NASA-TM-107069 19960001948

NASA Technical Memorandum 107069

Preliminary Design of a SP-100/Stirling Radiatively Coupled Heat Exchanger

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October 1995

National Aeronautics and
Space Administration

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Abstract

Several methods for coupling the SP-100 space nuclear reactor to the NASA Lewis Research Center's Free Piston Stirling Power Convertor (FPSPC) are presented. A 25 kWe, dual opposed Stirling convertor configuration is used in these designs The concepts use radiative coupling between the SP-100 lithium loop and the sodium heat pipe of the Stirling convertor to transfer the heat from the reactor to the convertor. Four separate configurations are presented. Masses for the four designs vary from 41 to 176 kgs. Each design's structure, heat transfer characteristics, and heat pipe performance are analytically modeled.

Introduction

In June of 1992, under the auspices of the Civil Space Technology Initiative (CSTI), the development of several heat exchanger concepts to couple the SP-100 nuclear reactor to the Space Stirling Power Convertor (SSPC) was initiated at NASA Lewis Research Center. The SP-100 reactor and the FPSPC were being developed under separate contracts and this was the first attempt to develop the interface for a complete system. This paper discusses four designs that utilize the high temperature lithium coolant of the SP-100 to radiatively couple the reactor with the Stirling convertor. These radiatively coupled designs have the advantage (over directly coupled designs) of separating the SP-100 lithium from the Inconel 718 superalloy of the Stirling convertor and thus minimize material incompatibility problems. These incompatibility problems arise from the fact that many of the superalloy constituent materials are soluble in lithium at these temperatures.

This design work includes: on the reactor side, the manifolds of the lithium supply and return lines of the SP-100 and the radiating plates used to transfer heat to the evaporator of the SSPC heat pipe, while on the Stirling convertor side the design includes the heat pipe housing, wicks, evaporator and adiabatic sections of this heat pipe. The condenser section of the heat pipe (called the Starfish heater head), which is used for transferring heat from sodium vapor to the helium working fluid in the convertor, is not included because it is an integral part of the Stirling convertor. For the four heat exchanger designs studied, the masses vary from 41 kg to 176 kg.

Descriptions of Systems

Four concepts are developed in this design study. The first (Figure 1, Figure 2, and Figure 3) uses a single radiator panel wrapped perpendicularly around the long axis of the convertor. This configuration was investigated because of its similarity with design work performed by Mechanical Technology Inc. and Thermacore Inc. in the design of a pool boiler for the ground test of the Component Test Power Convertor (CTPC). The CTPC, like the SSPC, uses a Starfish heater head.

The hot lithium from the reactor flows through an inlet manifold that distributes the flow to several Nb-1%Zr tubes. These tubes conduct the heat to fins which in turn radiate to the sodium heat pipe evaporators. The lithium flow is then collected in an exit manifold and returned to the reactor. The evaporated sodium flows through the heat pipe to the Starfish heater head where it is condensed, then pumped back to the evaporator through the capillary pumping action of arteries. Each sodium evaporator feeds half of the 25 kWe SSPC convertor. The Nb-1%Zr radiator plate is formed by the PLATECOIL[1] fabrication process. This technology seam welds two metal plates together and then hydraulically forms the channels around the flow circle.

The second concept, (Figure 4.) is identical to concept 1 except that it uses three radiator panels rather than the single panel. Again the PLATECOIL method of forming the panels would be used.

Concepts three and four (Figures 5. and Figure 6)., utilize toroidal evaporator and radiator plates rather than the flat plates used in concepts 1 and 2. Because mass is directly related to the cost of a space system, a torodial heat pipe is modeled with the expectation that the torus would reduce the amount of flat surfaces in the sodium heat pipe and thereby reduce the structural mass. Concepts three and four differ in that concept three has a single torus feeding both ends of the convertor, while concept four has two tori each feeding one half of a convertor. Both of these concepts also use the PLATECOIL method to form the radiator plate except that plate would be in the form of a tori.

Analysis

The analysis performed consisted of mathematically modeling the thermal, structural, and heat pipe characteristics of the heat exchanger concepts. The goal was to obtain preliminary sizing (mass and volume) estimates of the heat exchanger concepts so that a single concept could be selected and explored in greater detail.

It was desired that the heat exchanger design allow the Stirling convertor to directly replace the thermoelectrics in the primary loop of the SP-100. Therefore, during the design work the heat exchanger configurations were made to match, as closely as possible current thermoelectric SP-100 thermohydraulic primary loop characteristics. These requirements set parameters such as temperature drop (75 K), reactor materials (Nb-1%Zr), and pressure loss (~2.0 psi).

Thermal

The thermal analysis consisted of modeling the thermal resistance's of three components in series. The first component of the thermal resistance is convection from the liquid lithium to the tube wall, the second is the conduction through the tube wall to the radiating surface, and the third is radiation from the radiating surface to the heat pipe.

The SSPC design requires a Starfish inner wall helium side temperature of 1050 K. Calculations showed that a 16 K temperature drop can be expected from the inner wall through the heat pipe to the evaporator of the heat pipe. This requires that the evaporator of the heat pipe operate at 1066 K. From the 1312 K average lithium temperature and the required 1066 K heat pipe evaporator temperature, a total permissible thermal resistance of 2.46 K/kiloWatt is calculated.[2]

An emissivity of .9 was used for the radiator plates on both the superalloy Stirling convertor surface and the Nb-1% Zr side. These emissivities can be achieved due to the results of arc texturing research performed at NASA Lewis Research Center under the CSTI[3]. These values lead to theoretical minimum required radiator area of 1.28 m^2 to transfer 100 kWth between the surfaces at average temperatures of 1312 K on the lithium side and 1066 K on the superalloy side.

All four concepts use a parallel tube configuration for the high temperature radiator panels. Each radiator panel lithium flow passage has an inner diameter of .22 inches. This results in Reynolds numbers of approximately 10,000 and a total convective resistance of 1% of the allowable. Using a Nb-1%Zr radiator panel thickness of .05 inches and a total of 20, 1/4" diameter tubes, the total conductive resistance is estimated to be 10% of the allowable. With the addition of the radiation resistance the results give a required radiator area of 1.5 m^2. This is only 17% higher than the ideal radiator area of 1.28 m^2.

Structure

Calculations were made to evaluate required material thickness for each of the concepts. The material used in the heat pipe is Inconel 617 which has an allowable stress of 9000 psi for 60,000 hrs of life (1% creep). The maximum temperature this material is subjected to is 1066 K. Because of the large flat plate area and the resultant stress found in concepts 1 and 2, ribs are used to reduce the stress on the walls of the heat pipe. 10-and-20 rib configurations are modeled for both the single-and-triple fin heat exchangers. It was found that significant reductions in mass occurred if 20 ribs are used. The ribs all have holes placed along their surface to allow the free flow of sodium vapor circumferentially through the heat pipe.

Because of the large circular area in concept 3, ribs are not required. Concept 4, however, required several ribs because of the flat plate area required when placing the two halves of the convertor together.

In all concepts a burst disk is placed in the heat pipe wall to insure that if a high pressure helium leak occurs in the Stirling convertor/heat pipe interface the possibility of insertion of helium into the primary reactor loop is reduced. The internal pressure of the convertor is 2250 psia. Sizing the burst disk to fail at 150 psia led to a .0254 meter diameter disk.

Multi Foil Insulation

In all concepts it is desired to keep heat loss below 5% of the heat input because of increasing reactor and shield mass. Molybdenum multifoil insulation was chosen because of its light weight and excellent insulation properties when used in vacuum. Estimates of heat loss through the insulation are based on the temperature of the inner and outer layers of the multifoil and the heat flux through the insulation.[4] A 5% heat loss determined the required number of layers of insulation. For each of the concepts, varying layers of insulation are required due to the different geometries used to input heat. In concept 1, 20 layers of insulation are required while concept 2 required about 15 layers. Concepts 3 and 4 both required 20 layers of multifoil.

Sizing of Flow Channels

Pressure drop calculations are made based on flow channel equivalent lengths around the reactor side of the liquid metal heat exchanger. Pressure drops included are those in the inlet and outlet manifolds and the PLATECOIL heat exchangers. The liquid lithium heat transfer coefficients are based upon Reynolds and Prandtl numbers. The lithium flow tubes were sized to give reasonably low flow velocities (< 3 meters/second) to minimize pressure losses while always maintaining turbulent flow (Re>4000) to enhance heat transfer. The wall thickness of the tubes are sized for the 22 psi pressure of the lithium loop. The selection of Nb-1%Zr as the lithium side material led to initial sizing of the tubing at 1/4 inch in diameter and .025 inches thickness.

Wicking Considerations

A conservative 100 mesh stainless steel wick (diameter of wire is 1/100 of an inch) was selected for all the concepts. This conservatism is based on preliminary results from wick erosion tests currently under test through a Lewis Research Center program.

Preliminary results from these tests suggest that, without a coating, sodium erosion of the nickel in the stainless steel wicking is a concern. 100 mesh wire was selected as the wicking size of choice because tests indicate this wire size will survive the seven year life requirement (@ 20 watts/cm^2) of the reactor/power conversion system. Because higher mesh sizes provide increased capillary pumping ability it is desirable to use as fine a mesh wick as possible. Finer mesh sizes are considered and as more data becomes available this design choice may change. The 100 mesh wicking provides a pumping height of about .254 meters total. This is important because of ground testing considerations.

In each of the designs wicking and artery attachment became a significant factor. Attachment methods for the wick and artery and the relative ease of assembly influenced the choice of heat exchanger concept.

Concept 1- This concept provided the easiest attachment of both the wicking and the arteries while producing a relatively small pumping height. This concept provides easy access to both evaporator walls of the heat pipe because only a single side of each heat pipe is acting as an evaporator.

Concept 2- This concept, although similar to concept 1, greatly increased problems associated with the attachment of the wicking and arteries. These problems occurred because both sides of the plates are used to input heat and therefore both sides must be wicked with arteries attached. The only way to attach the wicks and artery on the final side was to enter the heat pipe from the ends. It is felt that entry from the ends increases the risk of this concept.

Concept 3- This concept allows for the attachment of wicks and arteries around the entire surface provided a section on the outside of the torus is cut away to allow access to the interior of the heat pipe. This reduces the radiating area of this configuration. Also, because of the relatively large size of the torus, a center separating plate is required between the two heat pipe sections to reduce the height the sodium has to be pumped. This provides greater design margin for the heatpipe by effectively reducing the pumping height in half.

Concept 4- This concept has the same problem as concept 3 except that it does not have the requirement of an additional separating plate between the two halves of the engine. An additional plate is not required because the tori are attached separately effectively replacing the separating plate. It does however provide additional complexities because of the smaller working space inside the torus to attach the wicking and arteries.

In all of the concepts no additional mass penalties are included due to the wicking attachment problems.

Conclusions

Mass results and component thicknesses of the analysis are given in Table 1 and Table 2. The table shows variations in total heat exchanger mass by varying both the ribs and heat exchanger configuration. The majority of the mass comes from the disks in concepts 1 and 2 or the outer cylinders in concepts 3 and 4. Because only a small fraction of the total mass comes from the addition of ten extra ribs in either the single or triple segmented configurations the dramatic drop in flat plate mass more than makes up for this increase. The triple fin configurations provide significant improvement over the single fin by reducing the flat plate area. The single and double tori provide the lightest overall systems.

Because of the large mass penalties associated with concept 1 and the difficulty in the attachment of the wicks in concept 2 neither of these was chosen as the baseline design. Concept 4 offered no discernible advantages over concept 3. Concept 4 was projected to be more difficult to fabricate due to the inclusion of ribs as well as the increased flat plate area. Concept 3 was chosen as the easiest to fabricate while also providing a lightweight interface between the SP-100 and the CTPC.

Additional analysis has been performed on a conductively coupled concept. This work will be presented at a later date.

Table 1.Weight Comparisons (kg)

		Disks	Outer Cylinder	Ribs	Fins	Insulation	Manifolds	Total
Concept 1a 10-Segment ribs	Single Fin	146	9	2	9	10	0	176 kg
Concept 1 b 20-Segment ribs	Single Fin	105	9	3	9	10	0	136 kg
Concept 2a 10-Segment ribs	Triple Fin	66	4	1	14	7	1	93 kg
Concept 2b 20-Segment ribs	Triple Fin	39	4	2	14	7	1	67 kg
Concept 3	Single Torus	10	0	0	18	11	2	41 kg
Concept 4	Dual Torus	11	7	4	11	7	2	42 kg

Table 2. Thickness Comparison (inches)

	Disks	Outer Cylinder	Ribs	Fins	Insulation	Manifolds
Concept 1a	0.22	0.0625	0.06	0.05	0.02	0.0625
Concept 1 b	0.159	0.0625	0.06	0.05	0.02	0.0625
Concept 2a		0.0625	0.06	0.05	0.02	0.0625
Concept 2b		0.0625	0.06	0.05	0.02	0.0625
Concept 3	0.033			0.05	0.02	0.0625
Concept 4	0.033			0.05	0.02	0.0625

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[1]Tranter Inc., "PLATECOIL, The Most Versatile and Efficient Prime Surface Heat Exchanger" Tranter, Inc., Texas Division, Wichita Falls, TX, 1990.
[2]Lubarsky, B., and S.J. Kaufman,"Review of Experimental Investigations of Liquid Metal Heat Transfer," NACA Tech Note 3336, Washington D.C., 1055.
[3]B. Banks, S.. Rutledge, M. Mirtich, T. Behrend, D. Hotes, M. Kussmaul, J. Barry, C. Stidham, T. Stueber, F. DiFilippo, "Arc-Textured Metal Surface for High Thermal Emittance Space Radiators," NASA TM 10894, 1988.
[4]Application of Multi-Foil Insulation to the Brayton Isotope Power System and Conceptual Design of Multi-Foil Insulation for the Flight System, Thermo Electron Corporation Report No. TE4209-100-76, June 11, 1976.

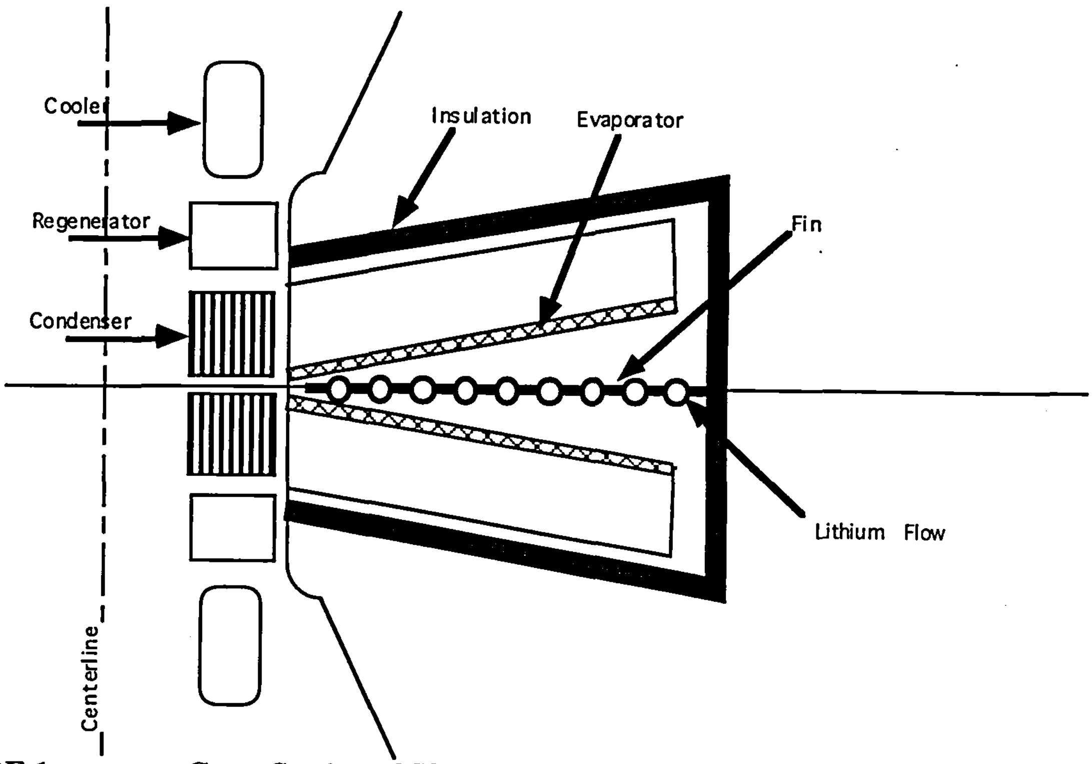

FIGURE 1. **Cross Section of SSPC Radiatively Coupled Heat Exchanger.**

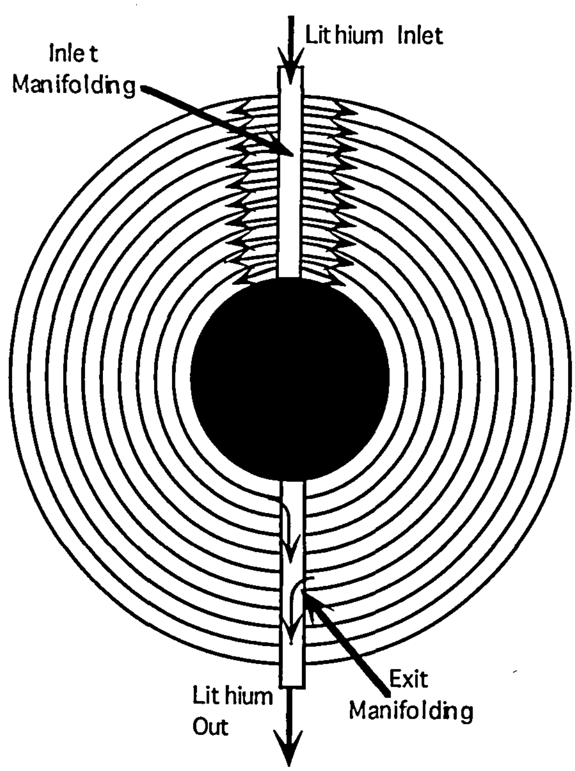

FIGURE 2. **Flow Path of Lithium in Radiatively Coupled Heat Exchanger.**

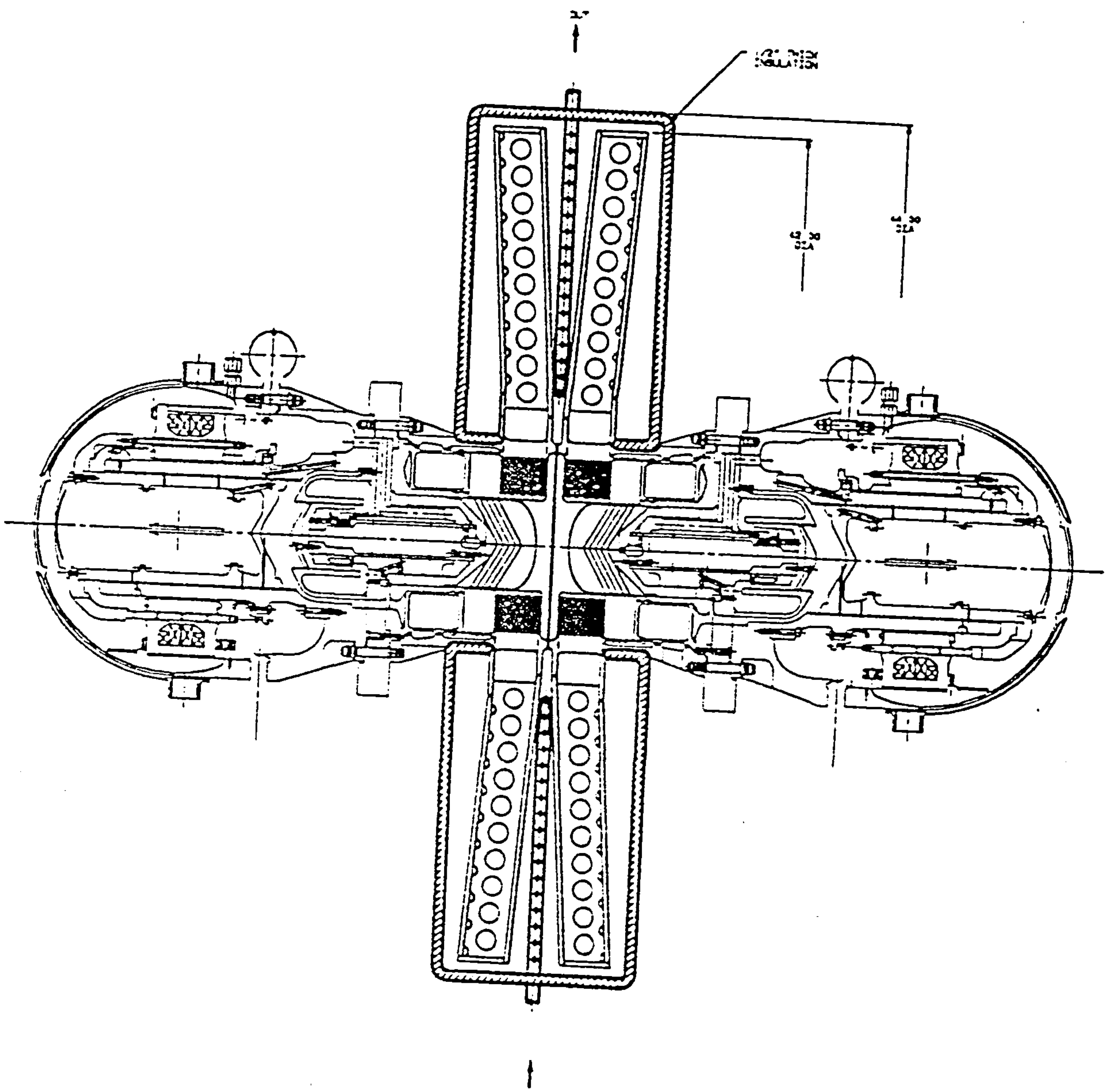

Figure 3 Single Plate Heat Exchanger

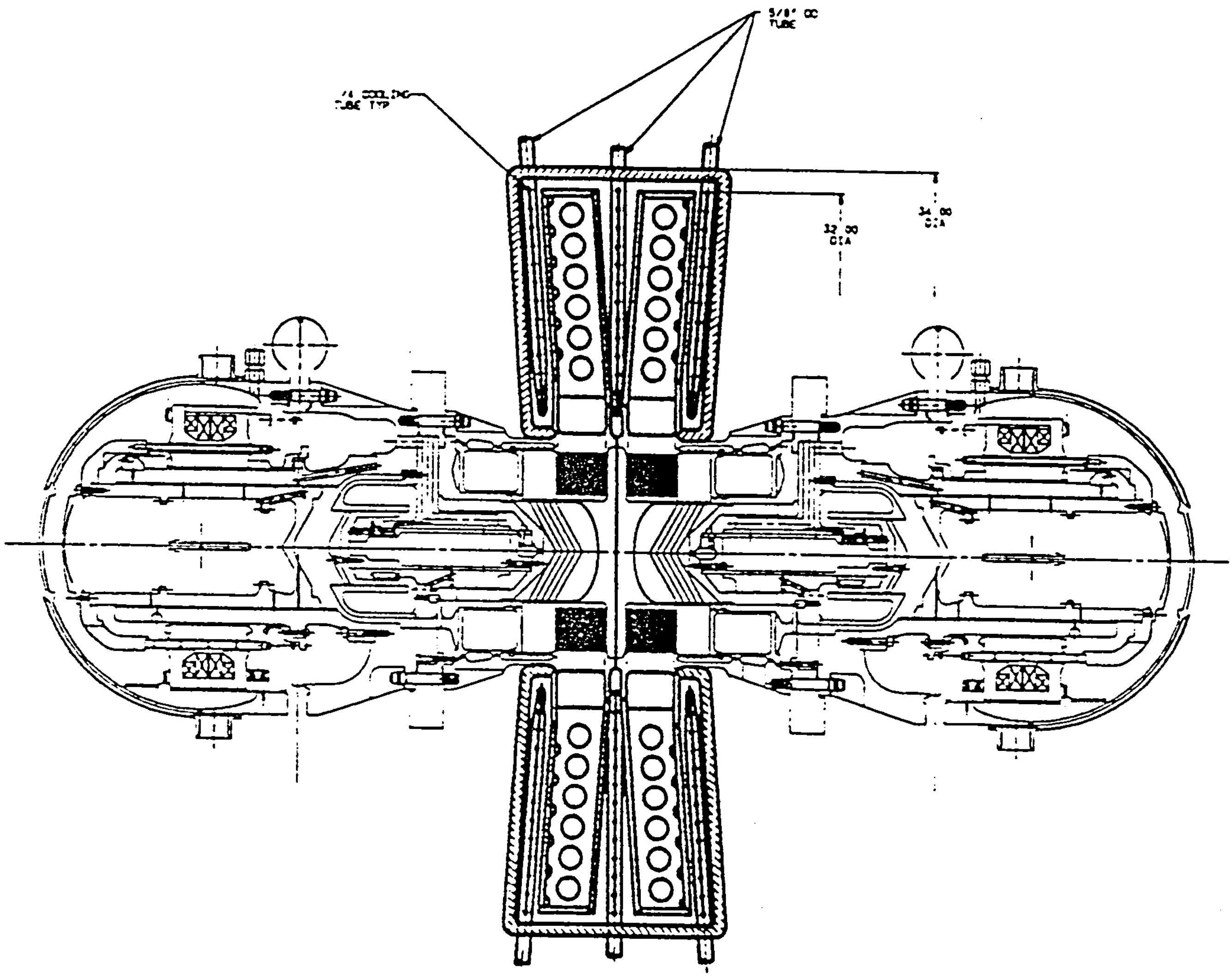

Figure 4 Triple Plate Heat Exchanger

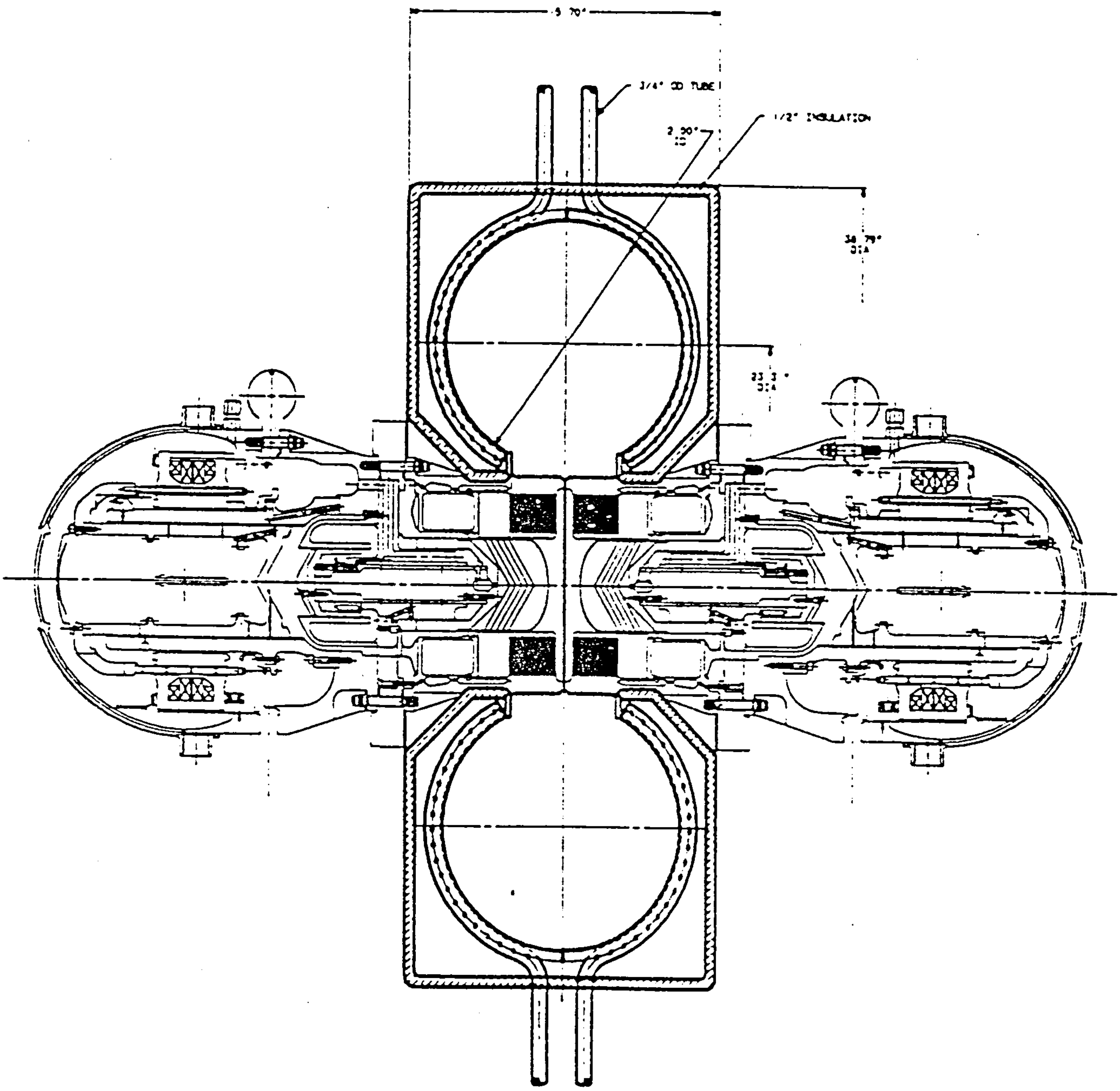

Figure 5. Single Torus Heat Exchanger

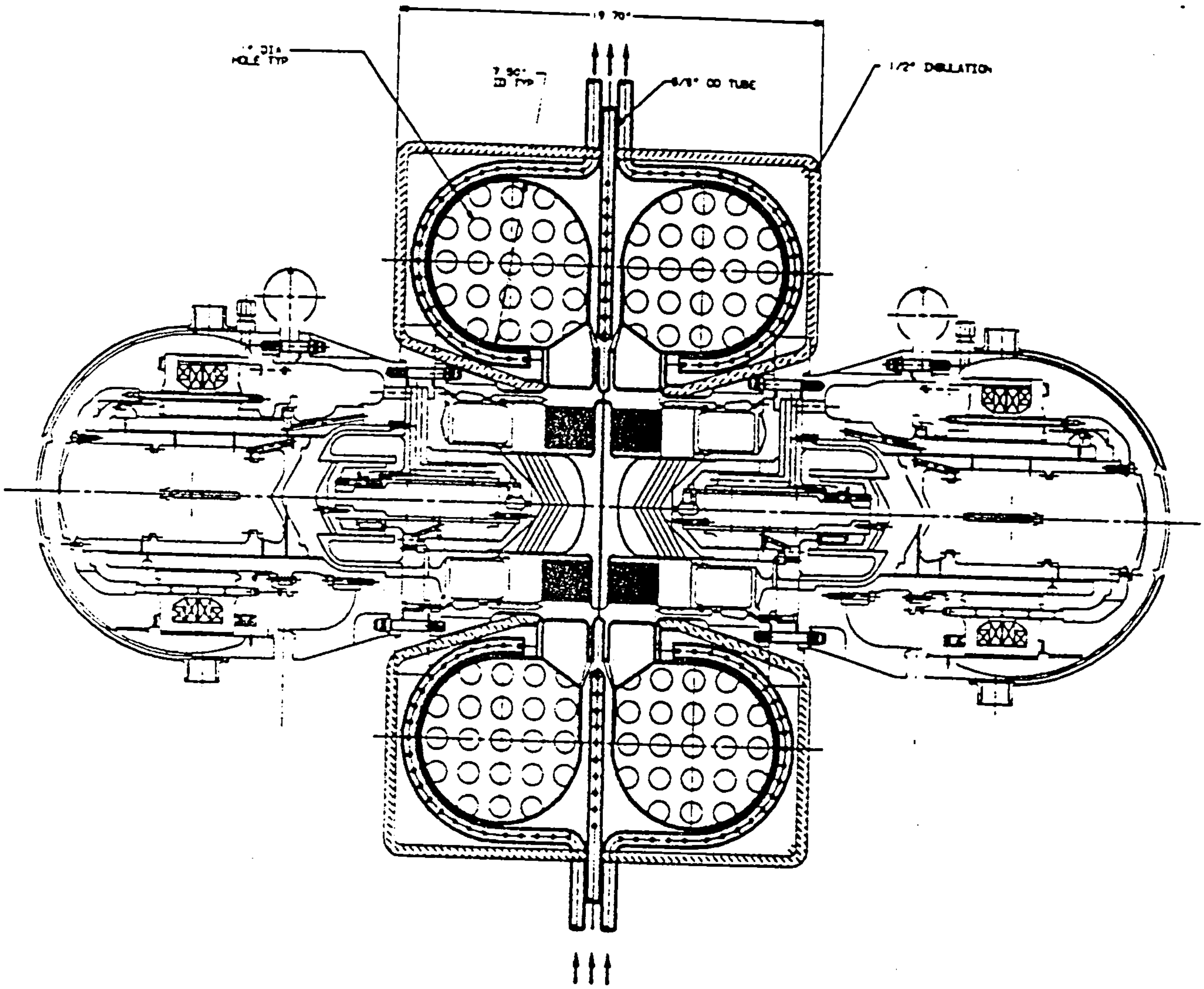

Figure 6. Dual Torus Heat Exchanger

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1995	Technical Memorandum

4. TITLE AND SUBTITLE

Preliminary Design of a SP-100/Stirling Radiatively Coupled Heat Exchanger

5. FUNDING NUMBERS

WU–590–13–51
WU–467–01–21

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–9933

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–107069

11. SUPPLEMENTARY NOTES

Paul Schmitz and Leonard Tower, Sverdrup Technology Inc., 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3–25265); Ronald Dawson, Aerospace Design and Fabrication Inc., Brook Park, Ohio 44142; Brian Blue and Pat Dunn, NASA Lewis Research Center. Responsible person, Brian Blue, organization code 5440, (216) 433–3801.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 20

This publication is available from the NASA Center for Aerospace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS

Nuclear; SP-100; Stirling; Analysis; CSTI; Convertor; Reactor; Space; Heat exchanger

15. NUMBER OF PAGES	16. PRICE CODE
12	A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	