailed study, carried out with a computer [30], which give the neutron dose scattered by the radiator in the direction of the crew compartment as a fraction of the design dose

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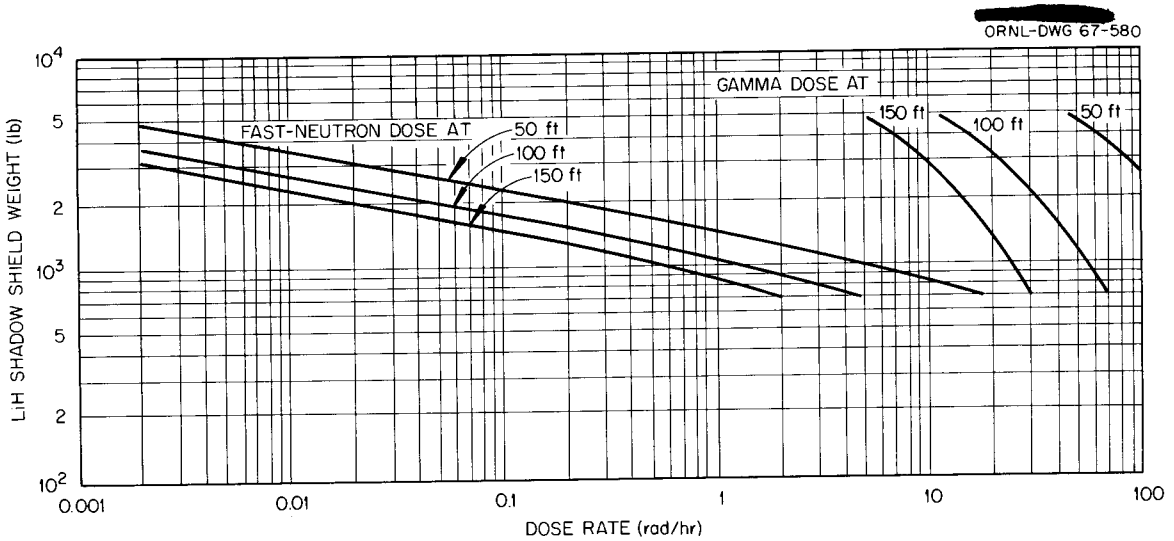

Fig. 16. Effects of Reactor-Payload Separation Distance and Fast-Neutron Design Dose Rate on the Shield Weight and Gamma Dose Rate for a Series of Lithium Hydride Shadow Shields Giving a 60° Included Angle Shadow Cone for a 1.0-Mw(t) Boiling Potassium Reactor.

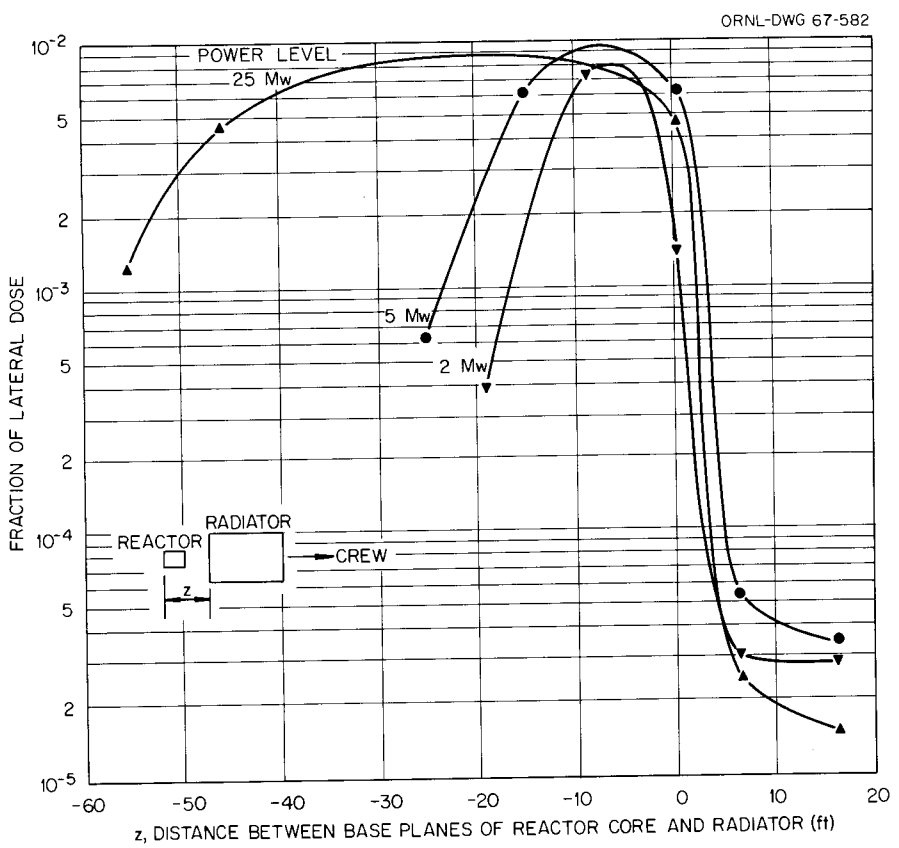

Fig. 17. Fraction of Lateral Neutron Dose Scattered to Crew Compartment by the Radiator.

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radially outward to the side of the reactor. The curves for scattered gamma radiation are essentially similar [30]. These curves indicate that there is no shield weight penalty associated with the configuration of Fig. 6 if the dose to the side of the reactor does not exceed 100 times the dose in the direction of the payload. If the ratio of the two doses is increased, it is still possible to avoid any shield weight penalty by displacing the radiator about 5 ft toward the payload so that it is largely in the shadow cone. The effects of other possible approaches can be deduced from Figs. 15, 16, and 17. For example, keeping the base of the radiator in the same plane as the base of the reactor, as in Fig. 6, gives a shield weight penalty of about 1000 lb, which should be compared with around 2000 lb in additional structural weight that would be required if the reactor were mounted in the tip of the nose cone.

Reliability of Mechanical Components

The relative reliabilities of one-, two-, and three-loop systems were investigated with the use of generic data on the mechanical reliability of components such as pumps, motors, and valves [16]. Statistical data were accumulated for over 10^9 component operating hours of well-developed industrial equipment running near room temperature and for over 10^6 component operating hours for moderately well-developed equipment operating in ORNL high-temperature liquid systems [16]. These data showed that after years of service testing of highly developed industrial equipment such as motors and valves the incidence of failures is of the order of 10^{-6} per component operating hour. Data for similar components operated in ORNL high-temperature liquid systems indicate failure rates about ten times higher. Similar data were accumulated for pumps, fuel elements, welds, bellows, and electric heaters. In applying the data to the space power plants, the incidence of failure for any given component was taken as three times that for the standard industrial equipment operating near room temperature. The results of this work, summarized in Table 6, indicate that the mechanical reliabilities of well-developed one-, two-, and three-loop systems for 10,000 hr of operation would be roughly 0.9, 0.7, and 0.6, respectively [16]. It must be emphasized that this study

Table 6. Comparison of the Mechanical Reliabilities of One-, Two-, and Three-Loop 367-kw(e) Potassium-Vapor-Cycle Systems

	Boiling Reactor, Direct Condenser	Liquid-Cooled Reactor, Direct Condenser	Liquid-Cooled Reactor, Indirect Condenser
Number of loops	1	2	3
Number of key mechanical components	9	14	31
Mechanical reliability for 10,000 hr	0.9	0.7	0.6

included only failures within the mechanical components themselves and did not include any allowances for difficulties in the electrical power supply or instrumentation and control systems.

Reliability of Control Systems

A study of the basic control functions required for normal operation, together with the vital instrumentation, yielded the numbers given in Table 7. The reliability of each instrumentation and control system was then estimated by examining the electronic circuitry required and the reliability of the basic components for that circuitry. It is clear from Table 7 that the complexity of the instrumentation and control equipment increases much more rapidly than linearly with the number of loops, and hence the reliability of the instrumentation and control equipment falls off rapidly with an increase in the number of loops. The values given for the two-, and three-loop systems are believed to be optimistic. One indication of this is that in the ground-test version of the four-loop SNAP-8 power plant at Aerojet there are 20,000 electrical connections in the main control panel,* as compared with 700 connections in an ORNL

*E. G. Brittain and R. D. Schilling, SL-1 Controls Evaluation and Phase II Proposal, Aerojet General Corp. Tech. Memo TM-4936:65-1-313, August 1965.

[redacted]

Table 7. Factors Affecting the Reliability of Instrumentation and Controls of One-, Two-, and Three-Loop Systems

	Boiling Reactor, Direct Condenser	Liquid-Cooled Reactor, Direct Condenser	Liquid-Cooled Reactor, Indirect Condenser
Number of loops	1	2	3
Number of control functions requiring electronic equipment			
Simple	1	2	2
Complex	0	2	2
Minimum complement of instrument sensors			
Vital for normal operation	3	7	9
Diagnostic	23	45	85
Electric power required for motors for a 367-kw(e) plant, kw	1	30	50
Estimated reliability of control system for 10,000 hr	0.9	<0.4	<0.2

single-loop system comparable in size [78]. This implies a far greater degree of complexity and hence a lower reliability than for the three-loop system of Table 7. While fewer connections would be required for a flight system, the number is still indicative of the way in which the instrumentation and control problems increase exponentially with the number of loops.

Zero-Gravity Problems

The control of free-liquid surfaces under zero-gravity conditions raises many problems in the design of a Rankine-cycle space power plant [13]. Unfortunately, there is little background of experience to serve as a basis for appraising the difficulty of these problems. Analyses indicate that the problems in the condenser are much the same irrespective of whether one-, two-, or three-loops are employed, and both the

[redacted]

analyses and the few tests that have been run indicate that the problems are manageable [13]. The problems in the boiler are more complex. Some feel that a once-through boiler will be less subject to gravitational effects than a recirculating boiler. On the other hand, once-through boilers in conventional power plants have given much more difficulty with boiling flow instability and system control than recirculating boilers, particularly at part load. These problems have proved to be so acute, in fact, that it has been found necessary to base the boiler controls for once-through boilers on complex electronic equipment that operates key valves according to a complex schedule, but even so the control characteristics are poor at less than about half load [16]. Recirculating boilers give much less difficulty with stability and control problems, but their much lower pressure drop may lead to difficulties with boiling instability under zero-gravity conditions. Analyses indicate that a recirculating boiler of the type used in the MPRE should be stable under zero-gravity conditions. Tests to investigate this have been devised and were scheduled to be run in the MPRE program.

Many space power plant designers have avoided free-liquid surfaces by employing a bellows of some sort to serve as the expansion tank in each fluid system. If this approach is employed, the system reliability is degraded by the instrumentation and control equipment required to control the volume of liquid in the bellows. Further, test experience indicates that the reliability of bellows is unacceptably low and that some other type of expansion tank will be required [16]. If a bellows-type of tank is not used, it appears that a multiloop system has much the same problems with respect to the control of the free-liquid surface in the expansion tank as a single-loop system, except insofar as the problems are aggravated by the greater number of tanks required.

A vapor separator is required for the recirculating boiler of the single-loop system, whereas it would not be for the once-through boiler commonly considered for the two- and three-loop systems. However, the problems of free-liquid surface control in the vapor separator and expansion tank of the proposed boiling-potassium reactor single-loop system appear manageable. Zero-gravity flight tests with an air-water model

of the MPRE vapor separator–expansion tank have been quite encouraging and indicate that the problem may be resolved satisfactorily by maintaining a swirl in the tank so that the free-liquid surface is stabilized by a centrifugal field [96].

Startup Problems

Studies of the problems of starting up the one-, two-, and three-loop systems indicated that all the five steps required for the single-loop system had essentially identical counterparts in the procedure for the three-loop system [16]. However, the three-loop system has seven additional steps that have no counterparts in the single-loop system; thus a more complex and less reliable startup system is implied. The two-loop system with a liquid-cooled reactor has two fewer steps in the startup procedure than would be required for the three-loop system. Experience with actual systems under zero-gravity conditions is required for a better evaluation.

Reliability and Hazards

For manned missions, hazards to the crew present complications. It is possible to bring some order to the confusing melee of possible failures by dividing all malfunctions into three categories: (1) those that cause some loss in power capacity, (2) those that cause a complete loss in electrical output but do not otherwise necessarily create a hazard for the crew, and (3) those that release fission products in such a way as to give a serious increase in the radiation dose to the crew [16]. It is evident that the simpler the system, the less likely will be difficulties with the first two items. The failures that lead to a release of fission products pose a special set of problems.

Leaking fuel elements constitute one major type of difficulty. It is obvious that a disadvantage of the single-loop system is that a fuel element leak would allow fission products to enter the radiator and that this could result in a serious increase in the radiation dose rate in the crew compartment. Analyses show that a leak from the MPRE fuel element near the end of life would release about 2.9 curies of gaseous fission products, and the consequent dose to a crew 150 ft away would be

less than 1 mr/hr [15]. The dose would gradually increase if the leak were large enough so that potassium vapor replaced the helium in the fuel capsules, but even so it would not exceed 1 mr/hr if the reactor power were limited to about 70%. The need for limiting the power might be eliminated by modifying the fuel element design to reduce the center-line temperature [18] or by designing the vehicle to make some of the equipment and supplies serve as a shadow shield for the crew. Essentially the same conditions would hold for a single-loop high-output refractory-metal boiling-potassium reactor with UO_2 fuel elements [17,18].

The most serious failures are those that stem from a loss of coolant flow through the reactor. While it is not difficult to provide for an automatic shutdown for the reactor, the afterheat will lead to trouble. If the coolant circulation stops in a liquid-cooled reactor, the temperature in the core will rise, the liquid will expand until the pressure rises sufficiently to rupture the system, and the coolant will boil off or be ejected. The fuel element temperature will continue to rise until the cladding melts, the UO_2 temperature exceeds 3000°F, and large quantities of fission products are released and leak to space [51]. These will tend to spread isotropically from the point of release, and experience with fogging of the external surfaces of the windows of Geminis 6 and 7 indicates that a substantial fraction of the fission products will tend to stick to the relatively cool surfaces of the spacecraft.

Reliability studies indicate that the probability of a loss of reactor coolant flow as a consequence of a system leak (including a meteoroid puncture of the radiator) can be kept to about 1%, with the one-, two-, and three-fluid systems differing by only a small factor [16]. The more probable cause of a loss-of-flow accident is a pump failure. This is far less likely in a free-turbine-driven pump than in an electric-motor-driven pump, since the latter involves not only the pump rotor and bearings but also the windings, the bore seal, a complete cooling system with its pump and radiators, and the electric power supply with its attendant switch gear and an inverter to supply ac power to the pumps from batteries in the event of a generator outage [16].

The general problem is difficult to analyze — a complete set of circuit diagrams for a specific system is really required — but even by the

extensive use of redundancy, including auxiliary electromagnetic pumps, it appears difficult to assure a 90% probability that forced circulation can be maintained through the reactor throughout a 10,000-hr mission [16]. There are so many links in the chain of a system that depends on electric pumps — instrumentation to detect difficulties and initiate appropriate action being not the least — that it may well be that the only acceptable solution will be to depend on the centrifugal field of a spinning vehicle to provide thermal convection. If this approach is taken, the boiling reactor has an important advantage in that only a small centrifugal field will suffice to maintain circulation because of both the low flow rate required and the large density differential between the riser and the return leg. As a point of interest, an ORNL study of system variations indicates that if a centrifugal field of 1/6 g or greater is available, a boiling potassium reactor can be designed to operate in a two-loop system so that thermal convection in the reactor circuit would serve for full-power operation, and no primary circuit coolant pump would be required [18].

Choice of Materials

Fuel Element

The heart of a reactor is the fuel element. For reactors designed to produce more than 30 kw(e) for periods of a year or more, deterioration of the fuel with burnup is a vital consideration. Metallic uranium and uranium alloys have received much attention, but even the best all-metal fuels have been subject to swelling and warping after relatively small amounts of burnup, particularly at temperatures above 800°F (the melting point of metallic uranium is 2060°F) [51]. The inherent limitations of metallic uranium have led to extensive work with uranium oxide. The dimensional stability of uranium oxide, with a melting point of 5070°F, is vastly superior at high temperatures to that of any of the metallic fuel materials, and uranium oxide is now used in virtually all the central-station reactors that have been built or are on order in the United States [51].

The good thermal conductivity and high atomic density of uranium carbide have made it appear attractive, but in-pile tests indicate that it is limited to a lower burnup than is possible with UO_2 under space reactor conditions [51]. Preliminary tests with uranium nitride are encouraging, but further tests must be run before it will be known whether uranium nitride will withstand as much burnup as UO_2 [51].

The burnup obtainable with a given fuel material is usually limited either by swelling or by fission-product-gas release. Figure 18 shows the effects of burnup on these two parameters for three different fuels in a typical space reactor designed for an outlet temperature of 2000°F [51]. It is not possible to operate metallic fuel elements at this temperature, but a dotted curve for uranium-zirconium hydride at 1400°F is also included as a point of interest. Even after full allowances for the wide scatter bands given by the test data, these curves show clearly the reason for the choice of UO_2 for the boiling-potassium reactor system [15].

Fluid Circuit

Liquid-metal systems constructed of nickel- or iron-base alloys have been found to be subject to corrosion and mass transfer at high temperatures because of the temperature-dependent miscibility of the container alloys in the fluid circulated. The equilibrium solubilities of conventional alloys are much higher at higher temperatures than at lower temperatures, and hence metal tends to be dissolved from the hot zone and deposited in the cold zone; this is the phenomenon known as "mass transfer." Difficulties of this sort have been particularly severe with lead, bismuth, and mercury at temperatures above about 900°F. Flocculent deposits of dendritic crystals tend to plug the small-diameter passages in the colder portion of the system. While filters are helpful, their effectiveness is limited by the fact that material tends to precipitate out of solution wherever there is a drop in temperature so that plugs may form ahead of, on, inside of, or downstream from the filter. An indication of the degree to which corrosion and mass transfer occurs is indicated by Fig. 19, which shows the corrosion rate as a function of temperature for several typical materials combination.

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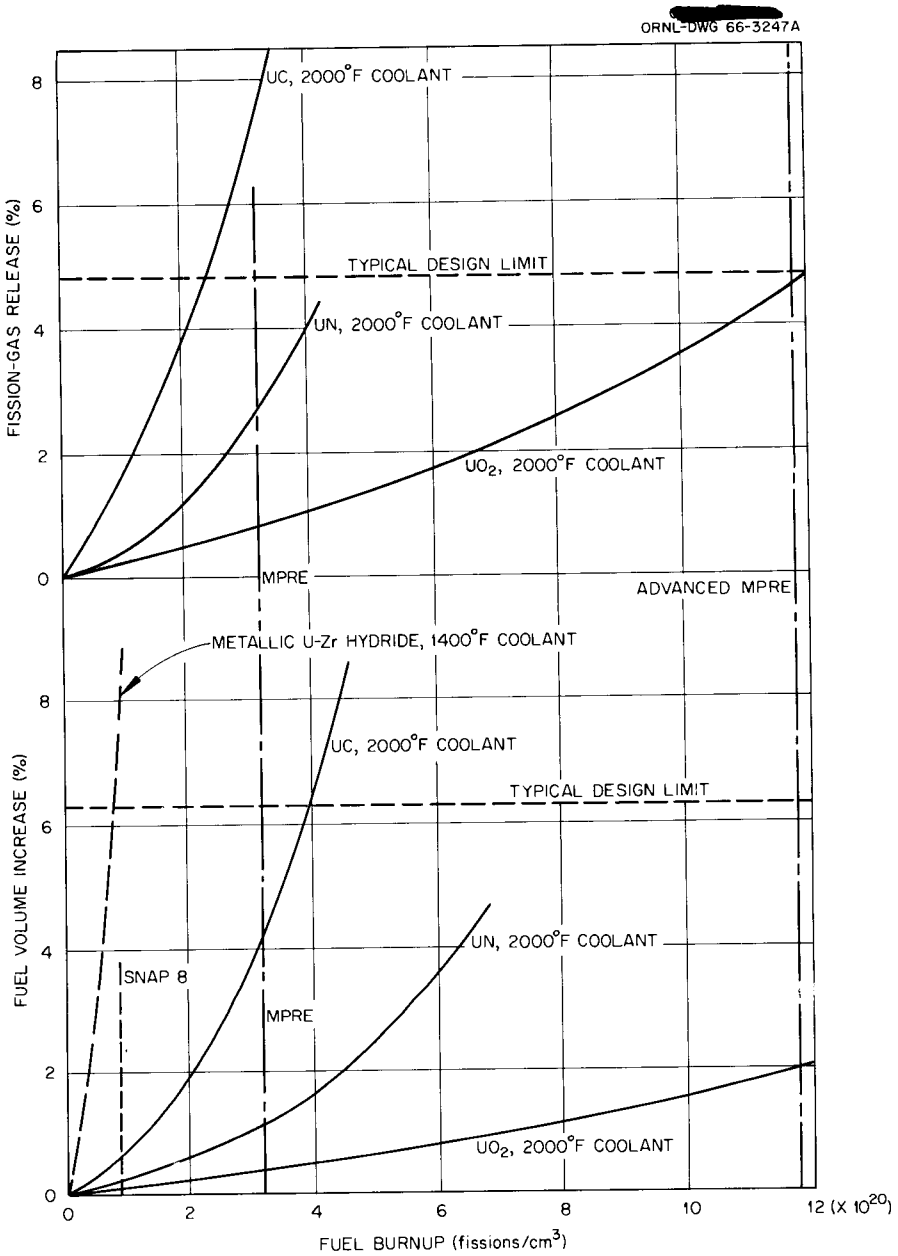

Fig. 18. Effects of Burnup on Swelling and Fission-Produc -Cas Release for Typical Fuel Materials in Fuel Elements Designed for a 2000°F Reactor. Data for UO_2, UC, and UN from Ref. 51; data for U-Zr ydride from pp. 16 and 130, Atomics International Report NAA-SR-992, September 1964.

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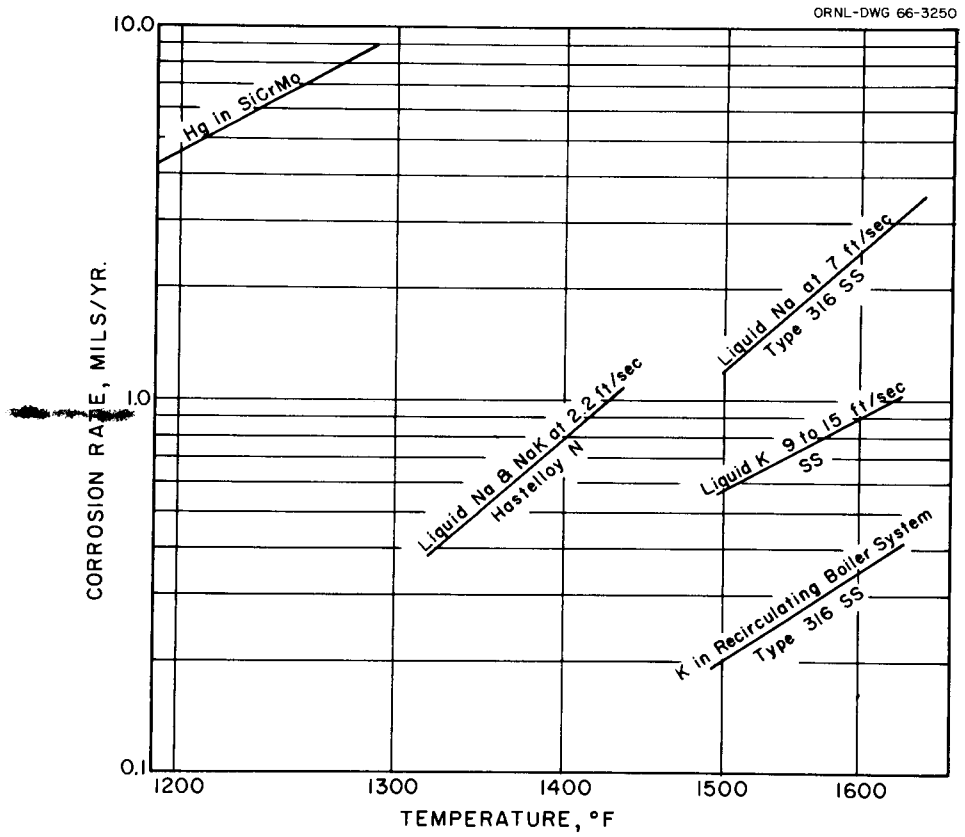

Fig. 19. Effects of Temperature on the Corrosion Rate for Typical Combinations of Materials for Rankine-Cycle Systems.

Extensive forced-convection corrosion loop tests have shown that sodium and potassium give very low mass transfer and corrosion rates in stainless steel or niobium systems if the oxygen content is kept down to around 20 ppm or less [55]. A large further reduction can be effected through the use of a recirculating boiler system (such as that of Fig. 1) in which the fluid leaves the hot zone of the system as a vapor so that it will not transport dissolved solids [55]. Thus the choice of potassium as a working fluid on the basis of component size and weight considerations is also sound from the materials compatibility standpoint [55].

A major consideration in the design of high-temperature systems is the ratio of the allowable stress in the structural material to the system pressure. For any given structural alloy and Rankine-cycle working fluid, this ratio falls off rapidly with temperature, partly because the alloy loses strength, and partly because the fluid vapor pressure rises

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fairly rapidly with temperature. The curves of Fig. 20 show that the lower vapor pressure of potassium permits a much higher system operating temperature than is possible with mercury for a given structural material, and that the greater strength of a refractory alloy makes it possible to design for an operating temperature hundreds of degrees higher than for a stainless steel system.

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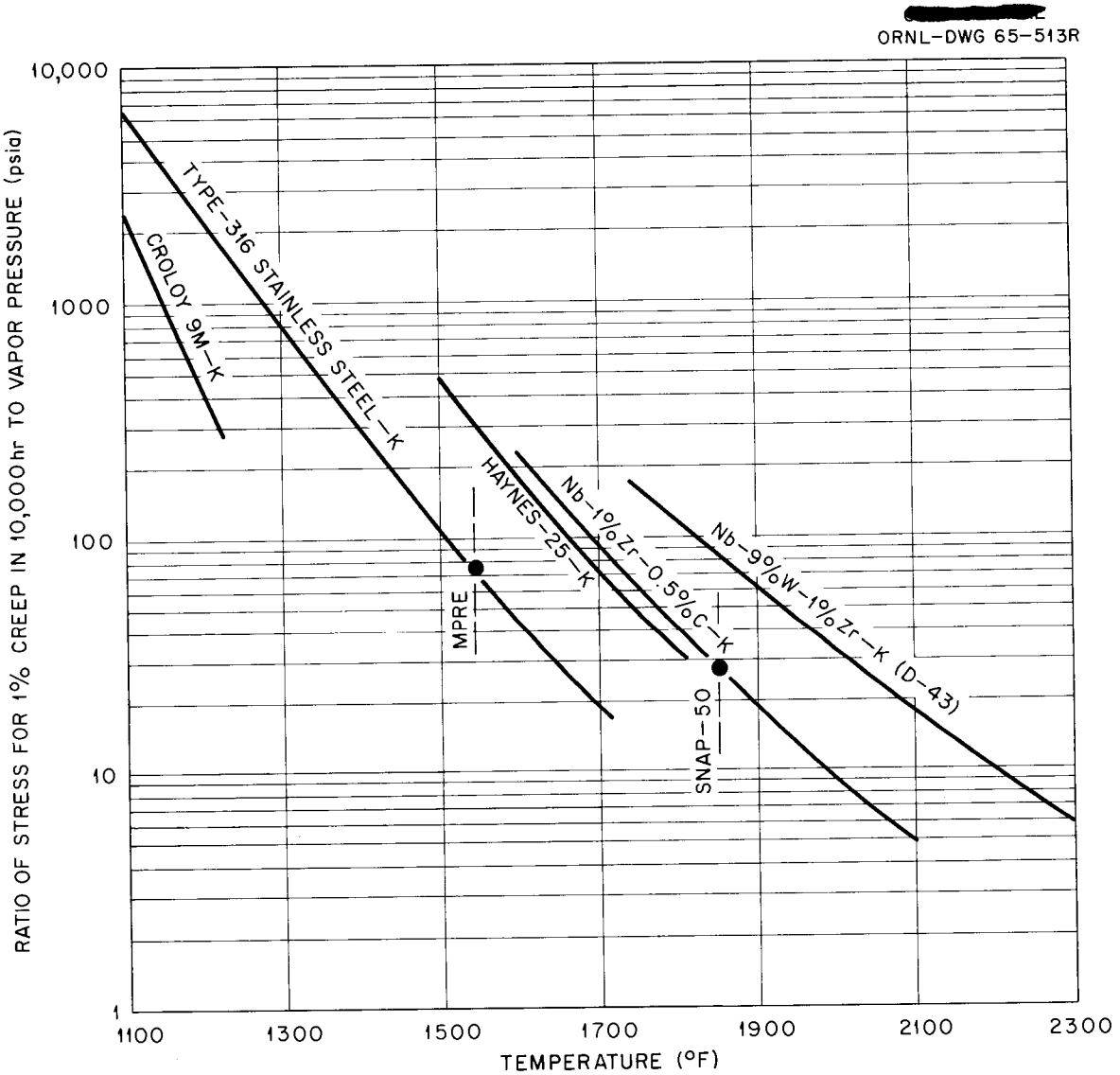

Fig. 20. Effects of Temperature on the Ratio of the Allowable Stress to the Vapor Pressure in the Boiler for Typical Combinations of Materials for Rankine-Cycle Systems.

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Radiation damage, creep, and fatigue constitute important limitations on the choice of a structural material. Sufficient test data are available to show that the mechanical properties of stainless steel [53,54] and BeO* are adequate for the MPRE design conditions.

DESIGN AND DEVELOPMENT PROGRAM

The concept selection work outlined in the previous section led to the conclusion that a single-loop Rankine-cycle system employing potassium vapor as the working fluid promises both a higher performance potential and a greater system reliability than any other cycle or system that has been given serious consideration. Such a system built of stainless steel gives a sufficiently high performance to satisfy the requirements for most of the missions that have been contemplated, and the cost and time required to develop it appear to be relatively modest. Thus the MPRE design and development program was directed primarily toward a stainless steel system. Once the concept was proved out with stainless steel, extrapolation of the experience to the design and development of a similar refractory metal system that would meet the performance requirements for the more difficult longer range missions should be relatively straightforward [55].

The various problems raised by the many innovations of the boiling-potassium reactor system were delineated insofar as possible at the beginning of the program, and what were considered to be the most vital were attacked first. This policy was continued as the program evolved; at each stage in the development work the funds available were applied to the problems deemed to be the most vital of the problems that remained.

Program Summary

A convenient way to summarize the more important results of the design and development program and to indicate the status of the development

*G. W. Keilholtz et al., Properties of BeO Compacts Irradiated to Fast-Neutron Doses Greater than 10^{21} Neutrons/cm^2 at 110, 650, and 1100°C, USAEC Report ORNL-TM-1011, Oak Ridge National Laboratory, December 1964.

effort as the MPRE program is being halted is to make use of Table 8. This is a modification of a table prepared early in the MPRE development program (referred to briefly in Ref. 82, p. 71 and later brought up to date in a modified form in Ref. 11) to highlight the principal feasibility problems and to indicate the principal experiments designed to cope with them. As indicated in Table 8, acceptable solutions to most of these problems have now been obtained (with about the effort originally contemplated), and the work carried out has been covered in the references listed at the end of this report. Note that the first ten categories in the list of references are the same as the column headings of Table 8.

The development test program was considered as both a means for resolving design problems not amenable to theoretical analyses and as a means for bringing to light subtle problems not recognized by the designer until they are stumbled over in the test work. Thus no sharp line of demarcation has been drawn in Table 8 between the design and test work, except that the purely analytical and design work is summarized largely in the first column, while the experimental work and related analyses are summarized in the other nine.

Feasibility Tests

During the first two years of work (under the ANP Program in FY 1960 and 1961), the effort was concerned with just two major areas; namely, an investigation of the mass-transfer and corrosion problems of boiling potassium in a stainless steel system in the 1500 to 1600°F range [48] and with the determination of the heat transfer coefficients and burnout-limited heat fluxes for boiling potassium under forced-convection conditions [32]. Favorable results from this work led to a formal program to establish the feasibility of the system, and tests of a vapor separator and jet pumps were run with water, while heated rod bundles were used to boil water and Freon to high exit qualities to investigate boiling-flow and flow-stability phenomena [81,82]. This work was supplemented by tests of a simple system with a free-turbine-driven feed pump to investigate the system stability and control characteristics and the problems of a bootstrap startup [82]. Concurrently with this work, reactor physics

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Table 8. Summary of Major Steps in the MPRE Program

Year	General Design and Analysis	Reactor Core Evaluation	Boiling Fluid Flow and Heat Transfer	Vapor Separator and Expansion Tank	Corrosion, Mass-Transfer, and Materials Problems	Turbine Pump and Turbine-Generator	Jet Pumps	Condenser-Radiator	System Stability and Control	System Endurance Tests
FY-59 -60 -61	Ten working fluids evaluated [1-3, 56]. One-loop, stainless steel-UO_2-potassium system devised and found to give smallest radiator, lowest specific weight, and highest reliability [1-3]. Boiling flow stability requirements defined [31]. Preliminary calculations indicated small negative void coefficient possible in a boiling-potassium reactor.		Heat transfer and burnout data from single-tube boiler showed potassium boiling heat transfer performance similar to that of water [32].		Capsule and natural-convection loop tests showed stainless steel compatible with boiling potassium [48].			Tests showed high effectiveness for proposed radiator tube-reflector assembly.		
FY-62	Basic development program outlined and preliminary layouts for 7- and 91-rod test rigs prepared [81]. Reactor-vapor separator-expansion tank assembly and basic system layout evolved [81]. Flow in tapered-tube condenser analyzed [66].	Reactor calculations defined 241-rod MPRE core with good power distribution and negligible void coefficient [81].	Four-rod water and seven-rod Freon boilers showed excellent internal flow stability consistent with analyses [81,82]. First Firerods tested in boiling potassium [80].	99% efficient liquid removal demonstrated with small toroidal air-water separator [82,83].		Small turbine-pump for seven-rod boiler built and tested with steam [82]. Tungsten carbide bearings run 4000 hr in potassium with 350 starts and stops under load [82,83].	Water tests showed that a jet-pump operated with cavitation suppression head <1 in. H_2O [81].		Small water-steam system with boiler and turbine pump gave smooth bootstrap start and stable operation over entire power range [82].	
FY-63	Effectiveness of capillary forces for controlling free liquid surfaces analyzed [83]. Analytical solution of system performance characteristics, flow distribution, and component matching requirements worked out [84].	Critical experiments verified calculated critical mass, power distribution, and negative void coefficient for potassium in coolant passages [21-23,83,84].	Good stable flow distribution demonstrated in 91-rod water boiler [83]. Explosive boiling problems evaluated [81]; hot fingers and nucleation rings found to be good solutions [84].	Greater than 99% removal of water demonstrated with toroidal vapor separators for 7- and 91-rod boilers using both air-water and steam-water mixtures [47].		Brittleness of molybdenum required design refinements in turbine-pumps with carbide bearings for SPS-1 and IPS [59]. Little erosion of simulated turbine bucket was found after 750 hr in 3000 fps jet of 84% quality potassium vapor [59].	Noncavitating performance determined for jet pumps for 7- and 91-rod boiler systems.	Zero-gravity tests of free liquid surfaces in tapered tubes run in NASA drop-test tower [83]. Test of 12-tapered-tube condenser with steam checked analysis [83].	Seven-rod water boiler system mockup showed good stability and control characteristics from bootstrap start to full power with cavitation control of liquid inventory distribution [83].	Forced-convection boiling potassium corrosion loop operated for 1000 hr [84].
FY-64	Launch package configuration evolved [10]. Preliminary design of test facility prepared [8]. Poor flow distribution at low condenser temperatures found in 12-tube potassium condenser corrected by deliberate design for choking at condenser tube inlets [68].		Burnout limitation data obtained with 7- and 91-rod water boilers [44].	Vapor separators developed for 91-rod potassium boilers and for zero-gravity test of air-water unit of seven-rod boiler size [47].	Forced-convection corrosion loop tests showed that molybdenum parts in stainless steel systems are sensitive to O_2 contamination of potassium. The use of hot traps is suggested [55].	World's first potassium vapor turbine operated in SPS-1. Tungsten carbide bearings did not scuff in 50 starts and stops [87]. No corrosion or erosion of molybdenum turbine pump or K-94 bearings [59,87,96].	Technique for obtaining good cavitation performance test data developed [87]. Basic relations for cavitation performance developed and correlated with jet pump test data [60].	Good flow distribution and good flow stability demonstrated with 144 tapered-tube condenser in water-steam system [71].	91-rod water boiler system mockup demonstrated good stability and control characteristics from bootstrap start to 125% power [72]. Seven-rod potassium boiler system mockup showed performance similar to that of seven-rod water boiler system [87].	Forced-convection corrosion loops operated 2820 hr [55]. SPS-1 ran 170 hr [88].
FY-65	Test facility designed and hazards report prepared [8,12]. Analytical design of MPRE and full-scale mockup largely completed [91,92].	Fuel elements specified and procured for hot critical experiment [52]. In-pile fuel element tests started. Effects of local variations in potassium reactivity coefficients investigated and found to be small [24].	Smooth initiation of nucleate boiling demonstrated in 91-rod potassium boiler both with hot fingers and with nucleation rings only [80].	Vapor separator-expansion tank for full-scale MPRE developed to give ~99% quality in air-water tests [47]. Zero-gravity tests with seven-rod size air-water separator in KC-135 airplane showed that a strong swirl is required for low lateral acceleration [89].	Specimens from loops showed that corrosion mechanism in a recirculating boiler system is quite different from that in all-liquid loops. Mass-transfer rates are much lower, and material moves from condenser to boiler [55].	Bearing trouble in seven-rod potassium boiler system showed that filter is essential in lube supply [59]. Bearing trouble in 91-rod system showed loads should be in same direction at both ends of shaft to avoid edge loading [59].	Extensive cavitation limit tests of jet pumps for MPRE show different types of cavitation and sensitivity to geometry [61].	Infrared photos prove excellent for investigating flow and temperature distribution in potassium condenser-radiator [68]. Flow distribution stable and uniform in 144-tube potassium condenser [68].	Electronic analog correlated well with 91-rod electrically heated mockups [71]; 91-rod potassium boiler system showed characteristics similar to those of water system [72].	Forced-convection corrosion loops operated 1540 hr [55]. SPS-1 ran 1376 hr. IPS ran 400 hr [91].
FY-66	Scale-up potential of MPRE to 30 Mw(t) and superiority of one-loop system in size, weight, and reliability shown [16,17]. Materials problems and limitations delineated in series of staff papers [50, 52-54]. Variations of MPRE system delineated to show the many degrees of freedom available [16,18]. Stress analysis of reactor pressure vessel completed [19].	Control-plug drive prototype completed 2000 scrams satisfactorily [27]. Fuel element in-pile tests show UO_2 expands and contracts as if monolithic and independent of cladding [95,96]. Two fuel elements completed 9500 hr in-pile at MPRE full-power design conditions [96].	Preliminary tests with potassium in seven-rod boiler showed burnout limit at least as high as for water [94]. Seven-rod-boiler zero-gravity test rig designed, built, and run upside down.	Revised toroidal vapor separator-expansion tank zero-gravity design developed in 91-rod boiler size. Bench tests show insensitivity to attitude [94]. Zero-gravity tests in KC-135 airplane showed fairly good behavior of free surface [96].	Tests showed that vapor-deposited tungsten protected brazed Al_2O_3-Covar joints better than nickel plate [96]. Specimens removed from seven-rod boiler system after 4500 hr showed little corrosion and mass transfer [96].	No erosion found in IPS turbine and pump after 2500 hr with cavitation in pump. Turbine driven by 2000 fps 95%-quality vapor [96]. Cavitation limit in electromagnetic pump depends on inert-gas pressure in expansion tank. New brazing technique gives corrosion-resistant joint for generator bore seal [96].	Compact jet pump layout developed for MPRE expansion tank [93]. Rig built for testing jet pumps in potassium. Test data correlated well with similar data for water [96].	Transparent condenser designed for zero-gravity tests operated in seven-rod water boiler system [94]. Tests run with electrically heated rod with fins and reflector checked performance calculations [69].	Good correlation between 91-rod potassium and water boiler systems and electronic analog, including control of liquid inventory distribution [71, 72]. Good stability and control characteristics found for electronic analog of MPRE reactor and turbine generator [73].	SPS ran 2900 hr [55]. IPS ran 2800 hr [78]. Completed 10,000 hr with forced-convection loops [55].

[redacted]

analyses were carried out, and it was found that a small reactor could be proportioned to give good nuclear characteristics [82].

System Mockups

As favorable results from the above work became available, a reference design for a full-scale launch package was laid out, and a series of reduced-scale mockups of the complete system was designed [76,81–83]. The boilers for these were based on the use of a commercially available electric cartridge heater having the diameter and length of the proposed fuel element (except for an extension at the bottom end of the heater for the electrical leads) [80]. Two basic sizes of rod bundle were employed, that is, the 7-rod and 91-rod bundles of Figs. 21 and 22 [76]. Since, as shown in Table 9, the physical properties of water and steam at around 240°F are almost the same as those of potassium at 1540°F (except that liquid potassium has a much higher thermal conductivity), essentially the same Reynolds, Mach, and Froude numbers could be maintained in both the liquid and vapor of a water system that would prevail in a potassium system having the same geometry. Thus, first the small and then the intermediate-size water mockups were built and tested. After good system stability and control characteristics were demonstrated with these systems, similar potassium systems were built and tested. Table 10 lists the principal component tests and Table 11 lists the principal mockups built to simulate the system.

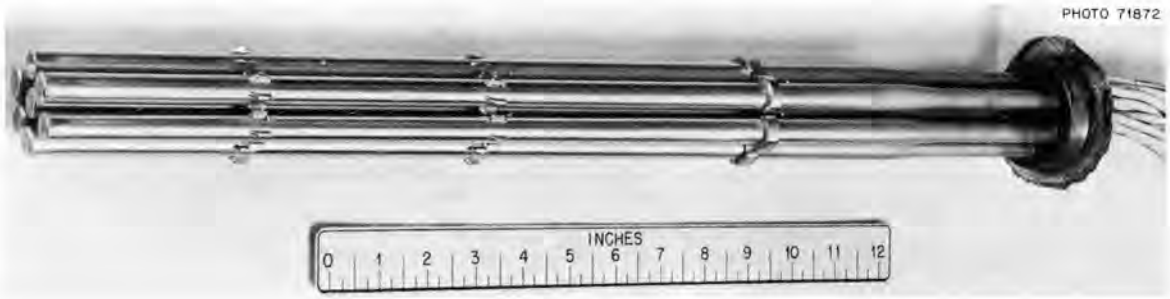

Fig. 21. Seven-Rod Bundle.

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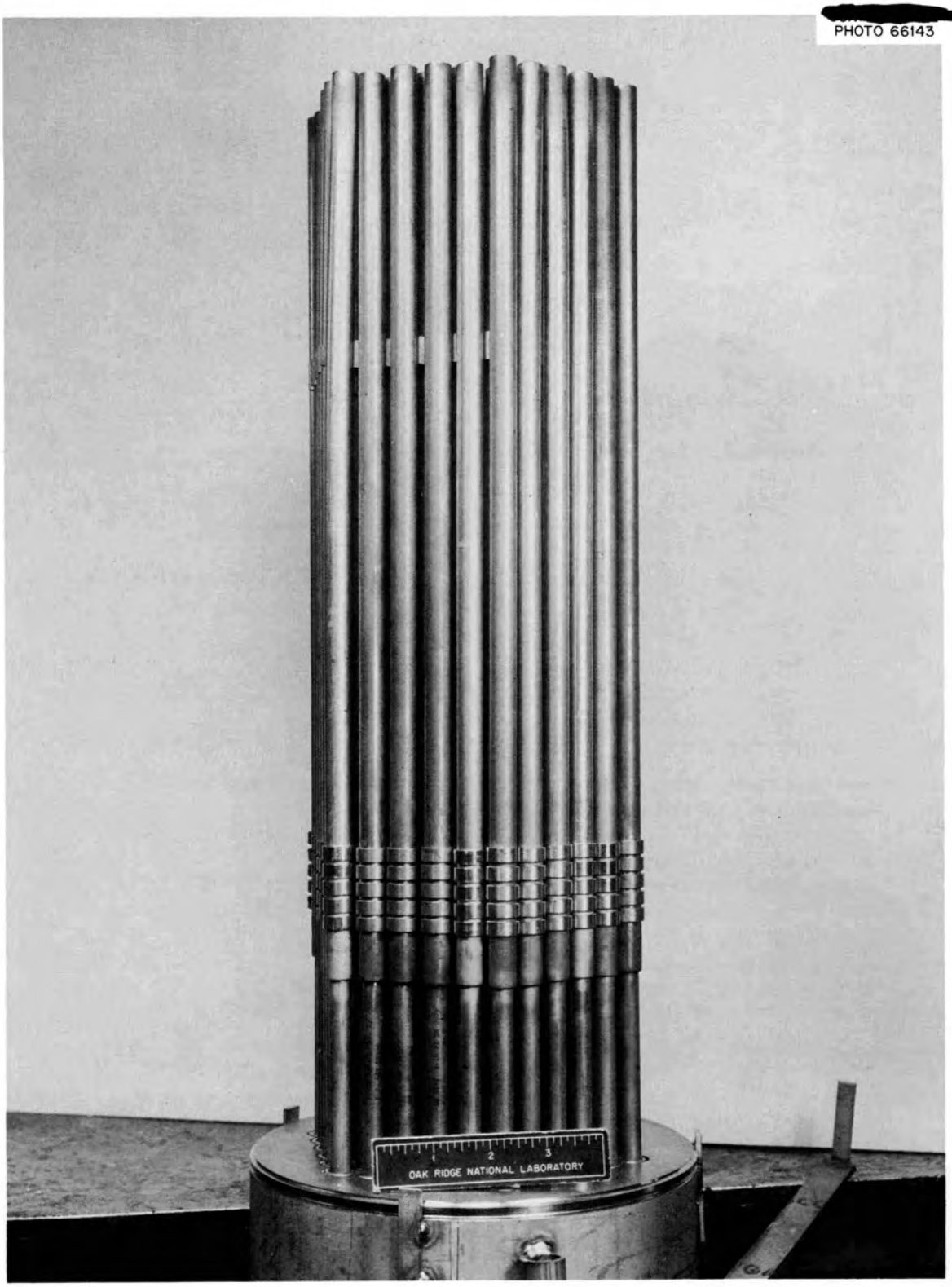

Fig. 22. 91-Rod Bundle.

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Table 9. Comparison of Physical Properties of Potassium and Water for Boiling Conditions

	Potassium		Water	
	Liquid	Vapor	Liquid	Vapor
Temperature, °F	1540.0		248.2	
Pressure, psia	29.02		29.02	
Specific volume, ft^3/lb	0.02469	17.667	0.01699	14.180
Enthalpy, Btu/lb	375.6	1210.5	216.90	1163.41
Heat of vaporization, Btu/lb	834.9		946.51	
Specific heat, Btu/lb·°F	0.1903	0.1263	1.014	0.44
Viscosity, lb/ft·hr	0.32	0.0253	0.572	0.034
Thermal conductivity, Btu/hr·ft·°F	17.0	0.00483	0.396	0.015
Prandtl number	0.00358	0.662	1.46	1.00
Surface tension, lb/ft	0.0031		0.00376	

Table 10. Component Development Tests Run in the Course of the MPRE Development Program

Test	References
Boiling heat transfer and burnout heat flux	32, 35, 36, 44
Nucleation in boiling potassium	39, 42, 44, 96
Vapor separator	47, 81, 82, 84
Jet pump performance	60, 61
Potassium-lubricated bearings	59, 83, 84
Electric heater rods	80
Free-turbine-driven feed pump	59, 96
Tapered-tube condensers	68, 69, 82, 95
Finned radiator tubes with reflectors	69
Control drives	25, 26
Instrumentation	77

Figure 23 shows an isometric drawing of one of the reduced-scale system mockups, that is, the intermediate-size 91-rod potassium boiler system [76,78]. To provide flexibility for test purposes, the system included quite a bit of plumbing and many valves that would not be included in a flight system. The radiator was operated in a double-walled box with cooling air flowing between the double walls but with the air inside

Table 11. Rankine Cycle Systems Employed in the MPRE Development Test Program

	Working Fluid	Power Level (kw)	Number of Rods in Boiler	Rod Center-Line Spacing (in.)	Number of Tubes in Condenser	Status as of October 1966
Small water system (SWS)	Water	28	7	9/16	12	Standby
Intermediate water system (IWS)	Water	364	91	9/16	144	Standby
Small potassium system-1 (SPS-1)	Potassium	28	7	5/8	12	Operating
Small potassium system-2 (SPS-2)	Potassium	28	7	9/16	3	Operating
Small potassium system-3 (SPS-3)	Potassium	28	7	9/16	3	Two-thirds complete; construction stopped
Intermediate potassium system (IPS)	Potassium	364	91	5/8	144	Standby
Large potassium system (LPS) (full-scale mockup of the MPRE)	Potassium	1000	241	9/16	96	Two-thirds complete; construction stopped

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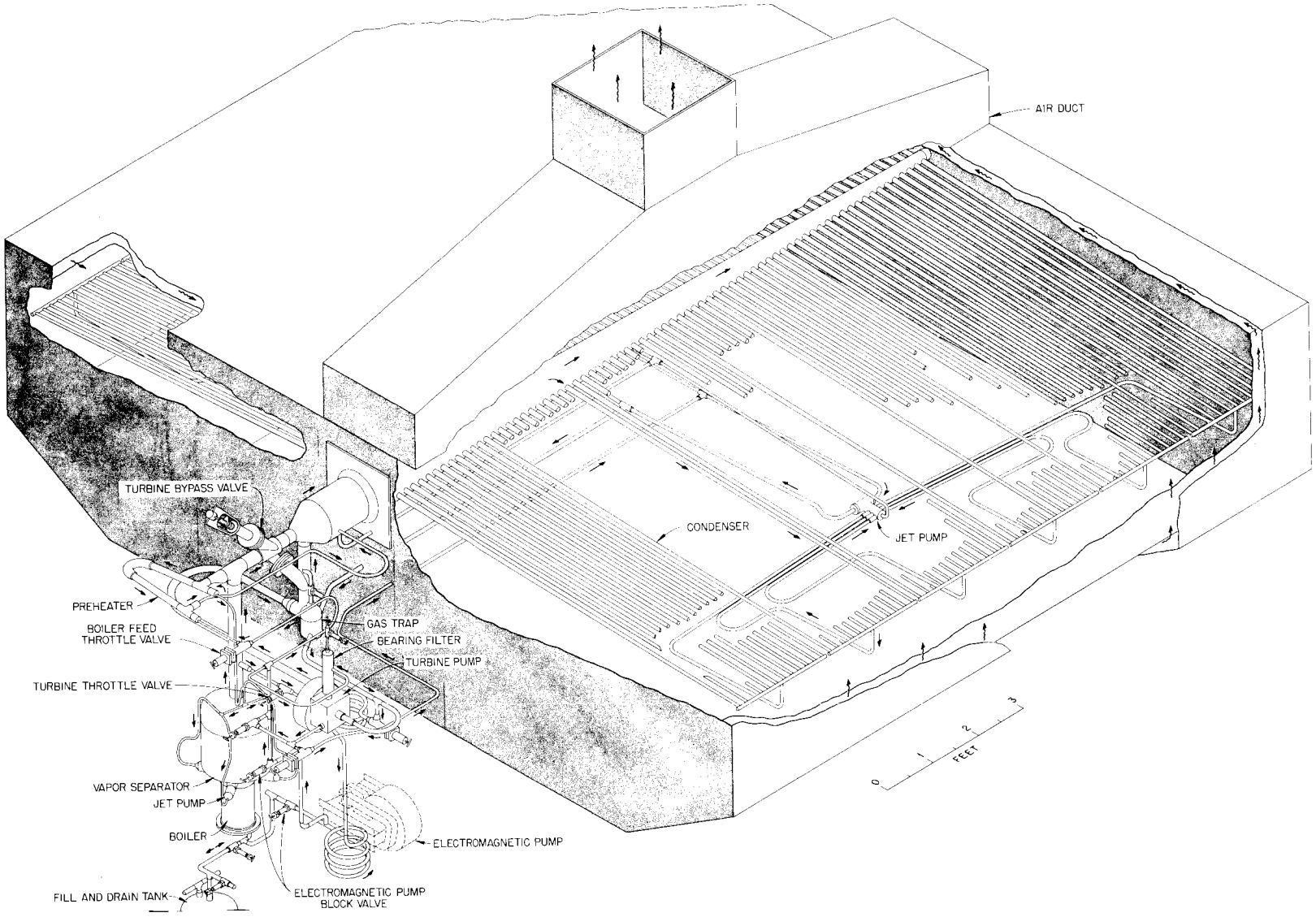

Fig. 23. Isometric View of the 91-Rod Potassium Boiler System with About One-Third the Thermal Power Output of the MPRE.

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the box stagnant. Approximately 90% of the heat loss from the radiator was by thermal radiation, with only about 10% dissipated by natural thermal convection of the air within the box. The system including the radiator operated for 4400 hr [78].

Accomplishments and Status of Work in Each Major Problem Area

General Design and Analysis

A substantial portion of the work covered by the first column of Table 8 was summarized in the preceding section on "Concept Selection" and was quite general in character. A second portion of that work was directed specifically toward particular components or problem areas of the MPRE and will be discussed later under the subtitles "Boiler Fluid Flow and Heat Transfer," "Condenser-Radiator," etc. The third major category of work covered in column 1 was concerned with the general design of the MPRE system, including the test facility. As indicated by Table 8, design work on the test facility [8], together with the MPRE preliminary safety analysis report [12], was completed. The test facility includes a 50-ft-diam spherical containment shell designed for operation with either an air atmosphere or a vacuum of around 10 μ inside the containment shell (see Fig. 9). The design work also included a thorough stress analysis of the reactor pressure vessel, including the penetrations [19].

Reactor Core Evaluation

Work on the reactor was divided into two major categories: namely, reactor physics and boiling heat transfer and fluid flow. The second column of the table is concerned primarily with the reactor physics problems [21–30], while the problems of boiling fluid flow and heat transfer are treated in the third column [31–44].

The first step in the reactor physics work was to determine the effects of the coolant passage volume fraction, the reflector material, and the reflector thickness on the reactor core diameter for criticality assuming fully enriched UO_2 in stainless steel capsules [27,28]. The radial power distribution and the reactivity effects of filling an empty core

with liquid potassium were also determined for each of the cases considered. The results indicated that it is possible to choose the core proportions to satisfy the principal boundary conditions, that is, to provide an acceptably flat power distribution with a substantial volume fraction for the coolant passages and a very small reactivity coefficient associated with filling the empty coolant passages with liquid potassium [24]. A critical experiment was then designed with a set of core proportions chosen for a 1-Mw(t) output reactor, with due consideration for the heat transfer and fluid flow requirements. A set of three critical experiments verified the multigroup calculations, particularly the potassium reactivity coefficient, which was thus eliminated as a potentially serious problem in the design of the control system [21–23]. The critical experiments also confirmed the core proportions chosen and made it possible to proceed with the specification and procurement of fuel elements for both a hot critical experiment and in-pile tests of full-scale fuel elements [52]. The radial and axial power distributions of Figs. 24 and 25 were confirmed, for example. Note that the sharp power spike at the core-reflector interface represents only about 25% of the diameter of a fuel element. Thus thermal-conduction effects are sufficient to reduce the peak surface heat flux to only about 1.5 times the average; this is at the core inlet where the low vapor quality gives a very high burnout heat flux.

Three methods of controlling the reactivity during operation were investigated [29]; of these, axial movement of the four quadrants for the end reflector was chosen for the MPRE because it gave an adequate amount of control with acceptable effects on the power distribution, as well as what appeared to be a simple, reliable system for the mechanical drives [25]. The control-plug drive mechanism was designed, two prototype units were built, and two units were cycled to over 2000 scrams with no difficulty [25,26].

One of the important features desired in the MPRE is a fast negative temperature coefficient associated with axial expansion of the column of UO_2 fuel pellets. Tests carried out in the experimental gas-cooled reactor (EGCR) program indicated that this expansion would occur independently

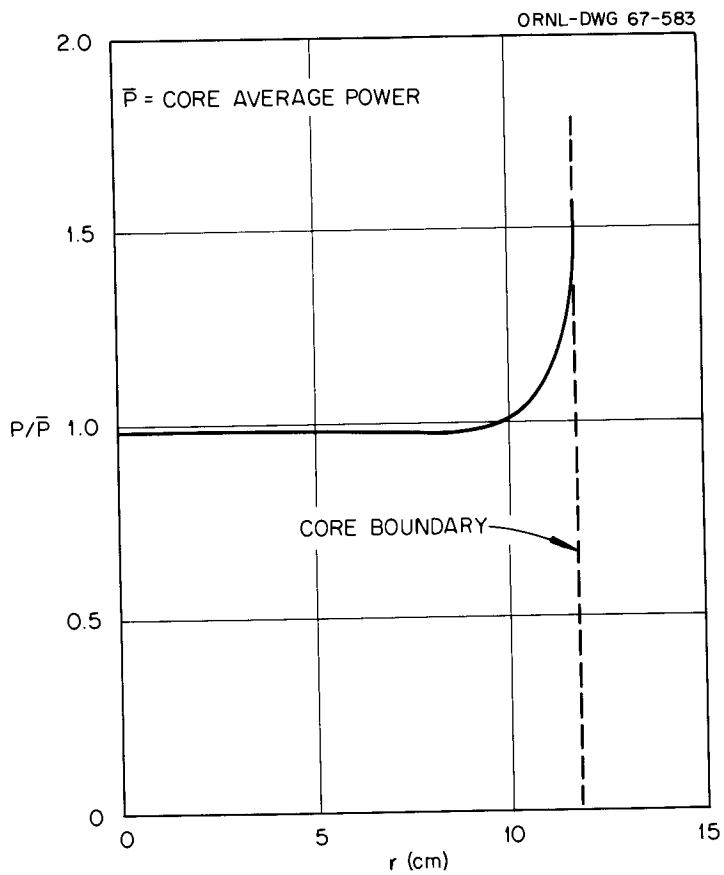

Fig. 24. Relative Radial Power Distribution at Midplane of MPRE Core.

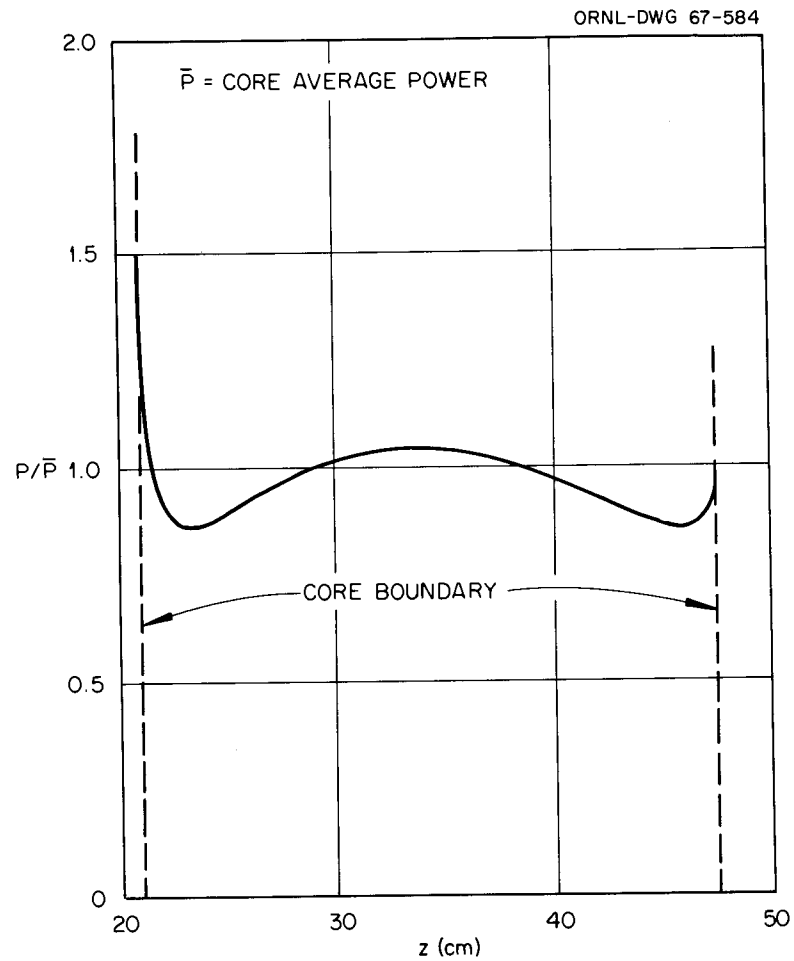

Fig. 25. Relative Axial Power Distribution 1.0 in. Out from the Center Line of the MPRE Core.

of the cladding if the fuel element were assembled with a few mils of diametral clearance between the UO_2 and the cladding. Two instrumented fuel elements were designed and built to investigate this problem, and 10,000 hr of accumulated test time with these fuel elements demonstrated that the UO_2 does, in fact, expand and contract independently of the cladding (Ref. 94, p. 83–89). Two other fuel elements were subjected to a simple endurance test at full design and temperature conditions. One of these was removed for inspection after completion of 10,000 hr of operation, while the other is scheduled to remain in-pile until it has completed approximately 15,000 hr of equivalent full-power operation (Ref. 95, pp. 84–86). Note that the load factor to be expected for a nuclear space power plant of 100-kw electrical output or more would probably be about 60% [14], and hence the fuel burnups of these two endurance tests are equivalent, respectively, to two and three years of normal operation.

Boiler Fluid Flow and Heat Transfer

The initial analytical work indicated that it should be possible to assure good boiling flow stability by preheating the feed flow almost to the boiling point [31], and that burnout could be avoided by providing sufficient recirculation to assure that the vapor quality at the boiler exit would not exceed 50%. Further, it appeared that the possibilities for lateral flow in a fuel-rod bundle should both contribute to the boiling flow stability and reduce the hot channel problem [46]. However, the data available at that time for axial flow through rod bundles were not adequate to make an accurate prediction of the pressure drop or the burnout limits for water, let alone for boiling potassium. (The only burnout test data available for potassium were those that had been obtained with potassium boiling inside a round tube during the preliminary study phase [32].)

The first tests were run with Freon as the coolant for a bundle of seven electrically heated rods. This Freon boiler showed excellent boiling flow stability with good flow distribution over a wide range of conditions, including operation of from one to five of the seven heater rods

at reduced or zero power while the remainder were operated at full power [81,82]. Similar results were obtained with water in a four-rod slab boiler [82].

The next step taken was to construct a reduced-scale mockup of the MPRE system consisting of a seven-rod boiler with a jet pump to provide forced recirculation. This approach was taken because flow stability in the boiler depends in part on the proportions of other components in the system, including the condenser and feed pump. Tests first with a seven-rod water boiler system and then with a 91-rod water boiler system showed excellent boiling flow stability and good flow distribution through the rod bundles, as indicated by direct visual observations of glass-walled boilers. Figure 26 shows the reason for the uniform, stable flow distribution — any small local increase in the vapor quality led to a reduction in the local pressure drop and hence an increase in liquid flow

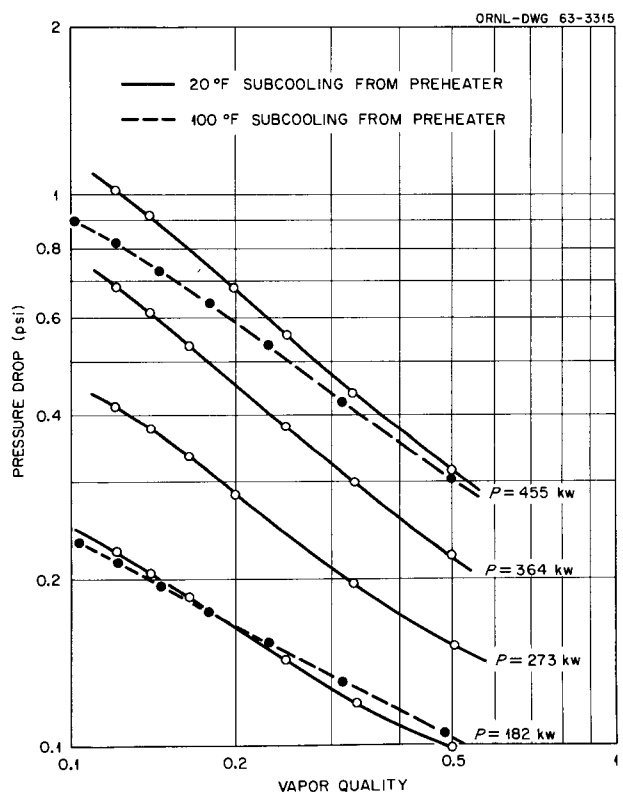

Fig. 26. Effects of Vapor Quality on the Boiler Pressure Drop for a Series of Power Outputs of the 91-Rod Water Boiler.

to that channel [46]. The boiler recirculation rate available with the jet pumps proved to be higher than anticipated, so it was found possible to operate with a boiler exit vapor quality of about 20% at full power. As shown by the data plotted in Fig. 27, the vapor quality for incipient burnout with water was found to be around 40% at the full-power heat flux of 10^5 Btu/hr·ft^2 with a 1/16-in. space between the rods [17,46].

Concurrently with this work some small forced-convection corrosion loops were built with electrically heated pot boilers, and some 4-ft-long 2-in.-diam capsules were built to investigate the endurance life and reliability of electric cartridge heaters [80]. Both entailed a simple pool-boiling heat-transfer mechanism. Yet, in both types of boiler violent temperature fluctuations were observed that were coupled with sharp reports that sounded much like water hammers and noticeably shook the test equipment (Ref. 83, pp. 113–122, and Ref. 84. pp. 54–65). This phenomenon was diagnosed and found to occur because, with a very clean stainless steel system, potassium dissolves all the impurities present and wets the stainless steel surfaces so tenaciously that there are no nucleation sites for initiation of bubbles. As a consequence, superheating of the liquid by 100 to as much as 600°F occurred [39,42]. Several varieties of nucleation site were found to be effective in initiating and maintaining stable boiling [32,44,85,95]. The most effective and convenient of these were nucleation rings shrunk on cartridge heaters as shown in Fig. 22.

Tests with 7- and 91-rod potassium boilers showed that increasing the number of rods increased the number of nucleation sites available and led to better initiation of boiling at low powers and boiler pressures as compared with single-rod capsule performance [78]. Tests to determine the burnout limit indicated that it is possible to go to at least as high a boiler exit vapor quality with potassium as with water for a given heat flux and boiler pressure (see Fig. 27).

A seven-rod water boiler test rig was built to investigate the effects of boiler attitude and zero-gravity on boiling flow stability. It was found possible to operate the boiler at all attitudes between its normal upright position and inverted, except nearly horizontal, where burnout conditions were encountered because gravitational forces caused

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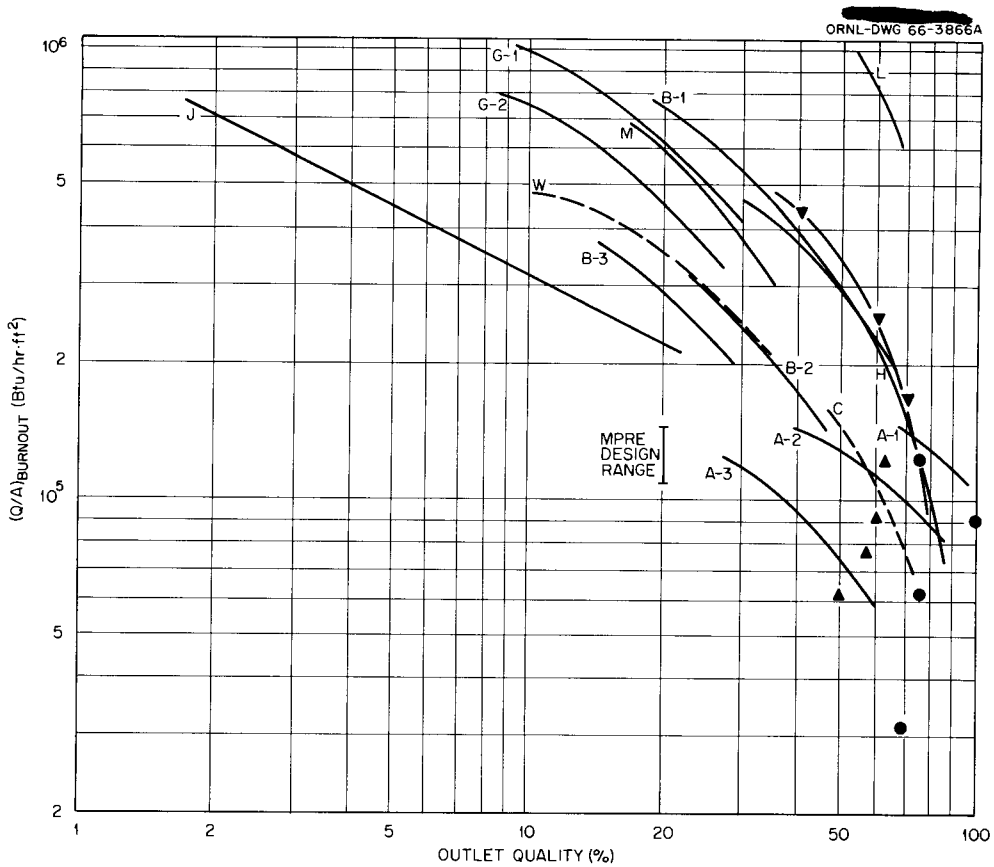

Curve No.	Number of Rods in Bundle	Space Between Rods (in.)	Flow Rate (lb/hr)	Boiler Pressure (psia)	Rod Diameter (in.)	Reference No.[a]
			Water Systems			
			$\times 10^5$			
B-1	7	0.24	0.3–6.0	440	0.51	21
B-2	3	0.24	0.3–6.0	118	0.51	22
B-3	3	0.24	0.3–6.0	84	0.51	22
M	19	0.08	5–20	1015	0.55	18
W	19	0.05	5–30	1215	0.587	18
C	19	0.05	1.5–14	515	0.60	18
J	4	1/8–1/4	0.5–5	30	0.25	23
A-1	7	0.1875	0.06–0.09	15	0.5	19
A-2	7	0.125	0.1–0.24	15	0.5	19
A-3	7	0.0625	0.2–0.6	15	0.5	19
△	91	0.0625	0.2–0.5	15	0.5	19
H	2	0.180	5–20	600	0.44	18
G-1	1	0.1 & 0.6	9–13	1000	0.54	24
G-2	1	0.033	9–13	1000	0.54	24
L (inside tubes)			10–50	15		17
			Potassium Systems			
●	7	0.125	0.03–0.09	30	0.5	
MPRE	241	0.0625	1.5	30	0.5	
▼	Inside tubes with 0.67-in. ID			38		16

[a]Note that the reference numbers given here are from the list of references at the end of Ref. 17, from which this illustration was taken.

Fig. 27. Effect of Boiler Exit Quality on Boiling Burnout Heat Flux as Measured for Various Conditions by Several Investigators. Except where noted in the legend, the data are for axial flow through rod bundle. Note that the reference numbers given here are from the list of references at the end of Ref. 17, from which this illustration was taken.

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preferential channeling of the liquid flow through the lower rods of the bundle. The rig was being modified for flight test in a KC-135 airplane when the work on the program was halted.

Vapor Separator and Expansion Tank

A number of types of liquid-vapor separator were considered early in the program because demonstration of an effective, compact liquid-vapor separator was considered to be one of the most difficult of the basic feasibility problems [81,82]. Analyses indicated that either air-water or steam-water mixtures would provide a good means for simulating potassium liquid-vapor mixtures [81]. Initial test work was carried out with air-water mixtures, because this reduced the cost of the test equipment and simplified the test procedures. The first vapor separator design employed vanes to swirl the flow into a helical path through a cylindrical drum, while the second made use of a toroidal swirl chamber with a catcher lip of the type shown in Fig. 2. The toroidal vapor separator was more compact and gave a higher separation efficiency, and hence it was chosen for further test work (Ref. 84, p. 115).

A series of vapor separators was designed and tested in air-water test rigs, and the units were modified to yield satisfactory separators for the 7-, 19-, 91-, and 241-rod boiler systems. Not surprisingly, it was found that these units could not be scaled exactly from one size to the next and, in each instance, the proportions had to be modified. However, in all instances good performance over a wide range of conditions was possible with vapor separator exit qualities generally of about 99% [47].

It was necessary to integrate the vapor separator, the expansion tank, and the boiler recirculating jet pumps into an assembly that would perform well throughout the operating range. These integration problems were relatively simple and straightforward for the 7- and 91-rod boiler systems but proved more formidable in preparing the design for the full-scale MPRE, where it was desired to obtain a unit that would be a better approximation to something that might be flown. A compromise design was evolved that satisfactorily met all the fluid mechanics and stress

analysis requirements [19,47], except those for zero-gravity operation, and this design was chosen as adequate for the MPRE.

Concurrently with the above effort, analyses indicated that the most difficult set of problems associated with the control of free-liquid surfaces in a Rankine-cycle system operating under zero-gravity conditions would be those relative to the expansion tank [13]. Going from 1-g to 0-g conditions would have no deleterious effect on removal of the liquid from the vapor, but constraining the separated liquid to flow into the expansion tank and from the expansion tank into the jet pumps without difficulties, with cavitation in the latter, is difficult. A series of three test rigs was built to investigate the effectiveness of swirling the liquid in a toroidal expansion tank under the vapor separator to stabilize the free-liquid surface there and to provide a small cavitation-suppression head for moving the liquid from the expansion tank into the jet pumps. Similarly, swirl vanes were incorporated in the vapor separator to take advantage of centrifugal force to carry the liquid away from the skimmer lip in the vapor separator and into the expansion tank. Flight tests of the first and second units were encouraging but less than satisfactory. Flight tests of the third unit were satisfactory except that they showed substantial entrainment of air bubbles in the swirl flow in the expansion tank. These bubbles should be eliminated if a steam-water or potassium liquid—potassium vapor mixture were employed because heat losses from the expansion tank would be more than sufficient to condense the amount of vapor that would be present. Both this work and supplementary work on a capillary type of expansion tank were terminated when the program was halted.

Corrosion, Mass-Transfer, and Materials Problems

Corrosion and mass-transfer in liquid-metal systems commonly take the form of dissolution in the hot zone and deposition in the cold zone [55]. In recirculating boiler systems, such as that of Fig. 1, this mechanism cannot occur because the fluid can pass from the hot zone to the cold zone in the form of vapor, and any structural materials in solution in the hot zone tend to remain in the boiler so that the liquid there

becomes saturated with the constituents of the structural alloy [55]. In the ideal case the vapor condensing in the low-temperature zone would yield pure liquid, and this would tend to dissolve small amounts of material from the condenser walls. However, at the condensing temperature the dissolution rate is so low that the amount of the material picked up from the condenser is very small. Further, the vapor leaving the boiler will not be perfectly dry but will tend to carry with it entrained droplets; for example, the vapor separator used in the MPRE system will yield about 1% moisture in the vapor. This moisture will carry with it dissolved solids. Since the solubility of iron, chromium, and nickel in liquid potassium is only about 1% as great at the MPRE condenser temperatures as at the boiler temperature, this liquid carry-over should reduce the dissolution rate in the condenser to a very low level [55]. Dissolution in the piping and feed heater might prove troublesome, but no difficulty has been experienced to date.

Endurance tests indicate that there is no appreciable problem with corrosion and mass-transfer with potassium in a recirculating boiler system built of stainless steel at boiler temperatures up to 1600°F if the oxygen content of the potassium is kept below about 20 ppm [55]. Figure 28 shows a typical photomicrograph of the surface of the sheath of a cartridge heater after 1500 hr of testing in the boiler of a seven-rod potassium boiler system, and Fig. 29 shows specimens taken from a condenser tube of the same system after approximately 4500 hr of operation. In both instances the attack was minor; as can be seen from the scales at the right of the photographs it was only a fraction of a mil.

Analyses have indicated that the boiler recirculating jet pump is the most likely spot for a mass-transfer deposit to form [55]. Some difficulty with deposits in the jet pumps was experienced, in fact, when oxygen entered the system apparently as a consequence of heater rod failures at one time and at another time as a consequence of porosity in a brazed joint at the base of an instrument pickup. No difficulty with jet plugging was experienced in the balance of the operation. Figure 30, for example, shows that there was no sign of a deposit in the boiler jet pump of the seven-rod potassium boiler system after a 1500-hr run. The hole

[redacted]

Fig. 28. Typical Photomicrograph of a Section Through the Stainless Steel Sheath of an Electric Heater Rod Run for 1500 hr at Around 1500°F in a Seven-Rod Potassium Boiler System.

in the jet for this pump is only 0.034 in. in diameter, whereas that for the full-scale MPRE would be about 0.125 in. and hence would be even less subject to plugging.

Dissimilar metals in a liquid-metal system sometimes give rise to mass-transfer and corrosion problems. One of the reasons for building and endurance testing the small-scale seven-rod and reduced-scale 91-rod boiler systems in the MPRE program was to investigate the effects of molybdenum turbine rotors running with tungsten carbide bearings in a stainless steel system having essentially the same area ratios and temperature distribution as planned in the MPRE. Addition of molybdenum and tungsten carbide turbine parts to the stainless steel system appeared to have no appreciable effect except that, in two tests with the smallest scale systems, that is, the forced-convection-corrosion loops with simulated turbine nozzle and bucket specimens, severe oxidation of the molybdenum parts

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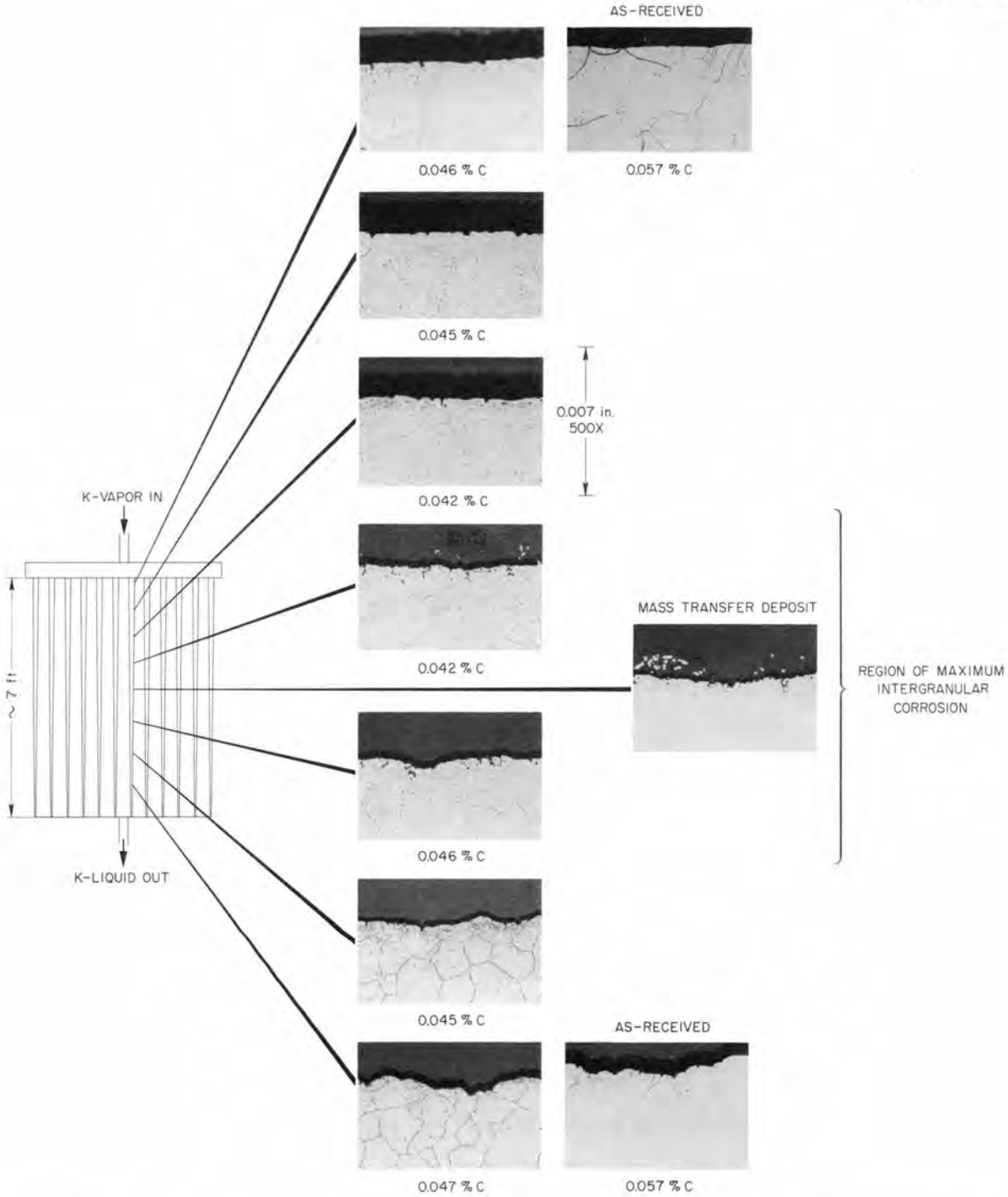

Fig. 29. Corrosion and Mass-Transfer Profiles of SPS-1 Condenser Tube After 4500 hr of Operation.

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occurred when substantial amounts of oxygen entered the system as a consequence of heater or thermocouple failures [55]. No difficulty was experienced with these systems when a zirconium hot trap was placed ahead of the boiler.

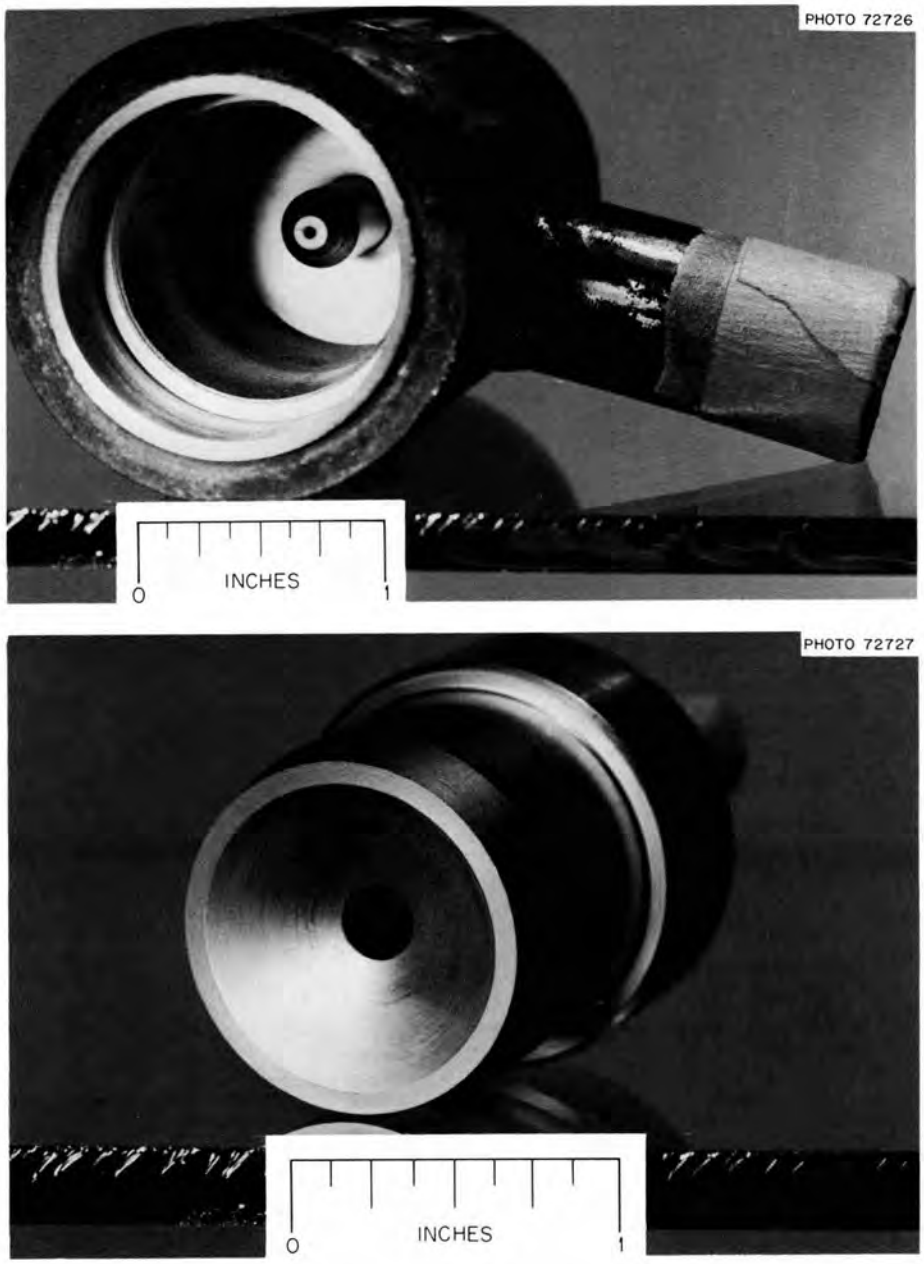

Fig. 30. Jet Pump Removed from the Seven-Rod Potassium Boiler System After a 1500-hr Test.

Probably the most difficult materials problem in the system is that associated with the bore seal in the turbine generator. There appears to be no way to insulate the windings of the generator with a material that will be adequate from the electrical insulation standpoint and will also withstand the attack of potassium liquid or vapor. In fact, extensive experience with thermionic cells indicates that only extremely pure alumina or beryllia with essentially no silica present will withstand attack by potassium liquid or vapor. The stator windings could be isolated from the rotor by a thin metal sleeve, but eddy current losses in the sleeve could cause it to melt in a high-performance generator. Thus, a ceramic sleeve of alumina or beryllia must be inserted between the rotor and the stator, and hermetically sealed joints must be made between this sleeve and the casing at either end. It has proved difficult to find a brazing alloy that will wet the alumina well to give a hermetically sealed joint and at the same time will be resistant to attack by potassium. Fortunately, this problem is less serious in a generator than in a thermionic cell because of the much lower temperatures at which the brazing alloy must operate. However, it still proved to be a difficult problem, and it was not until the spring of 1966 that what appears to be a satisfactory solution was found [96]. Both an 82% Ti–18% Cu brazing alloy without a protective plating and a silver-copper brazing alloy with a 3-mil vapor-deposited tungsten plating over a nickel electroplate on the brazing alloy resisted the attack of potassium vapor in 1000-hr capsule endurance tests [96].

Turbine Pump and Turbine-Generator

In the initial study work that led to the MPRE program, there seemed little doubt that a potassium-vapor turbine could be made to work from the aerodynamic standpoint; the crucial problem was whether potassium-lubricated bearings of adequate capacity could be installed in the turbine and would give the required high degree of reliability. Screening tests* and

*D. B. Vail, Compatibility of Materials in Liquid Metal, USAEC Report KAPL-589, Knolls Atomic Power Laboratory, August 1951.

some operating experience at KAPL in the early 1950's indicated that tungsten carbide running against tungsten carbide was the most promising materials combination for operation in sodium or NaK.* Application of the KAPL data to a representative turbine design indicated that potassium-lubricated tungsten carbide bearings should be satisfactory but that it was very difficult to find a mechanical design that would permit installation of a tungsten carbide bushing on a stainless steel shaft because the coefficient of thermal expansion of tungsten carbide is about 3×10^{-6} in./in.·°F as compared with 9×10^{-6} in./in.·°F for the stainless steel used in the rest of the system. The differential expansion problem in the vicinity of the bearings can be avoided by making the rotor of a molybdenum alloy, such as TZM. Molybdenum has a coefficient of thermal expansion very close to that of a tungsten carbide with 12% cobalt binder, and it is much stronger at high temperature than the austenitic stainless steels. Hence it was decided to match the coefficient of thermal expansion of tungsten carbide with that of a molybdenum alloy rotor in the region where clearances are most vital, that is, in the bearings, and make use of other provisions in the less-sensitive zone between the bearing supports and the casing [59]. The use of a molybdenum-alloy rotor offered the additional advantage that molybdenum is one of the few materials that shows promise for operation at 2000°F in potassium vapor.

The first step in implementing the development program was the operation of a bearing test rig that had been used in the molten-salt reactor development program.† The most expeditious approach to the use of this rig was to mount a stainless steel journal on the existing Inconel shaft and run it against a tungsten carbide sleeve bearing. This test consisted of a series of cycles in which the shaft was started up under light load, the load was then manually increased as the speed was increased, and then full load and speed were maintained for a period of 1 hr, after which the load and speed were proportionately reduced and the shaft was brought to

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*D. B. Vail, Life Test of Liquid Metal Lubricated Thrust Bearings, USAEC Report KAPL-521, Knolls Atomic Power Laboratory, May 1951.

†P. G. Smith, High-Temperature Molten-Salt Lubricated Hydrodynamic Journal Bearings, A.S.L.E. Trans., 4(2): 263–274 (1961).

a stop under the original starting load. In one test, a plain stainless steel journal running against a tungsten carbide bearing in 800°F potassium showed only a little change in the power required to drive the shaft after 160 cycles. On disassembly the journal was moderately scuffed. The test was repeated with a chrome-plated stainless steel journal running against a second tungsten carbide bearing. This test was run for 450 start-stop cycles with no sign of trouble, and at that point it was decided to shift to a continuous endurance test. The test bearing was still running nicely at shutdown after a total operating time of 4085 hr, and the journal and bearing were both in excellent condition [59,83].

Concurrent with the above work on bearings, work was initiated on the construction and operation of a small potassium-vapor turbine-driven feed pump employing a TZM molybdenum rotor with tungsten carbide journal bearing sleeves brazed to the shaft and tungsten carbide sleeve bearings mounted in a stainless steel housing with provisions to accommodate differential thermal expansion between them. This unit [59], the world's first potassium-vapor turbine, was a small unit with a turbine wheel diameter of 2.75 in. and an impeller diameter of 1 in. Over 500 hr of testing with this unit in the seven-rod potassium boiler system showed that there was no difficulty with scuffing of the bearings in starting or stopping (one unit was started and stopped 50 times with no sign of scuffing), there was no difficulty with mass-transfer or corrosion associated with the dissimilar materials in the stainless steel system, and there were no signs of either turbine bucket erosion or cavitation erosion in the impeller [59]. However, several bearing failures did occur, apparently as a consequence of small dirt particles that entered the bearings with the unfiltered lubricant.

Inasmuch as a larger potassium vapor turbine with potassium-lubricated bearings had been designed for the 91-rod potassium boiler system and included provisions for filtering the lubricant supply to the bearings, test work on the small potassium-vapor turbine was discontinued and subsequent efforts were centered on the larger turbine shown disassembled in Fig. 31. This basic unit was large enough to drive the feed pump for the MPRE when modified to increase the arc of admission to the partial admission turbine and the axial length of the pump impeller.

Fig. 31. Parts of a Free-Turbine-Driven Boiler Feed Pump for the 91-Rod Potassium Boiler System.

The first unit tested lost speed after 17 hr of operation and was disassembled for inspection. It was found that a design oversight had led to cocking of the shaft and severe edge loading of the bearings. This was corrected, the unit was rebuilt, and extensive tests of the system were carried out. One test was terminated after 2586 hr as a consequence of electric heater failures in the boiler. There was no sign of loss of performance in the turbine or pump during this test; the turbine pressure drop required for starting actually dropped off over 10%. When the

unit was disassembled, all parts were in excellent condition, with only a small amount of wear of the journal bearings that resulted from incomplete correction of the shaft-cocking problem. There were no signs of erosion of the turbine buckets or cavitation erosion in the pump impeller. The turbine had been operating with a vapor quality of the order of 93% entering the turbine wheel at about 2000 ft/sec with a wheel-tip speed of around 200 ft/sec. The pump had been cavitating with a cavitation coefficient of between 70 and 80% with an impeller-tip speed of around 100 ft/sec throughout virtually all the testing. Figures 32 and 33 show closeups of these parts after the test was completed.

Fig. 32. Closeup View of the TZM Turbine Buckets of a Free-Turbine-Driven Feed Pump After Over 2500 hr of Operation in the 91-Rod Potassium Boiler System.

Fig. 33. TZM Pump Impeller After Over 2500 hr of Operation in the 91-Rod Potassium Boiler System. Most of the operation was with a cavitation coefficient of 70 to 80%.

Bucket erosion has proved to be somewhat of a problem in steam turbines when operating with vapor qualities less than around 90% and tip speeds in excess of around 800 ft/sec. Analyses indicate that the problem should be less severe in potassium, in part because of its reduced density with respect to water and even more because of its much greater compressibility — about five times that of water. As in steam turbines, it is to be expected that the erosion problem will depend greatly on the detail design of the turbine and that proper provisions for moisture removal will make it possible to operate without difficulties with turbine-bucket erosion. Note in Fig. 1 that the MPRE system was laid out in such a way that substantial amounts of vapor could be bled off between stages in the main turbine to assist in the interstage moisture-removal process with a gain rather than a loss in cycle efficiency because the vapor is employed in the regenerative feed heater [83].

Cavitation erosion in the impeller of the feed pump was recognized as a possible problem in the MPRE system; however, experience with pumps

cavitating in water systems has shown that if the relative velocities in the impeller inlet can be kept below about 60 ft/sec, erosion should not be a problem. Again, in comparing potassium with water, it appears that the reduced density of the potassium coupled with its much higher compressibility should permit higher relative velocities without cavitation damage in potassium than is possible in water. Tests indicate that this is, in fact, the case.

Experience gained under the ANP and molten-salt reactor programs included a number of extensive endurance tests of 5,000 to 25,000 hr with the pumps cavitating. Little damage was observed when the pumps were disassembled after testing [75].

No development work was carried out on a turbine-generator unit at ORNL under the MPRE program, because it was expected that a unit would become available from the SNAP-50 program.

Jet Pumps

A literature search at the inception of the MPRE program failed to reveal any information on the cavitation performance of jet pumps, in spite of the fact that there have been numerous applications in which jet pumps have been operated in the cavitating regime. Test work disclosed that the cavitation suppression head required may be so low that it is very difficult to measure, since it may be equivalent to less than 1°F of subcooling [81]. A test system and procedure were evolved for use with water to give the required high degree of sensitivity, and tests were conducted to determine the effects of variations in the geometry of elements of the pump on its cavitation performance (Ref. 85, pp. 33–40). The data obtained were found to be correlated well by relations developed rationally [60].

Extensive tests were conducted to investigate the effects of variations in pump geometry [61] and to assure that the pump output would not collapse abruptly with the onset of cavitation. Figure 34 shows a Lucite jet pump operating in water with a small plume of vapor bubbles around the jet and a small, stable loss in performance as a consequence of cavitation.

[redacted]

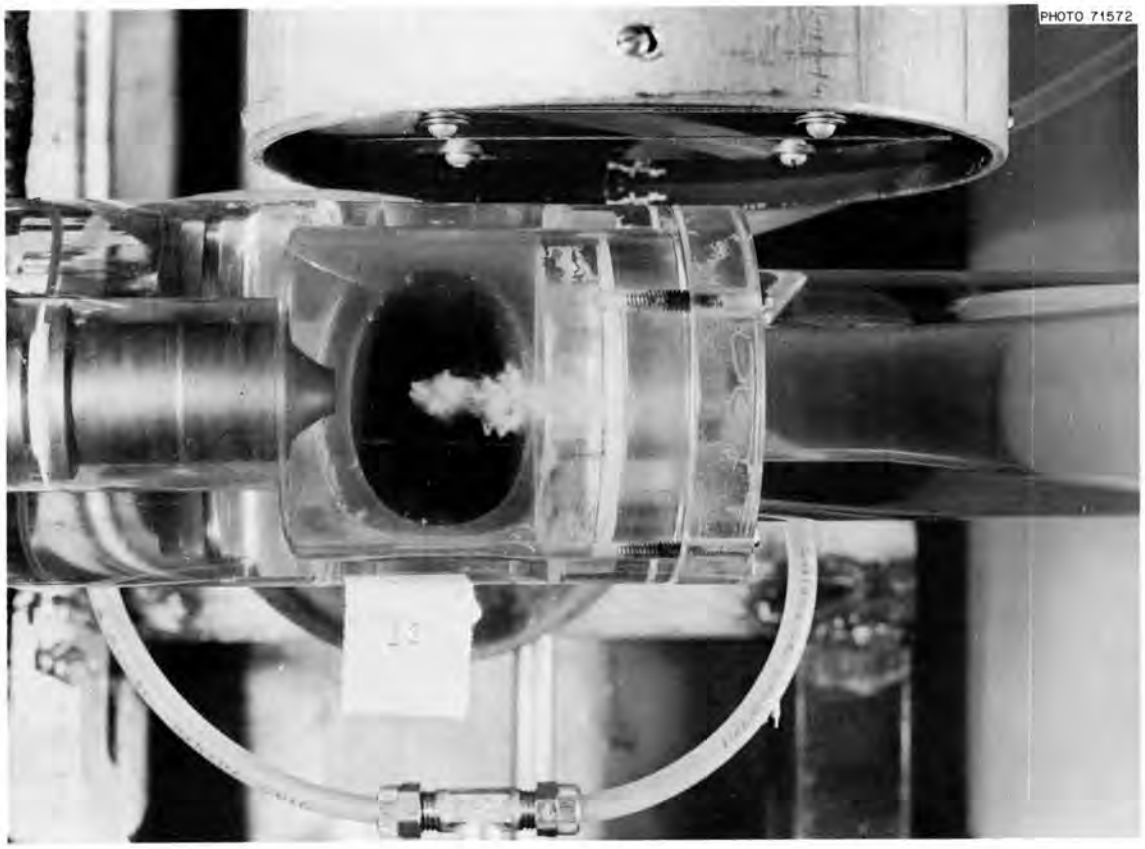

Fig. 34. Closeup of a Lucite Jet Pump Operating in Cavitation with Water. The driving jet enters through the nozzle at the left, the aspirated stream enters through the large oval port at the rear, and a plume of tiny vapor bubbles around the envelope of the jet extends downstream from the region where the center lines of the jet and the sidestream intersect.

On the basis of this background of experience, a compact jet-pump installation was worked out for installation in the expansion tank of the MPRE so that heat losses from the liquid returning from the vapor separator would be sufficient to assure that the boiler recirculating jet pumps would operate without losing performance because of cavitation. Similarly, the same set of basic data was used to design jet pumps to scavenge the radiator [61]. Because of the basic stability and control characteristics required of the system, the radiator scavenging jet pumps were designed to operate continuously in the cavitating regime [70].

To reduce costs and to facilitate testing, all the above test work was carried out with water. The data obtained later on the performance

[redacted]

of jet pumps operating in the cavitating regime in the system mockups run on potassium were consistent with predictions based on the tests with water, but the instrumentation was not adequate for a close check. Thus a test rig was designed and built for making accurate determinations of the cavitation performance of jet pumps operating with potassium. The noncavitating performance of a jet pump run with potassium in this system was found to correlate closely with the performance of the same pump operating with water [96]. Testing was stopped in July 1966 as a consequence of the cut in the MPRE budget.

Condenser-Radiator

In arriving at the basic radiator design to be used in the MPRE program, many different configurations were considered from the standpoints of free-liquid-surface control under zero-gravity conditions, scavenging, fluid flow distribution, part-load stability and control, differential thermal expansion, installation in the launch vehicle, the stresses and vibration induced by launch loads, and orbital startup. Analyses disclosed that there were too many boundary conditions to be met to permit a conventional optimization study — it appeared better to begin with a structure that would be well suited to withstand launch loads and at the same time would satisfy the fluid flow requirements [85]. The proportions were then modified to reduce the weight to something like a minimum [16]; this led to the reference design for a launch package shown in Fig. 6. The efficacy of this approach is indicated by the relatively low specific weight obtained for the resulting radiator — only 7 lb per kilowatt of electrical power output. This specific weight is for the complete radiator, including meteoroid armor, ducts, and the structure for launching. The background for this selection was outlined in several reports (Refs. 62 to 69) and in additional discussions of the problems presented by radiation scattering from the radiator and its effects on the shield design [30], meteoroid protection [16], two-phase flow in tapered tubes [6], and the effects of load on performance [16].

One of the difficult requirements to be met is to scavenge the condenser during a startup under zero-gravity conditions. An advantage of

the tapered-tube condenser is that, theoretically, capillary forces associated with the taper in the tubes should act to drive slugs of liquid toward the small end of the tube. Tests were devised, models were constructed, and tests were run in the drop tower at NASA Lewis Laboratory. The tests confirmed the analyses and also showed that internal fins could be used in the condensate lines to carry the liquid by capillary action from the condensate manifolds to the feed pump under zero-gravity startup conditions (Ref. 83, pp. 70–82).

Two of the test radiators were designed to investigate the behavior of the condensate flow on the walls of tapered condenser tubes under zero-gravity conditions. These condensers had hollow, rectangular copper bars sandwiched between Lucite plates to give a transparent flat-slab condenser and thus permit direct visual observation of the flow of the condensate film. Tests with these units showed that the liquid moves along the walls in the form of very thin films, perhaps 0.010 in. thick, as indicated by analytical calculations [95]. The design of a test rig for flight-testing in the KC-135 airplane had been prepared when work on the program was halted.

In laying out the development test program for the MPRE, it became evident that a number of component test systems would be required to investigate major problem areas and that condensers would be required for these systems. It was found that in many instances an adaptation of the tapered-tube elements of the radiator of Fig. 6 served to give about as inexpensive a condenser as could be obtained in any other way and that use of a properly designed and instrumented condenser would yield invaluable information on the performance of this type of direct condensing radiator. Since the most important single question that arose in the course of the design studies was concerned with the control of the free-liquid-surfaces in the condenser under zero-gravity conditions, it was decided to build some of these units for the test rigs so that they would operate with the tube axes nearly horizontal. Since it was important that the liquid drain from the tubes after the test, a series of condensers was built in the form of flat panels, as in Fig. 23, and run with the tubes at a small angle from the horizontal to facilitate drainage.

It is important to note that analytical work indicated that the drag forces acting to move liquid toward the outlets of these nearly horizontal tubes would be of the order of 100 times the gravitational forces under full power flow conditions. The tube taper was chosen so that under high power conditions there would be a nearly constant vapor velocity down the tube from the inlet to close to the outlet [66].

Seven condensers were built and operated — three at temperatures up to 1100°F — and all but one were operated as elements of systems rather than in rigs built expressly to test condenser-radiators. No effort was made to obtain good data on condensing heat transfer coefficients or surface emissivities; attention was directed primarily at problems of radiator design to obtain good flow distribution, flow stability, a sound structure, and good system stability and control from startup to full power. Particular attention was given to possible interaction between the flows in tubes operating in parallel and the flows in multiple banks of tubes [68].

The results of the tests with both steam and potassium vapor show that direct-condensing tapered-tube radiators can be designed and built so that they will operate with a stable, uniform vapor flow distribution across large tube banks over a wide range of operating conditions. The radiators tested scavenged well and ran with very little liquid holdup in the tubes, even with the tubes essentially horizontal so that gravitational forces had little influence on the liquid flow. One of many indications of this is the infrared photo of Fig. 35, which shows a remarkably uniform temperature (and hence flow) distribution in the nearly horizontal tube bank of the radiator of Fig. 23. The tests also showed that to obtain proper scavenging at part load, the heat losses at part load must be reduced substantially through the use of shutters or some similar device. Also the vapor manifold must be designed so that choking will occur at the tube inlets rather than somewhere in the vapor manifold [68]. Good correlation between the analytical work and the test data was obtained both in tests with steam and in tests with potassium vapor [68].

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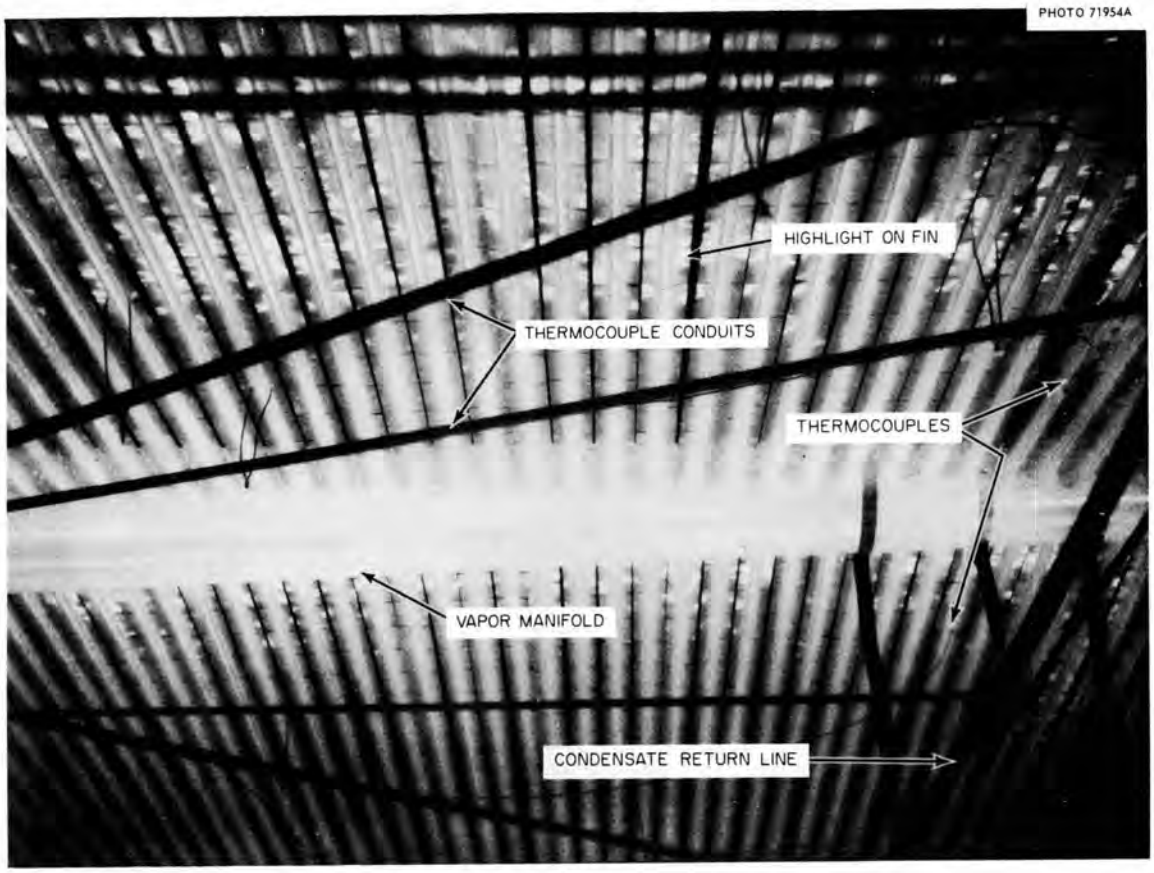

Fig. 35. Infrared Photograph of a Portion of the Horizontal Tubes of the Radiator of the 91-Rod Potassium Boiler System of Fig. 23 Showing the Uniform Temperature Distribution that Prevailed. The temperature difference between the roots and tips of the fins was about 25°F.

The performance of the Alzak aluminum reflector and shutters was investigated by using a 4-ft-long electric heater rod fitted with stainless steel-clad copper fins in the configuration of Fig. 8. The test unit was mounted in a vacuum test chamber, and tests were conducted both under atmospheric pressure and under vacuum conditions. The test results correlated well with the predicted performance of the unit [69].

The full-scale MPRE radiator shown in Fig. 36 was fabricated for the full-scale electrically heated mockup. No particularly difficult problems were encountered in the fabrication of this unit, and it was ready for installation in the system when the program was halted in the spring of 1966.

[redacted]

[redacted]

Fig. 36. Photograph of the 10-ft-Diameter 15-ft-Tall Radiator for the Full-Scale Electrically Heated Mockup of the MPRE.

System Stability and Control

The approach taken to the stability and control of the MPRE system was outlined in an earlier section describing the system. The problems associated with this concept can be clarified somewhat by dividing them into four major areas: (1) the nuclear stability of a boiling potassium fast reactor, (2) the stability of the two-phase flows that prevail in the parallel passages of the boiler and condenser, (3) the stability of

[redacted]

the system as a whole, including interactions between components such as the turbines and pumps, and (4) the stability of the liquid inventory distribution in the system. The analytical and experimental work carried out in connection with the first two items was covered earlier in this section. The last two problem areas were attacked analytically with both digital and analog computers and experimentally in the reduced-scale mock-ups of the MPRE system.

When all the components of a system are coupled together, it is important that the system as a whole respond smoothly to changes in power. All the analytical, analog, and electrical test rig experience is consistent and indicates that the MPRE system is stable and responds well to as much as a 30% step change in the heat input to the boiler [70–73] (see Fig. 37). The principal limitations observed are that the thermal inertia

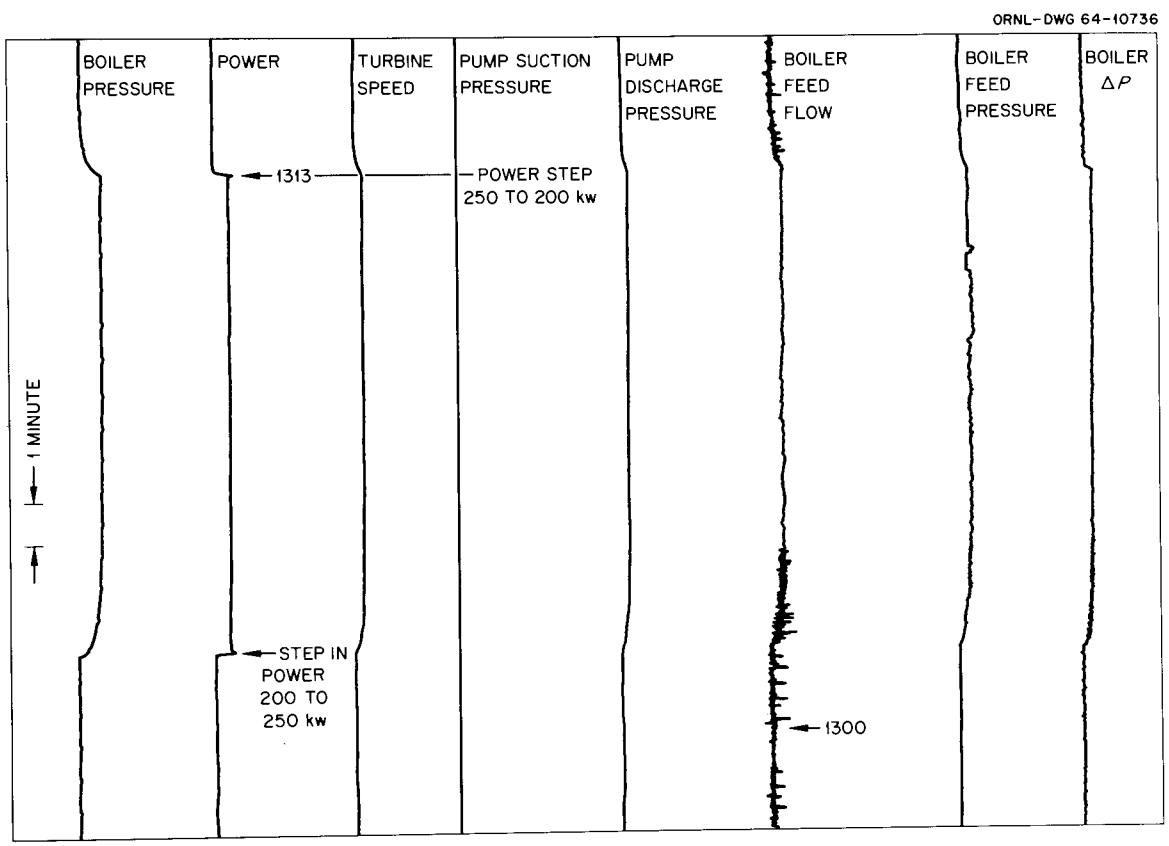

Fig. 37. Effects of Large Step Changes in the Electrical Power Input to the Boiler on Major Parameters in the 91-Rod Water Boiler System.

of the system is such that it is not possible to increase the "steaming rate" more rapidly than about 1% of full power per second. (Coal-fired steam plants are limited to about 2% per minute.) Reductions in steaming rate should not exceed about 0.3% per second for a power level change equal to about 20% of full power because foaming in the boiler and expansion tank might occur as a consequence of vapor release from superheated liquid under the reduced pressures at reduced power [72,78,79]. While no difficulty with burnout was experienced when foaming was encountered, it appears best to avoid this condition. From the nuclear reactor control standpoint, there is a strong incentive to limit the rate of change of the boiler heat output to about 0.3% per second. A survey of space vehicle requirements has indicated that this is an acceptable value [14].

The vapor passages constitute the bulk of the volume in a Rankine-cycle fluid system. Since it is important that the boiler not run dry, the bulk of the liquid must be kept in that portion of the system in which it belongs and not be allowed to accumulate in some portion of the vapor region. This is accomplished in the MPRE system by keeping the vapor velocities sufficiently high to sweep along any small accumulations of liquid. This can be done throughout the vapor system, except close to the outlet of the condenser tubes. The vapor velocity will vary roughly as the square root of the absolute temperature. This leads to only a 12% decrease in velocity in the vapor region at boiler pressure in going from full to 10% power. In the condenser outlet region the effect is much greater, but there the passage diameters are sufficiently small that, as discussed above, surface tension draws the liquid film on the walls into slugs of liquid interspersed between bubbles, and the slugs are impelled toward the outlet by both surface tension forces and differences in vapor pressure associated with the drop in temperature in the direction of flow. Thus the problem of maintaining the desired liquid inventory distribution becomes one of assuring that the liquid will be scavenged as fast as it accumulates near the tube outlets so that the condenser will be maintained in a "dry sump" condition [70,72]. A portion of the work with the analog and the electrically heated system mockups was concerned with this problem. Work with both the analog and the test rigs showed

that by operating with the boiler feed pump cavitating, the liquid inventory distribution was stable and no control action was needed from the operator to allow for normal changes in power, condenser temperature, or the like [70–72].

While lack of a turbine-generator made it out of the question to conduct experimental work on the entire system, it was possible to carry out an electronic analog study of the complete MPRE system, including the turbine-generator and the reactor [73]. Two types of electrical load were considered in the study; the first was an entirely resistive load, and the other was similar to that imposed by induction-motor-driven pumps. Two control schemes were used. In control scheme No. 1, the generator terminal voltage-error signal was the input to a controller that regulated the reactor control-plug position, and the generator frequency-error signal was the input to a controller that regulated the generator field current. The controller input signals were interchanged for scheme No. 2. With a simple resistive load the system was found to be stable and controllable when using either control scheme (see Fig. 38); however, the

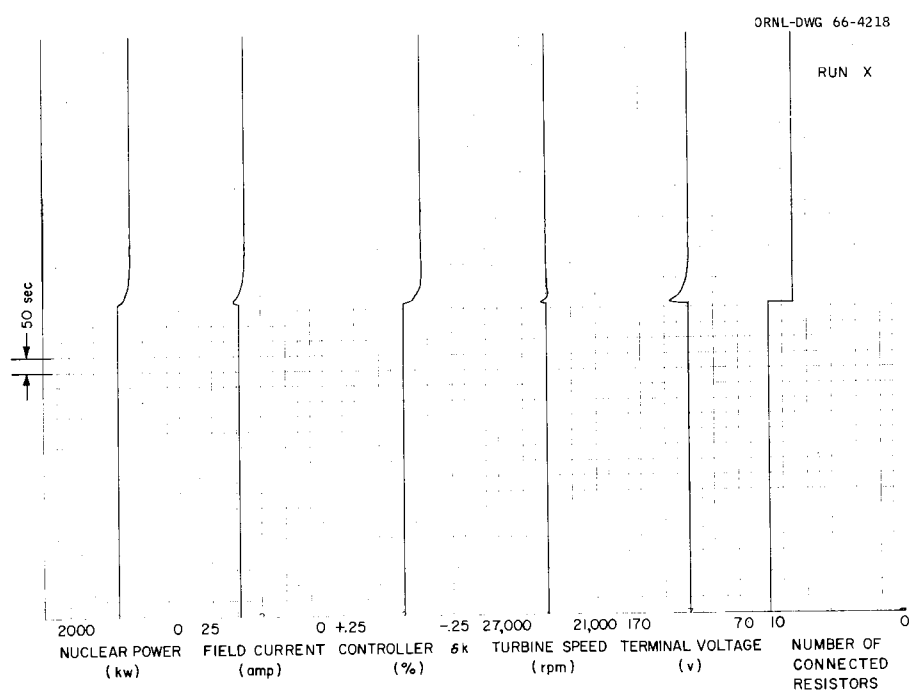

Fig. 38. Response of the Electronic Analog of the MPRE System to a Sudden Loss of Two of Ten Equal Load Resistors with Control Scheme No. 1.

response characteristics were much better for scheme No. 1. With the simulated induction motor load, scheme No. 2 was acceptable, although not as good as those for the resistive load. Stable plant operation was not achieved when using control scheme No. 1 with the induction-motor load. As may be deduced from Fig. 38, the time lags for the system were found to be relatively short, with the time constant for the boiler being about 12.5 sec [73].

System Endurance Tests

The substantial operating experience accumulated with boiling potassium systems in the MPRE program is summarized in Table 12. Also included in Table 12 is the operating experience with refractory metal systems obtained under the high-temperature materials program.

The most important results of the endurance test work were summarized above in the sections on corrosion and turbines. However, much valuable operating experience was obtained with other components, particularly instruments, and this led to design changes that improved both the accuracy and the service life of temperature, flow, pressure, and liquid-level measuring equipment [77].

By far the most important source of difficulty in the test program has been the electric heaters used to simulate the fuel elements [80]. In most instances these heaters were connected in electrical circuits fitted with protection devices designed to shut off the power within about one cycle when the leakage current to ground exceeded 1 or 2 mamp. Most of the failures were internal and did not damage the sheath of the heater. About one failure in six involved arcing from the resistance windings to the sheath and resulted in a hole in the sheath that was sometimes as much as 0.5 in. in diameter. In no case did one of these failures lead to any appreciable leakage of potassium from the system, although dirt particles from the heater failures did result in the failure of bearings in a number of the small turbine units that were not fitted with filters in the lubricant stream supplied to the bearings. Diagnosis of the failures led to a series of improvements in the quality control and inspection techniques employed by the vendor, and this in turn gave progressive improvements in the service life of the heaters [80].

[redacted]

Table 12. Summary of Operating Experience at ORNL with Potassium Systems up to October 1966

	Accumulated Operating Time (hr)	
	Stainless Steel Systems Operated Up to 1500 to 1600°F	Niobium Systems Operated Up to 2000°F.
Corrosion tests		
Thermal-convection loops	22,000	15,000
Forced-convection loops[a]	12,000	3,300
Component tests		
Electric heater	95,000	
Centrifugal pumps	(4,100)[b]	
Turbines	(4,100)[b]	
Bearing test rig	4,500	
Generators		
Heat exchangers	(13,000)[b]	
Heat transfer	2,800	
Miscellaneous	15,000	
MPRE reduced-scale mockups	9,000	
Reactor tests	0	
Total	160,000	18,300[c]
Fuel element in-pile tests (in NaK-filled capsules)	34,000	

[a]One system has been operated 5500 hr, and the test is continuing as of December 1966.

[b]Parentheses around numbers indicate that there is duplication, e.g., the 13,000 hr of heat exchanger testing was part of the simulated system testing.

[c]In addition, there has been 42,000 hr of capsule testing.

Only a few potassium leaks to the atmosphere were experienced in all the testing, and all these stemmed from poorly designed or installed penetrations for instrument elements or from electric heater failures.

A small amount of endurance testing is continuing under an MPRE close-out program in FY 1967. This includes continuation of a test run of a forced-convection corrosion loop with some simulated turbine buckets

[redacted]

and nozzles until the test objective of 10,000 hr of operation is reached. A seven-rod potassium boiler system with a full-scale Mark II MPRE free-turbine-driven feed pump is to be operated for as long as possible, hopefully about 5000 hr. Two fuel elements are continuing to operate in-pile as long as the space remains available in the ORR – probably until one element has completed 15,000 hr of equivalent full-power operation.

REMAINING PROBLEMS

It seems worthwhile to set forth for the record a list of the major tasks that remain before a power plant based on the MPRE system could be launched if the program were reinstated. The tasks envisioned may be summarized as follows:

1. Determine the effects of rod size and spacing on the burnout-heat flux and pressure drop for boiling potassium flowing axially through rod bundles.

2. Demonstrate the desired service life with high reliability by operating at least one full-scale and four reduced-scale boiling-potassium–stainless steel systems for at least 10,000 hr each.

3. Demonstrate a low fission-product-release rate from a defective fuel element in potassium by an in-pile test, and subject four fuel elements to 10,000- to 20,000-hr tests.

4. Demonstrate good control of free liquid surfaces by zero-gravity tests of steam-water mockups of individual components and a complete reduced-scale system in a KC-135 airplane.

5. Demonstrate on the ground the startup and restart capability of a small system mockup with all components in a horizontal plane.

6. Demonstrate by testing in a manned orbiting laboratory the startup and operating characteristics of a reduced-scale electrically heated steam-water mockup of the system.

7. Demonstrate the feasibility and reliability of a potassium vapor turbine-generator unit.

8. Demonstrate in a ground test (the MPRE) the stability and control characteristics of a complete system, including the reactor and turbine-generator, and run a 10,000-hr endurance test.

9. Demonstrate satisfactory system startup and free-liquid-surface control characteristics under zero-gravity conditions by orbiting a potassium-vapor power plant complete except for the reactor, which would be replaced by a chemically fueled heat source.

10. Demonstrate the reliability of a launch package power plant configuration by subjecting three complete nuclear plants to endurance tests of 10,000 to 20,000 hr.

11. Demonstrate flight worthiness of a complete power plant launch package by testing in an environmental test chamber.

The above tasks may be divided into four major groups. The first three groups (tasks 1 to 8) are primarily concerned with feasibility, and involve, first, the extensive testing of systems already built or under construction at ORNL and, second, the construction and operation of the MPRE. The fourth group of tasks is concerned with the demonstration of the reliability and flight worthiness of a complete flight-configured power plant.

The heat transfer and extensive endurance testing called for in tasks 1 and 2 could be carried out with the systems already built and operated or nearly completed. These would make it possible to accumulate a total of about 25,000 hr of system operation per year with a free-turbine-driven feed pump operating on potassium-lubricated bearings in each system and thus provide a basis for estimating the reliability of a flight system. The third task has to do with application of the MPRE to manned spacecraft. Analyses based on the test data available for UO_2 stainless steel fuel elements in NaK, sodium, water, and helium indicate that a leaking fuel element would not introduce an unacceptably high level of radioactivity in the radiator of a single-loop system. However, there are no data for fuel elements operated in boiling potassium, and hence additional tests should be run to give a definitive answer. These could be carried out readily with a modified form of the present in-pile test equipment.

If a Rankine-cycle system is to be operated on the moon or in a space vehicle that is spun to generate an artificial gravitational field, there would be no zero-gravity problem. However, if the system is to

be used in a space vehicle that is not spun, the control of the free-liquid surfaces in the boiler, condenser, and expansion tank presents problems. Task 4 represents the next step toward solving these problems for the MPRE. It entails completion of modifications to the bench-test systems cited in the previous section to make them suitable for flight testing in a KC-135 airplane and conduct of the projected flight test program in that vehicle. This approach should serve to solve the problems in a reasonably convincing fashion with relatively inexpensive water systems having key parts fabricated of transparent glass or plastic. Concurrent with this work, the zero-gravity start and restart capability of the small system of task 5 could be investigated with all the components in a single horizontal plane. After satisfactory completion of this work, the next logical step would be task 6, the investigation of the startup, operating, and restart characteristics of a reduced-scale electrically heated steam-water mockup of the system in a manned orbiting laboratory.

The cost of the work on the first six tasks would be modest, and favorable results should provide a clear basis for justifying the remaining five more expensive tasks involving the full-scale MPRE.

A small amount of work is continuing in FY 1967 on tasks 1, 2, and 3 under a closeout program.

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