POOL BOILER REFLUX SOLAR RECEIVER FOR STIRLING DISH-ELECTRIC SYSTEMS

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ABSTRACT

The feasibility of competitive, modular bulk electric power from the sun may be greatly enhanced by the use of a reflux heat pipe receiver to combine a heat engine such as Stirling with a paraboloidal dish concentrator. This combination represents a potential improvement over previous successful demonstrations of dish-electric technology in terms of enhanced performance, lower cost, longer life, and greater flexibility in engine design. There are, however, important issues and unknowns which must be addressed to determine engineering feasibility of these devices.

In the pool boiler reflux receiver, concentrated solar radiation causes liquid metal (sodium or potassium) to boil. The vapor flows to the engine heater heads, where it condenses and releases the latent heat. The condensate is returned to the receiver absorber pool by gravity (refluxing). This is essentially an adaptation of heat pipe technology to the peculiar requirements of concentrated solar flux, and provides many advantages over conventional heated tube receiver technology. Boiling theory indicates that long-term stable boiling of liquid metal may be difficult to achieve.

Laboratory scale experiments have been performed. Initial tests confirmed that boiling is unstable in a baseline boiler. Boiling stability was established after the addition of "artificial cavities" to the heated surface, and successful boiling of sodium was demonstrated for 100 hours. Other stabilizing influences may have been present, and will be discussed. The flux and geometry closely simulated a real receiver. The results of these tests are presented, along with the design of a full scale receiver for on-sun testing and considerations for long term operation.

INTRODUCTION

The work recounted here was motivated by the need for improved receivers for Stirling-engine dish-electric systems. The development of these systems is an important element in the Department of Energy's Solar Thermal Technology Program, because of their potential to meet the Program's goals for long-term levelized energy cost [1]. The ability of Stirling-engine dish-electric systems to operate at high efficiency has been demonstrated in equipment built and tested by Advanco Corporation and McDonnell Douglas Corporation [2,3,4]. Figure 1 shows the Advanco-Vanguard module. When operated at a working-gas temperature of 760 °C, this module produced in excess of 26 kW and demonstrated a gross efficiency of 31.6% for conversion of incident solar power to electricity [5].

Both the Advanco and the McDonnell Douglas modules used directly-illuminated tube receivers. These receivers have a number of problems: (1) non-uniform illumination of the tubes degrades system performance and causes thermal stresses that shorten the receiver lifetime; accurate and therefore expensive concentrators would be required to minimize non-uniformity of the incident solar flux distribution; (2) optimization of the tubing configuration for lifetime and receiver efficiency is in conflict with its optimization for engine efficiency; and (3) it would be difficult to hybridize the directly-illuminated tube receiver with fossil fuels.

The reflux heat-pipe receiver using liquid sodium or potassium as the heat-transfer medium has been proposed as a solution to the problems just presented [6]. Liquid metal is evaporated at the absorber and condensed at the engine heater tubes. The condensate is returned to the absorber by gravity and/or wick capillary forces. This receiver has the advantage of isothermal operation even when the solar-flux distribution is non-uniform. It allows the separate optimizations of the absorber surface and the engine heater tubes, and has the potential to be readily hybridized.

A dish-electric receiver-development program based on the reflux heat-pipe receiver concept has been underway at Sandia National Laboratories for the past 18 months. The Sandia program evolved out of earlier efforts elsewhere, and complements several programs currently underway at other laboratories. The technology background and the various current programs have recently been

reviewed [7]. In Sandia's reflux heat-pipe receiver program, the two concepts being considered are the pool-boiler receiver and the wicked-absorber receiver. The two approaches are being competitively developed during the first phase of the program. The pool-boiler receiver has the advantage of simplicity, but uses a significant quantity of liquid metal. It relies on nucleate boiling at the heated surface. Uncertainty is introduced by the poor state of knowledge regarding the boiling behavior of liquid metals and its effects on the heated surface. The wicked-absorber receiver has the advantage of requiring a minimal sodium inventory, at the expense of added complexity (the wick structure). The wicked heat pipe is a well-established technology that has already been studied with regard to long-term behavior. Its application to receivers introduces some new elements that will require attention, including the unique geometry and the large vertical and areal extent of the heated surface.

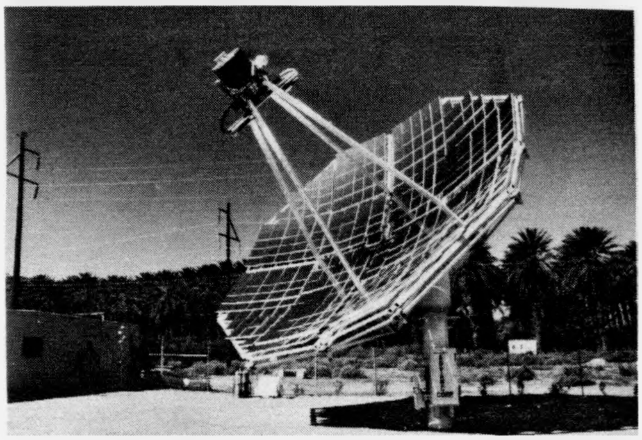

Figure 1. Photograph of the Advanco Dish-Stirling module, which holds the current record for solar-to-electric conversion efficiency. The mirrored parabolic dish concentrates the sunlight directly on the engine heater tubes at the dish focal point.

Sandia's two competing receiver concepts are being developed initially to transfer 75 kW_{th} at 800 °C, using sodium as the heat-transfer medium. The development of each approach involves bench-scale testing of the concepts, design and fabrication of full-scale receivers based on the concepts, and testing of each full-scale receiver on a Test Bed Concentrator. In this paper, the pool-boiler design, current status, and test plans are presented. The design of a bench-scale receiver, recent test results, and implications for the full-scale receiver are also presented.

FULL SCALE RECEIVER DEVELOPMENT PROGRAM

Sandia National Laboratories has designed and begun fabrication on a full scale pool boiler receiver for testing on a $75kW_{th}$ Test Bed Concentrator (TBC). The receiver is designed for proof-of-concept testing, performance evaluation during solar operation, and will also allow comparison with alternate approaches such as the wicked heat pipe receiver. Figure 2 is a cross-sectional view of the receiver attached to the TBC mounting ring. The gas-gap calorimeter used to simulate the engine during the tests is shown schematically. The absorber surface is a 0.032-inch-thick spherical-shell segment with a radius of curvature of 8.6 inches and a base diameter of 16 inches. The relatively-small size permits testing at high heat fluxes in order to establish the limits of the technology. The incident concentrated solar flux is expected to be on the order of 70 W/cm^2 with hot spots as high as 90 W/cm^2. The receiver's small size also permits a sodium inventory of only 12.7 pounds. A minimal inventory is desirable for both cost and safety reasons.

A number of considerations influenced the full-scale receiver design. The first full-scale receiver will be fabricated out of type 316L stainless steel; this material was selected on the basis of availability as well as adequacy for short-term tests [8]. Finite-element stress analysis was used to determine required material thicknesses. In the stress analysis, the high operating temperature and the expected magnitude and radial distribution of the incident heat flux were taken into account. Starting transients were analyzed and the possibility of creep damage was considered. The steady-state stresses were calculated and are acceptable for the short-term (100 hour) tests.

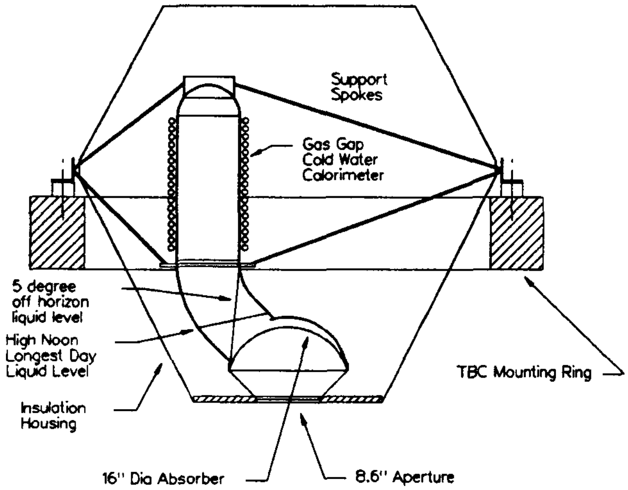

Figure 2. Schematic of the Sandia Pool Boiler Receiver mounted in the TBC mounting ring. The engine is simulated by a gas-gap cold-water calorimeter.

The receiver is designed to operate at 800 °C with a heat input of $75kW_{th}$, for up to 100 hours of on-sun testing. Testing will begin with reduced input power, attained by masking selected mirror facets. The sodium inventory will be electrically pre-heated for the initial tests. The input power will be increased until full power is attained, and then testing will continue for several weeks while performance data is collected. Testing will continue under varying conditions of increasing severity up through solidified cold starts or failure. Conditions will include reduced temperature operation and hot re-starts (cloud transients).

BENCH SCALE TEST MOTIVATION

During the early stages of this program, it became apparent that a number of concerns regarding the full-scale tests could only be settled by experimental means. Foremost among these concerns was the boiling behavior of sodium and its implications for safe operation. After consultations and literature reviews [9], a list of un-answered boiling-behavior questions remained. The basic objectives of the bench-scale test were to answer the following questions:

1. At startup with full solar flux, will film boiling and subsequent heated-surface burnout occur due to the low vapor pressure of sodium below 600 °C?

2. Will the wall temperature before boiling begins (incipient boiling superheat) become objectionably-high, leading to an automatic safety shutdown? Will this happen on cold starts? Will it happen on hot-restarts (i.e., cloud transients)?

3. Once boiling begins, will it remain stable, and if so over what range of input heat flux and operating temperature?

4. If unstable boiling occurs, what simple and inexpensive means will stabilize it? Artificial cavities of various geometries have been proposed and in some cases demonstrated [10,11]. However, their effectiveness over long periods of time and under conditions specific to the pool-boiler receiver is not known.

5. Will rapid wall-temperature fluctuations due to bubble departure result in cyclic-thermal-stress fatigue failure of the heated surface during the short-term tests?

6. Will the boiling behavior deteriorate with time as a result of chemical or thermal effects on the heated surface?

In addition, the bench-scale tests were to determine the suitability of various temperature measurement devices such as infrared pyrometers and different style thermocouples. Operation would also test the control, safety, and data systems for application to full scale tests.

The primary objective was to determine if stable boiling of sodium would occur naturally in the solar receiver, and if not, to determine what special measures would ensure stability. The bench-scale test was judged to be a safer, quicker, and more economical means of answering these questions than proceeding directly to full-scale tests.

BENCH-SCALE RECEIVER TEST

A detailed description of the bench-scale receiver test is given in Reference 9. The five major components of the bench-scale pool-boiler receiver test were the receiver, the heat source, the calorimeter, the data-acquisition system, and the control system. The test setup is illustrated in Figure 3. The test was designed to be similar to the full-scale test in as many ways as practical. Table 1 compares the bench-scale and full-scale tests.

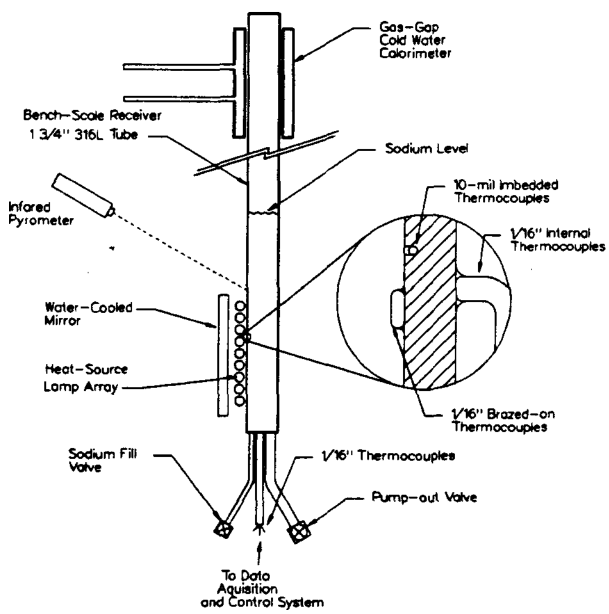

Figure 3. Schematic of the Sandia Pool Boiler Bench Test Receiver. The inset details the thermocouple mounting techniques.

The test was carried out in the Engine Test Facility at Sandia's Solar Test Facility in Albuquerque. The bench-scale receiver was made from a 3-foot-long section of 1.75-inch-diameter, 0.049-inch wall, type-316L welded-seam tubing. The heated area, opposite the seam side, was 1.4-inches wide and 6-inches high, with its lower end 1 inch above the bottom of the tube. Welded to the lower cap were tubing extensions for vacuum pumping, thermocouple feedthroughs, and sodium filling.

Instrumentation on the bench-scale receiver consisted of type-K Inconel-600 sheathed thermocouples mounted internally and externally. The mounting methods used externally were tested in advance in electrical and solar furnaces.

Five 1/16-inch-diameter sheathed thermocouples were used internally and brought out of the bench-test receiver through a brazed feedthrough, detailed in Reference 9. Three of the internal thermocouples were furnace brazed to the wall of the tube. The junction of one was about 4 inches from the top of the tube in the condenser section. The other two were on the vertical centerline of the heated surface, one inch above and below its horizontal centerline. The remaining two internal thermocouples were used to determine the pool and sodium-vapor temperatures: the former was positioned about 4 inches above the bottom of the tube on the tube axis, and the latter was located 18 inches below the top of the tube.

TABLE I.

Comparison of full-scale and bench-scale tests

	Full-Scale Test	Bench-Scale Test
Heat input	Radiant	Radiant
Temperature	800 °C max.	800 °C max.
Heat flux	70-90 W/cm^2	70 W/cm^2 peak
Material	316L stainless steel	316L stainless steel
Wall thickness	0.032 inches	0.049 inches
Pool depth, absorber midpt.	8 inches at a.m. startup; variable through day	7.7 inches
Nearest weld to heated area	1.2 inches	1.0 inch
Thermal inertia	0.17 lbs sodium/kW	0.31 lbs sodium/kW
CHF [12] safety factor	6.3	11.1
Total test time	20 days, 5 hours/day	4 days, 24 hours/day
Thermal cycles	20 minimum	24 minimum

Six thermocouples were furnace-brazed to the external heated surface. Two of the thermocouples were 1/16-inch diameter, flattened to about 1/32-inch thick at the junction. The junctions were positioned on the heated-surface central point and one inch above it. The other four external thermocouples, 0.010-inch diameter, were brazed into four grooves in the heated surface, on one-inch centers symmetric around its horizontal centerline. The junctions were positioned on the vertical centerline, and the sheaths emerged from the grooves outside of the heated area. The exposed sheaths were blanketed with argon. In addition to thermocouples, a solar-blind (8-14μ) infrared pyrometer was used to monitor the receiver wall temperature, to correlate its reading with that of the thermocouples in a high flux environment.

Precautions were taken to ensure that the bench-scale receiver was in a standardized clean condition before filling with sodium. The cleaned receiver was evacuated and baked for 48 hours at 540 °C. The sodium shipping container was heat-soaked under argon cover gas at 150 °C for 48 hours to ensure chemical equilibrium with regard to dissolved oxygen [13]. After the transfer of sodium to the bench-scale receiver, the room-temperature pool depth in the receiver was found to be equivalent to 11.4 inches at 800 °C, using neutron radiography.

Two metal-sheathed electrical pre-heaters were spiral-wound around the bench-scale receiver between the heated and cooled ends. The receiver was initially insulated with a single wrap of 2-inch-thick 6 lb/ft^3 mineral wool. After the initial tests a second wrap was added.

Solar input to the bench test was simulated with nine 1500-Watt 1/2-inch-diameter quartz-halogen lamps mounted horizontally on 0.7-inch centers. The lamp assembly was placed 1/16 to 1/8 inch from the receiver surface. Water-cooled aperture plates defined the sides of the heated area. Thermal analysis [9] has established that the lamps provided an average net flux into the sodium pool of 35 W/cm^2 and a peak net flux along the vertical centerline of 70 W/cm^2.

A water-cooled gas-gap calorimeter [14] was used to remove heat from the bench-scale receiver, controlling its temperature. A mixture of helium and argon flowed through the 0.048-inch gap between the calorimeter and the receiver. By changing the ratio of helium to argon, the thermal conductance of the gap could be varied. A temperature controller sensed temperature at the condenser and varied the gas proportions to maintain a set-point temperature. The calorimeter was 4.5-inches long, and could remove 3.23 kW_{th} from the receiver, with a turndown ratio of 4.25.

The initial bench-scale receiver tests showed that stable boiling in the full-scale receiver could not be expected without special measures to ensure stability. The most extensive studies of the nature and causes of boiling instability in liquid metals are those of Rohsenow and his students [10,11,15] They showed theoretically and experimentally that boiling can be stabilized by natural or artificial cavities in the wetted surface of the heated wall. To ensure stability, the heat flux must be high enough and the cavity
must be deep enough that the temperature at its bottom prevents condensation.

Cavities for boiling stabilization can be formed by several means, including mechanical drilling, electrical discharge machining, and laser drilling. In the present case, a 50-Joule YAG shop welding laser was available. If successful, it would have the advantage of speed and low capital cost, and it would enable cavities to be drilled in the bench-scale receiver without complete disassembly.

A combination of laser parameters was found that produced cavities typically 0.008 inches in diameter and 0.040 inches deep, which, according to the theory, should ensure stability. Using this method, artificial cavities were drilled in the bench-scale receiver. The sodium was distilled away from the heated end of the receiver, which was then filled with ultra-high purity argon. A 1/4-inch diameter hole was opened in the back side opposite the heated surface, using a gas tungsten arc welding torch. Through this hole, a number of laser pulses were fired into the heated surface. Throughout the process, a small flow of argon was maintained.

A cap was then welded over the 1/4-inch hole. The cap included two thermocouples to help determine if the new weld was acting as a nucleation site. If boiling occurred in that area, the input heat would have to traverse the pool, producing an observable temperature difference. The receiver was re-evacuated and the heat-input end was baked under vacuum.

RESULTS

Initial Test

The primary objective of the initial tests was to establish whether the baseline pool boiler would initiate and maintain stable boiling in a safe condition.

Figure 4 shows a sample of the boiling-behavior data for several thermocouples. The brazed thermocouple is on the exterior wall, the imbedded thermocouple is a 0.010-inch sheathed thermocouple imbedded in the wall, and the other two are in the sodium pool and the vapor space. The boiling is not stable. Short periods of "stable" boiling are followed by complete and abrupt failure to boil. When boiling stops, the wall and pool temperatures climb, while the vapor temperature drops. When sufficient superheat is attained, boiling begins again, sometimes violently enough to shake the entire test apparatus. Typical temperature excursions were about 100 °C. Often, as shown at the end of this plot, the superheat was sufficiently great to cause an automatic safety shutdown before boiling re-started. The plot also shows the power extracted at the calorimeter. No change in boiling characteristics was noted during the duration of the 4-hour test and subsequent testing.

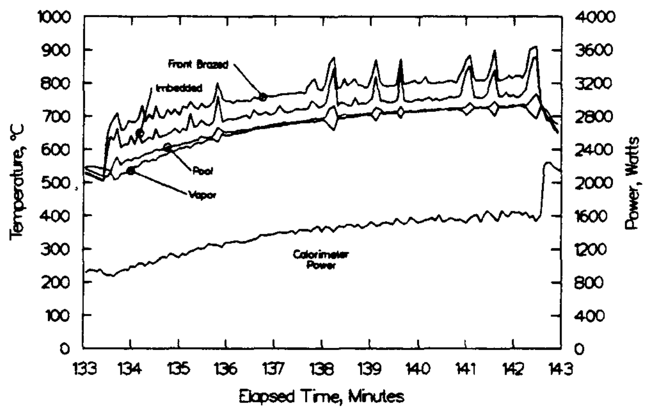

Figure 4. Typical temperatures and calorimeter power during unstable boiling.

When the test setup was dis-assembled after the initial tests, it was discovered that two adjacent center lamps had failed. During the initial tests the lamp current was not monitored, so that it was not obvious when the lamps failed. A review of the data shows extracted power levels consistent with the two lamps being off throughout the test, so it is likely that they failed during one of the first unstable starting transients.

Cavity Stabilization Tests

The primary objective of the stabilization tests was to determine whether the addition of artificial cavities resulted in stable boiling of the sodium. A secondary objective was to prepare the data/control system for safe unattended operation.

Figure 5 shows a typical startup from room temperature. A single "bump" (incipient boiling superheat) was usually seen around 600 °C, followed by stable boiling as temperature rose to 800 °C. The particular data shown here shows two minor bumps during startup. Once boiling began, the vapor temperature continuously tracked the pool temperature, and no evidence of instability was noted. The vapor temperature was typically about 2 °C lower than the liquid temperature. Figure 6 shows the 4 imbedded-thermocouple temperatures arranged in the same sequence as their physical locations. The artificial cavities are between the top-two imbedded thermocouples. The temperature fluctuations are greatest at thermocouple #4, furthest from the cavity. However, these fluctuations are only about 10 °C.

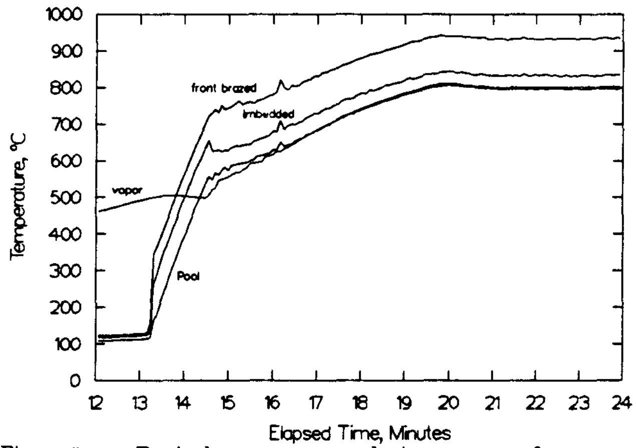

Figure 5 Typical temperatures during startup from room temperature after cavities were added to the device. Two small "bumps" occur before the operating temperature is reached, but boiling is stable thereafter.

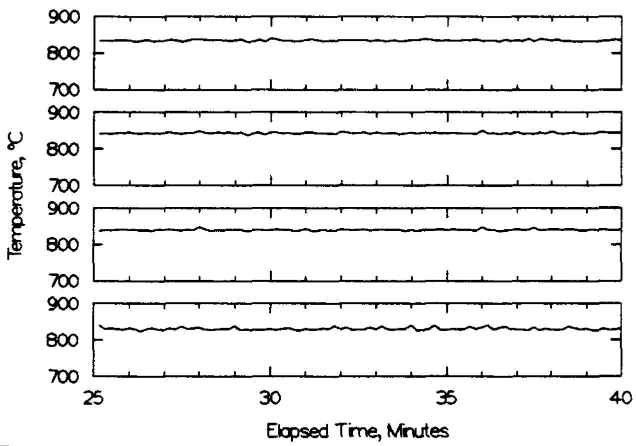

Figure 6. Imbedded thermocouple temperatures during stable boiling. The sequence shown here matches the physical layout. The cavities are between the top two thermocouples.

The test was run for 2.5 hours with no change in performance. The test was concluded with a short run at 700 °C, with no change in stability detected. The liquid-to-vapor superheat at 700 °C was typically 7 °C, due to the lower vapor pressure and therefore higher velocity and pressure drop in the vapor flow to the condenser.

Another run of 4.5 hours was performed to tune the automatic control system in preparation for unattended operation. Automatic control was verified for various lamp-power settings and system disturbances.

100-Hour Test

The objective of the 100-hour test was to simulate 1 month of on-sun testing to determine effects on stability and materials. The test was run for 4 days, around the clock, with un-attended operation overnight. Twenty shutdowns were performed during attended operation to simulate daily transients.

Figure 7 shows a pool temperature, representing the entire period of testing. A complete set of data plots for this test and samples from the earlier tests are presented in reference 9. Note that the small temperature overshoot at 800 °C was due to the PID controller characteristics, rather than the sodium boiling characteristics. No significant changes in performance were noted during the duration of the test or during any of the startup sequences.

The periodic shutdowns were performed only during normal work hours. The power was returned to the lamps when the pool reached approximately 200 °C. Several shutdowns resulted in lower temperatures or even freezing during periodic equipment maintenance performed during the shutdowns. The normal shutdowns lasted approximately 20 minutes.

Followup Tests

Three followup tests were performed after the completion of the 100-hour test. The objectives of these tests were to 1.) Determine the hot-restart (cloud transient) behavior, 2.) Determine reduced power stability, 3.) Determine reduced temperature stability at full and partial power, and 4.) Verify that the cavities were the stabilizing influence in the system.

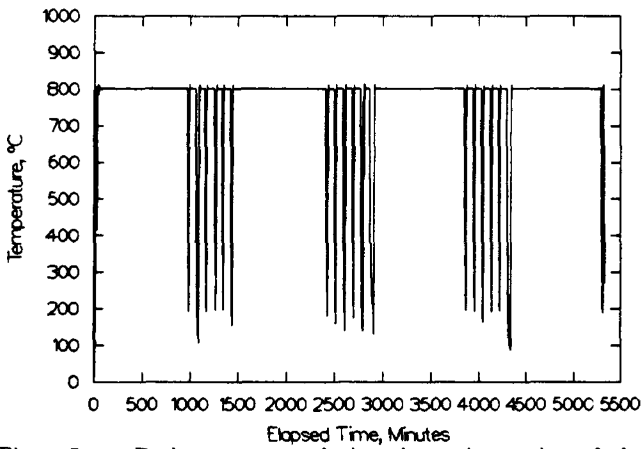

Figure 7. Pool temperature during the main portion of the 100-hour test. Transients to "room temperature" occurred only during the daytime.

Each hot-restart test was begun by shutting off the lamps completely. The lamps were turned back on when the pool reached a pre-selected temperature. The first temperature selected was 775 °C, and was decreased by approximately 25 °C each test. The first few shutdowns showed no bump during the re-start, indicating that boiling had never stopped, or at least that all nucleation sites had not been quenched. When the pool temperature was allowed to reach anywhere from 720 °C to 680 °C, the restart resulted in a wall superheat sufficient to cause a safety shutdown before boiling was re-initiated. Figure 8 details selected thermocouple readings for one such test. Note that during the first re-start, the condenser temperature never responds, indicating that boiling has not initiated. Pool temperature excursions below 680 °C resulted in restarts that had a single bump at a safe wall temperature.

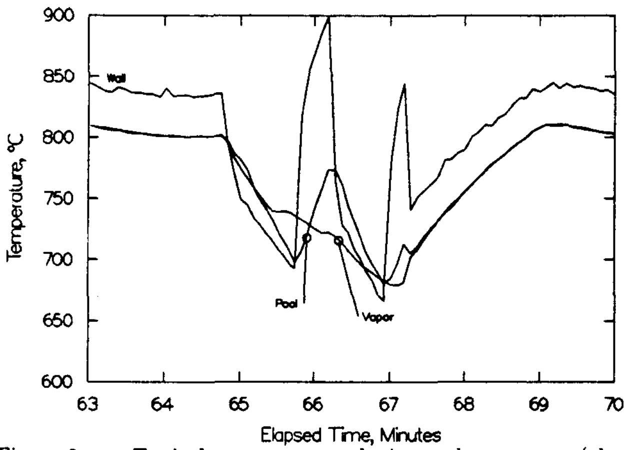

Figure 8. Typical temperatures during a hot restart (cloud transient). The first attempt at re-starting resulted in an over-temperature shutdown before boiling could start.

The theory outlined in Reference [9] based on Rohsenow [11] predicts that the stability of nucleate boiling is decreased by reductions in either temperature or input power. Over the range of values explored in the present case, this effect was not large. The results are presented in Figure 9.

The lamp electrical current was successively reduced from 100 to 88, 73, and then 65 percent on five-minute intervals, while the heat rejection was controlled to maintain temperature. At the lowest lamp power, the set-point temperature could no longer be maintained. Next, the set-point temperature was changed to 700 °C. Again, the lamp electrical current was varied, first back up to 100 percent, and then down to 57 and finally 52 percent.

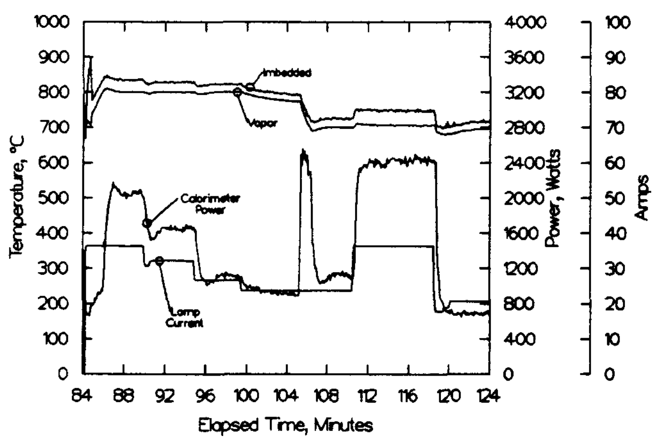

Figure 9. Temperatures, lamp current, and calorimeter power during the low-power and low-temperature tests. Boiling remained stable throughout operating regime.

Figure 9 shows the current supplied to one of the phases of the lamp-array. The vapor temperature is also displayed in Figure 9. The two periods when power was not sufficient to maintain the set-point temperature are clearly evident. The next-largest temperature variations are the overshoots corresponding to imperfect calorimeter control. The temperature indicated by imbedded-thermocouple number 1 is also presented in Figure 9. The magnitude of the temperature fluctuation at this thermocouple does not change noticeably as power is reduced at 800 °C. However, when the temperature is reduced to 700 °C, the fluctuation is seen to increase in magnitude, and some sensitivity to power level is apparent. As in all of the other data, the fluctuation in temperature was progressively greater for imbedded thermocouples 2, 3, and 4 (not shown here).

Finally, the power extracted by the calorimeter is given in Figure 9. The large spike that occurs just after the set-point temperature was adjusted down to 700 °C corresponds to transient extraction of stored energy. Also as expected, the extracted power is greater at 700 °C than at 800 °C for the same lamp power, because the thermal parasitics decrease with the temperature.

In the final followup tests, the heat flux at the artificial cavity area was reduced or eliminated by first removing lamps and finally shielding the area with a water-cooled tube.

After 3 lamps were removed, several bumps were noted during startup, but the boiling was stable at 800 °C. Next, a water-cooled tube was inserted in the lamp holder in place of one lamp to shield the cavity area from the lamp flux. Again, significant instabilities were noted during startup, but stable boiling was observed at 800 °C. A sheet-copper extension was torch-brazed to the shield and contoured to ensure that no light fell on the cavity area. Figure 10 shows the temperature as indicated by imbedded-thermocouple number 4. This data was taken during the final test, when the cavities were most effectively shielded.

Post Test Analysis

The objective of the post test analysis was to determine the effects of operation on the materials.

The results of the metallographic examination showed no significant changes in material properties. No significant changes were noted in the heated wall topography or microstructure and no embrittlement due to fatigue was noted. One feedthrough tube and weld was embrittled due to intermetallic precipitation at grain boundaries. One crack was found in a puddle of braze material, but was determined to have occurred during the brazing operation.

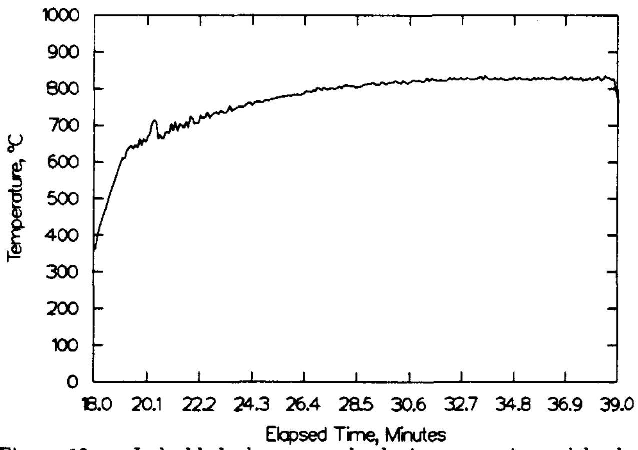

Figure 10. Imbedded thermocouple during operation with the cavity area shielded from all flux. The startup transient shows signs of instability, but boiling is stable once operating temperature is reached.

DISCUSSION AND CONCLUSIONS

A full-scale sodium pool-boiling solar receiver has been designed and is under construction. A proof-of-concept test plan has been written and preparations are nearly completed for the actual test. The test will explore the limits of the technology by proceeding in stages to progressively harsher operating conditions. Concerns about safety and control prompted the formulation of a bench-scale receiver test. The primary objectives of this test were to determine what modifications to the receiver design, if any, would be necessary to ensure stable boiling, and to prove the adequacy of safety systems.

The initial bench-scale tests showed that stable boiling could not be expected in the baseline boiler design. The magnitude of the temperature excursions, the impossibility of automatic control, as well as the observed vibrations and material deformation made clear that this mode of operation was unacceptable. At the same time, it was encouraging that the experiment did not result in wall burnout, and that the emergency control systems would be adequate even during unstable boiling. Based on the results of the initial tests, it was decided to add artificial cavities to the benchscale receiver.

After the artificial cavities were added to the receiver, the 100-hour test was run. The results of this test suggest that stable boiling should be achievable by making at most minor changes in the original design of the full-scale receiver. After each startup transient was passed, stable nucleate boiling was observed. Wall-temperature fluctuations were smallest near the site of the artificial cavities, suggesting that the cavities were functioning as expected.

The 100-hour test also demonstrated that the instrumentation, control and data acquisition systems that were used will be adequate for the full-scale test. Flattened Inconel-sheathed thermocouples brazed to the receiver absorber surface will have adequate lifetime. The thermocouples and the solar-blind infrared pyrometer have been shown to be accurate enough in the high flux region for the emergency-shutdown control system.

Instability during the starting transient was routinely observed. It was manifested as wall temperatures considerably in excess of that required for stable nucleate boiling, with a rapid drop usually occurring when the pool temperature reached 600 to 650 °C. The followup tests showed that the starting-transient instability is sensitive to conditions immediately prior to the application of input heat. The highest wall temperatures were observed during "hot restarts" in which heat was re-applied when the pool temperature had fallen to the range 680 to 720 °C. This will have an impact on how a full-scale receiver is controlled during cloud transients and it may impact receiver lifetime.

The followup tests also demonstrated stable boiling at every condition that was tried. Wall-temperature fluctuations did not change noticeably at 800 °C as peak net heat flux into the sodium was reduced from 70 to 48 W/cm^2. When the wall temperature was decreased to 700 °C, fluctuations increased slightly. This is expected, since stability is predicted to decrease with decreasing temperature.

During tests to verify that the cavities were responsible for boiling stability, boiling always stabilized as the set-point temperature was approached. This suggests that other stabilizing influences were present. Any such influences could not have been operative in the initial tests when boiling was unstable. Two possibilities have been considered: an increase in oxygen content during the laser drilling, and the (previously noted) braze-puddle crack. Oxygen content increase during drilling is estimated to be at most a few ppm; since the quantitative effect of oxygen on stability is unknown, no conclusion can be drawn. The braze-puddle crack was located in a low heat-flux area in the initial tests because two adjacent lamps were out. Thus it should have been ineffective in the initial tests, yet may have been operative in the final tests. Unfortunately, its dimensions were too small to be effective, unless enhanced, perhaps by the diffusion of noncondensable gas into it from the wall material [15]. In summary, no additional stabilizing influences have been positively identified. Additional discussion can be found in Reference 9.

The post-test analysis showed that no significant changes had occurred in the heated surface during the 100 hours or more of testing. The dimensions of the deepest laser-drilled cavities were not determined because of loss of a specimen. We estimate that the deepest cavity was 0.01-inch deep and 0.01-inch in diameter.

The observation of embrittlement in some of the parts incidental to the boiler body will impact plans for the full-scale receiver test. The material, type 316L stainless steel, has never been contemplated for long-term application at 800 °C in the present program, but was believed to be adequate for short-term tests [8]. As a result of the present findings, high-temperature testing and analysis of a full-scale mockup already fabricated will be carried out, and the findings will be applied to the full-scale receiver before it is charged with sodium.

The design, construction, test, and post-test analysis of the bench-scale receiver have resulted in the following conclusions:

1. The baseline design of the full-scale receiver will probably result in unstable boiling.

2. The addition of an array of artificial cavities with nearest neighbors within 4 inches should stabilize the baseline design.

3. The automatic safety shutdown system used in the bench-scale test should prevent excessive overtemperatures even if the full-scale receiver experiences unstable boiling.

4. Optimal hot-restart temperatures, minimizing incipient-boiling superheats, were observed in the bench-scale tests, and should be determined for the full-scale receiver in order to extend lifetime and facilitate automatic control.

5. Lifetime of brazed-on sheathed thermocouples, using the techniques tested here, should be adequate for the full-scale test.

6. The use of 316L stainless steel in the full-scale test dictates that special attention be paid to the possibility of material and weldment embrittlement. High-temperature testing and analysis of a mockup of the full-scale receiver will be carried out before tests with sodium are begun. Test time will be limited to 100 hours.

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