2

Conf-940970--3

SAND94-1758C

RECENT REFLUX RECEIVER DEVELOPMENTS UNDER THE US DOE PROGRAM

C.E. ANDRAKA, R.B. DIVER, J.B. MORENO, T.A. MOSS, D.R. ADKINS
Solar Thermal Technology Department
Sandia National Laboratories
Albuquerque, New Mexico, USA

SAND 94-1758C

1. ABSTRACT

The United States Department of Energy (DOE) Solar Thermal Program, through Sandia National Laboratories (SNL), is cooperating with industry to commercialize dish-Stirling technology. Sandia and the DOE have actively encouraged the use of liquid metal reflux receivers in these systems to improve efficiency and lower the levelized cost of electricity. The reflux receiver uses two-phase heat transfer as a "thermal transformer" to transfer heat from a parabolic tracking concentrator to the heater heads of the Stirling engine. The two-phase system leads to a higher available input temperature, lower thermal stresses, longer life, and independent design of the absorber and engine sections.

Two embodiments of reflux receivers have been investigated: Pool boilers and heat pipes. Several pool-boiler reflux receivers have been successfully demonstrated on sun at up to 64 kWt throughput at SNL. In addition, a bench-scale device was operated for 7500 hours to investigate materials compatibility and boiling stability. Significant progress has also been made on heat pipe receiver technology. Sintered metal wick heat pipes have been investigated extensively for application to 7.5 kWe and 25 kWe systems. One test article has amassed over 1800 hours of on-sun operation. Another was limit tested at Sandia to 65 kWt throughput. These devices incorporate a nickel-powder thick wick structure with condensate return directly to the wick surface. Circumferential tubular arteries are optionally employed to improve the operating margin.

In addition, DOE has begun a development program for advanced wick structures capable of supporting the Utility Scale Joint Venture Program, requiring up to 100 kWt throughput. Promising technologies include a brazed stainless steel powdered metal wick and a stainless steel metal felt wick. Bench-scale testing has been encouraging, and on-sun testing is expected this fall.

Prototype gas-fired hybrid solar receivers have also been demonstrated. While recent successes have significantly advanced reflux receiver technology, continued testing, development, and simplification is needed to assist in the commercial deployment of heat pipe and pool boiler receivers.

2. KEY WORDS

Solar thermal electric; dish/Stirling; pool boiler; relfux receiver; heat pipe; partnerships

3. INTRODUCTION

Dish-Stirling systems have demonstrated the potential to produce economical environmentally-acceptable electric power from the sun. In 1984, the Advanco-Vanguard dish-Stirling module demonstrated a world record peak net conversion efficiency of sunlight to electricity of 29.4% [1]. McDonnell Douglas Corp. further developed and nearly commercialized a system based on the Advanco module [2]. Recently, dish-Stirling system development by the Department of Energy (DOE) through SNL and the National Renewable Energy Laboratory (NREL) and industry has shifted from component research and development to an emphasis on commercialization of dish-Stirling systems.

The modules demonstrated by Advanco and McDonnell Douglas used a United Stirling of Sweden engine with its heater head directly illuminated by concentrated solar flux. The non-uniform flux and temperature distributions severely limit the lifetime and performance of the engine and receiver [3], and require accurate (costly) concentrators. In order to reduce peak flux intensities, the heater head tubes were extended, which increased engine dead volume and reduced engine performance. Heat balance among the four engine cylinders was difficult to maintain, further reducing performance. Hybridization (addition of fossil fuel heating) without

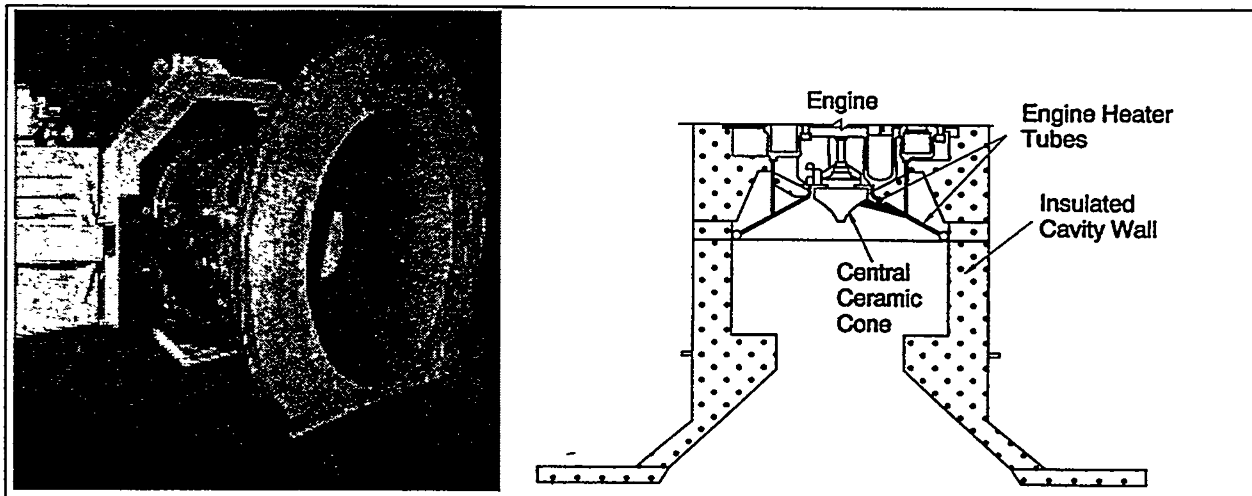

Figure 1. United Stirling of Sweden 4-95 engine with MDAC receiver. The drawing shows the location of the extended heater head tubes that directly absorb the solar flux.

compromising the solar receiver design of this type of receiver design is also difficult. Figure 1 shows the layout of the direct illumination heater head used in these tests.

The reflux receiver was conceived as an improvement over directly illuminated tube receivers [4]. Sandia has been conducting a dish-Stirling receiver-development program to support design, development, and testing of the reflux receiver concept. Through joint-venture commercialization programs with industry Cummins Power Generation (CPG), and Science Applications International Corporation, (SAIC), the DOE program has actively promoted the use of demonstrated technology reflux receivers in dish-Stirling systems. Sandia and NREL have also continued development of advanced reflux receiver technologies.

In the reflux receiver, liquid metal (sodium and/or potassium) is evaporated at the solar absorber and condensed at the engine heater tubes, supplying the latent heat of vaporization to the engine. The liquid at the absorber may be a pool that floods the surface (pool boiler) or a wick saturated with liquid metal that covers the absorber surface (heat pipe). The condensate is returned to and distributed over the absorber by gravity (refluxing), wick capillary forces, or a combination thereof. The reflux receiver has the important advantage of nearly-isothermal operation even with non-uniform incident solar-flux distributions. In addition, the reflux receiver permits independent design and optimization of the absorber (receiver) and the engine heater tubes. Finally, the reflux receiver has the potential to be readily hybridized, partly because of flexibility as to where the fossil-fuel burner can be located.

Sandia's reflux receiver program is currently evaluating both pool-boiler and heat-pipe receivers. The pool-boiler receiver is simpler than the heat-pipe receiver, but uses a larger quantity of liquid metal. Compared to heat pipes, the physics governing pool-boiler performance are poorly understood. Although heat-pipe technology has been extensively studied and is relatively well understood, its application to solar receivers introduces new elements to the design, including the unique geometry and the large vertical and areal extent of the heated surface.

The DOE program has made significant progress through teaming with industry and internal development efforts towards the application of reflux receivers in commercial systems. Laboratory testing has progressed to full-scale on-sun testing with hardware that reflects the requirements of long life and manufacturability.

4. POOL BOILERS

In a pool-boiler reflux receiver, the absorber surface, illuminated by the concentrated solar flux, is entirely immersed in a pool of liquid metal. Nucleate boiling takes place at the interface between the wall and the liquid, and the vapor then transfers the latent heat to the condenser section. Bubble inflation occurs at existing active nucleation sites, which may be naturally occurring or artificially added to the surface. The engine heater head tubes must remain above the pool surface, limiting operation to azimuth-over-elevation drive dishes.

During 1989-90, a refluxing liquid-metal pool-boiler solar receiver designed for dish-Stirling application at 75 kWt throughput was successfully demonstrated at SNL [5]. Significant features of this receiver included (1) boiling sodium as the heat transfer medium, and (2) electric-discharge-machined (EDM) cavities as artificial boiling stabilization nucleation sites. This demonstration set the standard for reflux receiver on-sun operation, and held the throughput power record (62.2 kWt) for a number of years. As a follow-on study, Sandia designed a second-generation receiver to bring the concept closer to commercialization [6].

The second generation pool-boiler was fully fabricated by a commercial manufacturing facility to Sandia specifications. The receiver was built from Haynes 230 alloy for long life. For increased safety factors against flooding and local film boiling, the vapor flow passages and the absorber area were increased. A brazed powder-metal coating replaced the EDM cavities in the interest of cost savings. The use of NaK-78 for the working fluid eliminated the need for electric preheating, reducing costs and maintenance. Approximately 1/3 torr of xenon was added to the receiver to reduce the incipient boiling superheat during hot restarts (cloud transients). Figure 2 is a photo of this receiver.

Figure 2. Second generation Sandia Pool-Boiler Reflux Receiver installed in the intermediate mounting ring.

The second-generation pool boiler has operated with over 64 kWt throughput at 750°C on Sandia's Test Bed Concentrator (TBC). The receiver exhibited 92.3% thermal efficiency, and boiling was stable during all phases of operation. The receiver was subjected to over 189 hot restart cycles without difficulty.

During the same time frame as the second-generation receiver, an advanced-concepts receiver was also tested on Sandia's TBC [6]. This receiver was a replica of the first-generation pool-boiler receiver with the exception that the EDM cavities were eliminated. This step was motivated by bench-scale test results that showed boiling stability improved with increased heated-surface area, tilt of the heated surface, and the addition of xenon [7]. These bench-scale results suggested that stable boiling might be possible without heated-surface modifications in a full-scale receiver. Boiling in the advanced-concepts receiver with 1/3 torr of xenon added was stable under all operating conditions, confirming the bench-scale results. This demonstration will impact the cost and manufacturability of commercial pool-boiler solar receivers.

Long-term liquid-metal boiling stability and materials compatibility with refluxing NaK-78 cannot be predicted and instead must be determined experimentally for each pool-boiler-receiver design. Until our recent work, no liquid-metal boiling system had been demonstrated for a significant duration with the current porous boiling enhancement surface and materials. At least one theory explaining incipient-boiling behavior of alkali metals indicates that favorable start-up behavior should deteriorate over time. Many factors affect the stability and startup behavior of the boiling system. Therefore, it is necessary to simulate the full-scale pool boiler design as much as possible, including flux levels, materials, and operating cycles. However, on-sun testing is impractical because of the limited test time available.

A sub-scale boiler was constructed with the same materials and methods utilized in the second-generation pool-boiler receiver [8, 9, 10]. The vessel was heated with a quartz lamp array providing about 90 W/cm² peak incident thermal flux. It was operated at 750°C around the clock, with a 1/2-hour shutdown cycle to ambient every 8 hours. Temperature data were continually collected. Figure 3 shows a schematic of the test apparatus.

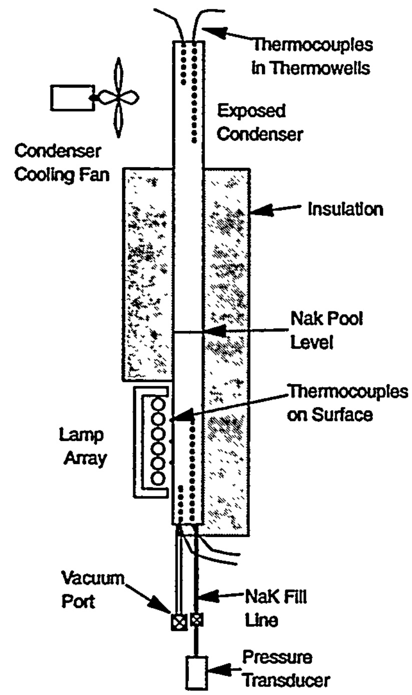

Figure 3. Schematic of the durability bench-scale receiver test.

The test completed 7500 hours of lamp-on operation time, and over 1000 startups from ambient. The test was terminated when a small leak was detected in an Inconel 600 thermowell. The failure was due to grain-boundary attack of the Inconel 600 combined with thermo-mechanical fatigue due to over-constraint. Initial materials studies show that the Haynes alloy 230 withstood the alkali metal and air-side corrosion sufficiently for the projected 60,000 hour life [11]. The stainless-powder boiling surface showed no deterioration either.

The Utility-scale dish-Stirling systems require power dispatchability, which is best accomplished with gas burners, or hybridization. This allows operation past sunset or on cloudy days. Stirling Technology Corp. (STC) designed and fabricated a 10-kWt pool-boiler receiver for hybrid operation. The device was built to demonstrate the feasibility of switching between the two thermal inputs and operating in a combined mode. STC burned the gas in a flame-holding porous refractory frit, which then radiated the thermal energy to the rear support dome of the receiver. The spherical solar absorber design followed conventional practices demonstrated at Sandia. Both surfaces incorporated a brazed stainless steel boiling stabilization surface. The receiver was successfully operated at the NREL solar furnace at full solar, full gas, and intermediate conditions. Figure 4 is a photo of the receiver prior to testing.

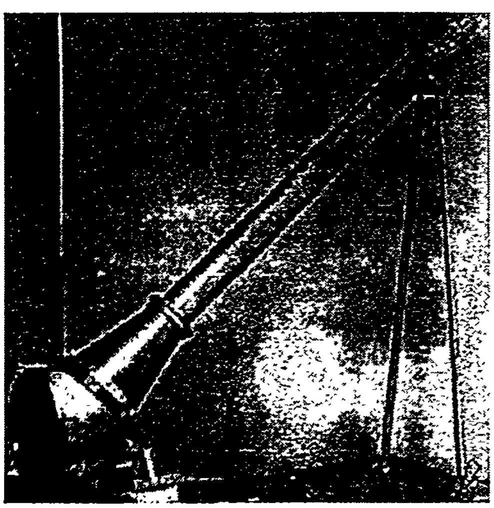

Figure 4. The STC 10 kWt pool-boiler receiver prior to the addition of the gas-burning equipment.

5. HEAT PIPES

The heat pipe concept uses a very small inventory of excess liquid metal. The metal is distributed across the solar absorber surface by a capillary wick structure, which may include tubular arteries [4]. The heat-pipe concept enjoys a better set of modeling and design tools than the pool boilers. However, fabricating long-life wick structures on convex surfaces that have the properties required in the design has proven difficult. Typically, planar wicks with good properties can be made, or wicks with lesser properties can be formed on domes, but succeeding at both simultaneously has been elusive. However, significant progress has been made at Sandia and with the CPG team in the last few years.

CPG has relied on the advanced technologies of their team member, Thermacore Inc., for heat pipe development and fabrication. Thermacore uses a sintered nickel powder technology, and has developed methods to ensure good adherence to the dome substrate. Thermacore also incorporates circumferential tubular arteries as needed to enhance performance, although improved wick performance may eliminate these costly additions. Thermacore has also begun to incorporate directed refluxing with good results. In this case, the condensate is directed to the wick surface from the condenser rather than dripping back to the supply pool.

The CPG 7.5 kWe dish-Stirling system uses a 16-inch diameter hemispherical receiver with a design throughput of 35 kWt. The receiver is fabricated from Haynes alloy 230 for long life, and the working fluid is sodium at 675°C. Thermacore has fabricated about a dozen of these receivers, and has continually improved the design. Some have been outfitted with gas-gap cold-water calorimeters, while others have been integrated with Stirling engines. One receiver has amassed over 1800 hours on sun in daily operation, while an earlier model reached 500 hours. Another sample has been run over 2000 hours, mostly on a quartz-halogen solar simulator at 26 kWt throughput in a test cell. This sample is cycled to room temperature every 4 hours of operation, and continues to accrue hours. Figure 5 shows the Thermacore receiver mounted on a Stirling engine.

Thermacore has extended the 35-kWt technology and constructed several receivers designed for at least 65 kWt throughput [12]. They enlarged the dome to 20 inches, incorporated directed refluxing, and use of a circumferential artery. The receiver was designed for use on Sandia's TBC and for eventual integration with the Stirling Thermal Motors 4-120 25 kWe Stirling

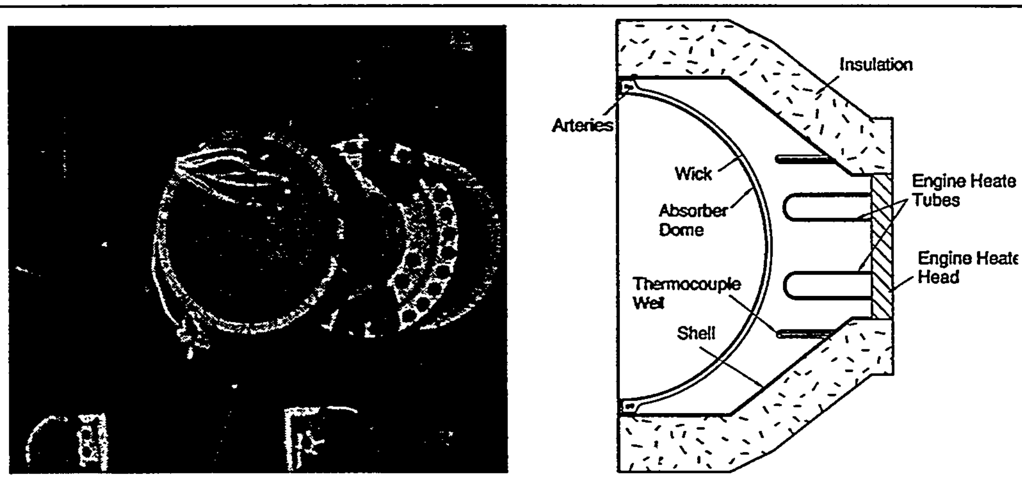

Figure 5. Cummins/Thermacore 35kWt heat pipe receiver shown mounted to a Sunpower Stirling engine.

engine. The initial receiver operated well at about 60-kWt throughput, but exhibited difficulties during startup. During the initial startup of the day, the receiver had hotspots just above the pool in high-flux regions. Subsequent restarts and rapid startups did not exhibit this behavior. The receiver performed well during one frozen-sodium start with full dish power incident on the receiver. Figure 6 shows this receiver prior to testing at Sandia.

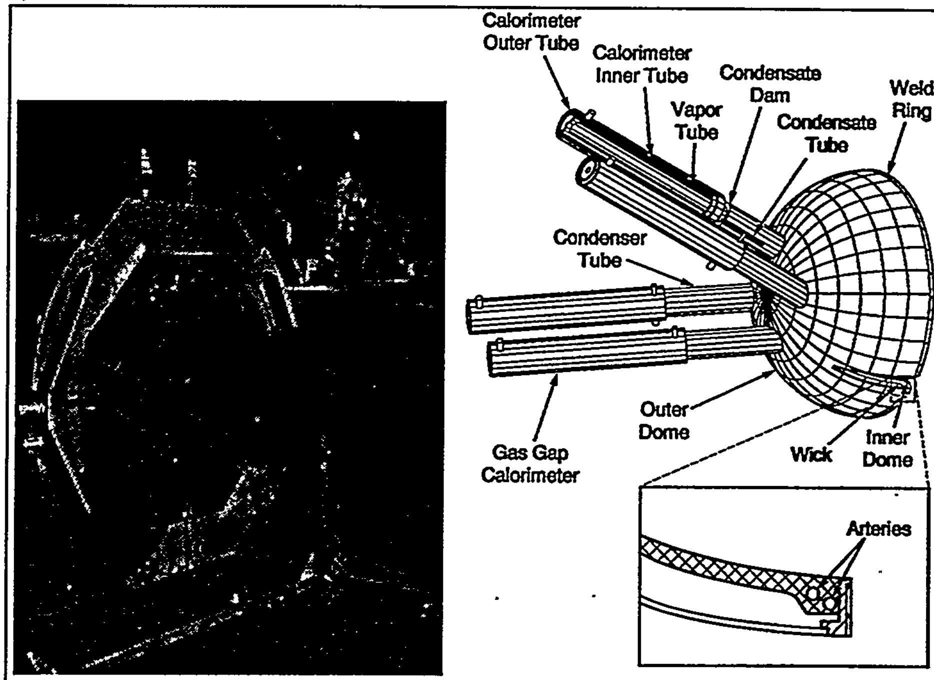

Figure 6. Cummins/Thermacore 65kWt heat pipe receiver is readied for test. The four separate condensers are designed to mate with the STM 4-120 engine.

A second Thermacore high-power receiver has just been tested at Sandia, and the startup problems have been eliminated. Several key design changes contributed to the improvement. The wick structure permeability has been improved such that the design tools predict performance in excess of 120 kWt, compared to 75 kWt on the first receiver. The gap between the absorber and the aft support dome was quadrupled to eliminate vapor pressure drops. Finally, the receiver was thoroughly baked out while monitored with a residual gas analyzer, until the hydrogen and water peaks were minimized. It was theorized at Sandia that free hydrogen in an improperly cleaned system forms hydrides as the receiver cools to ambient. Upon startup, the pressures generated by decomposing hydrides would be sufficient to de-prime the wick structure, causing hot spots. This second receiver operated well to the limit of the dish, and demonstrated a throughput of over 65 kWt to a gas-gap calorimeter. This, we believe, is currently the record for a solar-driven heat pipe receiver.

Sandia has been actively identifying and testing potential high performance wicks, both to improve upon Thermacore's capabilities, and to provide a secondary technology in case problems are identified. Sandia has identified a stainless steel felt supplied by Porous Metal Products of

Jacksboro, Texas. This felt is very uniform in appearance, and has premeability properties that exceed powder metal technologies. Figure 7 shows a small sample of the felt wick. A permeability of 225 μm^2 has been measured on a dome, with a maximum pore radius of 80 μm. While the pore radius is slightly higher than the powdered technologies, the permeability is very attractive. This translates to a throughput capability predicted by our current models over 200 kWt, though actual throughput must be demonstrated. A bench-scale receiver has been tested at Sandia, and the device operated continuously at full lamp power, transferring nearly 5 kWt from the wick. The tops of the lamps were 17 inches above the pool, and the average flux was 67 W/cm^2. In addition, several hot restarts were performed, again with no apparent difficulty. These results exceeded any previously-tested bench-scale device at Sandia. Based on these results, Sandia is currently constructing a full-scale receiver for test on the TBC. This receiver contains the felt wick in a Haynes 230 alloy shell. The receiver does not incorporated directed refluxing or arteries in order to limit performance to within the dish capabilities. Operation of the receiver up to the point of dryout is necessary to verify the performance models. The receiver is expected to dry out at approximately 40 kWt throughput. Once the model is verified, a second receiver will be built with directed refluxing to demonstrate high-power operation.

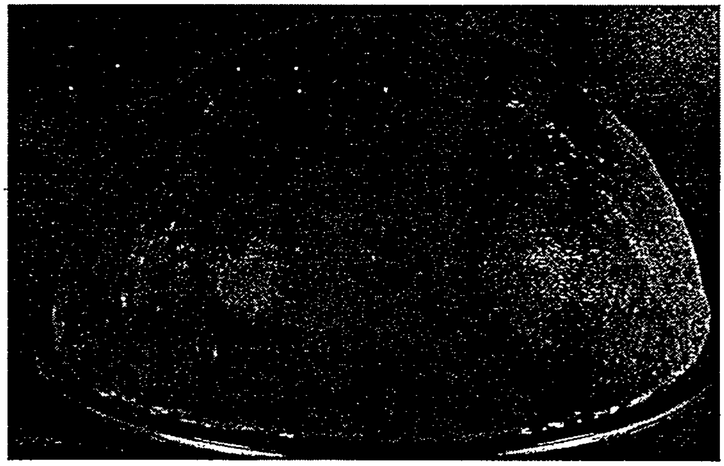

Figure 7. A sintered sample of the Porous Metal Products felt heat pipe wick.

Cummins Power Generation, under contract to NREL, has developed a hybrid heat-pipe receiver for their 7.5 kWe dish-Stirling system [13]. This receiver is constructed around their successful 16-inch hemispherical solar-only receiver. The outer cylindrical shell is extended slightly, and a wick added. The outer wall is heated by the gas burner and hot flue gasses, and an integral recuperator preheats the incoming air. Figüre 8 is a schematic drawing of the Thermacore hybrid receiver. Fabrication of the receiver is complete, and on-sun testing is anticipated this fall in Lancaster PA.

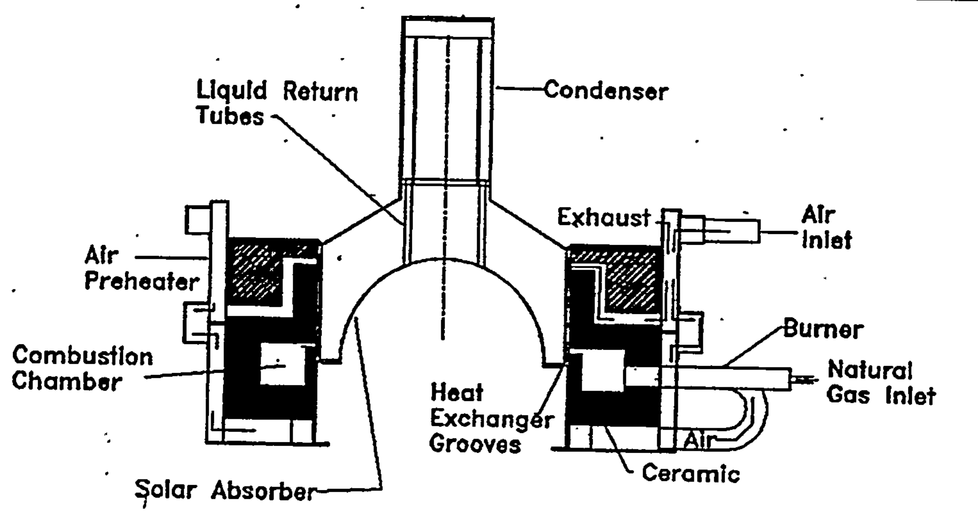

Figure 8. Schematic drawing of the Thermacore 35 kWt hybrid heat pipe receiver.

6. DEVELOPMENT ISSUES

The pool-boiler receiver has been successfully demonstrated on-sun at power throughput levels appropriate for 25 kWe dish Stirling systems. However, the design tools are severely limited. The effects of design changes or changes to the incident flux pattern are not predictable. The pool-boiler concept has not yet been combined with an engine, so condenser-end issues have not been identified or resolved. This is especially important on multiple-cylinder engines with separate heater heads. Since the mechanism for successful restarts with the addition of xenon is not well understood, the effect of condenser geometry changes cannot be predicted. The combination of a pool-boiler with a single-heater-head engine should be relatively straightforward, although the safety issue of a large liquid metal inventory must be considered.

Until recently, the primary issue with heat pipes was the demonstration of a unit on sun at power throughput levels appropriate to 25 kWt dish-Stirling systems. However, recent work with the Cummins/Thermacore team, as well as Sandia's felt wick development, show promise. Both wick options must be studied and tested for long-term materials compatibility and structural stability. This will be done through round-the-clock automated solar simulator testing with cycles to ambient.

Hybrid receivers have been demonstrated at a small scale with single prototypes. The scale-up of the heat exchangers may not be trivial, as heat-input area may be limited. In addition, the burner and recuperator assemblies must be simplified considerably for a cost-effective design. Long-term compatibility of the materials with the flue gas must be considered. Hydrogen permeation from the flue gas into the receiver may also be an issue, especially in the heat pipe option.

7. SUMMARY

Reflux receiver development has shown significant progress in recent years. The heat pipe and pool boiler approaches have both been demonstrated at power levels appropriate to large dish-Stirling systems. The efficiency and adaptability of reflux receivers promise to significantly improve the performance and lifetime of dish-Stirling systems.

Continued advanced development of liquid-metal reflux receivers is needed in support of the higher-powered Utility-Scale Joint Venture Program. The heat pipe concept, recently demonstrated at high power levels, needs life verification tests. While the boiling behavior of a particular pool boiler has been well characterized, the applicability of our data to different geometries is unclear. In addition, the effect of condenser and heater-head design on boiling behavior is unknown. A small-scale program has demonstrated the feasibility of hybridizing the reflux receivers, but larger hybrid receivers must be designed and tested. The long-term materials interactions must be fully characterized to ensure safe operation for up to 30 years.

8. ACKNOWLEDGEMENTS

This work performed by Sandia National Laboratories supported by the U.S. Department of Energy under contract DE-AC04-94AL85000.

Special appreciation to Merri Lewis for her administrative support and efforts on this paper.

9. REFERENCES

1. Washom, B., "Parabolic Dish Stirling Module Development and Test Results," Paper No. 849516, *Proceedings of the 19th IECEC*, August 1984.

2. Coleman, G.C. and Raetz, J.E., "Field Performance of Dish Stirling Solar Electric Systems," Paper No. 869136, *Proceedings of the 21st IECEC*, August 1986.

3. Washom, B.J., *Vanguard I Solar Parabolic Dish-Stirling Engine Module Final Report*, DOE-AL-16333-2 (84-ADV-5), 1984, pp. 105, 120-125.

4. Diver, R.B., Andraka, C.E., Moreno, J.B., Adkins, D.R., and Moss, T.A., "Trends in Dish Stirling Solar Receiver Design," Paper No. 905303, *Proceedings of the 25th IECEC*, August 1990.

5. Andraka, C.E., Moreno, J.B., Adkins, D.R., and Moss, T.A., *Sodium Reflux Pool-Boiler Solar Receiver On-Sun Test Results*, SAND89-2773, Sandia National Laboratories, Albuquerque, June 1992.

6. Moreno, J.B., Andraka, C.E, Moss, T.A., Cordeiro, P.G., Dudley, V.E., Rawlinson, K.S., *On-Sun Test Results from Second-Generation and Advanced-Concepts Alkali-Metal Pool-Boiler Receivers*, SAND93-1251, Sandia National Laboratories, Albuquerque, May 1994.

7. Moreno, J.B., and Moss, T.A., *Bench Scale Screening Tests for a Boiling Sodium-Potassium Alloy Solar Receiver*, SAND92-2253, Sandia National Laboratories, Albuquerque, June 1993.

8. Andraka, C.E., Jones, S.A., Moreno, J.B., and Moss, T.A., "NaK Pool-Boiler Bench-Scale Receiver Durability Test: Test Design and Initial Results," Paper No. 93IEC-294, *Proceedings of the 28th IECEC*, August 1993.

9. Andraka, C.E., Goods, S.H., Bradshaw, R.W., Moreno, J.B., Moss, T.A., and Jones, S.A., "NaK Pool-Boiler Bench-Scale Receiver Durability Test: Test Results and Materials Analysis," Paper No. AIAA-94-3865-CP, *Proceedings Of the 29th IECEC*, August, 1994.

10. Andraka, C.E., Jones, S.A., Moreno, J.B., and Moss, T.A., *NaK Pool Boiler Solar Receiver Durability Bench Test, Volume 1: Test Design and Results*, SAND94-1538, Sandia National Laboratories, Albuquerque, to be published 1994.

11. Goods, S. H. , and Bradshaw, R. W., *NaK Pool Boiler Solar Receiver Durability Bench Test, Volume 2: Metallurgical Analysis*, SAND94-8235, Sandia National Laboratories, Livermore, to be published 1994.

12. Andraka, C.E., Diver, R.B., Adkins, D.A., Rawlinson, K.S., Cordeiro, P.G., Dudley, V.E., and Moss, T.A.; "Testing of Stirling Engine Solar Reflux Receivers," Paper No. 93-IEC-295, *Proceedings of the 28th IECEC*, August, 1993.

13. Hartenstine, J.R., and Dussinger, P.M. "Development of a Solar and Gas-Fired Heat Pipe Receiver for the Cummins Power Generation 7.5 kWe Dish/Stirling System," Paper No. AIAA-94-3864-CP, *Proceedings of the 29th IECEC*, August 1994.