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# Test Results from a Full-Scale Sodium Reflux Pool-Boiler Solar Receiver

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## ABSTRACT

A sodium reflux pool-boiler solar receiver has been tested on a nominal 75-$kW_t$ parabolic-dish concentrator. The purpose was to demonstrate the feasibility of reflux-receiver technology for application to Stirling-engine dish-electric systems. In this application, pool boilers (and more generally liquid-metal reflux receivers) have a number of advantages over directly-illuminated tube receivers. The advantages, to be discussed, include more uniform temperature, which results in longer lifetime and higher temperature available to the engine. The absorber in the present case was a $70^{o}$-half-angle spherical segment with an 8.63" radius, positioned behind an 8.65"-diameter aperture. The relatively-small size of this receiver, which minimized thermal losses, fabrication costs, and sodium inventory, was possible because of its excellent internal heat-transfer characteristics. The receiver was instrumented both externally and internally with thermocouples, and externally with an infrared pyrometer. A microphone was used to monitor boiling sounds. A water-cooled gas-gap calorimeter was used to thermally load the receiver and to determine the power that would be available to an engine. Planned tests were run at sodium temperatures up to $800^{o}C$ and receiver-input power levels as high as 67 $kW_t$. Input power as a function of direct normal insolation was determined calorimetrically during pre-test characterization of the concentrator. At maximum input power, the peak in the solar-flux distribution on the absorber was calculated to be 73 $W_t/cm^2$. Receiver efficiency was about 90% when the input power and sodium temperature were at their maximum tested values. To promote stable boiling, the receiver design included 35 equally-spaced artificial cavities in the absorber wetted surface. In all of the tests, stable boiling was always observed. Under certain conditions during both real and simulated cloud transients, very-high incipient-boiling superheats were observed. It was found that this behavior could be suppressed either actively, by momentarily increasing the thermal load on the receiver, or passively, by the addition of a small amount of xenon into the boiler. The paper that follows presents the reflux receiver program background, design, test details, results, and future plans.

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## INTRODUCTION

An important element in the U. S. Department of Energy's Solar Thermal Energy program is the development of Stirling-engine dish-electric systems [1]. These systems have been identified as having the potential to meet the program's long-term goal for levelized energy cost [2]. A notable example of this technology is the

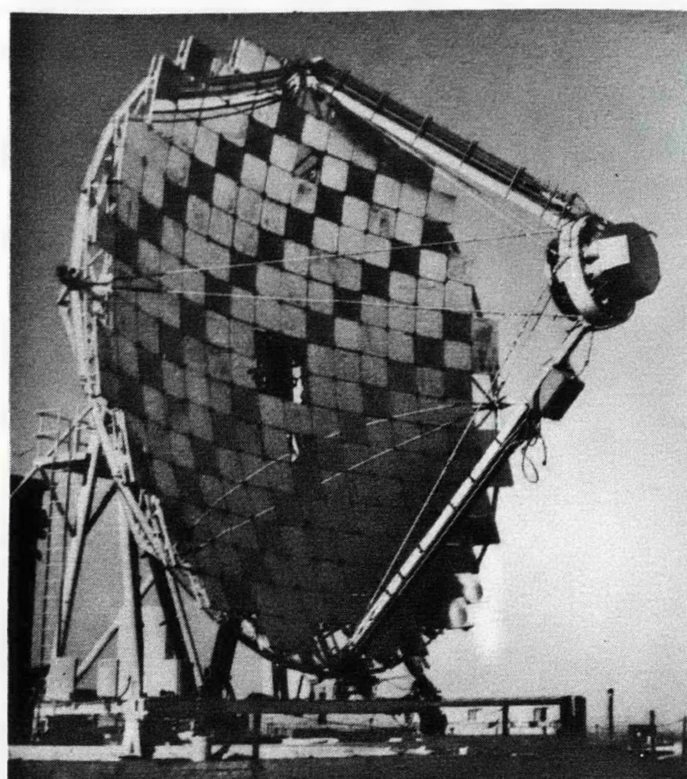

Figure 1. Photograph of test bed concentrator (TBC) with Sandia Reflux Pool-Boiler Receiver mounted in insulation housing at the focus. The TBC is configured for 3/4-power test.

Advanco-Vanguard module, which in 1984 demonstrated a peak gross conversion efficiency of 31.6% while operating at an engine gas temperature of 760°C [3]. One drawback of the Advanco-Vanguard module was that the engine heater-head tubes were directly illuminated by focused sunlight. The resulting non-uniform temperature distribution has been calculated to adversely affect creep life, thereby limiting lifetime, performance, and costs [4]. Other drawbacks of tube receivers have been suggested. For example, it is unlikely that any choice of tubing dimensions and layout can simultaneously optimize both receiver and engine performance. Also, it would be difficult to hybridize the tube receiver (adapt it to use both solar and fossil-fuel energy), in part because the burner would have to be incorporated into the receiver cavity.

The liquid-metal reflux receiver was conceived as an improvement over directly-illuminated tube receivers [5]. In this approach, liquid metal is evaporated at the solar absorber and condensed at the engine heater tubes, supplying latent heat of vaporization to the engine. The liquid at the absorber may be a pool that floods the surface, or it may saturate a wick that covers the surface. The condensate is returned to and distributed over the absorber by gravity, wick capillary forces, or a combination thereof. The reflux receiver has the important advantage over tube receivers of nearly-isothermal operation even though the incident solar-flux distribution is nonuniform. Also, the excellent heat-transfer characteristics of the liquid metal allow a very small receiver, and therefore minimize air-convection 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.

Various liquid metals have been considered for use in the reflux receiver, including sodium, potassium, NaK-78 (a mixture of sodium and 78 wt. % potassium, having a freezing point near -12.6°C), and other mixtures. The choice of metal will be dictated mainly by design temperature and pressure, cost, boiling characteristics, and operating convenience. For example, if operation at a pressure below atmospheric at 800°C is desired, then sodium would be dictated. Sodium is also less expensive than potassium or NaK-78. On the other hand, theory indicates that boiling stability should be easier to achieve with potassium or NaK-78. This becomes more important as the design temperature is lowered because stability becomes more difficult. NaK-78 also offers the convenience of using a heat transfer fluid that does not freeze at room temperature.

A dish-electric receiver-development program based on the reflux receiver concept was initiated at Sandia National Laboratories in early 1988. The Sandia program evolved out of earlier efforts and complements several programs underway in industry and at other laboratories. The technology background and the various programs were reviewed in Reference 6. Sandia's reflux-receiver program is currently evaluating both the pool-boiler and the wicked-absorber (heat pipe) concepts introduced above. The pool-boiler receiver is simple and robust but uses a larger quantity of liquid metal. Uncertainty is introduced by the poor state of knowledge regarding the boiling behavior of liquid metals and its effects 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 receivers introduces new elements that will require attention, including the unique geometry and the large vertical and areal extent of the heated surface.

Sandia's two competing receiver concepts are being developed to transfer 75 $kW_t$ 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 on-sun testing of each full-scale receiver. Following full-scale tests, the most promising approach will be chosen for further development, including hybridization.

At the time of this writing (autumn 1989), bench-scale testing of the heat pipe concept is in progress. Bench-scale testing of the pool-boiler concept was completed in early 1989 and the results have been documented [7,8]. Subsequently, design and fabrication of a full-scale pool-boiler receiver have been completed, and all goals of its on-sun test plan have been successfully met. Figure 1 shows the receiver in its housing mounted at the focus of Test Bed Concentrator #1 (TBC-1) at Sandia National Laboratories' Solar Thermal Test Facility. In this paper, the receiver design and test details will be described, results presented and discussed, and future plans outlined. A more detailed account can be found in Reference 9.

## POOL BOILER DESIGN

Figure 2 is a schematic of the pool-boiler receiver mounted in its support structure on the TBC mounting ring. The absorber consisted of an 8.63"-radius spherical dome with a 70° half angle. The rim diameter was 16.3". 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. The gap dimension was 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. When the return flow is prevented, the condition is called the "flooding limit". The remainder of the receiver was a condenser section of 304L stainless steel 8" pipe designed to mate with a gas-gap cold water calorimeter for power extraction. The receiver sodium inventory was 12.7 pounds, which at operating temperature flooded the entire absorber surface in all orientations. Electrical pre-heaters were spot-welded to the aft dome to permit the sodium to be melted before each test. The same absorber geometry will be used for a heat pipe receiver, allowing direct comparison of the two approaches.

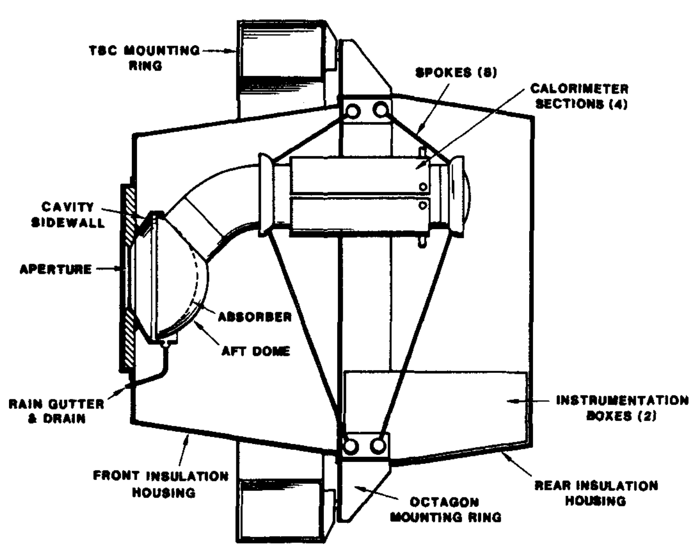


Figure 2. Schematic of the Sandia Reflux Pool-Boiler Receiver.

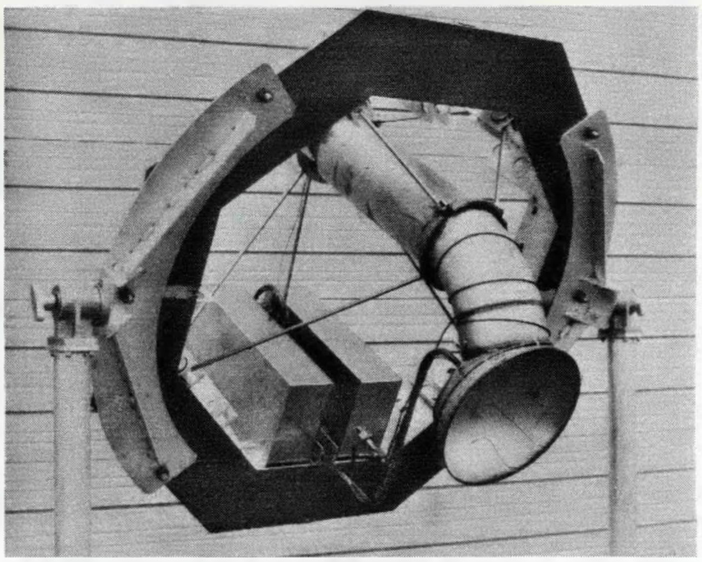

Figure 3. Photograph of the Sandia Reflux Pool-Boiler Receiver in its octogon support ring.

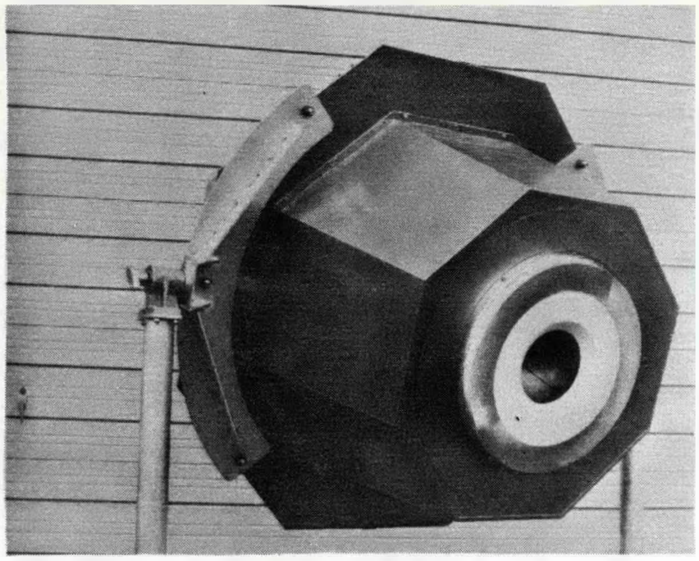

Figure 4. Photograph of the Sandia Reflux Pool-Boiler Reciever in its insulation housing.

The mounting structure featured a "spoke and hub" arrangement that permits precise positioning of the receiver while minimizing conduction losses. It is also capable of supporting a wide variety of receiver sizes and geometries. Photographs of the pool boiler receiver in the octagon 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 insuring virtually no conduction heat loss except near the receiver's aperture. The receiver cavity was formed by the spherical absorber and a stainless-steel conical-sidewall section. The conical sidewall was supported by the front insulation housing and held a 2"-thick Fiberfrax 3000 alumina-silica insulation board with an 8.65"-diameter aperture. The aperture and sidewall divergence angle were greater than the rim angle of the TBC to avoid direct solar flux on the sidewall. The conical sidewall included a rainwater collection gutter and drain tube just behind the rim of the spherical absorber. The insulation housing was sealed with weather stripping, tested, and found to be rain-tight.

Figure 5 shows the incident solar flux distribution on the absorber surface, as predicted by CIRCE2, a new version of the computer model CIRCE [10]. The distribution is highly non-uniform, which is typical. It illustrates why, if thermal stress is to be minimized, a receiver with excellent heat transfer characteristics is necessary. The design peak flux was calculated to be about 73 $W_t/cm^2$ at a total power of 75 $kW_t$. Since the performance of TBC-1 was found to be severely degraded as a result of mirror corrosion, it was decided to place the absorber approximately 0.79" closer to the focal plane than was assumed in the calculation. The opposite effects of this displacement and the degraded mirrors resulted in approximately the same predicted peak flux but lower flux levels near the absorber rim. Lower flux near the rim was desired because of concern that cooling by the sodium would be least effective in the narrow gap in that area.

Stress analyses were performed on the receiver design considering both startup and operating thermal and pressure stresses. Where needed, approximations to the actual temperature distributions were used. The calculated startup stress was greatest at an absorber temperature of

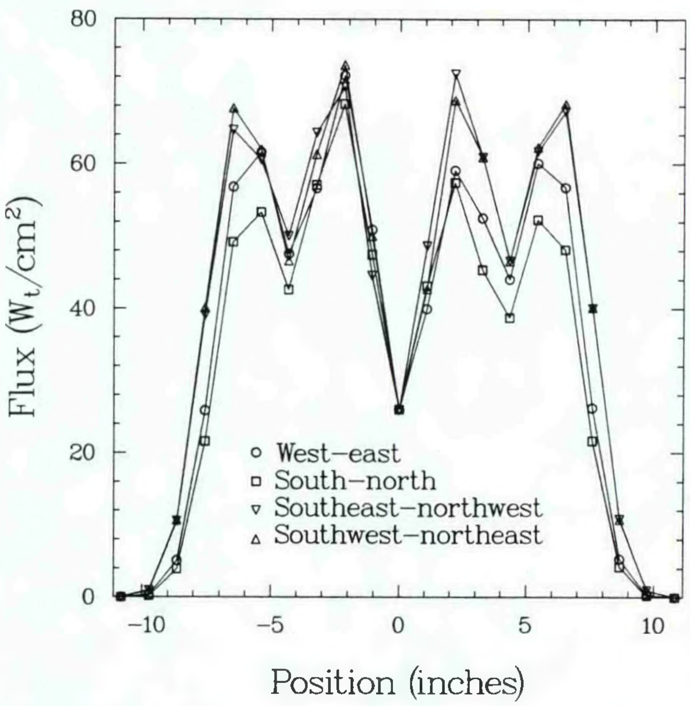


Figure 5. Design incident solar flux on the Sandia Reflux Pool-Boiler Receiver as calculated by CIRCE2. Flux distribution as a function of position along bisectors of the absorber is shown for four compass directions as viewed from concentrator. Negative positions correspond respectively to west, south, southeast, and southwest of the center of the absorber.

550°C. A peak in the stress distribution was found near the rim, amounting to about 10,000 psi in bending. A second peak of nearly 12,000 psi in bending was found 6.4" out from the center as measured along the surface. This larger stress is just under 80% of the yield stress of 316L stainless steel at 550°C. During steady operation, the tensile stress caused by differential pressure across the absorber dome was calculated to be 1,325 psi. The combination of pressure stress plus 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 2/3 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 were 0.006" in diameter, 0.02" deep, and spaced approximately 4" apart, electric discharge machined (EDM) into the sodium side of the formed dome. The stress concentration in the vicinity of the cavities has been considered. During startup it will be about 15,000 psi in the worst case at 550°C, close to the yield strength of 316L stainless steel at that temperature. During steady operation at 800°C, the stress concentration associated with pressure loading will be about 4,000 psi, well below the yield strength of 316L stainless steel, and approximately the value for creep to rupture in $10^4$ hours. The stress concentration associated with bending will be about 12,000 psi, just under the yield strength of 316L stainless steel at 800°C. In summary, the stress analyses indicated that the design would be adequate for short-term testing, but that further development would be required for a long life receiver.

The receiver domes were hydroformed and then annealed at 1090°C for 15 minutes in vacuum. 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. Using a helium leak detector, no response to helium was seen in the $10^{-9}$ cc/sec range.

Before the receiver was assembled, concerns arose about the suitability of 316L stainless steel at elevated temperatures. It has been shown that complex carbides and intermetallics can precipitate at the grain boundaries within 100 hours at 800°C in 316L, lowering the ductility and toughness. The precipitation rates depend on the prior history of the metal as well as its exact composition [7]. Samples of the welds and materials were taken from a mock-up of the receiver and baked in air for 100 hours at 800°C. The strength was then measured and compared to un-baked samples. Only the weld that joined the aft dome to the 8" pipe showed a significant change, amounting to a 50% loss of strength. Because the joint strength was far in excess of the expected load, this was not a concern. The tests determined that the use of these 316L parts was suitable for limited testing, but that further materials evaluation would be required before long-term receiver operation.

After assembly, the receiver was vacuum-baked at 600°C for 48 hours. A long-term leakup test indicated an acceptable leak rate of less than $2 \times 10^{-8}$ cc/sec. 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.

Using the defined-volume procedure described in Reference 7, sodium was added to the reciever. The sodium level in the receiver was confirmed radiographically.

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

## TEST DETAILS

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 filler metal. They were brazed to the absorber along their entire length to prevent failure from the high incident flux. Using the same pattern, nine 1/16"-diameter 316L-stainless-steel sheathed thermocouples were brazed to the rear surface of the absorber with BNi-3. These were brought out of the receiver via a brazed feed-through. Additionally, 3 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 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. Its purpose was to detect hot spots not detected by the thermocouples. A microphone was attached to a support spoke to monitor boiling sounds. Pressure switches and transducers monitored helium and argon gas pressures and flows. All of the instruments were read and recorded using the site data acquisition system, based on an HP 9845 computer and an HP 3497 data system. The maximum scan rate for the entire set of data was about 10 seconds. Additionally, selected thermocouples, the flowmeters, and the pyrometer were scanned by the control/safety system.

The control/safety system consisted of another HP 9845 computer and HP 3497 data system. This computer was used to quickly scan a selected set of data and compare them to preset limits. If a limit was exceeded, the receiver shutter was automatically closed. The scan rate was approximately 3 seconds. The most critical temperatures and the pyrometer were read and displayed by digital displays with built-in limit alarms, 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 recorded on stripcharts.

An automatic system was used to control receiver temperature by regulating the calorimeter gas-gap mixture of argon and helium. An LFE-brand proportional-integral-derivative temperature controller was used to compare the set-point temperature to the temperature indicated by one of the condenser thermocouples. The controller output was a 0-5 volt signal, sent to a mass-flow gas-control valve that regulated the supply of argon to the calorimeter. The signal was also "inverted" (subtracted from 5 volts) and sent to a similar gas-control valve for helium. The controller was tuned to provide fast response to cloud transients with a minimum of overshoot.

Prior to receiver testing, TBC-1 performance was characterized with a steady-flow cold-water calorimeter [12]. In order to accurately quantify the incident power available to the receiver, the steps described below were taken.

Accurate flow and temperature measurement devices were utilized and checked for calibration. A 20-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. A turbine flow meter made by Flow Technologies, Inc. and calibrated with an uncertainty of no greater than ±1%, was used to measure water flow rate. Flow rates were periodically checked with a bucket, scale, and stopwatch and were always found to be within specification.

Calorimetry was performed over a range of mirror cleanliness conditions and for the half, three-quarter, and full power conditions used in the reflux pool-boiler receiver tests. Multiple tests performed over a period of weeks indicated that performance measurements were repeatable, independent of water flow rate, and not significantly affected by 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. Tests with the aperture removed indicated only a 300 $W_t$ difference in collected power.

Consistency was maintained between cold-water calorimetry and receiver testing. The same flow, temperature, and insolation measurement devices were used in both sets of tests. Identically-shaped apertures positioned in the same location were utilized. The water-cooled aperture shield and shutter used in both sets of tests were maintained in the same location.

The absolute uncertainty in TBC-1 power 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, is dominated by uncertainties in mirror cleanliness and was estimated to be ±1 $kW_t$ for these tests.

## TEST RESULTS AND DISCUSSION

Eight separate tests of the receiver were run between August 31 and October 19, 1989, for a total of 34 hours at or above 700°C.

The objective of tests 1-3 was to demonstrate well-behaved boiling at 1/2, 3/4, and full power. The power was attenuated by covering selected mirror facets on TBC-1. Figure 1 shows the mirror coverage for the 3/4-power test. Two specific concerns in these initial tests were boiling instabilities and flooding limits [7]. Test #1 totaled 96 minutes at 1/2 power, with eight minutes of steady operation at 800°C condenser temperature. Pure argon was used in the calorimeter gas gap, so temperature varied with insolation. In tests 2 and 3, the gas mixture was automatically controlled, and nearly all test time was at 800°C. Time totaled 204 minutes at 3/4 power and 180 minutes at full power. Figure 6 shows extracted power and temperatures measured during the full-power test. Receiver efficiency was about 90% when the input power and sodium temperature were at their maximum tested values. The temperature measurements show that temperature was quite steady and nearly isothermal within the receiver. This steadiness and uniformity indicate that stable nucleate

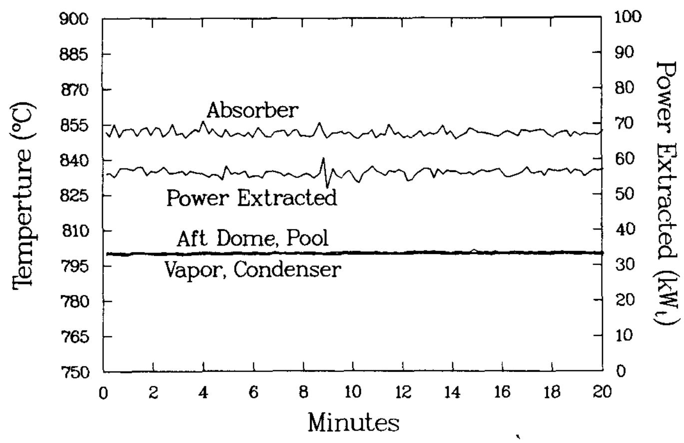


Figure 6. Temperatures and extracted power the during full-power run.

boiling was achieved. The absorber temperature shown was taken 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 1/2 and 3/4 power, and in brief runs at 700 and 750°C at 1/2 and full power.

Figure 7 illustrates the temperature distributions along vertical and horizontal diameters of the absorber during startup and near steady state, at full power. The temperatures are as 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

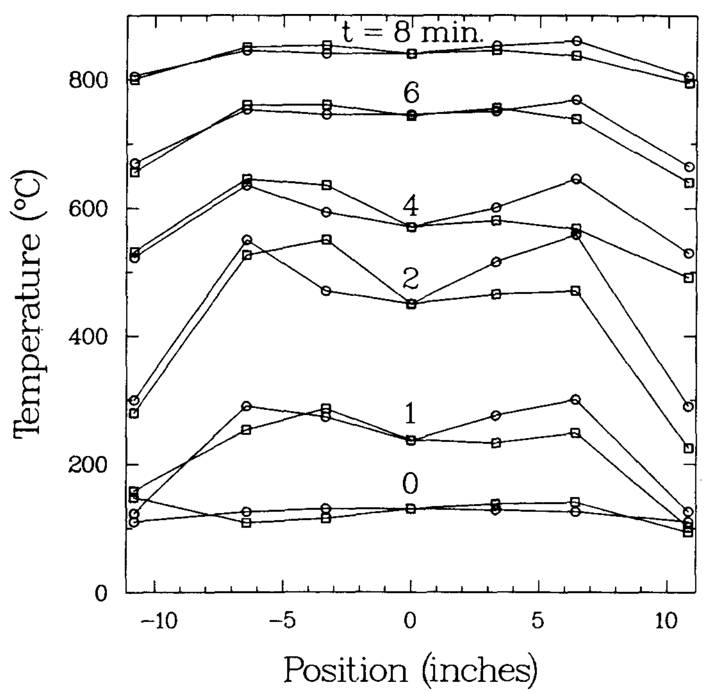


Figure 7. Temperatures indicated by thermocouples brazed to the air side of the absorber along the horizontal (circles) and vertical (squares) bisectors. The abcissa has the same meaning as in Figure 5.

conduction and convection tend to moderate the effect of the flux non-uniformities, resulting in relatively-uniform temperatures even during startup. The 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.

The objective of tests 4 and 5 was to study the "hot restart problem" identified during simulated cloud transients in earlier 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 8. 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 will now be 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 not into the calorimeter gas gap, but rather 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. 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 while the hot restart problem still could not be repeated. Typical results are presented in Figure 9. In contrast to the cycles shown in Figure 8, 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 last test in the series was run to determine behavior over the full range of receiver orientations for a typical day, and to collect data for comparison with existing performance models. The detailed comparisons will be presented in Reference [9]. The test was run on a clear day with operation nearly from horizon to horizon. Figure 10 shows power levels and representative temperatures for

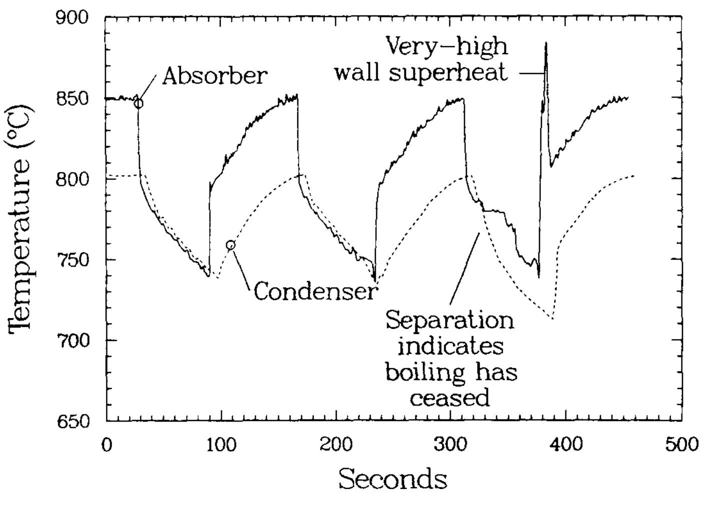


Figure 8. Shutter-simulated cloud transient data before xenon addition.

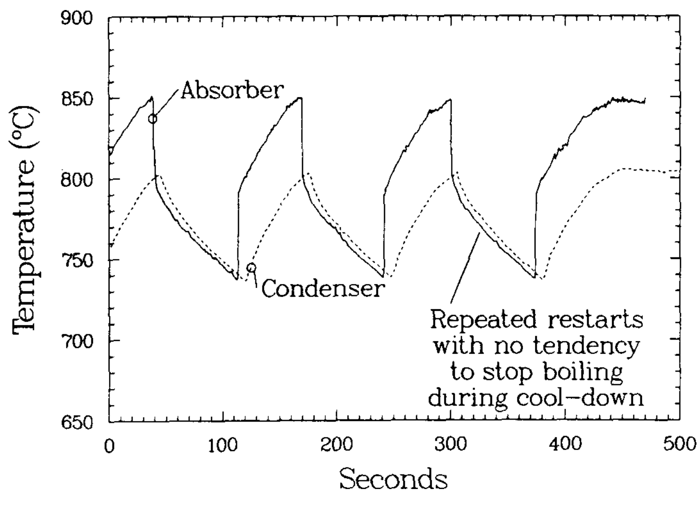


Figure 9. Shutter-simulated cloud transient data after final adjustment of xenon addition.

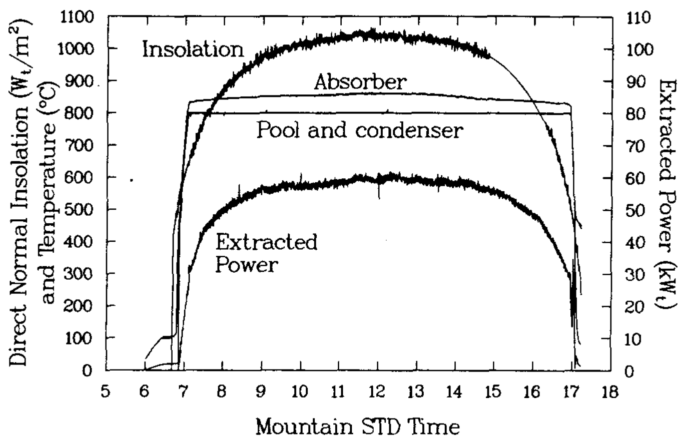


Figure 10. Direct normal insolation, temperatures and power levels during an all-day test. Insolation measurements between 1500 and 1620 hours were blocked by an adjacent structure, and are estimated here in order to calculate receiver efficiency. The receiver daily efficiency on this day was about 89%.

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.

Further tests are planned to characterize receiver performance. Also, x-ray cinematography will be attempted during operation to observe bubble sizes, active nucleation sites, void fraction, and the free surface in the pool. This information will be used to decide if the current vapor-flow clearances in the boiler have adequate safety factors and if there are too few or too many artificial cavities. Additionally, an infrared camera will be used to observe the temperature distribution over the absorber surface. This information will supplement the thermocouple and pyrometer measurements.

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 possible materials and methods improvements that have been identified. For example, alternatives to 316L stainless steel are being considered that do not have the embrittlement problem mentioned earlier. The boiling behavior on the selected material will need to be checked. 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. Again, its boiling behavior under the conditions of interest will have to be determined. Finally, it is planned to investigate methods of boiling stabilization that might be less costly to implement than EDM artificial cavities. Possibilities range from laser-drilled holes and sintered-powder coatings to the addition of xenon to a boiler having no surface modification.

Once the material and methods for the next-generation 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, and long-term stability of the boiling itself.

## CONCLUSIONS

1. Stable boiling was achieved at all power levels in the temperature range investigated - from 700 to 800°C (a total of 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 followed 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 seen during over 34 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 at the end of a full day of clear-sky operation was about 89%.

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