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Space Reactors

July—September 1981

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Prepared by Donna Stevens, Group Q-13

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SPACE REACTORS
July-September 1981

Compiled by
William A. Ranken
Space Reactors Project Leader

ABSTRACT

Progress in technology development for the Space Power Advanced Reactor (SPAR) project is reported for the period July 1-September 30, 1981. The weights of neutron and gamma shields required to protect the SPAR system payloads for a range of permissible exposures have been determined, and initial results are reported. SPAR reactor safety in the case of water immersion has been modeled. Approval-in-Principle has been received for the SPAR fuel test in the Experimental Breeder Reactor-II (EBR-II); the heat pipe developed for this test is performing well. SPAR system design variations are being examined under the possibility of using long core heat pipes. Testing of the initial molybdenum/sodium artery heat pipe continued, with ambiguous results. Fabrication of the first all-bonded thermoelectric units has been completed and testing has been initiated.

I. EXECUTIVE SUMMARY (W. A. Ranken, Q-13)

Components for a 10-100-kW_e space nuclear reactor electric power plant are being designed, fabricated, and tested. Such a power plant will consist of (a) a nuclear reactor for generating heat, including heat pipes for transferring the energy from the reactor to the power conversion equipment; (b) a radiation shield to attenuate radiation to an acceptable level for the payload; (c) thermoelectric (TE) converters to convert heat to electricity; and (d) a radiator for rejecting waste heat to space. The components being designed and tested, when incorporated into a power plant, will provide a power source for nuclear

electric propulsion systems being developed by NASA for missions to study the outer planets, as well as a relatively inexpensive, compact power source for large, earth-orbiting satellites that the Department of Defense is evaluating for communication and surveillance.

Significant results have been obtained in the design and experimental programs, as follows.

- The Los Alamos MCNP Monte Carlo code has been used to determine neutron and gamma shield weights required to protect payloads of the SPAR system. No specific gamma shielding is required for the baseline SPAR system operating at 1.2 MW_t if a payload (at 25 m) can tolerate a lifetime gamma dose of 10^7 rad. Reducing the dose to 10^6 rad requires a 250-kg tungsten addition to the front face of the shield.
- Detailed neutronic modeling of the SPAR reactor has shown that water immersion safety can be achieved by putting eight removable blades of enriched boron carbide (B_4C) into slots in the core. The total B_4C requirement is 2.5 kg.
- Approval-in-Principle has been obtained for the SPAR fuel irradiation tests to be conducted in the EBR-II. The gravity-return temperature-control heat pipe being developed for this unit has achieved a heat throughput of 10 kW at 1425 K, somewhat higher than design expectations.
- The possibility of using long ($\sim 8 \text{ m}$) core heat pipes is being investigated. This would make possible SPAR system design variations, such as radiative coupling from the heat pipes to an array of TE elements, which are closely patterned after those used for radioisotope TE generators. It also makes possible distributed direct coupled systems that may prove to be lighter than the baseline SPAR system.
- Testing of the initial molybdenum/sodium artery heat pipe has been continued in the tilt test apparatus. Performance results are consistent with analytical predictions for a pipe with a relatively coarse screen mesh, but interpretation is somewhat clouded by partial sagging of one artery away from the distribution wick. Improved methods of welding the arteries to the distribution wick are under active development.
- The first all-bonded TE elements have been fabricated, and testing has been initiated. These units incorporate a stress-relieving member that provides mechanical decoupling of the hot and cold sides of the element without causing an excessive temperature drop.

II. MISSION REQUIREMENTS (D. Buden, DAD/NP, H. W. Lorber, S-2, and R. H. Drake, S-4)

A review of the effect of space development on economic growth has indicated that the large impact to date may be expected to be much greater in the future, provided that coming space systems are not limited by inadequate power sources. Examples of definite present benefits to society include the existence of new and more skilled jobs (some half-million people work in space-related jobs); increased productivity, such as demonstrated in the telecommunications industry; lower prices, such as experienced by long-distance telephone users; psychological benefits, such as the pride from recent Voyager pictures; and an expanded resource base provided by space stations that enhance communications processes and make possible inexpensive observation of the Earth's surface.

Direct economic benefits are received from those items or services people buy and pay for and, thus, are the easiest to quantify. For instance, telecommunications is now a \$1.5 to 2.0 billion industry, providing new services such as worldwide television, home television in remote areas, and cable television. The unit costs continue to drop (see Fig. 1); a voice-circuit-year link that cost \$40 000 in 1970, cost only \$5 760 in 1979, even with inflation, and still provided a 2% per year growth in revenues. Other measurable economic benefits will come from the revenues private use of the Space Transportation System will generate.

Externalities are benefits external to the original purpose of an effort. Space technology developments have led to major innovative improvements in, among other things, computers, electronic entertainment, watches, calculators, medical monitoring sensors, freeze-dried foods, and management technology.

Another area upon which space technology has had a major impact is "public good." These are public services that do not have easily measurable economic benefits. For instance, what is the value of daily satellite weather coverage, leading to the fact that no lives have been lost from hurricanes through lack of warning since the mid-1960s? Today's 24-hour forecasts are as accurate as 12-hour forecasts were 15 years ago; it is anticipated that in another 15 years, 5-day forecasts will be as good as today's 24-hour forecasts. It is estimated that this alone will save agriculture and aviation \$5.5 billion annually. Significant benefits also accrue to the nation from space satellites that map natural resources, measure agricultural development and progress, define crop

Fig. 1. Estimation of annual consumers' surplus for INTELSAT telephone traffic in 1980, based on experience from 1970 to 1980, inclusive. Consumers' surplus is \$300 million per year and is equal to the shaded area. Dollar figures have been adjusted to 1980, using the U.S. GNP deflator.

disease areas, inventory forest, and provide information for water management. These satellites also provide navigational aid to ships and aircraft.

The economic and societal benefits to be gained from space-based operations are just beginning to be realized. Space-based manufacturing processes can produce many products, especially electronics components, more cheaply and with greater precision than ever before; new products that are impossible to manufacture in the Earth's gravity field or that require vacuum can be developed, maintaining the U.S. lead as a major exporter in international space and aeronautic industries. It should be noted that innovative research and development activities can lead to major economic benefits, whereas research and development aimed at marginal improvements, such as a better bolt, do not have the same economic benefits.

Satellite and lunar-based industries will require large amounts of power. The nonexistence of such power supplies is a decided impediment to progress in achieving fuller utilization of space. Timely development is needed to remove this impediment.

In a paper presented at the XXXII International Astronautical Congress in Rome, Italy, by Joseph A. Angelo, Jr., and D. Buden, entitled "Space Nuclear Reactors - Energy Gateway into the Next Millennium," it was pointed out that space technology allows man to accept his greatest challenge and to initiate the next major phase of planetary development--the off-planet expansion of the human resource base. The development of advanced space nuclear power systems like SPAR is a critical technology step in the humanization of space.

Supporting studies have been continued on the Integrated Tactical Surveillance System, a space-based-radar study. A nuclear power plant is needed on a much faster schedule than we are now pursuing if the system is to be efficiently fielded.

III. POWER PLANT SYSTEM

A. Space Reactor Shielding Studies (R. G. Palmer, Q-13)

A series of calculations was performed to ascertain the amount of shielding required for the SPAR system payload as a function of reactor power. The power was varied from 0.6 MW_t to 2.0 MW_t , and two sets of constraints were used for acceptable radiation doses at the payload (25 m from the reactor), namely, 10^{12} nvt neutrons/ 10^6 rad gammas and 10^{13} nvt neutrons/ 10^7 rad gammas. The shield half-angle was maintained at 15° .

The Los Alamos MCNP Monte Carlo code was used in several stages. K_{eff} calculations were made for each reactor power to determine the magnitudes and spectra of the neutrons and gammas leaking from the reactor. Over the range of power levels covered, the leakage spectra were similar within the statistics of the MCNP tallies, and the magnitudes of the leakages were such as to justify linear relationship between magnitude and power.

Two types of shielding calculations were performed. Some of the neutrons leaving the reactor produce gammas by absorption and inelastic scattering in the shield and in the TE and radiator components between the reactor and the payload. Thus the MCNP code was used in the dual neutron-gamma mode to predict the neutron fluence and gamma dose resulting from neutron interactions external to the reactor. This gamma dose was added to that calculated by MCNP in the gamma mode, based on the fates of the gammas leaving the reactor.

The reactor-shield configuration is shown in Fig. 2. The four design parameters θ , ψ , ω , and L are shown in the figure. Previous shielding studies

Fig. 2. Reactor-shield configuration used for SPAR shielding studies.

indicated an asymptote of dose vs decreasing ψ . To avoid any problems arising from the interference of overlapping shields with cooling of control rods and radial reflector surfaces by radiation heat transfer, the optimum value of ψ was chosen to be 30° . The next step was to determine the optimum value of ω for a given value of L . A separate study showed that the minimum dose rate for a given shield weight occurred when the value of ω was such that the ratio of the length of the conical outside surface of the shield L_s to the centerline thickness L was about 0.95. This behavior is shown for two shield masses, 400 kg and 700 kg in Figs. 3 and 4, respectively.

The shield design was assumed to be a tungsten-face gamma shield several centimeters thick, followed by a lithium hydride (LiH) neutron shield (plus stainless steel (SS) structure) between 65 and 90 cm thick. The neutron fluence vs mass of LiH + SS for a reactor power of 1.2 MW_t is shown in Fig. 5. Figure 6 shows the effect of adding a tungsten gamma shield on the dose rate at the payload. The results of the study are shown in Table I, which gives the required neutron and gamma shield masses for two sets of dose criteria.

B. Water Immersion Studies (R. G. Palmer, Q-13)

Previous calculations of the quantity of B_4C required to compensate for the reactivity effects of water immersion of SPAR in a lake or ocean assumed, for computational expediency, that the B_4C could be placed in 12 of the core heat pipes. More practical arrangements were studied in which radial slots in the fuel between core heat pipes (see Fig. 7) are occupied by enriched B_4C until a safe orbit is achieved, when the B_4C will be displaced by molybdenum.

Fig. 3. Effect of ratio of shield side length to central thickness on shielding effectiveness for a constant shield mass of 400 kg.

Fig. 4. Effect of ratio of shield side length to central thickness on shielding effectiveness for a constant shield mass of 700 kg.

Fig. 5. Neutron fluence as a function of shielding mass for a reactor power of 1.2 MW_t . The numbers associated with each data point represent the shield thickness.

Fig. 6. Effect of added tungsten gamma shield on dose rate at payload.

TABLE I
NEUTRON, GAMMA, AND TOTAL SHIELD WEIGHTS FOR VARIOUS
REACTOR POWERS AND PAYLOAD RADIATION LIMITATIONS

P MW	$10^{12} \text{ nvt}/10^6 \text{ rad}$			$10^{13} \text{ nvt}/10^7 \text{ rad}$		
	LiH + SS kg	W kg	Total kg	LiH + SS kg	W kg	Total kg
0.6	370	175	545	225	0	225
0.8	400	215	615	265	0	265
1.0	432	250	682	300	0	300
1.2	455	275	730	325	0	325
1.4	475	300	775	345	20	365
1.6	495	320	815	360	40	400
1.8	515	335	850	370	60	430
2.0	533	350	883	380	85	465

Fig. 7. Diagram showing radial slots in fuel between core heat pipes.

The previous calculations considered only water entering the core heat pipes and not the spaces between fuel tiles, which allow some fuel swelling with burn-up. The effects of water entering both the heat pipes and the swelling spaces have now been calculated. The results for various dry and flooded configurations and with B_4C and molybdenum in the radial slots are shown in Table II. The total amount of enriched B_4C in the eight core slots is 2.5 kg.

TABLE II
CALCULATED RESULTS FOR VARIOUS DRY AND FLOODED CONFIGURATIONS

	<u>Dry</u>	<u>Heat Pipes Flooded</u>	<u>Heat Pipes and Void Flooded</u>	
90%-enriched control drums	0.912 ± 0.004	1.080 ± 0.003	1.104 ± 0.003	Mo in slots
	0.812 ± 0.004	0.924 ± 0.003	0.950 ± 0.003	B_4C in slots
50%-enriched control drums	0.935 ± 0.005	1.096 ± 0.004	1.122 ± 0.004	Mo in slots
	0.891 ± 0.004	1.010 ± 0.003	0.998 ± 0.002	B_4C in slots

It can be seen from Table II that the additional effect of water entering the swelling spaces is also a positive reactivity. With the control drum (50%-enriched B_4C) in the shutdown position, the effect of flooding renders the core just short of criticality when B_4C is in the slots and supercritical with molybdenum in the slots.

C. In-Pile Test of SPAR Fuel (A. J. Giger, J. T. Sena, E. S. Keddy, and L. A. Hiteman, Q-13)

1. General. The SPAR fuel in-pile test, which will be conducted in the EBR-II reactor, received Approval-in-Principle from the Reactor Research and Technology Division of DOE. The experiment, testing prototype UO_2 fuel in wafer form for the SPAR reactor, will provide data on the behavior of the fuel/fin system under irradiation conditions. Specific objectives are examination of fuel swelling; heat transfer between fuel, fin, and heat pipe; fuel migration; heat pipe performance; and chemical compatibility of fuel, fin, and heat pipe materials.

A preliminary draft of the Experiment Description and Hazards Analysis was completed. Submission of the completed report to Argonne National Laboratory is the next step in experiment acceptance procedure.

2. Design. A comprehensive, detailed, in-depth design review of the SPAR fuel test was prepared for presentation to DOE personnel. This review is of a programmatic nature and is not part of, or applicable to, the experiment acceptance procedure for the EBR-II reactor.

An alternate fin design, consisting of sleeves with integral fins, is being evaluated. The advantages over individual, brazed-on fins are (a) better control of fin spacing; (b) separation of braze material from UO_2 fuel, allowing use of lower temperature zirconium instead of platinum (1900 vs 2075 K); (c) simplification of assembly; and (d) direct correspondence to the "shish kebob" concept in SPAR reactor design. A possible disadvantage is a more involved braze bond inspection.

The capsule design has been modified by reducing the gap between the upper heat pipe and the niobium capsule wall to 0.13 mm. This was done to lower the required heat pipe calibration temperature in the region to a nominal 817 K (formerly 973 K).

3. Analysis. The sodium bond region between the inner and outer capsules (niobium and stainless steel, respectively) shows a differential volumetric expansion of 17.4 cm^3 between cold and hot operating conditions. Coupled with

an expected 29.1-cm^3 change in bond sodium volume and an arbitrary initial cold gas volume of 23.4 cm^3 , an initial cold pressurization to $8.36 \times 10^4\text{ Pa}$ with neon will result in a cover gas pressure of $4.48 \times 10^5\text{ Pa}$ at the hot operating condition.

The maximum sodium vapor pressure to be suppressed under all conditions (to prevent loss of the thermal bond) is $1.48 \times 10^5\text{ Pa}$. This corresponds to a sodium temperature of 1199 K, which could occur if the fuel should melt and fall into the vacuum bottle bottom. Under normal operating conditions the condenser section sodium temperature of 856 K produces the maximum vapor pressure, $2.54 \times 10^3\text{ Pa}$.

Overall heating of the experiment as presently configured is given in the following table.

<u>Source</u>	<u>Gamma heating (W)</u>	<u>Fission heating (W)</u>
EBR-II SPAR fuel test assembly (excluding fuel)	6920	--
MK M-1A irradiation subassembly	2400	--
UO ₂ fuel	<u>1674</u>	<u>4374</u>
	10994	4374
Total	15368 W	

Calculated heat fluxes for the experiment as presently configured are:

<u>Test Bay</u>	<u>Heat flux (W/cm²) at o.d. of heat pipe</u>
I	156
II	203
III	287
IV	156

The SPAR reactor is currently rated at 100 W/cm^2 , but developmental testing of the in-pile heat pipe recently achieved $152\text{-}156\text{ W/cm}^2$. If no higher values are established experimentally, it may be necessary to derate the experiment by removing some fuel wafers from experiment bays II and III.

4. Development. Numerous individual fin samples were made up to check fabrication, assembly, and brazing techniques. Of the brazes tried, zirconium appears to be the best, followed closely by platinum. Palladium is a distant third. Figures 8 and 9 show specimens brazed with zirconium and palladium, respectively. A fixture to accurately assemble and locate the fins was designed and fabricated.

5. EBR-II Heat Pipes (E. S. Keddy, L. A. Hiteman, and H. E. Martinez, Q-13). Two molybdenum heat pipe assemblies were fabricated and tested. One assembly was constructed with sodium as the working fluid; the second contained lithium. Performance tests were conducted on both heat pipes, and the molybdenum/lithium assembly was determined to be the best suited for the EBR-II in-pile test.

a. Fabrication. The heat pipes are 432 mm in length, with an outside diameter of 15.9 mm. Both heat pipe assemblies were constructed in the same manner. One layer of 150 mesh molybdenum screen was placed against the inner wall of the heat pipe; a second layer of 20 mesh screen was placed over the distribution wick to minimize the entrainment of the returning fluid. The heat pipes were cleaned by full immersion in 800-K sodium and subsequently fired in high vacuum to 1700 K for 2 h. End caps were electron beam welded in place, and each pipe was loaded with sufficient fluid (sodium for one and lithium for the other) to fill the wick structure and form a 20-mm pool.

b. Testing of EBR-II Molybdenum Heat Pipes. In order to make performance measurements of these heat pipes, it was necessary to construct a calorimeter facility. This facility provides an inert gas environment for the heat pipe and a variable-conductance gas gap in the heat rejection section, while holding a relatively low thermal leakage path in the evaporator section of the heat pipe. To accomplish this, a dual gas flow calorimeter system, as shown in Fig. 10, was constructed. The figure shows a water-cooled, gas-gap calorimeter partly enclosed in a quartz envelope. The calorimeter is centered by an alumina insulator support, which includes a vent for the inert gas. The heat pipe is centered in the calorimeter by an insulating plug, which includes a hypodermic tube to introduce the argon-helium mixture into the gas gap. The heat pipe's position can be changed to vary the lengths of the evaporator and condenser sections. Heat is supplied by an induction coil. The heat input section of the system contains slowly flowing argon, which is introduced at the bottom of the quartz envelope. The argon exits through the insulator support. Because of the low

Fig. 8. Molybdenum fin zirconium-brazed to molybdenum tube.

Fig. 9. Molybdenum fin palladium-brazed to molybdenum tube.

Fig. 10. EBR-II molybdenum heat pipe test configuration.

thermal conductivity of argon, this arrangement tends to minimize the thermal loss to the quartz tube surrounding the evaporator.

Heat rejection to the calorimeter in the condenser section of the heat pipe is controlled by adjusting the ratio of argon to helium in a separate inert gas flow system. This gas mixture is introduced into the gap by a feed line through the insulator centering the heat pipe. The gas flows slowly through the gap region and eventually leaves the system through the same vent used to complete the argon flow circuit.

A temperature-difference meter and water flowmeter are used to measure the power transferred by the heat pipe into the water flowing through the calorimeter. The heat pipe temperature is measured by optical pyrometry at the evaporator exit, i.e., the region between the induction coil and calorimeter.

Performance testing of both heat pipes has been completed using a 100-mm induction coil to provide heat input. The results for the sodium heat pipe are shown in Fig. 11. The performance exceeded the predicted entrainment curve up to a heat transfer rate of 7.7 kW at 1300 K, but fell off above this temperature. As shown in Fig. 12, the lithium heat pipe exceeds the predicted curve for entrainment throughout the measurement range and shows a throughput of 10 kW at 1425 K. Performance testing of the lithium heat pipe included a radial heat flux test. Powers up to 1.58 MW/m^2 were attained.

6. Fuel Fabrication (K. V. Davidson and R. E. Honnell, CMB-6). Three fuel loadings for the SPAR fuel irradiation test in EBR-II have been fabricated. The fuel specifications and isotopic analyses on the starting ceramic-grade urania powders were reported in the April-June 1981 Quarterly Report. The fuel was prepared in the form of washers by conventional ceramic processing techniques, a description of which follows.

a. Urania Powder. Urania powder of relatively fine particle size was prepared by the method of peroxide precipitation from uranyl nitrate (UO_4). The UO_4 was converted to U_3O_8 by calcining in air, and the U_3O_8 reduced to

Fig. 11. Performance limits of molybdenum/sodium heat pipe. Data points represent performance of heat pipe with calorimeter.

Fig. 12. Performance limits of molybdenum/lithium heat pipe. Data points represent performance of heat pipe with calorimeter.

UO₂ by heating in hydrogen. Typical UO₂ powders produced by this process have B.E.T. surface areas in the 3-4-m²/g range and mode particle sizes of 1 to 2 μm.

A binder of 3-wt% vinyl acetate was added to the as-received UO₂ powders. The acetate binder was dissolved in an excess of acetone, and the solution hand-stirred into the powders. The urania-binder mixture was dried, pressed into cylinders at 103.4 MPa (15 ksi), crushed, and screened -250 μm (60 mesh).

b. Pressing Operation. The following procedure was used to press the -250-μm powder into disks of 37- and 41-mm diam and of 1.77- and 2.92-mm thickness. The bottom punch height in the die body was adjusted to accommodate a weighed charge of UO₂ powder that had been struck off level with the top of the die. The top punch was inserted, rotated, and the pressing charge pushed from 12 to 25 mm into the die cavity. A pressure of 103.4 MPa was applied to the punches; the pressure was released and then reestablished for a 2-min hold. The pressure was applied slowly to facilitate powder movement. The pressings were readily ejected from the die and had sufficient green strength for handling.

c. Sintering. The pressed disks were sintered at 2073 K (1800°C) for 16 h in 293 K (20°C) dew-point hydrogen. The heating cycle consisted of a 50°C/h rate to 873 K (600°C) and a 100°C/h rate for the remainder of the cycle. The disks were sintered in "poker chip" stacks of five, resting on a 4-mm-thick tungsten plate. The plate was lightly sprinkled with 250-μm-diam Al₂O₃ grains before the stacked disks were positioned, then placed in a molybdenum boat. The disks were readily separated after sintering and exhibited minimal warpage. Sintered densities obtained by the Archimedes technique on three different specimens randomly selected from lots of 40 are shown in Table IV. Sintering shrinkages for the three pellet lots ranged from 25 to 28%. The differences in density between lots is caused by subtle differences in the morphology of the UO₂ particles in the lots' starting powder.

d. Machining. The sintered disks were machined by surface-grinding eight disks at a time to the required thickness. The disks were then core-drilled on the inside and outside diameters, using an ultrasonic rotary grinder with diamond tooling. The chamfered inside diameter was ground with a shaped diamond tool on the same machine. Some of the disks experienced edge chipping during core drilling, which may have been caused by disk lamination or tool chattering.

TABLE IV
SINTERED DISK DENSITIES^a

<u>Powder Lot</u>	<u>Enrichment, %</u>	<u>Density, g/cm³</u>	<u>% Theoretical</u>
CUØ-907	Natural	10.27	93.6
CUØ-907	Natural	10.38	94.6
CUØ-907	Natural	10.28	93.7
CUØ-908	27.31	10.37	94.5
CUØ-908	27.31	10.42	95.0
CUØ-908	27.31	10.40	94.8
CUØ-909	6.22	10.41	94.9
CUØ-909	6.22	10.41	94.9
CUØ-909	6.22	10.40	94.8

^aUncorrected for isotopic content and based on a theoretical density of 10.97 g/cm³.

D. Power Plants with Distributed TE Converters (D. R. Koenig, Q-13)

The reference SP-100 power plant employs very compact TE converter assemblies, bonded to the condenser end of relatively short (2-m) core heat pipes. The waste heat from the converters is rejected to space by coupling the cold shoes of the converters to a large heat pipe radiator. This separate radiator assembly could be eliminated entirely by using, instead, distributed TE converters, which are spread out over an equivalent area and whose cold shoes radiate the waste heat directly into space. Two concepts for coupling the distributed TE converters to the core heat pipes, which now have to be very long (~8 m), are being investigated; namely, direct thermal contact and radiative heat transfer.

The direct-coupled concept is illustrated in Figs. 13 and 14. Here the core heat pipes extend out along a surface that, in the reference design, would define the radiator. TE converters are attached to the core heat pipes, not all the way around the pipe but over only a portion of the circumference, facing away from the center axis of the power plant and outward into space. The cold shoes of the converters consist of many small heat pipes that radiate directly into space. This cold-shoe design makes possible a radiating area many times greater than the cross-sectional area of the TE couples without incurring the

Fig. 13. Direct-coupled distributed TE converter design.

Fig. 14. Distributed TE converters coupled directly to heat pipe.

temperature drop of a conventional fin. The cold shoes are segmented at the thermocouple junctions to permit the elimination of a cold junction electrical insulator. The heat pipes and the thermocouples are thermally insulated with multifoil, wrapped as shown in Fig. 14. The multifoil provides good meteorite protection for the heat pipes, and this configuration offers the possibility for substantial size and weight reductions by radiating power from both sides of the cold shoe.

The radiatively coupled, distributed-TE-converter power plant is depicted in Figs. 15 and 16. The core heat pipes fan out around the radiation shield and then extend for 5-6 m in a circular bundle concentric with the axis of symmetry of the power plant. These are surrounded at some distance by the converter assembly, which follows essentially the outline of the reference design radiator. The major advantage of this concept is that reactor and converters are physically separate systems that can be assembled and tested separately, then mated without stringent tolerances during final assembly. Another significant advantage is that the TE converter assembly is similar in concept to existing radioisotope TE generator technology. The converters do not require a hot shoe electrical insulator, and their design is completely independent of the core heat pipe design.

This attractive concept is not without drawbacks. In common with the direct-coupled system, it has long core heat pipes that are difficult to fabricate and that complicate assembly of the reactor core. Due to the nature

Fig. 15. Radiatively coupled nuclear power system design.

Fig. 16. TE module cross section for radiatively coupled system design.

of radiative heat transfer, there will be, for a system of practical dimensions, a large (>100 K) temperature differential between the core heat pipes and the converter hot shoes, even if high-emissivity surfaces can be developed. This loss of temperature results in a proportional reduction in electrical conversion efficiency of the power plant that can be offset by raising the reactor power level or core temperature, both of which increase plant size and weight. The concept requires the development of high-emissivity surfaces that are stable at 1400-1500 K. Cooling the radiation shield located between the reactor and the converters may pose a problem because it is exposed on all sides to the hot core heat pipe temperature.

A mass analysis is currently being done for these two distributed converter systems to aid in evaluating their relative merits.

IV. CORE HEAT PIPE DEVELOPMENT (M. A. Merrigan, Q-13)

A. Heat Pipe Fabrication.

1. SPAR-5 Fabrication (M. A. Merrigan and G. W. Fly, Q-13). Fabrication development for the SPAR-5 core heat pipe has been initiated. This will be an annular wick heat pipe similar to SPAR-1B, but employing lithium as a working fluid. Thermal design of the pipe is based on a maximum operating temperature of 1500 K, with a peak heat transfer capability of more than 20 kW. Current plans are to use a 150 mesh screen wick rolled and drawn to reduce pore size to approximately 50 μm .

2. Processing, Filling, and Testing System Construction (G. W. Fly, H. E. Martinez, and E. O. Ferdinand, Q-13). A gas-gap-controlled calorimeter for high-power testing of the SPAR-4 heat pipe was fabricated, and assembly into the test chamber was begun.

A second, similar calorimeter for high-power core heat pipe testing is being designed to employ a four-stage, vacuum-pumped labyrinth seal rather than a welded flange seal. This design will permit the heat-rejection region of a heat pipe to be varied and will greatly reduce the time required for installation and removal of test items from the performance test set-up.

3. Core Artery Heat Pipe Fabrication (J. Runyan, Q-13). Development has started on a successor to the SPAR-4 heat pipe, also of artery design. It will have improved arteries and wick, making use of 350 to 400 mesh molybdenum screen instead of the 150 mesh screen used in the SPAR-4 heat pipe. Design revisions based upon experience with SPAR-4, together with learning-curve technique improvement, will provide improved reliability in this second generation artery heat pipe. Improved performance is expected through better control of contaminants, more secure artery attachment, and more complete contact between the wick and the tube wall. Other design changes planned include the use of a wick structure that will provide more uniform pore size in both artery and distribution sections and improved getter geometry.

Development of joining methods for molybdenum heat pipe components has concentrated on refinement of methods for spot welding arteries to the distribution wick. Figure 17 shows the configuration of a heat pipe design for which an internal artery-attachment welding head has been designed and built. A rolling contact wheel of tungsten is pressure-loaded to hold the artery against the bore of the wick and provide a low-resistance electrical path to the spot weld.

Fig. 17. SPAR core heat pipe internally welded, dual-artery configuration.

Delrin rollers serve the dual function of electrically isolating the head and providing an adjustable spring load opposing the tungsten contact point. The spring loading ensures relatively constant contact pressure, despite dimensional changes either as a result of deformation in the weld zone or due to variations in starting dimensions. Preliminary trials have shown adequate current-carrying capacity of the head. Stainless steel sample screens have been successfully welded. Initial molybdenum screen-to-screen weld attempts were unsuccessful when tried in air with unfired screen, apparently due to high electrical resistance at the screen surface. A combination of chemical cleaning, vacuum furnace firing, and welding of molybdenum under a cover of argon gas is currently being tested as a means of improving weld quality. A cover gas arrangement, using the heat pipe tube as the gas enclosure, should prove an improvement over the liquid submersion technique employed in SPAR-4 assembly.

4. Fine Screen Production (L. B. Lundberg, Q-13). The screen woven from low-carbon arc-cast (LCAC) molybdenum was delivered from Dürer Metaltuch. The screen is a twill weave of 25- μ m-diam wire woven into a 350 x 388 mesh, and it was delivered as a single piece 15.2 cm wide by about 3 m long. The bubble-point pore diameter of this screen was measured to be 60 μ m.

Molybdenum-41 wt% Re alloy wire has been drawn by Metallwerk Plansee to 25- μ m diameter and has been delivered to Dürener Metaltuch in West Germany for weaving into 400 x 400 mesh screen. This screen will be used to fabricate developmental artery wicks. Production facilities for this material and scheduling of the fabrication were discussed with Dürener Metaltuch personnel in the course of a facility inspection tour by Los Alamos National Laboratory personnel during this reporting period. Agreed-upon schedules call for delivery of the woven screen material during November, 1981.

B. Core Heat Pipe Testing

1. SPAR-1B Testing (H. E. Martinez, Q-13). The SPAR-1B 2-m molybdenum/sodium heat pipe was assembled to a gas-gap-controlled calorimeter. The heat pipe and calorimeter were installed in a vacuum chamber for testing. The heat pipe was tested, using an rf heater, to 14.4 kW at 1385 K, where an evaporator dryout was encountered. A second test on the heat pipe resulted in a dryout at 6.0 kW at 1340 K. Additional testing produced less power throughput at lower temperatures. Thermal performance of the heat pipe had permanently decreased as a result of the dryout. Therefore, the testing was terminated, the heat pipe disassembled, and posttest evaluation begun.

2. SPAR-4 Testing. (H. E. Martinez, Q-13). SPAR-4 is the first molybdenum/sodium heat pipe with an arterial wick configuration. It has two arteries, placed 180° apart, that are attached to a distribution wick by spot welding. The distribution wick lines the inner wall of the molybdenum heat pipe envelope. It is made of six layers of 150 mesh molybdenum screen, compressed to less than 50% of stack height by swaging to reduce the pore size. During the previous reporting period, the SPAR-4 heat pipe was assembled, filled, and operated in tilt tests to determine the effective pore size and other performance characteristics of the artery design. The heat pipe was radiographed before these tests, and it was found that one of the arteries had become separated from the distribution wick in the evaporator area. The test data reported in the last quarterly report were taken with the heat input coil placed in the region where only one artery was attached to the wall. The results of these initial tests were used to predict the performance of the heat pipe with two arteries functioning. In the tests conducted in this reporting period, the two-artery performance predictions were verified by operating the heat pipe with the heating coil located where both arteries were attached to the distribution wick. Before these tests were conducted, the heat pipe was placed in an

isothermal vacuum furnace and heated at 1025 K for 72 hours in an attempt to improve wet-in and to getter impurities with the hafnium and zirconium present in the evaporator end of the heat pipe. This additional heat pipe conditioning was carried out because it was believed that the impurities could be the cause of some of the performance variations previously observed. Following this conditioning, the heat pipe was removed from the isothermal vacuum furnace and placed in an inductively heated, quartz, vacuum tube furnace, and the effects of the wetting-in evaluated by reheating in the single-artery section. Repeated tests showed that there were no apparent improvements in the heat pipe performance.

For the initial two-artery performance tests, the 32-cm-long rf heating coil was moved to the middle of the heat pipe to provide a condition where both arteries would feed liquid to the distribution wick. These tests showed improved performance, as shown in Fig. 18. The effective head is the distance from the top of the liquid pool to the top of the evaporator coil when the heat pipe is tilted to work against gravity. The gravity-assist component of flow from the heater location to the upper end of the heat pipe was not evaluated separately, so its effect on the overall performance was not known. From the results, it was not apparent whether both arteries were working properly.

The heat pipe was then set up with the evaporator coil at the condenser end of the heat pipe, where the arteries were open to the vapor space of the heat pipe. Under this condition the arteries can generate only a small capillary force, determined by the artery radius. Tests were performed with the heat pipe operating against gravity and in the gravity-assist mode. The results, shown in Fig. 19, for 0- to 4-cm effective head, show the capillary pumping ability of the open arteries. The rapid fall-off with increasing gravity head relative to the data in Fig. 18 shows that at least one artery was operative in the earlier tests. The data between 0- and -3-cm effective head indicate an increasing performance in the gravity-assist mode. The step change at 0 cm indicates the effect of puddle flow.

The evaporator coil was moved to 30 cm from the end of the heat pipe at the evaporator end so that it was just past the sagged portion of the flawed artery. Testing produced power of 2.6 kW at 50-cm effective head, which was higher than any previous tests. It appeared that the heat pipe contained impurities and that operation of the heat pipe with heat input at the condenser end moved the impurities from the evaporator and provided an impurity-free evaporator when the pipe was tested to the high-power level.

Fig. 18. SPAR-4 heat pipe tests: comparison of performance with heat input at end and at two-artery location.

Fig. 19. SPAR-4 heat pipe tests with heat input at open end of arteries.

The mechanism of transfer of the impurities in the heat pipe is not fully understood, since previous gettering operations did not significantly alter the operation of the heat pipe.

In light of this high performance, work was begun on assembling a gas-gap calorimeter on the heat pipe and assembling the heat pipe in a vacuum testing chamber for a low-power, long-time operation. This extended operation period is intended to provide time to getter the impurities in the heat pipe.

3. Core Heat Pipe Analysis (F. C. Prenger, Q-13). Further analysis has been performed on the artery design for the core heat pipe. Pending the development of operating flow characteristics data for the distribution screen and artery wall material, the core heat pipe performance analysis is based on ideal flow through porous media where the permeability K is given as

$$K = \frac{\epsilon r_c^2}{t} ,$$

where ϵ is the void fraction,

r_c is the pore radius, and

t is the tortuosity.

The pressure drop is then calculated by

$$\Delta p = \frac{\mu L \dot{m}}{\rho K A},$$

where μ is the liquid viscosity,

L is the flow path length,

$\dot{m}$ is the flow rate,

ρ is the liquid density, and

A is the wick cross-sectional area.

Figure 20 shows predicted sodium heat pipe performance as a function of artery diameter and distribution/artery wall thickness for a four-artery configuration, assuming a tortuosity of 16, a pore size of 35 μm , and a void fraction of 0.43. The analysis shows a performance maximum at an artery diameter of

Fig. 20. Artery sizing for SPAR core heat pipe.

2.3 mm. If permeabilities smaller than those assumed are demonstrated in the test, changes in the artery diameter will be made to optimize the design.

Boiling limits similar to those encountered in the SPAR-1A heat pipe, which used sodium as the working fluid, are a potential problem with this artery design if the artery mounting system causes significant temperature gradients to be established across the artery diameter when sodium is used as a working fluid. An analysis was performed to determine the approximate artery geometry required to avoid boiling in the heat pipe arteries at design power levels. Figure 21 shows the nucleation site size required for bubble growth as a function of contact width between the artery and the distribution wick. The analysis is for sodium working fluid. An estimated range of nucleation site sizes for the SPAR-1A heat pipe is also shown in Fig. 21. This range of sizes is based on the experimentally determined operational limits of the SPAR-1A heat pipe, assuming full re-wetting was achieved between each dryout. It is apparent that even for arteries whose contact width is comparable to the artery diameter ($\delta \approx 0.36$ cm), the allowable nucleation site radii are large compared to those

Fig. 21. Nucleation site size as a function of contact width between artery and distribution wick.

observed for SPAR-1A. When the contact width is reduced by an order of magnitude, the boiling potential becomes very low. For lithium the allowable nucleation sites are approximately 100 times larger still; hence, the boiling potential for lithium is miniscule.

C. Alternative Artery Wick Fabrication

1. Chemical Vapor Deposition Wick Experiments (K. L. Meier, Q-13, and W. McCreary, CMB-6). Chemical vapor deposition (CVD) experiments are being conducted to attempt to uniformly reduce the porosity of SPAR core heat pipe wicks. The goal of these experiments is to use readily available 150 mesh screen for arteries and distribution wicks and subsequently reduce the porosity by a CVD process.

Previous experiments have shown the difficulty of obtaining a uniform coating both axially and circumferentially using CVD molybdenum. Therefore, present experiments are concentrated on CVD of tungsten. To demonstrate feasibility, 100-mm-long by ~13-mm-diam cylinders formed of 100 mesh molybdenum screen were coated with tungsten. The reaction $WF_6 + 3H_2 \rightarrow W + 6HF$ was performed at ~10-15-torr pressure and 725 K. Results are shown in Fig. 22. Pore size was reduced from 120 μm to ~40 μm . Scanning electron micrographs in this figure also show the rough pyramidal surface of the CVD tungsten. The pore size and surface of the coated screen should make an acceptable wick.

The coating apparatus was scaled up to coat a wick ~305 mm long. Photographs and microscopic measurements indicated very uniform porosity, with <10% variation.

Further scale-up involved the fabrication of a 1-m-long CVD apparatus that has clam-shell electric heaters and a motor that continuously rotates the screen tube during the coating process. Reacting gases are introduced into the chamber through perforated tubes extending toward the axial center from both ends. After a few initial system malfunctions, a 1-m-long, 2-1/4-layer loose-wrapped 150 mesh molybdenum screen tube was successfully coated. Figure 23 shows a 70X photomicrograph of this tube. The coating thickness variation over the 1-m length was an acceptable $\pm 10\%$. Varying the hole size as a function of length in the perforated gas supply tubes is expected to further reduce the coating thickness variation.

The loose-wrapped screen porosity was reduced from 170 μm to 117 μm . Preparations are under way for producing a 5-1/4-wrap screen lightly compacted by

drawing. This process is expected to yield a screen tube with porosity in the range of 60 to 80 μm . CVD coating will reduce the porosity to about 40 μm .

Design of a 2-m-long CVD apparatus has begun. It will use electric clam-shell heaters, a motor to rotate the screen tube, and perforated tubes for gas supply. A fluid flow analysis will be conducted to determine the proper perforated tube hole size as a function of axial position and to establish the hole spacing which will produce a uniform coating over the 2-m length.

2. Packed Sphere Artery Wicks (L. B. Lundberg, Q-13, C. Wojcik, Teledyne Wah Chang Albany). Teledyne Wah Chang Albany (TWCA) has been working on a process for fabricating a porous metal artery wick by bonding niobium spheres together and to the inside surface of a molybdenum tube. The 10-cm-long sample that was mentioned last quarter has been evaluated sufficiently to determine that this type of wick has good potential for performing well in a molybdenum heat pipe. Both the porosity and the permeability of the wick have been measured. The pore diameter of the arteries, measured by the bubble-point method, was 32 μm . The permeability of the wick was measured by sealing its internal surface and flowing 190-proof ethanol through it in a circumferential direction. The specific permeability derived from Darcy's law is listed, along with porosity and permeability data obtained from various other niobium wick samples, in Table V. These data are being used to guide the design of the artery geometry.

TABLE V
WICK PROPERTY MEASUREMENTS

<u>Sample Description</u>		<u>Specific permeability (m^2)</u>	<u>Effective pore diameter (μm)</u>
Packed Nb sphere artery wick (~75% dense)		9×10^{-14}	32
85% dense packed Nb sphere slab	unsintered	6.6×10^{-13}	39
	sintered	4.6×10^{-13}	39
70% dense packed Nb sphere slab	<u>unsintered</u> 6 mm thick	1.3×10^{-11}	72
	0.8 mm thick	7.4×10^{-12}	70

A. UNCOATED

→ | 400 μ m | →

B. COATED

→ | 400 μ m | →

C. COATED

→ | 80 μm | ←

D. COATED

→ | 20 μm | ←

Fig. 22. Scanning electron micrographs of 100 mesh molybdenum screen coated with CVD tungsten.

Fig. 23. Photomicrograph of CVD tungsten-coated molybdenum screen tube.

3. Felted Metal Wicking Structures (J. V. Milewski, CMB-6). An alternate approach to making an artery wick for molybdenum heat pipes involves the felting of fibers of molybdenum or niobium in the desired shape and porosity. Refractory metals such as tungsten, molybdenum, niobium, and tantalum, which have been shown to be compatible with molten sodium, are being investigated. It is believed that fibers in the 2- to 20- μ m-diam range, felted to 15 to 30% solids, will produce a wick with good performance. Two companies that make niobium superconductor cables from micron-size niobium fibers have been contacted and samples have been obtained from each company. The cable matrix has been etched away to provide fine discrete fibers suitable for felting. Based on these initial investigations, materials are being selected for procurement in larger sample sizes for felting experiments.

D. Facilities (K. L. Meier and L. N. Vikdal, Q-13)

Assembly of additional vacuum chambers and test facilities is proceeding. Fabrication and assembly have been completed on the following items of test chamber #2: coolant water lines, flow switches, flowmeters, ΔT meters, calorimeter gas supply manifold, heater power supply, electrical cables,

insulation, connectors, thermocouple vacuum passthroughs, and thermocouple terminal blocks. This chamber will initially be used to test the conduction heater furnace. Assembly of the conduction furnace has begun. Chromel alumel, W/W26Re, and W5Re/W26Re thermocouples are being installed in various places on the furnace to measure temperature drops between heater rods, spacers, half shells, and the heat pipe.

An alumina powder coating is being placed on all heater parts to prevent self-welding, which precludes disassembly. The fine alumina powder will fill the interstices between the parts and enhance thermal conductivity. Applied to the parts as a water slurry, the alumina becomes slightly adhesive after the water evaporates and, therefore, remains in place.

The conduction furnace is enclosed in a water-cooled, Zircar-insulated heat shield to reduce heat loss by radiation and protect the environs. This shield has been fabricated and assembled.

A gas-gap calorimeter has been designed and fabricated to simulate a heat pipe during conduction furnace testing. This device, shown schematically in Fig. 24, will allow more complete and efficient testing of the furnace without the complications of an experimental heat pipe. The calorimeter has the same 15.9-mm-o.d. molybdenum tube as a SPAR core heat pipe and transfers the furnace heat inwardly through a helium-filled gas gap to a stainless steel center tube containing flowing water.

E. Materials

1. Molybdenum Heat Pipe Corrosion Studies (L. B. Lundberg, Q-13, S. T. Kosiewicz, CMB-1). The study of the corrosion of molybdenum heat pipes containing sodium as the working fluid (Mo/Na heat pipes) continues. The experimental program under way simulates the thermochemistry of Mo/Na heat pipes in a SPAR reactor core environment. This is done by sealing UO_2 under vacuum inside a close-fitting molybdenum or TZM/molybdenum alloy capsule, which is, in turn, sealed inside a Mo/Na or TZM/Na heat pipe. The wick inside the heat pipe consists of a loosely wrapped, 150 mesh molybdenum screen, and the tube containing the UO_2 is centered in the heat pipe bore by a mating recess in the center of the blind end cap and by wire supports located near the fill end cap.

A list of the experimental samples presently under test is given in Table VI. The UO_2 /Mo/Na/Mo sample has developed a sodium leak, and posttest examinations to determine the cause are in progress. This sample failed shortly after restart following a shutdown for radiography. The radiograph did not reveal any

significant defects in the heat pipe before failure. The remainder of samples listed in Table VI continues in test to failure.

TABLE VI
MOLYBDENUM/SODIUM HEAT PIPE CORROSION TEST SUMMARY

Sample Description	Temperature (K)	Time (h)
UO ₂ /Mo/Na/Mo	1500	4475 ^a
TZM/Na/Mo	1500	5190
UO ₂ /TZM/Na/TZM	1390	439
UO ₂ /Mo/Na/TZM	1355	439

^aTime to failure

Chemical analysis continues on samples taken from Mo/Na heat pipes that have operated for extended periods of time. Some of the data collected so far are listed in Table VII. Analyses of these data indicate that in some cases impurities are being removed from the condenser wicks and redeposited in the

Fig. 24. Schematic diagram of gas-gap calorimeter.

evaporator and at the condenser exit. This latter area of the SPAR-1 heat pipe was immersed in liquid sodium during most of the heat pipe operation and probably acted as a cold-trap for impurities. The container tubes corresponding to the wick samples listed in Table VII show only slight bulk chemical changes.

TABLE VII
INTERSTITIAL ANALYSIS OF MOLYBDENUM SCREEN WICKS

<u>Sample Description</u>	<u>Chemical Analysis (ppm)</u>		
	<u>Carbon</u>	<u>Oxygen</u>	<u>Nitrogen</u>
Cleaned and stress-relieved 150 x 150 molybdenum screen	85	220	40
Molybdenum screen from evaporator exit of UO ₂ /TZM/Na/Mo corrosion sample that failed after 13.5 h at 1435 K	220	260	30
Molybdenum screen from condenser of previous sample	240	160	20
Molybdenum screen tube from SPAR-1 evaporator center	90	300	4
Molybdenum screen tube from SPAR-1 condenser center	30	100	3
Molybdenum screen tube from SPAR-1 condenser exit	100	1350	6

This bulk chemical analysis of SPAR-1 screen samples was complemented by Auger spectra analysis of the surfaces of similar screen samples. Three samples from the evaporator section of the SPAR-1 screen tube were examined. An electron energy scan to 2000 eV on a blackened area inside the screen tube indicated the presence of molybdenum, carbon, oxygen, sodium, silicon, and possibly aluminum on the screen surface. This same area was sputter-etched to a depth of several micrometers and the elemental concentrations were remeasured. The molybdenum and silicon concentrations increased with depth of scan, while most of the rest of the other elements decreased in concentration. In a second sample of this type no aluminum was detected, although the other concentrations were similar. A third sample from the SPAR-1 evaporator screen tube included an area where crystallites had deposited on the inside surface. This crystallite-covered area was scanned several times, and molybdenum, carbon, oxygen, silicon, sodium, and

possibly nitrogen were detected on the surface. The surface was very heterogeneous, especially in carbon content, and the depth profiles showed molybdenum concentration increasing and carbon and oxygen decreasing with increasing sputtering time.

A sample of screen tube from the center of the condenser of SPAR-1 was also analyzed by Auger spectroscopy. Molybdenum, carbon, oxygen, sodium, and possibly nitrogen were detected on the outside surface of this sample in a 0-2000-eV scan. The asymptotic carbon and oxygen concentrations in this sample were lower than those in the evaporator, in agreement with the bulk chemical analysis data. A companion sample of the container tube was examined on its inside surface, and molybdenum, carbon, oxygen, sodium, and iron were detected in the 0-2000-eV scan. During depth profiling, the molybdenum and silicon concentrations increased to relatively high values, while the carbon concentration decreased to a relatively low value.

A sample from the condenser exit of the screen tube wick from SPAR-1 was also examined by Auger spectroscopy. As indicated in Table VII, this region of the screen tube wick was highly contaminated with carbon and oxygen. Molybdenum, carbon, oxygen, and sodium were detected in the 0-2000-eV Auger scan of the inside surface of this sample, and there was an apparent sulfur contribution to the molybdenum peak at 148 eV.

The Auger data from SPAR-1 tend to suggest that carbon, oxygen, silicon, and sodium are the primary impurities in the Mo/Na heat pipes. More data are needed to determine the mechanism of corrosion in Mo/Na heat pipes, and efforts to develop this information are continuing.

2. Molybdenum-Rhenium Alloy Development (L. B. Lundberg, Q-13, V. Vigil, and R. A. Patterson, CMB-6). The production of Mo-13 wt% Re alloy ingots at Oak Ridge National Laboratory (ORNL) continues. Two ingots have been vacuum, consumable-electrode arc-melted and machined for extrusion. One of the ingots has been extruded, but because of a furnace failure, ORNL has not been able to extrude the second ingot. After both ingots are extruded, they will be remelted in the vacuum arc-melting facility and re-extruded.

Evaluation of the Mo-13 Re tube fabricated from powder-metallurgical-produced alloy and obtained from Metallwerk Plansee has continued. Chemical analysis of the tube indicated it contained 14.5 wt% rhenium, 410 ppm oxygen, 10 ppm nitrogen, 3 ppm hydrogen, and less than 10 ppm carbon, but electron microprobe analysis indicated the rhenium concentration was rather nonuniform throughout the

sample. In fact, some rhenium-rich inclusions containing about 90% rhenium were visible in the microstructure. Improvements in the production of this alloy by powder-metallurgical techniques will be required to make it usable for a sodium or lithium heat pipe container material.

V. RADIATOR DEVELOPMENT

Radiator Heat Pipe Testing (S. P. Girrens, Q-13, and D. Ernst, Thermacore)

Preparations are continuing for testing the 5.5-m titanium heat pipe, RAD-3. A 4-turn rf coil, constructed of 0.64-in. flat traveling-wave tube, will be used to provide input heat into the 60-cm length of evaporator. The rf is coupled only to the flat side of the heat pipe. The vacuum fill and test chamber has been leak checked, and the distillation pot has been assembled and is ready to be loaded with potassium. Heat pipe fill and testing are estimated to begin in the latter half of October.

VI. TE MODULE DEVELOPMENT

Thermocouple Design and Fabrication (G. W. Fly, Q-13)

The basic thermocouple design has been completed and fabrication of the thermocouples has begun. During the fabrication process, some cracking occurred in the silicon test pieces when thick (1-mm) sections of molybdenum were brazed to the silicon and to the alumina insulators. Consequently, the molybdenum was replaced with tungsten for these tests to obtain a better expansion match with the silicon. Additional bonding tests were required to develop brazing methods for the tungsten. Figure 25 shows the actual layout of the test thermocouple. Additional pressure was required to obtain a titanium diffusion bond between the tungsten and the metallizing layer on the alumina insulator. The silver-silicon braze on the cold side had to be replaced with a 95% silver-5% aluminum braze material to obtain wetting of the tungsten. No cracks in the silicon developed after changing to tungsten, but significant time was lost in developing the new brazing techniques.

Thicker sections of metal were required in the test pieces to facilitate instrumentation. Only thin sections will be required in the actual hardware and, since no cracking of the silicon has occurred with thin sections of molybdenum, the basic design can be retained. Comparison of the current test piece

Fig. 25. Section of thermocouple showing interface layers.

and a thermocouple with thin molybdenum sections will indicate any differences in interface temperature drops, but no significant differences are expected.

A thermocouple subassembly was received from Syncal Corporation for final bonding, instrumentation, and testing. The instrumentation holes in the p leg of the thermocouple subassembly were missing, but to expedite testing and not risk damaging the thermocouple during drilling, it was decided to test the thermocouple without this instrumentation. The final bonding steps were completed, the thermocouple was instrumented, and the heater was attached, making the thermocouple ready for testing. In addition, a second thermocouple subassembly was received toward the end of the reporting period. A method of attaching larger lead wires to this thermocouple was developed to reduce the extraneous external resistance. This thermocouple still lacks a heater and the final bonding step must be performed, but otherwise it is complete.

1. Testing. The test chamber has been completed and instrumented. The first thermocouple was put on test toward the end of the reporting period. Two runs were attempted, but both had to be aborted due to heater failures. The insulators on the heater broke down due to the high temperature and high-voltage stresses on the heater. A reaction between the insulator and the molybdenum

heater element then caused an open circuit after about 100 h of operation. New heaters using uncoated tungsten-rhenium wire are being constructed.

Although the test duration was limited to about 100 h, data were obtained at hot junction temperatures of about 1000 K. These data are currently being reduced and analyzed, and efforts are being made to get the test running again.

2. Insulators. The aluminum nitride samples that were hot-pressed in tantalum liners under an argon atmosphere had reduced carbon content. The measured carbon content was 25 ppm. The compact was sliced into 0.5-mm slices, which are currently being coated with molybdenum. Relatively high carbon levels (250 ppm) were detected in the 15R Sialon samples, but carbon content is not as critical in the Sialon. The Sialon, however, appeared to be quite inhomogeneous. This problem is currently being investigated.

The furnaces for the insulator test have been wired in and the chambers have been fabricated. The pumping station and the chambers must be assembled and the samples must be instrumented.