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ISOTOPE KILOWATT PROGRAM
QUARTERLY PROGRESS REPORT
For Period Ending
June 30, 1970

A. P. Fraas, Program Director

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REACTOR DIVISION

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Oak Ridge, Tennessee
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FOREWARD

In 1968 the Oak Ridge National Laboratory started work on a program to evaluate various types of radioisotope energy conversion systems for the production of 1 to 10 kw of electric power for terrestrial and under-sea applications. This program is being carried out for the U. S. Atomic Energy Commission Division of Reactor Development and Technology and the Naval Facilities Engineering Command. The first phase of the program was a parametric and engineering analysis comparing the principal isotope fuels and the principal types of energy conversion system that have been proposed for applications of this sort, and the preparation of a set of conceptual designs for the more attractive systems. That work was completed in the summer of 1969 and was reported in Ref. 1. In October of 1969 ORNL was asked to proceed with a detailed engineering study of the three most promising systems selected from those covered in Phase I of the program. These three systems now under study are a 2-kw(e) thermoelectric system, a 3-kw(e) steam Rankine cycle system, and a 5-kw(e) organic Rankine cycle system.

The first step in the effort was to evolve a program plan for a three-year effort to be carried out in calendar years 1970, 1971 and 1972. The conceptual designs presented in Task I were reexamined and possible improvements were considered with particular attention to the difficult development problems. A variety of engineering tests was considered as a means of evaluating the technology, solving the principal technical problems, and investigating engineering uncertainties that should be resolved before settling on the design of a prototype power plant. In view of the limited funds and the desirability of narrowing the field to a single Rankine cycle system, particular attention was given to the relative merits of the steam and organic Rankine cycle systems.

The first quarter of 1970 was devoted to firming up reference designs for the three types of system, selecting the most crucial experiments required to evaluate the technology, and settling on a program plan for the three-year effort. With this first quarter's work as a foundation, the second quarter has been devoted to firming up the details of the reference designs, firming up details of the experiments to be conducted, and

preparation of topical reports covering the three reference designs with their associated experiments. Subsequent quarters will be devoted to a series of tests designed to investigate vital questions in the technology. As the results of these tests become available, the reference designs will be revised accordingly. The objective is to evolve by December 1972 a set of designs for two prototype power plants with a clear delineation of the development program required in each case including firm estimates of the cost and time for the various programmatic steps.

This is the second in a series of quarterly progress reports. Topical reports are being prepared to present the work carried out in particular areas when key tasks are completed. For example, three reports are now going to press; two present the reference designs for the thermoelectric and organic Rankine systems and one presents a comprehensive summary of the information on heat pipes. Others being prepared as the quarter ended include a report delineating the reference design for the steam system, a report covering tests of a re-entry tube steam boiler for the steam Rankine cycle, and a comprehensive report on designs for the heat block-shield assembly and the problems they pose.

CONTENTS

	<u>Page</u>
1.0 SUMMARY	1
2.0 ORGANIC RANKINE CYCLE SYSTEM DESIGN	2
Heat Block-Shield Design	2
Relation Between Boiler Design and Fluid Degradation Rate .	11
Noncondensable Gas Formation Rate	11
Organic Fluid Evaluation Tests	15
Thermal Fuse and Insulation	18
3.0 STEAM RANKINE CYCLE SYSTEM DESIGN	19
4.0 THERMOELECTRIC SYSTEM DESIGN	19
Heat Pipe Design	20
Inert Gas Atmosphere	20
Axial Loading for Good Thermal and Electrical Conduction ..	21
Heat Pipe Diameter	21
Accommodation of Axial Differential Expansion	23
Choice of Thermoelectric Material	23
5.0 FUEL CAPSULE DESIGN	25
Stress Analysis of Modified Heavy-Walled Capsule	25
REFERENCES	26

1.0 SUMMARY

A heat block-shield design has been evolved that is suitable for all three power conversion systems under study. This unit has the further advantage that it can be used with either SrTiO_3 or SrF_2 fuel.

The reference design for the organic Rankine cycle system has been completed and a near final draft of a topical report delineating the design has been prepared².

The reference design for the thermoelectric power conversion unit presented in the previous quarterly report¹ has been modified to conform with recommendations made by 3-M. The topical report covering this design³ has been reviewed by 3-M in rough draft form and their recommendations together with others from AEC Headquarters are being incorporated before sending the final draft to reproduction.

A topical report presenting a comprehensive background on the problems and performance characteristics of heat pipes has been prepared and is ready for reproduction⁴.

A preliminary design for a reduced scale test loop to evaluate the thermal radiation stability characteristics of Dowtherm A has been prepared and is being reviewed critically.

A conceptual design of a heat pipe test has been prepared, and preliminary arrangements for fabrication of a test unit have been initiated.

The design and construction of a full-scale thermoelectric module has been discussed with 3-M and it has been concluded that the principal problems associated with integrating the junctions into a complete heat pipe module assembly are much the same for lead telluride and the more efficient advanced material under development. As a consequence, it appears that the next step after a test of a heat pipe tailored to this special application should be a test of a full scale thermoelectric module with lead telluride junctions. A firm proposal from 3-M to fabricate such a unit is expected early in the next quarter.

2.0 ORGANIC RANKINE CYCLE SYSTEM DESIGN

The reference design reported in the first quarterly report¹ has been studied in some detail with the principal emphasis on the heat block-shield assembly and simulation of the system with a smaller organic fluid test loop containing only a feed pump and a surrogate turbine-generator.

The principal characteristics of the full scale organic Rankine cycle system have been defined in a topical report covering the reference design. The principal dimensional and performance data are summarized in the attached table, and the revised layout is shown in Fig. 1. For further details the reader is referred to the topical report².

Heat Block-Shield Design

Revised heat block-shield designs that can be used with all three systems under consideration (organic and steam Rankine cycles and the thermoelectric system) have been evaluated. The fuel materials are SrTiO_3 and SrF_2 and the heat block-shield material is iron. In comparison to the shield designed for the organic system in the first quarterly report¹, the fuel diameter was reduced from 4.1 to 3.4 in. This will reduce the shield diameter about 3 in., increase the length about 14 in., and increase the weight several hundred pounds.

The revised designs have a number of advantages over the previous unit. The first unit could not be used with the thermoelectric system because the fuel capsule temperatures were too high. It was also found that, with the safety devices now being considered, the temperature of the capsules during an accident condition would be very close to the maximum allowable. Also, the longer shield is a decided advantage to the steam system because it allows a longer re-entry boiler tube which greatly improves the performance of this type of boiler.

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Fig. 1. Vertical Section Through the Reference Design for a 5 kw(e) Organic Rankine Cycle System.

Table 1. Performance and Dimensional Data for the Reference Design
5 kw(e) Isotope Powered Organic Rankine Cycle
Energy Conversion System

Plant Performance

Isotope heat output (beginning of life), kw(t)	34
Isotope heat output (end of life), kw(t)	30
Net power output (beginning of life), kw(e)	5.7
Net power output (end of life), kw(e)	5.0
Design life, yr	5

Fuel Capsules

Fuel material	SrTiO ₃
Number of fuel capsules	7
Fuel capsule OD, in.	4.10
Fuel pellet OD, in.	3.40
Fuel capsule length, in.	39.8
Fuel length, in.	38.4
Fuel capsule centerline spacing, in.	5.65

Heat Block-Shield

Material	Iron
Diameter over fin tips, in.	40.5
Height, in.	59.2
Fin height, in.	2.50
Fin thickness, in.	0.50
Fin centerline spacing, in.	2.50
Number of fins	45
Radiation dose at surface, mr/hr	200
Heat block-shield assembly weight, lb	17,200

Heat Block-Shield and Fuel Temperatures

Normal Operation

Maximum fuel temperature, °F	1940
Maximum cladding temperature, °F	1400
Maximum block temperature, °F	1250

Block surface temperature, °F	875
Shipping	
Maximum fuel temperature, °F	1580
Maximum cladding temperature, °F	1020
Maximum block temperature, °F	870
Block surface temperature, °F	480
Accident Conditions (loss-of-coolant)	
Maximum fuel temperature, °F	2400
Maximum cladding temperature, °F	1890
Maximum block temperature, °F	1810
Block surface temperature, °F	1360
Heat loss during normal operation, kw	3
Boiler	
Heat load, kw	31 - 27
Temperature, °F	613 - 600
Pressure, psia	51.6 - 45.6
Total vapor flow rate, lb/hr	500 - 436
Boiler tube linear heat rating, Btu/hr·ft	1885 - 1640
Average heat flux, Btu/hr·ft ²	9730 - 8480
Number of tubes	12
Centerline diameter of tubes, in.	31
Outer tube OD, in.	1.050
Outer tube ID, in.	0.742
Inner tube OD, in.	0.540
Inner tube ID, in.	0.302
Vapor riser OD, in.	0.840
Vapor riser ID, in.	0.546
Boiler drum OD, in.	8.625
Boiler drum ID, in.	7.981
Maximum radiation dose rate in boiler tubes, r/hr	3.5
Maximum radiation dose rate in boiler drum, r/hr	0.15

Regenerator

Effectiveness, %	90
Liquid temperature in, °F	223
Liquid temperature out, °F	420
Vapor temperature in, °F	485
Vapor temperature out, °F	250
Log mean temperature difference, °F	43
Liquid flow rate, lb/hr	436
Vapor flow rate, lb/hr	436
Liquid volumetric flow rate, ft ³ /sec	0.00205
Vapor volumetric flow rate, ft ³ /sec	51.8
Heat load, Btu/hr	40,000
Required (U x A), Btu/hr·°F	930
Vapor pressure loss, psia	0.05
Vapor-side face area, in. ²	162
Length of matrix, in.	12

Condenser

Temperature, °F	223
Pressure, psia	0.10
Vessel surface area, ft ²	8.3
Volume	10

Pressure Vessel

Material	Hy-100 Series Steel
Design depth, ft	12,000
Outside diameter, in.	51
Inside diameter, in.	48
Height, in.	150
Weight, lb	11,600
Internal operating pressure, psia	0.1
Internal gas	air
Total system liquid inventory, lb	23
Total weight of complete power unit, lb	29,500

Figures 2 and 3 show the weight and dimensions for the designs for the SrTiO_3 and SrF_2 fuel capsules as functions of the surface dose rate and the spacing between the holes in the block. The values shown for the diameter do not include the height of the axial fins located on the OD of the block. The fins will add 5 in. to the diameter.

The maximum fuel, cladding, and block temperatures for both basic designs and for various heat block ligament thicknesses between fuel capsules are shown in Tables 2 and 3. Table 2 is for SrTiO_3 and will have seven fueled positions in the central region of the block. The reference temperatures in the first column are for the assumed block temperature just outside the fuel region. The actual distance between this reference point and the outermost fuel is one-half the ligament thickness for all cases. The 1000°F reference temperature is in the range expected during normal operation. For the organic system this temperature will be about 1000°F while for the steam or thermoelectric systems the temperature will be about 1100°F. The 1400°F reference temperature cases are expected to be typical of accident conditions.

Table 3 shows similar data for SrF_2 fuel pellets. The power density in SrF_2 is about 18% greater than for SrTiO_3 , thus only six rather than seven fuel elements are required.

A topical report is being prepared to cover the details of the above analysis together with additional calculations that are being carried out for a nickel heat block-shield.

ORNL DWG. 70-7673

Fig. 2. Heat Block-Shield Dimension and Weight vs. Surface Dose Rate and Ligament Thickness for 34 kw and 4.15 in. Diameter Fuel.

Fig. 3. Heat Block-Shield Dimensions and Weight vs. Surface Dose Rate and Ligament Thickness for 34 kw and 3.40 in. Diameter Fuel.

Table 2. Maximum Fuel, Cladding, and Block Temperature for
7-Element Design with SrTiO_3 Fuel

Reference Temperature (°F)	Fuel Diameter (in.)	Ligament Thickness (in.)	Maximum Temperature (°F)		
			Fuel	Cladding	Block
1000	4.15	0.50	2578	1799	1680
1000	4.15	0.75	2493	1712	1576
1000	4.15	1.00	2440	1656	1509
1000	4.15	1.50	2371	1583	1420
1000	3.40	1.00	1971	1433	1296
1000	3.40	1.50	1932	1392	1246
1400	3.40	1.00	2343	1820	1727
1400	3.40	1.50	2304	1781	1683

Table 3. Maximum Fuel, Cladding, and Block Temperature for
6-Element Design with SrF_2 Fuel

Reference Temperature (°F)	Fuel Diameter (in.)	Ligament Thickness (in.)	Maximum Temperature (°F)		
			Fuel	Cladding	Block
1000	3.40	1.00	2262	1382	1248
1000	3.40	1.50	2253	1352	1203
1400	3.40	1.00	2549	1746	1661
1400	3.40	1.50	2547	1730	1638

Relation Between Boiler Design and Fluid Degradation Rate

One of the most important questions that arose in the course of the design of the organic Rankine cycle system was the choice between a once-through and a recirculating boiler. Past experience at ORNL with control problems has indicated that the once-through boiler gives a much simpler control system. Further, it is much less subject to difficulties with hot spots. Sundstrand personnel suggested that the recirculating boiler might entail a much higher fraction of the liquid inventory at an elevated temperature so that it would lead to a higher rate of thermal decomposition than is the case with a once-through boiler. However, a study of this problem has indicated that, by reducing the temperature of the boiler from 650 to 600°F, the recirculating boiler system as laid out by ORNL should yield a lower rate of thermal decomposition than the once-through boiler system.

Noncondensable Gas Formation Rate

The rate of formation of noncondensable gases from the pyrolysis of biphenyl and the eutectic mixture of biphenyl (26.5%) and phenyl ether (73.5% by weight) are shown in Figs. 4 and 5, respectively. The data for the biphenyl were taken from the works of L. B. Yeatts, Jr. of ORNL⁵ and W. J. Pummer of NBS⁶. The data for the eutectic were taken from work of Pummer. These data were obtained from experiments performed in pyrex containers. One experimental point for each of the fluids was obtained in the presence of stainless steel. These values are included in Figs. 4 and 5. The gas evolution rate in the presence of stainless steel was obtained by assuming that the activation energy for the formation of noncondensable gases was the same for the pyrex and stainless steel surfaces.

The data from the operation of the thermal stability loops with biphenyl and the eutectic by Sundstrand⁷ was used to determine the noncondensable gas formation rate for a dynamic system fabricated from stainless steel. The operating conditions for these loops are shown in Table 4.

ORNL DWG. 70-10522

Fig. 4. Volume of Noncondensable Gas Produced from the Pyrolysis of Biphenyl.

ORNL DWG. 70-10523

Fig. 5. Volume of Noncondensable Gas Produced from the Pyrolysis of the Eutectic Mixture of Biphenyl and Phenyl Ether.

Table 4. Operating Conditions for the Thermal Stability Loops
Operated by the Sundstrand Corporation⁷

Loop Number	Fluid	Temperature (°F)	Design Operating Time (hr)	Total Operating Time (hr)	Shutdown Time (hr)	Number of Shutdowns	Longest Uninterrupted Run (hr)	Reason for Termination
4	B	650	2,500	2736	547	10	700	Test Complete
1A	B	700	10,000	3282		16	950	Lost Inventory
2	B/BEE	650	10,000	6420		7	2000	Condenser Coolant Leak
3	B	650	10,000	8929	286	11	1850	Pump Failure
1B	B/BEE	700	10,000	6367		13	2800	Bath Temperature (1300°F)

B = Biphenyl
B/BEE = Biphenyl-Biphenyl Ether Eutectic

The gas formation rates for these loops were obtained by taking the slope of the noncondensable gas buildup curves obtained from the operation of the stability loop. The specific formation rates were obtained by assuming that the full boiler inventory of 1.5 lb at 650°F and 1.6 lb at 700°F as reported was responsible for the formation of the noncondensable gases. These formation rates are shown in Figs. 4 and 5. As can be seen, the values are well within the accuracy that would be expected from the extrapolation of the stainless steel data obtained from Refs. 5 and 6.

The effective boiler inventory of the recirculating boiler used in the reference design of the 5 kw(e) organic isotopic power system is estimated to be 8 lb of eutectic at 600°F. Using the gas formation rate curve for stainless steel shown in Fig. 5 the formation rate of noncondensables for the recirculating boiler is estimated to be $0.6 \times 10^{-7} \text{ ft}^3 \text{ (STP)/hr}$. This is lower than the estimated rate for the once-through boiler given by Sundstrand of 1.05×10^{-7} at 650°F and $9.6 \times 10^{-7} \text{ ft}^3 \text{ (STP)/hr}$ at 700°F.⁷

Organic Fluid Evaluation Tests

Uncertainties in the rates of thermal decomposition of organic working fluids, particularly if radiation proves to have a catalytic effect, raise serious questions as to the unattended life that could reasonably be obtained from a hermetically sealed isotope power plant operated on the ocean floor. The limited data available for Dowtherm A indicate that the evolution of noncondensable gases may occur at a sufficiently high rate so that serious deterioration on the performance of the condenser for the Rankine cycle may result.

An excellent way to investigate this problem would be to simulate a full scale system with the proper distribution of fluid inventory in the various temperature regions and the proper surface-volume ratios in each region. Further, one ought also simulate the proper degree of re-entrainment of noncondensable gases near the condenser outlet as this will act to drive these gases back into solution in the liquid to favor their recombination with heavier molecules. In a test proposed a

canned rotor feed pump would be used and the turbine-generator-regenerator unit would be simulated with an orifice and heat dump system. This and the rest of the system including the boiler and condenser would be reduced in scale to reduce costs. The system contemplated is shown in Fig. 6.

The system would be operated with the proper temperature distribution for the reference design full-scale system. Great care must be employed to assure that the system is hermetically sealed prior to initiating operation, and the temperature difference between the vapor leaving the simulated turbine and the metal temperature distribution in the condenser would be monitored to give an indication of the accumulation of noncondensables in the system. The fluid in the system would not be sampled until the condenser temperature data indicated a serious buildup of noncondensables.

The reference design for the organic Rankine cycle system would result in a relatively low (~ 1 to 10 r/hr) dose rate at the boiler. To accelerate the test, a higher level of radiation can be provided for the boiler in the test loop by using a small radioisotope source mounted in a small electrically heated heat block-shield unit. Current plans are to use $1/8$ in. diam cold-pressed SrTiO_3 pellets in a capsule about 36 in. long located at the center of the heat block. The electric heaters would be placed around the outer perimeter while the boiler tubes would also be located in the central part of the heat block about 1 to 1.5 in. from the radiation source. The dose level would be about 10 to 100 r/hr. This dose rate is much greater than the 3.5 r/hr expected in the full scale unit, but should not contribute significantly to the decomposition rate unless it does have a catalytic effect. The electric heaters would be located in the outer part of the block. The outside diam of the block will have to have a diameter of about 16 or 17 in. to keep radiation dose levels to personnel sufficiently low so as not to interfere with work on the test loop.

Fig. 6. Vertical Section Through a Reduced Scale System Designed to Investigate the Thermal and Radiation Stability of Dowtherm A in the Organic Rankine Cycle System of Fig. 1.

Thermal Fuse and Insulation

The purpose of the Thermal Fuse and Insulation Task is to develop a means to prevent overheating of the isotope fuel cladding in the event some accident interferes with the normal heat removal from the heat block by the power conversion system. The approach taken to the solution of this problem has been to find a type of thermal insulation for the heat block that would limit the heat losses to about 5 to 10% during normal operation yet have a melting point such that if its temperature were to rise 200 or 300°F, the thermal insulation would melt and flow from the heat block to the pressure vessel. The total heat generated in the fuel thus could be removed by thermal radiation without melting of the fuel cladding if something interfered with the normal heat removal process.

After a literature review of possible insulation materials, and unsatisfactory results from preliminary tests on cellular glass insulation,¹ aluminum wire screen was selected for testing. An insulation matrix composed of a large number of layers of aluminum screen appears to offer the possibility of keeping the operating heat loss within acceptable limits with an over-all thickness of 2 to 4 in. Using experimental data obtained on stainless steel screen matrices for gas-cooled reactors in France⁸, the thermal conductivity was estimated to be about 0.042 Btu/hr·ft·°F at a mean insulation temperature of 400°F for a screen composed of 0.010 in. diameter wire on a mesh of 16 x 18 wires per inch.

It is anticipated that the cavity effect of the voids in the screen will yield an effective emissivity of from 0.9 to 1 so that the temperature difference required to radiate the heat from the heat block will be minimized. Under accident conditions, the temperature of the block and screen would increase until the screen reached its melting point. From that point, the temperatures should remain constant as the screen continued to melt. Eventually, the screen thickness would be decreased to the point that the heat losses through the screen would equal the heat generated in the block and no further melting would occur.

The first tests planned for the insulation were described in the last quarterly report¹. The construction of the experiment was delayed by the two-month strike of hourly employees, but progress is now being

made. The installation of the thermocouples has been completed and the spacers between the heater rod and the insulation specimen are being fabricated. The tests can be initiated following the assembly of the heater into the insulation specimen and making the connections to the electrical power supply.

The preliminary tests will now be extended to include measuring the thermal conductivity and melting characteristics in a partial vacuum, with emphasis on a pressure of 0.1 psia, since it now appears that it may be desirable to run the organic system with the pressure vessel evacuated to the condenser pressure to reduce inleakage to the condenser.

3.0 STEAM RANKINE CYCLE SYSTEM DESIGN

The two-month strike of hourly employees at ORNL and Y-12 during this quarter prevented completion of the test program on the re-entry tube steam boiler. These tests are scheduled for completion by the end of the summer. The test data will then be used to complete the reference design for the steam Rankine cycle system using the revised heat block-shield design developed for the organic Rankine and thermoelectric systems.

4.0 THERMOELECTRIC SYSTEM DESIGN

A reference design for the thermoelectric system was outlined in the previous quarterly report¹. A fairly comprehensive draft of a topical report delineating this design in some detail was sent to Minnesota Mining and Manufacturing Company (3-M) on April 3, 1970 for their review, criticism, and recommendations. Subsequent analyses at 3-M and discussions between AEC, 3-M, and ORNL personnel have led to the conclusion that the basic layout appears to be the most attractive proposed to date, but that substantial changes in the detail design of the thermoelectric module should be made to incorporate features found to be important in 3-M development tests. These changes are discussed

below. In addition, the proposed heat pipe design was discussed with Los Alamos personnel and their suggestions were adopted.

Heat Pipe Design

Discussions with G. M. Grover and J. E. Kemme at Los Alamos indicate that the heat pipe design projected for the thermoelectric modules is sound except that an axial jolt or other shock load with the heat pipe in the vertical position could break the capillary surface tension and dump the liquid into the bottom of the heat pipe where it would render the heat pipe ineffective. This difficulty can be avoided by laying the power plant unit on its side. This will have the advantage that the center of gravity will be lower and the unit will be in its most stable position. Further, the convection cooling of the casings around the thermoelectric module will actually be improved.

Inert Gas Atmosphere

Tests at 3-M have shown that the thermoelectric junctions are sensitive to moisture in the air and oxidation^a, hence the module should be designed so that it can be assembled and hermetically sealed at the factory under an inert gas such as argon. This could be accomplished by surrounding each thermoelectric module assembly with a tube to provide a hermetically sealed envelope around the junctions. Unfortunately, this approach leads to an additional temperature drop of about 70°F as a consequence of the additional gas gap introduced between the module envelope and the bore of the pressure vessel housing the module. This would reduce the over-all efficiency by about 7%. The envelope installed around the thermoelectric junctions at the factory could be a thin-walled sleeve (perhaps 0.010 in. thick) with an axial convolution between each row of junctions so that the envelope would be expansible. The module would be assembled and shipped inside a rugged sleeve having the same bore as the pressure vessel tubes. For assembly in the pressure vessel, the shipping sleeve could be positioned in a pilot in the outboard end of the pressure vessel tube, and the module could be pushed out of the

shipping sleeve into the pressure vessel tube in much the same way as an automobile engine piston assembly is pushed through a piston ring compressor into the engine cylinder.

Axial Loading for Good Thermal and Electrical Conduction

The relative merits of the flattened tube and the usual coil spring-end cup-cold shoe arrangement employed by 3-M were discussed at some length. The 3-M personnel prefer the coil spring because they have had a great deal of experience with it and are uncertain as to the effectiveness of the flattened tube. Inasmuch as ORNL has no particular preference, the 3-M approach has been adopted. Figure 7 shows a layout evolved by 3-M that fits within the basic envelope proposed by ORNL but uses their conventional coil spring-cup-cold shoe arrangement.

Heat Pipe Diameter

It was pointed out by 3-M that they would prefer to work with a shorter unit of larger diameter, and they suggested that the heat pipe diameter be increased from 1 to 2 in. This would be satisfactory from the standpoint of heat pipe performance but will give large holes in the shield and excessive radiation leakage losses through these holes because the radiation leakage varies as the square of the diameter-to-length ratio of the holes. Further, a larger diameter tube would be relatively inflexible and would not accommodate differential thermal expansion between the heat block-shield assembly and the pressure vessel assembly. As a consequence, ORNL suggested that the 1-in.-diam heat pipe be retained and a 2-in.-diam nickel sleeve be brazed over the heat pipe to provide a larger base circle on which to mount the thermoelectric units. This approach was adopted. It will result in a small loss of about 25°F temperature drop through the nickel sleeve.

Fig. 7. Revised Design for the Thermoelectric Module with Modifications Recommended by 3-M.

Accommodation of Axial Differential Expansion

During heating and cooling cycles there is a relatively large amount of differential axial expansion between the hot heat pipe and the cold outer sleeve surrounding the cold junctions. This differential expansion must be accommodated by slippage either between the hot shoes and the surface on which they seat or the cold shoes and the surface on which they seat. The possibility of using a lubricant between the cold shoe and the surrounding outer sleeve so that slippage occurs in that plane - rather than under the hot shoe as in previous 3-M designs - has been discussed. Past experience at 3-M has been largely with cold junctions having temperatures in the range of 300 to 400°F. As a consequence, the use of a petroleum lubricant in this region has led to difficulty with the formation of sticky tars and gums so that the lubricant would be converted to an adhesive. ORNL personnel believe that, in an inert atmosphere, a silicone grease operated at the temperatures expected in this application (less than 250°F) should not deteriorate and lead to difficulty. In view of this, differential thermal expansion along the axis of the module might be readily accommodated through the use of a lubricant between the cold shoe and the outer surrounding sleeve. However, 3-M favors the use of a coating of plasma-sprayed Al_2O_3 on the hot shoes and their mating surfaces. Such a coating can be ground to a smooth finish for good sliding contact, and it will also serve as electrical insulation. Extensive tests at 3-M have validated this approach, and hence it has been chosen.

Choice of Thermoelectric Material

Lead telluride has been developed into a very reliable thermoelectric junction material after many years of effort. The fabrication procedures, quality control measure, and installation requirements are well established to assure a long life with a high reliability. However, this background of experience shows clearly that, for the 3 to 5 year life desired for naval applications, the hot junction temperature should not exceed 1050°F. Further, the overall efficiency of a complete lead telluride thermoelectric module probably will not exceed about 8%. As a consequence, there is a

strong incentive to develop an advanced thermoelectric material capable of operation at a substantially higher hot junction temperature. If possible the new material should yield a higher efficiency for a given temperature difference between the hot and cold junctions. It appears that 3-M now has a suitable material for one leg (the P junction) and is working on the development of a new material for the other leg (the N junction). If and when this development program is successful, it will permit an increase in the overall efficiency of thermoelectric power unit to perhaps 12%, a value competitive with a Rankine cycle system.

In attempting to choose a thermoelectric material for the reference design it has been difficult to decide whether to assume that the current program on an advanced material will be completely successful or whether to play safe and design around the lead telluride. The specialists at 3-M feel that only the detail design of the parts in the thermoelectric junctions themselves will be affected, and that the overall envelope of the module will be independent of the thermoelectric junction material. In light of this, the reference design has been prepared on the basis that lead telluride will be used for the initial development test program, and a preliminary design for module employing the advanced material will be prepared to make sure that either the lead telluride or the advanced material can be used in the basic module design employed in the ORNL development test program. Thus the initial tests can be carried out with lead telluride, and the advanced thermoelectric junction material can be substituted at a later date when it becomes available.

To take full advantage of the advanced material it will be necessary to operate the heat block-shield assembly at a temperature sufficient to give a 1350°F hot junction temperature. The thermal conductivity of iron is such that this leads to uncomfortably high fuel capsule temperatures if one allows a temperature overshoot for emergency conditions. Further, there are some phase changes in iron in this higher temperature regime that might lead to some difficulties with distortion of the heat block. In view of these considerations, a nickel heat block-shield assembly appears preferable. A comprehensive analysis of both iron and nickel heat block-shield assemblies and the problems associated with each of them will be undertaken in the coming quarter.

Test Program

Two tests are planned to investigate and evaluate the reference design. The first will entail the construction and test of a heat pipe designed to meet the design conditions of the full scale power unit. This test will be run with electric heaters to simulate the heat block. Heat will be removed through a water jacket of the same length as the thermoelectric junction region. The heat load will be adjusted by changing the composition of a helium-argon mixture in the gas gap between the heat pipe and the water jacket.

The special problems of the complete module will be investigated by building a full scale module using lead telluride as the thermoelectric junction material.

5.0 FUEL CAPSULE DESIGN

Stress Analysis of Modified Heavy-Walled Capsule

A stress analysis was performed on the modified SNAP-23 capsule which was proposed in earlier monthly reports. A summary of stresses produced by an external pressure of 10,000 psi for the various components of the capsule is shown below:

1. Center of bottom cap
 - a. Outside 62,900 psi
 - b. Inside 42,900 psi
2. In bottom weld
 - a. $t_w = 0.110$ 19,700 psi
 - b. $t_w = 0.080$ 38,800 psi
3. Thickness of threaded cap
 - a. Required 0.996 psi
 - b. Actual 1.000 psi
4. Number of threads
 - a. Minimum required 2
 - b. Actual 4
5. Rotation of head due to pressure of 10,000 psi if unrestrained 0.0016 in.

6. Stresses in cylinder remote to ends

a. Circumferential	6.11×10^4 psi
b. Longitudinal	3.34×10^4 psi
c. Radial	0.566×10^4 psi

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