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REFLUX POOL-BOILER AS A HEAT-TRANSPORT DEVICE FOR STIRLING ENGINES: ON-SUN TEST PROGRAM RESULTS

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ABSTRACT

The efficient operation of a Stirling engine requires the application of a high heat flux to the relatively small area occupied by the heater head tubes. Previous attempts to couple solar energy to Stirling engines generally involved directly illuminating the heater head tubes with concentrated sunlight. In this study, operation of a 75-kW$_t$ sodium reflux pool-boiler solar receiver has been demonstrated and its performance characterized on Sandia's nominal 75-kW$_t$ parabolic-dish concentrator, using a cold-water gas-gap calorimeter to simulate Stirling engine operation. The pool boiler (and more generally liquid-metal reflux receivers) supplies heat to the engine in the form of latent heat released from condensation of the metal vapor on the heater head tubes. The advantages of the pool boiler include uniform tube temperature, leading to longer life and higher temperature available to the engine, and decoupling of the design of the solar absorber from the engine heater head. The two-phase system allows high input thermal flux, reducing the receiver size and losses, therefore improving system efficiency.

The receiver efficiency was about 90% when operated at full power and 800°C. Stable sodium boiling was promoted by the addition of 35 equally spaced artificial cavities in the wetted absorber surface. High incipient boiling superheats following cloud transients were suppressed actively by varying the thermal load on the receiver, and passively by the addition of small amounts of xenon gas to the receiver volume. Stable boiling without excessive incipient boiling superheats was observed under all operating conditions.

The receiver design is reported here along with test results including transient operations, steady-state performance evaluation, operation at various temperatures, and x-ray studies of the boiling behavior. Also reported are a first-order cost analysis, plans for future studies, and the integration of the receiver with a Stirling Thermal Motors STM4-120 Stirling engine.

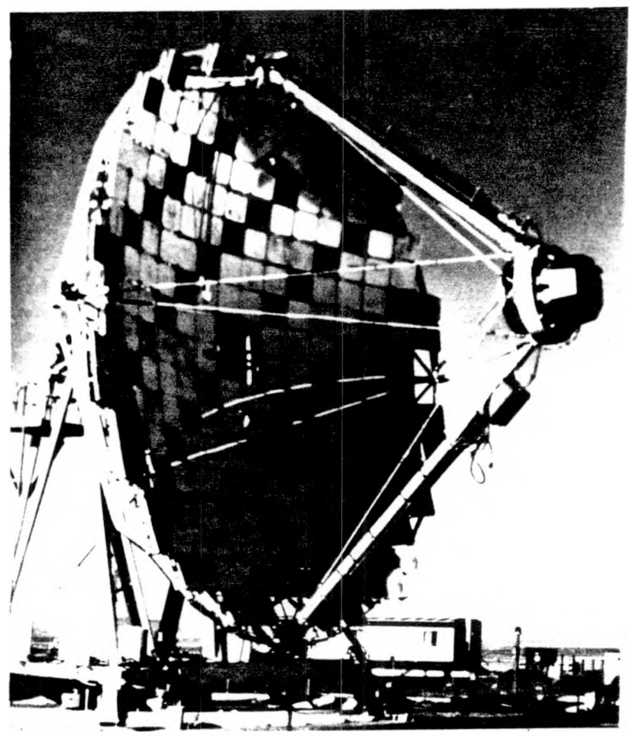

Figure 1. Photograph of test bed concentrator (TBC) with Sandia reflux pool-boiler receiver mounted at the focus. The TBC is configured for the 3/4-power test.

INTRODUCTION

Sandia National Laboratories, together with the U.S. Department of Energy, has identified dish-Stirling electric systems as having potential to meet the Solar Thermal Energy Program's long-term goals for levelized energy cost [1,2]. In 1984, the Advanco-Vanguard dish-Stirling module demonstrated a peak gross conversion efficiency of solar-to-electric of 31.6% while operating at an engine gas temperature of 760°C [3]. The module used a United Stirling of Sweden engine with its heater head directly illuminated by the concentrated solar flux. The non-uniform flux and temperature distribution severely limits the lifetime and performance of the heater heads [4], and puts stringent (costly) demands on the concentrator accuracy. In order to reduce peak fluxes, the heater head tubes were extended, which increased engine dead space and reduced engine performance. Heat balance among the four cylinders of the engine was difficult to maintain, further reducing performance. In addition, it is difficult to efficiently hybridize (gas fire) the heater heads without compromising the solar efficiency.

The liquid-metal reflux receiver was conceived as an improvement over directly illuminated tube receivers [5]. In early 1988, Sandia initiated a dish-electric receiver-development program to support design, development, and testing of the reflux receiver concept. Contracts with industry are supporting the development of Advanced Stirling Conversion System (ASCS) units, reflux receivers, and cost-effective concentrators for 25-kW$_e$ systems.

The goals of these projects are to improve performance and life while reducing costs, so that dish-Stirling systems can be a cost-effective means of electric power generation. Cummins Power Group is privately pursuing the commercialization of a 5-kW$_e$ dish-Stirling system that incorporates a reflux receiver.

In the reflux receiver approach, liquid metal 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, wick capillary forces, or a combination thereof. Due to its two-phase nature, the reflux

receiver has the important advantage over tube receivers of nearly-isothermal operation even though the incident solar-flux distribution is non-uniform. Also, the excellent heat transfer characteristics of the liquid metal allow a very small receiver, and therefore minimize heat losses. In addition, the absorber surface and the engine heater tubes in the reflux receiver are separate components, so they can be independently optimized. 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 the pool-boiler and the wicked-absorber (heat pipe) concepts [6]. The pool-boiler receiver is simple and robust but uses a larger quantity of liquid metal than the heat-pipe receiver. Uncertainty in the design of pool boilers is introduced by the poor state of knowledge regarding the boiling behavior of liquid metals and their effect on the heated-surface material. The heat-pipe receiver uses much less liquid metal, but it has the added complexity of a wick structure. Although the technology has been extensively studied, 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. This paper concentrates on Sandia's efforts with the pool-boiler concept.

Bench-scale proof-of-concept testing of the pool-boiler receiver was completed in early 1989, and the results have been documented [7,8]. Design and fabrication of a full-scale pool-boiler receiver have been completed, and operation over the full range of conditions called for in the test plan has been successfully demonstrated. Figure 1 shows the receiver in its housing mounted at the focus of Test Bed Concentrator #1 (TBC-1) at the National Solar Thermal Test Facility in Albuquerque NM (Sandia National Laboratories). The receiver uses sodium at 800°C, and can transport up to 75-kW_t. In this paper, the receiver design and test details are described, results presented and discussed, and future plans outlined. A more detailed account can be found in Andraka [9].

POOL BOILER DESIGN

Figure 2 is a schematic drawing of the pool-boiler receiver mounted in its support structure on the TBC mounting ring. The absorber consists of an 8.63"-radius spherical dome with a 70° half angle and a 16.3" rim diameter. The dome was 0.032"-thick 316L stainless steel, and was supported by a 0.125"-thick dome of the same material. The design gap between the domes was 1.2" to 1.5" at the widest point, based on a modified Kutateladze flooding criterion [7], which dictates a width such that the vapor generated by boiling will not prevent the return flow of liquid to the absorber surface ("flooding limit"). The remainder of the receiver is a condenser section of 304L stainless steel 8" pipe designed to mate with a gas-gap cold-water calorimeter for controlled power extraction. The receiver sodium inventory was 12.7 pounds, which at operating temperature floods the entire absorber surface in all dish orientations. The sodium was melted with electric heaters before operation. The same absorber geometry will be used for a heat-pipe receiver, allowing direct comparison of the two approaches.

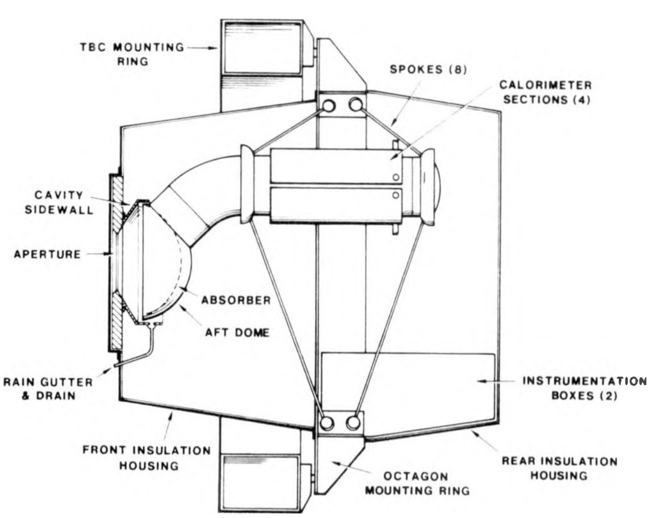

Figure 2. Schematic of the Sandia reflux pool-boiler receiver.

Photographs of the pool-boiler receiver in the octagonal mounting ring and insulation housing are shown in Figures 3 and 4. Insulation for the receiver was provided by two to three wraps of 2"-thick Cerablanket insulation. The entire housing was then filled with vermiculite, thus minimizing conduction heat loss. The receiver cavity was formed by the spherical absorber and a conical stainless-steel sidewall section. The 8.65" diameter aperture is defined by a 2" thick Fiberfrax 3000 insulation board. The aperture and sidewall divergence angle were greater than the rim angle of the TBC to avoid direct solar flux on the sidewall. The insulation housing was sealed with weather stripping, tested, and found to be rain-tight.

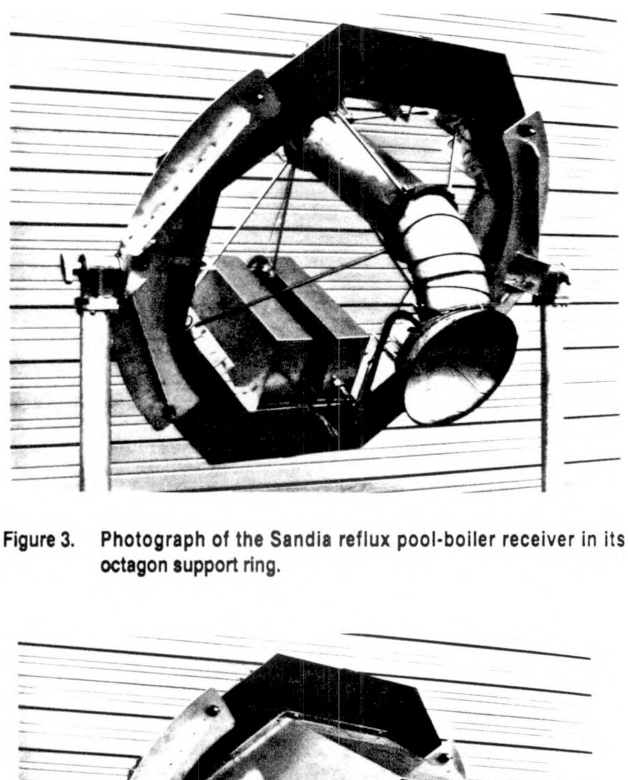

Figure 3. Photograph of the Sandia reflux pool-boiler receiver in its octagon support ring.

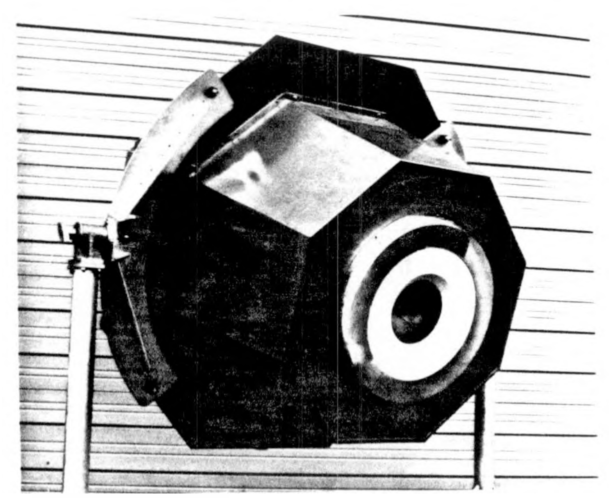

Figure 4. Photograph of the Sandia reflux pool-boiler receiver in its insulation housing.

Figure 5 shows the incident solar flux distribution from Sandia's Test Bed Concentrator on the absorber surface, as predicted by CIRCE2, an updated version of the computer model CIRCE [10]. The non-uniform flux distribution illustrates why, if thermal stress is to be minimized, a receiver with high heat transfer characteristics is necessary. Commercially viable dishes will probably be more non-uniform because cost issues preclude a heavy, accurate structure and facets. The peak flux was calculated to be about 73 W_t/cm^2 at a total power of 75 kW_t.

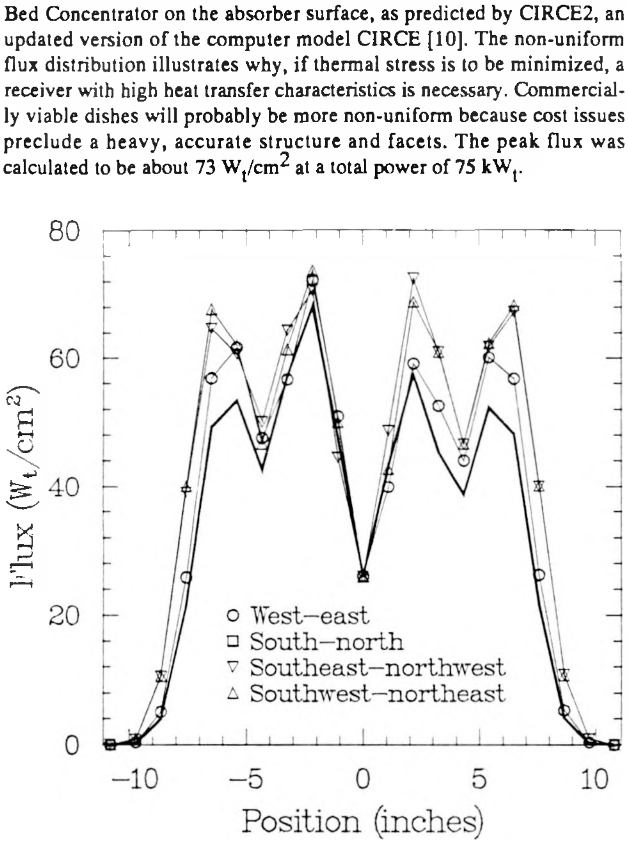

Figure 5. Design incident solar flux on the Sandia reflux pool-boiler receiver as calculated by CIRCE2. Flux distribution as a function of position along bisectors of the absorber is shown for four compass directions as viewed from the concentrator. Negative positions on the x-axis correspond respectively to west, south, southeast, and southwest of the center of the absorber. The zero position corresponds to the center of the receiver.

Stress analyses were performed on the receiver design considering both the startup and operating thermal and pressure stresses. The peak calculated startup stresses were about 12,000 psi in bending, which is under 80% of yield for the stainless steel. During steady operation, the combination of pressure stress and thermal stress resulted in a bending stress in the dome of up to 7,400 psi tensile and 4,750 psi compressive. These stresses are less than two-thirds of the yield strength of 316L stainless steel at 800°C. The pressure-induced stress is well below the value for creep to rupture in 10^5 hours. The bending stress will relax to a lower value in time and is of less concern.

A bench-scale simulation of the receiver was previously operated in order to characterize the liquid-metal boiling behavior [7,8]. The bench test was designed to closely simulate the operating conditions of the full-scale receiver. The operation of the bench test showed that stable boiling from an as-delivered stainless-steel surface was not assured. Based on these and other results from the bench test and on prevailing theories of boiling stability [11], 35 cavities were formed in the absorber surface of the current receiver. The cavities, 0.006" in diameter, 0.02" deep, and spaced approximately 4" apart, were electric discharge machined into the sodium side of the formed dome. Stress analyses of the cavities indicated that the design would be adequate for short-term testing.

The receiver domes were hydroformed from sheet stock. The remainder of the receiver was built from 304L stainless-steel schedule-10 pipe, pipe cap, and elbow. A 3/4" tube for vacuum pumpout and a 3/8" tube for sodium fill were also included. The closure on each tube was an all-metal welded bellows valve. All joining was accomplished using manual gas-tungsten-arc welding. Filler metal was used on the pipe welds, and the inside of the receiver was purged with argon during all welding operations. The final weld was the absorber dome to the back dome, which was autogenous. A helium leak detector was used to check all of the welds, and no response to helium was seen in the 10^{-9} cc/sec range.

After assembly, the receiver was vacuum baked at 600°C for 48 hours. A long-term leak-up test indicated an acceptable leak rate of less than 2 x 10^{-8} cc/sec, based on the absolute pressure rise in the vessel over several days. A residual gas analyzer showed that argon (used during welding to purge the receiver of air) was the dominant species, confirming that this was primarily a virtual leak. Sodium was added to the receiver using the defined-volume procedure described in Moreno [7]. The sodium level in the receiver was confirmed radiographically.

TEST DETAILS

The reflux pool-boiler receiver was tested on TBC-1 using a gas-gap cold-water calorimeter to measure performance. The calorimeter is a 20"-long water-cooled cylindrical shell divided lengthwise into four 90° segments. A gap is maintained between the segmented water jacket and the condenser with 0.037"-diameter stainless-steel wire. The gap is flooded with a controlled mixture of helium and argon to regulate the thermal conductance of the gap and therefore control the receiver temperature and heat load.

An automatic system controlled the receiver temperature by regulating the calorimeter gas-gap mixture of argon and helium. A PID temperature controller compared the set-point temperature to the condenser temperature. The controller output operated mass-flow gas-control valves that regulated the supply of argon and helium to the calorimeter gap. The controller was tuned to provide fast response to cloud transients with a minimum of overshoot. The calorimeter could be used to maintain a constant temperature as the insolation varied, as shown in Figure 6, or to change the operating temperature of the receiver at a given insolation level.

Prior to receiver testing, TBC-1 performance was characterized with a cold-water calorimeter [12] over a full range of power levels and mirror cleanliness. Total power delivered to the receiver (normalized to a direct normal insolation of 1 kW_t/m^2) ranged from 64.1 kW_t with dirty mirrors to 66.6 kW_t after cleaning, repeatable over a period of weeks. A 20-

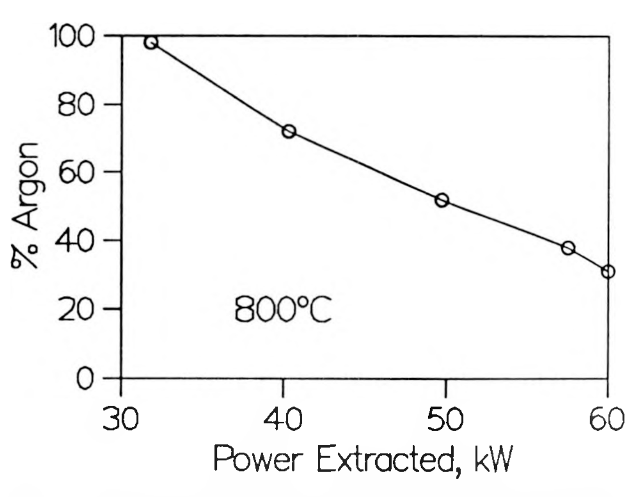

Figure 6. Calorimeter control for maintaining constant temperature. As the insolation varies, the controller automatically varies the argon percentage to maintain the setpoint temperature.

junction thermopile made by δelta-T Co., accurate to within 0.04°C, was used to measure the cooling water temperature change between the calorimeter inlet and outlet. Water flow rate was measured by a turbine flow meter made by Flow Technologies, Inc. calibrated within ±1%, and was periodically checked with a bucket, scale, and stopwatch. The same instrumentation was used for the receiver for consistency. The absolute uncertainty in the TBC-1 power measurement was estimated to be 1.3% [12]. Uncertainty in the receiver's heat loss, which is the difference between TBC-1 power and the power delivered by the receiver, dominated by uncertainties in mirror cleanliness, was estimated to be ±1 kW_t for these tests.

The receiver was heavily instrumented with Type K thermocouples. Nine 1/16"-diameter Inconel-600 sheathed thermocouples were furnace-brazed to the front surface of the absorber in a cross pattern using Incuro-60 braze. They were brazed to the absorber along their entire length to prevent failure from the high incident flux. Nine 1/16"-diameter 316L-stainless-steel sheathed thermocouples were brazed to the rear surface of the absorber with BNi-3 using the same pattern as the air-side thermocouples. These were brought out of the receiver via a brazed feed-through. Additionally, three thermocouples were brazed to the condenser wall and one each was provided in the vapor space and in the upper end of the pool. These were also brought out via a brazed feed-through. Seven thermocouples were tack-welded to the exterior of the receiver on the aft dome and nine were welded to the optical cavity sidewalls. Additional thermocouples were used to monitor water, support spoke, and calorimeter temperatures.

An infrared (8-14μm) pyrometer with a field of view slightly smaller than the aperture viewed the absorber surface. A microphone was attached to a support spoke to monitor boiling sounds. Pressure switches and transducers were used to monitor helium and argon gas pressures and flows. All of the instruments were read and recorded using the site data acquisition system. The maximum scan rate for the entire set of data was about 10 seconds.

Another computer was used to quickly scan a selected set of signals and compare them to preset limits. If a limit was exceeded, a water-cooled aperture shutter was automatically closed. The scan rate was approximately 3 seconds. The most critical temperatures were monitored by digital displays with built-in limit alarm relays, providing very fast shutter response to abnormal readings. All of the hardware displays, as well as the computer and stop button, were monitored by a first-out indicator to help determine what failed first in a rapid chain of events. Finally, selected thermocouples were also recorded on stripcharts.

TEST RESULTS AND DISCUSSION

Nine separate tests of the receiver were run between August 31 and December 19, 1989, for a total of 36 hours at or above 700°C.

The objective of tests 1-3 was to demonstrate well-behaved boiling at half, three-quarter, and full power. The power was attenuated by covering selected mirror facets on TBC-1. Figure 1 shows the mirror coverage for the three-quarter power test. Two specific concerns in these initial tests were boiling instabilities and flooding limits [7]. Test #1 totaled 96 minutes at half power, with eight minutes of steady operation at 800°C condenser temperature. In tests 2 and 3, nearly all test time was at 800°C. Time totaled 204 minutes at three-quarter power and 180 minutes at full power. Figure 7 shows extracted power and temperatures measured during the full-power test. Receiver thermal efficiency was about 90% when the input power and sodium temperature were at their maximum tested values. The temperature was quite steady and nearly isothermal within the receiver, indicating that stable nucleate boiling was achieved. The absorber temperature shown was measured with by a flattened thermocouple brazed to the air side of the absorber. Because the thermocouple was about as thick as the absorber, this temperature is estimated to be as much as 15 to 20°C higher than at the surface of the absorber and is dependent on the local heat flux. Qualitatively similar temperature results were obtained at half and three-quarter power, and in brief runs at 700 and 750°C at half and full power.

Figure 8 illustrates the temperature distributions along vertical and horizontal diameters of the absorber during startup and near steady state, at full power. The temperatures are indicated by flattened thermocouples brazed to the air side of the absorber. As expected, the temperature distributions are qualitatively similar to the calculated flux distributions (Figure 5). However, sodium conduction and convection tend to moderate the effect of the flux non-uniformities, resulting in relatively uniform temperatures even during startup. The temperature distribution on the rear dome (not shown) was even more uniform. These absorber temperatures were always consistent with conduction of the incident solar flux through the absorber into the sodium pool. This confirmed that the boiler design was adequate to avoid a flooding limit [7] at all tested orientations and input power levels.

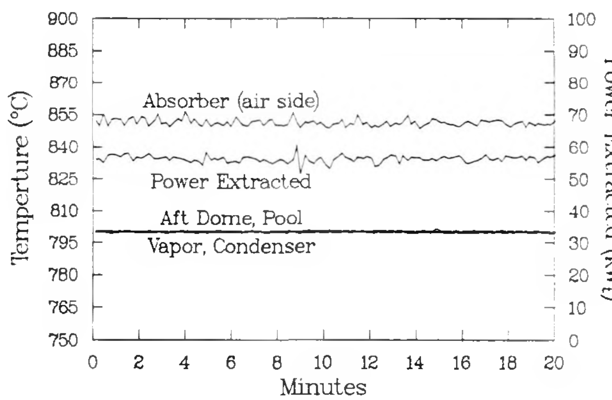

Figure 7. Temperatures and extracted the power during a 20 minute portion of the full-power steady-state test.

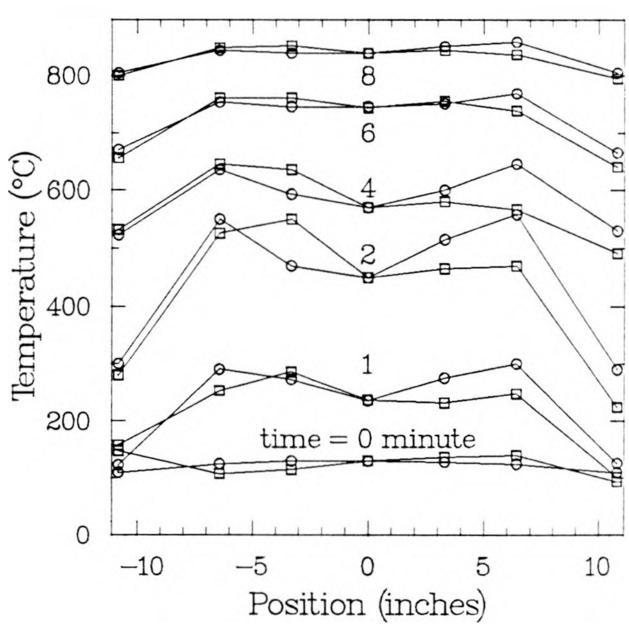

Figure 8. Temperatures indicated by thermocouples brazed to the air side of the absorber along the horizontal (circles) and vertical (squares) bisectors during initial startup. The abcissa has the same meaning as in Figure 5.

The objective of tests 4 and 5 was to study the "hot restart problem" identified during simulated cloud transients in the bench-scale tests [7,8]. In those tests, power was interrupted, pool temperature was allowed to drop into the range 680 - 720°C, and then power was re-applied. Temperatures indicated by thermocouples brazed to the heated surface would quickly exceed 900°C, causing safety-system automatic shutdowns. In the present tests, cloud transients were simulated using the receiver shutter. More than 80 hot restarts were studied. It was found that the system had to be "conditioned" before an over-temperature would occur. Once an over-temperature had occurred, it would repeat on every succeeding cycle. Conditioning amounted to repeating a cloud cycle several times without steady operation between cycles. A typical example showing two cycles of conditioning followed by a third cycle with an over-temperature is presented in Figure 9. During the third cycle cool-down, it can be seen that the condenser and absorber temperatures diverged. This was taken as evidence that boiling had stopped, reinforced by the simultaneous observation that the sounds of boiling had stopped. Significantly, in every case of over-temperature, boiling had stopped by the time the shutter re-opened. Such behavior is consistent with the fact that it takes a much larger wall-to-pool temperature difference to initiate boiling (incipient boiling superheat) than to maintain boiling (nucleate boiling superheat) [13]. This suggests several remedies that are discussed.

An active-control solution to the hot-restart problem was successfully demonstrated in test #5. During closed-shutter cool-downs, whenever signs of boiling cessation occurred, boiling was forced to continue by immediately adding helium to the calorimeter gas gap. The effect of the helium was to lower the condenser temperature and thus the system pressure, thereby assisting bubble inflation at the heated surface. This procedure was automated so that helium was added whenever the pool and condenser temperatures diverged by more than 10°C. Repeated tests suggested that this control strategy is a way to eliminate the hot restart problem. In a receiver-engine combination, the same effect during cool-down could be produced by increasing the engine load whenever the absorber and heater-head temperatures diverged.

A passive solution to the hot restart problem was suggested by Elric Saaski [14]. This involved introducing a small amount of inert gas into the vapor space in the boiler. Xenon was chosen because of its reported high solubility in sodium [15]. The possible beneficial effect of dissolved gas on incipient-boiling superheat has been discussed by others [16] and tried in a bench-scale device [17]. The purpose of tests 6 and 7 was to try this idea in the full-scale receiver. In test #6 about 128 standard cc (3.7 torr) of xenon was added to the receiver. Following the addition, the hot-restart problem could not be reproduced using the previously repeatable procedure. However, the xenon had an adverse effect on heat transfer. Before the addition, with pure helium in the calorimeter gas gap and the pool at 700°C, about 60 kW_t could be extracted. After the addition, the same conditions required a pool temperature of 760°C. To correct this problem, most of the xenon was pumped out when the boiler was cold. About 1.3 cc of free xenon remained, plus an estimated 2.8 cc or less dissolved in the sodium. This restored the heat transfer characteristics to their initial values and the hot restart problem could not be repeated. Typical test results are presented in Figure 10. In contrast to the cycles shown in Figure 9, these results show repeated cycles made without over-temperature. It can be seen that the absorber and condenser temperatures quickly converged and remained close during cool-down, indicating that cessation of boiling did not occur. These results show that the hot restart problem can be controlled by the addition of a very small amount of xenon into the boiler. This passive solution is preferable to the active control method because of its simplicity and low cost.

The next test in the series was run to determine receiver behavior over the full range of orientations for a typical day, and to collect data for comparison with existing performance models. The detailed comparisons are presented in Andraka [9]. The test was run on a clear day with operation nearly from horizon to horizon. Figure 11 shows

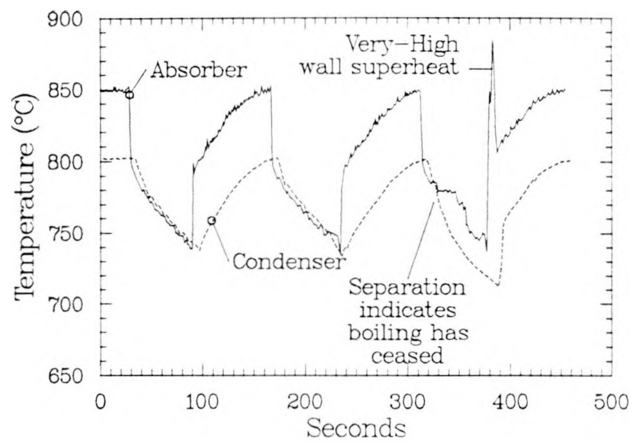

Figure 9. Shutter-simulated cloud transient data before xenon addition.

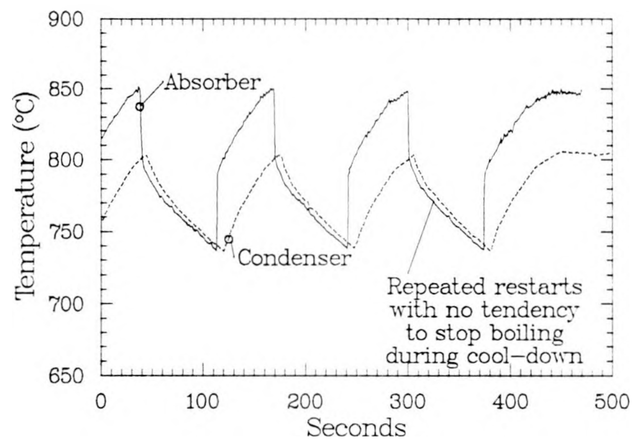

Figure 10. Shutter-simulated cloud transient data after final adjustment of xenon addition.

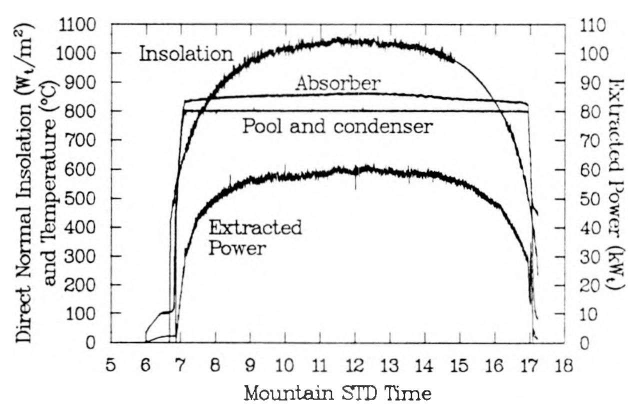

Figure 11. Direct normal insolation, temperatures and power levels during an all-day test. Insolation measurements between 1500 and 1620 hours were blocked by an adjacent structure and are estimated here in order to calculate receiver efficiency. The receiver daily efficiency on this day was about 89%.

power levels and representative temperatures for the day-long test. The very steady temperatures show that boiling stability and automatic temperature control were not a problem. Daily receiver efficiency, determined from the total energy input to the receiver and extracted by the calorimeter, was about 89%. This result demonstrates the potential of the pool-boiler receiver for high efficiency. It is in part attributable to the small size of receiver cavity, which minimizes the loss to air convection. The small size in turn is possible because of the excellent internal heat transfer characteristics of the receiver.

The final test performed involved real-time x-ray cinematography of the boiling sodium. Due to physical constraints around the receiver housing, only a small portion near the top of the pool could be viewed. The fluorescent plate intensity was measured before the sodium was melted (through structure and vacuum), after melting and thermal expansion (through structure and sodium liquid), and during boiling (through structure, liquid, and voids). The void fraction during boiling could then be inferred from these measurements. Light leaks and background skewing caused some apparent negative void fractions. When corrections were applied for these effects, void fractions of 33-46% were calculated at 800°C and 60 kW_t.

FUTURE PLANS

Further x-ray studies will be conducted with individual detectors rather than a fluorescent plate and camera, and void fraction results should be obtained this year. Void fractions will be measured from the side through the gap between the domes, where the flooding limit is most critical. These results will be useful in determining flooding limit safety factors.

In addition to void fraction, we hoped to be able to use the x-ray studies to determine the locations of the active nucleation sites on the absorber surface during startup and steady boiling. This requires x-ray viewing coaxial with the concentrator axis. The sodium pool thickness between the domes is less than 1.5", and so the difference in the amount of x-rays absorbed by the vacuum and sodium-filled states is only 3.3%. This makes nucleation site determination difficult at best.

In addition to the further x-ray studies, additional full-day characterization testing and infrared thermography tests are planned. Additional hot-restart tests will be performed during the full-day tests to verify the benefits of xenon addition over the full range of operating conditions. The infrared thermography will map absorber surface temperatures for comparison with directly illuminated tube receivers and for input into receiver thermal models.

A next-generation receiver is currently being designed. The primary goals are to demonstrate operation of a receiver that has long life potential, low cost, and a manufacturable design. Materials experts at Sandia have identified Haynes-230 as the leading candidate for the receiver shell. Other promising alloys include Inconel 600 and 617. The Haynes alloy has significantly superior oxidation resistance, thermal stability, and strength at temperature, but sodium compatibility must be demonstrated, and the cost is higher than stainless steel or inconel. The Haynes alloy has a solar absorptance of 92% after 280 hours exposure to air at 800°C, compared to the stainless steel and Inconel absorptivity of 85-87%. This should offset some of the higher material cost with higher efficiency, and eliminate the need for expensive absorptive coatings (Pyromark paint). Both In 600 and In 617 have better oxidation resistance and thermal stability than 316L stainless.

Alternate methods of promoting boiling stability are also being considered, due to the stress, corrosion, and cost implications of the electric discharge machined artificial cavities. Thermacore, Inc., a leading heat pipe manufacturing and development firm, has demonstrated boiling from sintered porous structures with xenon and helium present in the vapor space. Sandia will test similar surfaces with and without inert gases present. Sandia is also considering cost-effective laser-drilled pits, which are functionally identical to the EDM cavities. Boiling from an un-modified surface with the addition of xenon will also be tested. The boiling behavior on the selected receiver shell material, with the above mentioned modifications, will also be characterized with bench-scale tests.

Another possible improvement is the use of NaK-78 rather than sodium. Because NaK-78 freezes near -12.6°C, the need for electrical preheating could be eliminated. Theory indicates that boiling stability should be easier to achieve with potassium or NaK. NaK has a higher vapor pressure than sodium, and therefore can provide heat to an engine at lower engine operating temperatures. Stirling engine operating temperatures below 800°C are being considered to extend the life of the engine. The boiling behavior of NaK under the conditions of interest will be characterized.

Before the next-generation receiver is designed and built, a set of short-term bench-scale tests will be run. The purpose of these tests is to screen the materials and methods improvements that have been identified above. Once the material and methods for the next-generation pool-boiler receiver have passed the short-term screening, a long-term bench test will be run. Particular concerns in this test will be the long-term effects of boiling on the absorber surface, long-term stability of the boiling, and material compatibility in a two-phase liquid-metal system. A next generation receiver will be built and tested on sun in parallel with the long-term test.

A reflux receiver will be designed and constructed for integration with the STM 4-120 Stirling engine. Current plans are to use the first generation receiver design, but improvements will be incorporated as they are proven in the bench tests. The STM engine is a four cylinder kinematic engine. The reflux receiver concept provides balanced power to all cylinders without the difficult dish-alignment strategies involved with directly illuminated heater heads. This integration effort will provide experience necessary to guide the commercialization of dish-Stirling electric systems.

RECEIVER COST ANALYSIS

Sandia has begun a reflux receiver comparison to identify the advantages and disadvantages of the heat pipe and pool-boiler concepts, with the intent of making a selection or recommendation for further development. A portion of this comparison includes a cost analysis of the reflux receiver concept.

A first-order estimate of the cost of a reflux receiver has been performed, based on the current on-sun design. No attempt was made to optimize the design for this analysis. Two pool-boiler concepts were considered, as well as a screen-wick heat pipe receiver. The design used Haynes-230 alloy and NaK-78 working fluid. The two pool-boiler designs differed in boiling stabilization techniques. The first used laser-drilled pits, while the second used a sintered-powder coating. The engine end of the receiver was left unspecified. The mounting system and housing costs were also estimated. The resulting estimated costs are

Pool boiler with laser-drilled pits:	$1950
Pool boiler with sintered-powder coating:	$2050
Heat pipe receiver with screens:	$2500
Mount and housing:	$1500

These cost estimates include all materials and processing labor, and are based on production of 10,000 units per year. All of the support and capital costs were combined into a 500% overhead rate. This overhead rate is based on Cummins preliminary design cost estimates for the ASCS project [18]. Sandia also considered an extensive list of machine capital costs and lifetime, floor space costs, and engineering support instead of the 500% overhead, and the total cost estimates were about 6% less. This more detailed cost estimate neglected costs such as utilities, insurance, and plant maintenance, which are included in the 500% overhead figure. Thermacore estimated $1030 for a similar heat-pipe receiver [19] based on a sintered nickel powder wick structure. The approximately $1450 difference between Sandia's heat pipe cost estimate and that of Thermacore is primarily due to materials costs

(316L stainless steel rather than Haynes-230) and a larger overhead estimate. The DOE Solar Thermal Program goals specify a total receiver cost of $6400 (escalated to 1989 dollars) at 90% annual efficiency. Sandia will consider these cost estimates, as well as performance data, life estimates, and several qualitative factors, to guide development of commercializable reflux receiver designs.

CONCLUSIONS

1. Stable boiling was achieved in a liquid-metal pool-boiler reflux receiver at all power levels in the temperature range investigated - from 700 to 800°C (35 artificial cavities 0.006" in diameter and 0.02" deep, equally spaced about 4" apart, were put in the absorber surface to promote boiling stability).
2. When boiling stopped during the cooldown phase of simulated cloud transients, very high incipient-boiling wall superheats usually occurred in the restart phase (the "hot restart problem").
3. Cessation of boiling during cloud transients was delayed by active control of the heat-extraction rate, thereby suppressing the hot restart problem.
4. Cessation of boiling during cloud transients was also delayed by the addition of a small amount of xenon to the boiler, thus passively suppressing the hot restart problem.
5. No evidence that flooding limits were exceeded was observed in over 36 hours of testing.
6. Thermal and mechanical stresses in the absorber were estimated to be less than the material yield strength during both startup and steady operation; the design is suitable for short-term testing but further development will be necessary for long-term operation.
7. Peak flux incident on the absorber surface was calculated to be 73 W_t/cm^2.
8. Power available from TBC-1 after cleaning was measured to be 66.6 kW_t per 1 kW_t/m^2 direct normal insolation.
9. Daily receiver thermal efficiency for a full day of clear-sky operation was about 89%.
10. Preliminary x-ray analysis of the Sandia pool-boiler receiver indicates bubble void fractions of 33-46%.
11. The reflux receiver concept has the potential to meet the DOE Solar Thermal Program cost and performance goals.

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