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United States Department of Energy Solar Receiver Technology Development*

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ABSTRACT

The United States Department of Energy (DOE), through Sandia National Laboratories, has been conducting a Solar Thermal Receiver Technology Development Program, which maintains a balance between analytical modeling, bench and small scale testing, and experimentation conducted at scales representative of commercially-sized equipment. Central receiver activities emphasize molten salt-based systems on large scales and volumetric devices in the modeling and small scale testing. These receivers are expected to be utilized in solar power plants rated between 100 and 200 MW. Distributed receiver research focuses on liquid metal refluxing devices. These are intended to mate parabolic dish concentrators with Stirling cycle engines in the 5 to 25 kW_e power range.

The focus of the molten salt receiver technology development is the Direct Absorption Receiver (DAR). In the DAR, a film of molten salt (possibly blackened) flows down a panel and is directly exposed to concentrated sunlight. The appeal of this concept lies in its high efficiency, low cost, simplicity, and reliability. Potential problems with this approach are flow stability, panel stresses and deformation, wind interaction, and stability of the blackener suspended in the molten salt. The Panel Research Experiment (PRE) has been fielded to address these potential problems. The PRE is a 1 meter wide by 7 meter long tensioned flat stainless steel panel mounted on a structural steel frame. The panel is fitted a distribution (inlet) manifold at its top and a collection manifold at the bottom as well as plumbing and associated apparatus necessary to melt and flow salt. The panel may be tilted up to 15° from the vertical. At this writing, the PRE is being water flow tested in order to check system operation. Non-solar and on-sun molten salt test phases will follow.

The effort in the area of volumetric receivers is less intensive and highly cooperative in nature. A ceramic foam absorber of Sandia design was successfully tested on the 200 kW_t test bed at Plataforma Solar during 1989. Material integrity during the approximately 90-test series was excellent. A second, less dense absorber will be tested under this International Energy Agency Program with the objective of realizing higher energy conversion efficiencies. Interactions with Bechtel National have influenced our choice of potential absorber materials for optical and thermal characterization. Bechtel, as a member of the PHOEBUS consortium, has a commercial interest in this technology. Analytical modeling of absorbers is aimed at both electric and chemical applications.

Significant progress has been made with parabolic dish concentrator-mounted receivers using liquid metals (sodium or a potassium/sodium mixture) as heat transport media. Intended primarily for use with Stirling engine convertors, these refluxing receivers have two basic designs. Both designs reduce thermal stresses

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on the heat input side of the engine by immersing the heat input surfaces in a constant temperature environment. The pool boiler, as the name suggests, boils liquid metal in a simple vessel directly heated by concentrated sunlight. The metal vapor rises and condenses at the heat input side of the Stirling engine. The condensed liquid then returns to the pool for repeat boiling. Heat-pipe receivers utilize a wick structure attached to the rear of a solar absorber. Capillary action causes a relatively small inventory of liquid metal to flow through the wick and cover the rear surface of the absorber. The metal evaporates and then transports its energy to the engine in a manner exactly like that of the pool boiler. The condensed vapor returns to the wick for repeat evaporation.

Sandia has successfully solar-tested a pool boiling reflux receiver sized to power a 25 kW Stirling engine. Boiling stability and transient operation were both excellent. Sandia's design tools, both analytical and experimental, have been used to support Cummins Engine Company in the development of a heat-pipe receiver for their commercial 5 kW_e dish/Stirling system. The Thermacore, Inc. sintered-nickel wick heat-pipe receiver used in system demonstrations has operated as intended at modest power levels. Sandia's assistance has been given to other manufacturers proposing screen-type wick constructions.

The presentation will describe these activities in detail and will outline plans for future development.

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United States Department of Energy solar receiver technology development ★

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The United States Department of Energy (DOE), through Sandia National Laboratories, has been conducting a solar thermal receiver technology development program, which maintains a balance between analytical modeling, bench and small-scale testing, and experimentation conducted at scales representative of commercial-size equipment. Central receiver activities emphasize both molten salt-based systems and volumetric air devices. These receivers are expected to be utilized in solar power plants rated between 100 and 200 MW_e. Distributed receiver research focuses on liquid metal refluxing devices. These are intended to mate parabolic dish concentrators with Stirling-cycle engines in the 5 to 25 kW_e power range. This paper describes recent progress in this development program and discusses future plans.

1. Introduction

Sandia National Laboratories, the lead laboratory for the United States Department of Energy's (DOE) solar thermal electric program, has been developing solar thermal receiver technology for use in electrical generation systems. Central receiver development over the past twelve years has evolved toward systems that use molten nitrate salt as the working fluid. This salt (60% sodium nitrate/40% potassium nitrate, by weight) is desirable as a working fluid because its high density and specific heat make it attractive for thermal storage systems, and it is chemically stable at high temperatures. Molten salt receivers having the least degree of uncertainty in their performance and reliability are those in which the salt flows through tubes onto which solar insolation is directed. Three scale-model 5-MW_t salt-in-tube receivers have been tested at the National Solar Thermal Test Facility (NSTTF) in Albuquerque, New Mexico, USA. Salt-in-tube receivers have been developed and tested to the point that the next step is a 10- to 30-MW_e receiver for use in a generating plant. A potentially more cost-effective molten salt receiver concept is the direct absorption receiver (DAR) [1,2]. In a DAR, the salt flows in a thin, wavy film down a flat, nearly vertical panel and absorbs the concentrated solar flux directly. This concept is presently being evaluated at the 3-MW_t scale at the NSTTF. Some work is also being done with volumetric air receivers, which use

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porous solar absorbers. Air flows through the absorber, and energy is convectively transferred from the absorber to the air. Activities here essentially involve characterizing and testing candidate absorber materials and improving modeling capabilities.

Because of the nearer-term commercial potential for smaller, modular distributed systems to produce low-cost solar electric power, Sandia has been developing receivers that integrate parabolic dish concentrators to Stirling engines rated at 25 kW_e or less. This receiver technology is presently evolving from tube-type directly illuminated devices to those that use a liquid metal in a refluxing mode (gravity assisted) as an intermediate heat transfer medium. There are two basic types: the pool boiler and the heat pipe. In both types concentrated solar energy vaporizes the liquid metal (sodium and/or potassium), and the vapor then condenses on the heater tubes of the Stirling engine, thereby isothermally transferring the solar energy to the engine working gas. It is primarily this thermal stress-reducing feature that makes the reflux receiver more desirable than the directly illuminated tube receivers. The condensed liquid is then passively returned to the absorber by gravity (refluxing), as the engine is always located above the absorber. Sandia has recently completed testing of a 75-kW_t pool-boiler receiver in Albuquerque and has been interactively involved in heat-pipe development with Thermacore, Stirling Thermal Motors, and the U.S. National Aeronautics and Space Administration (NASA).

2. Central receiver technology

2.1. Panel research experiment

The present emphasis of the U.S. program is on molten nitrate salt receiver development, and, in particular, the DAR. The appeal of this concept lies in its potential for high efficiency, low cost, simplicity and reliability. There are several potential problems, however, with this approach. They include molten salt flow stability, panel stresses and deformation, wind interaction, and the stability of the blackener suspended in the molten salt. The Panel Research Experiment (PRE) has been fielded to address these potential problems. Evolving from several small-scale, proof-of-concept tests at Sandia and the Solar Energy Research Institute [3–5] and a commercial design study performed by Foster Wheeler [6], the PRE is a 1-meter wide by 6-meter long tensioned flat stainless steel panel mounted on a structural steel frame. The panel is fitted with a distribution (inlet) manifold at its top and a collection manifold at the bottom as well as plumbing and associated apparatus necessary to melt and flow salt. A schematic of the PRE panel is shown in fig. 1. The panel may be tilted up to 10°C from the vertical. There are also provisions for the installation of an intermediate manifold, one of the proposed solutions for the flow stability problem. This intermediate manifold collects the fluid before droplet ejection from the waves occurs, and then reintroduces the fluid onto the panel in a smooth film. Fig. 2 shows the PRE with such an intermediate manifold being flow-tested with water. As can be seen, the intermediate manifold successfully

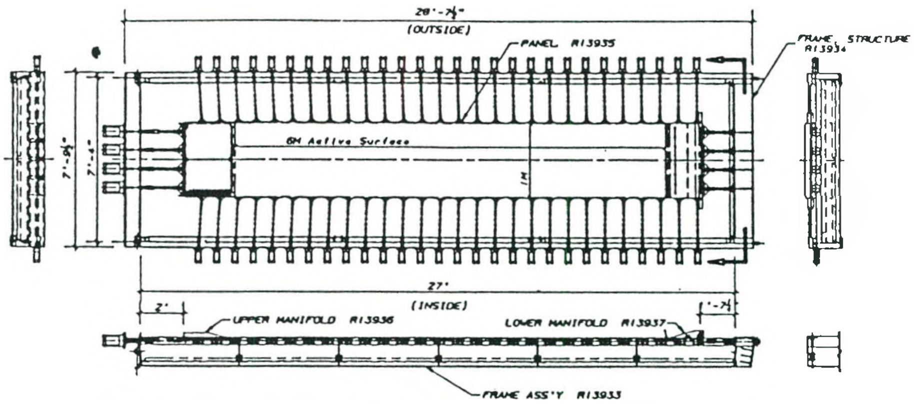

Fig. 1. Schematic of the direct absorption receiver Panel Research Experiment (PRE).

collects the wavy film and reinitializes a stable film flow before any wave breaking and droplet ejection take place. Water film Reynolds numbers are very close to those of a molten salt film, and much has been learned regarding flow stability and control with the user-friendly water as the fluid. Non-solar testing of the PRE is presently underway. Should this prove successful, and should there be sufficient funding available, an on-sun test phase will follow.

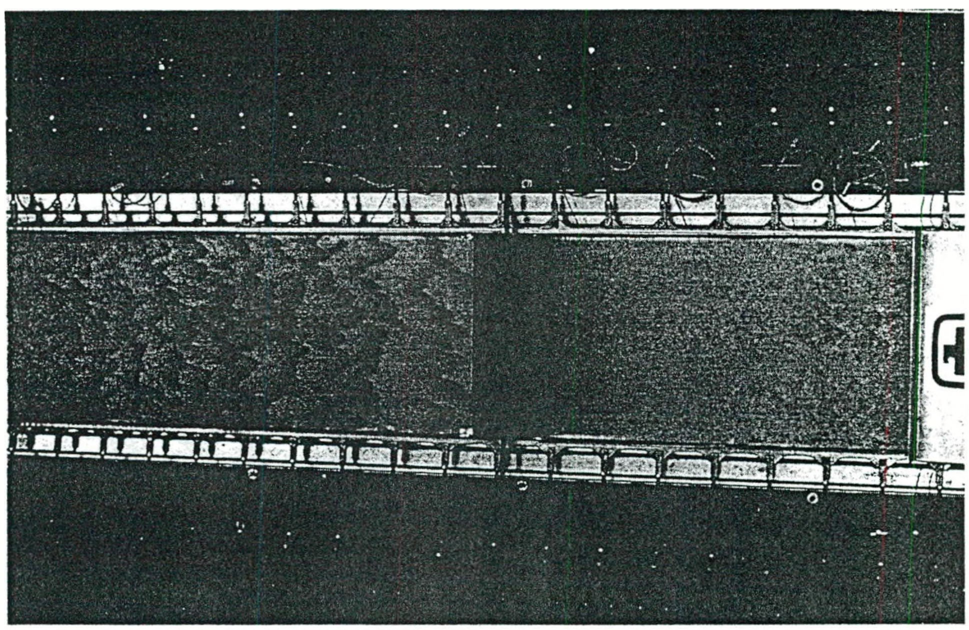

Fig. 2. Water flow on PRE with intermediate manifold.

Bottom

Turn 90°

2.2. Quad-panel direct absorption receiver

Kolb and Chavez [6] have proposed a DAR design that addresses the potential problem areas of salt droplet ejection due to flow stability and wind interaction. Called the Quad-Panel DAR, it uses insulated wind spoilers and an active air curtain to redirect any ejected salt droplets (fig. 3). Four panels with a surround heliostat field were chosen over a single panel with a north field in order to reduce panel length, a major factor in droplet ejection rate. Having four panels instead of one would also increase plant availability. Cost and performance studies of a 100-MW_e power plant using this concept were compared to those of a similar power plant using the originally proposed cylindrical, commercial-scale DAR [6]. Results show the capital cost of the quad system to be higher, but anticipated increases in reliability should compensate. Therefore, the initial conclusion is that the quad-panel system would produce electricity at a similar levelized cost to that predicted for the

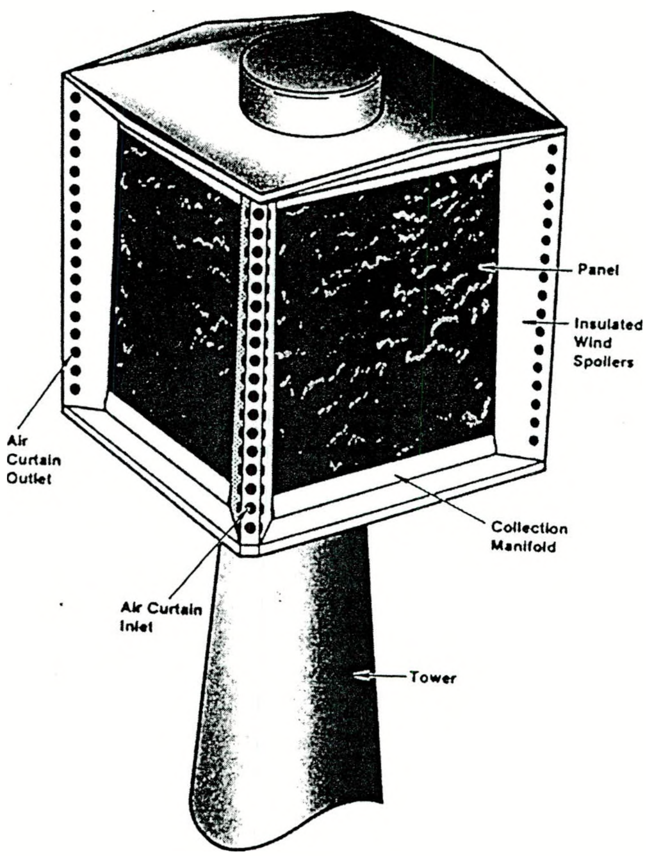

Fig. 3. Quad-panel direct absorption receiver.

original commercial cylindrical DAR [7], i.e., 15–20% below that of a comparable system with a salt-in-tube receiver.

2.3. *Volumetric air receivers*

The effort in the area of volumetric receivers is less intensive and is highly cooperative in nature. As reported in references [8] and [9], a porous, ceramic-foam absorber was successfully tested in an 87-test series on the 200-kW_t test bed at the Plataforma Solar de Almeria as part of the International Energy Agency Solar Test Program (Task VII). This 92% alumina foam, chosen because of its structural strength, high-temperature capability, low cost and potential for using smaller pieces to build up an absorber, performed very well over the test series. Subjected to peak flux levels of 1200 kW/m^2 and producing outlet temperatures of 730°C, the porous ceramic exhibited excellent structural integrity and reasonable thermal efficiencies. Fig. 4 is a schematic of the nominal 80% porosity, eight pores-per-cm absorber. Figs.

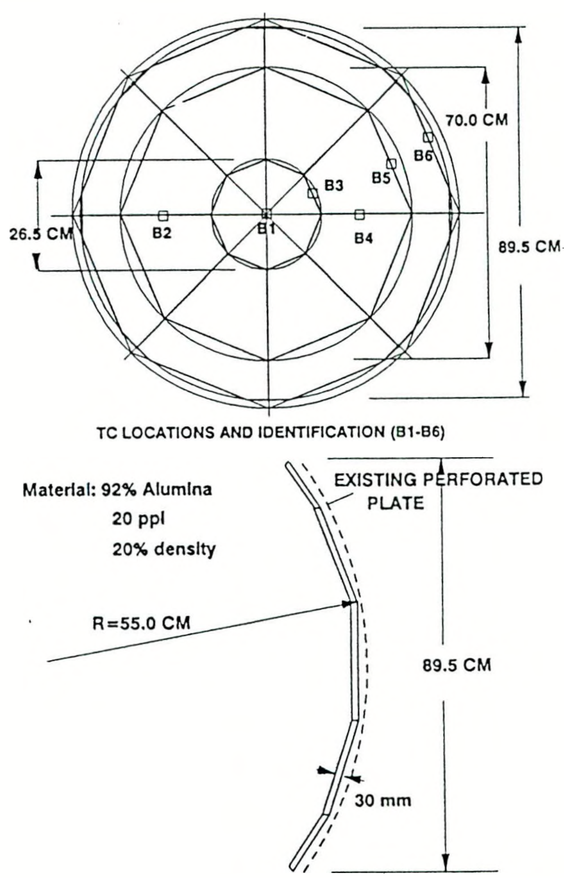

Fig. 4. Schematic of a 92% alumina, 20 ppi ceramic foam absorber.

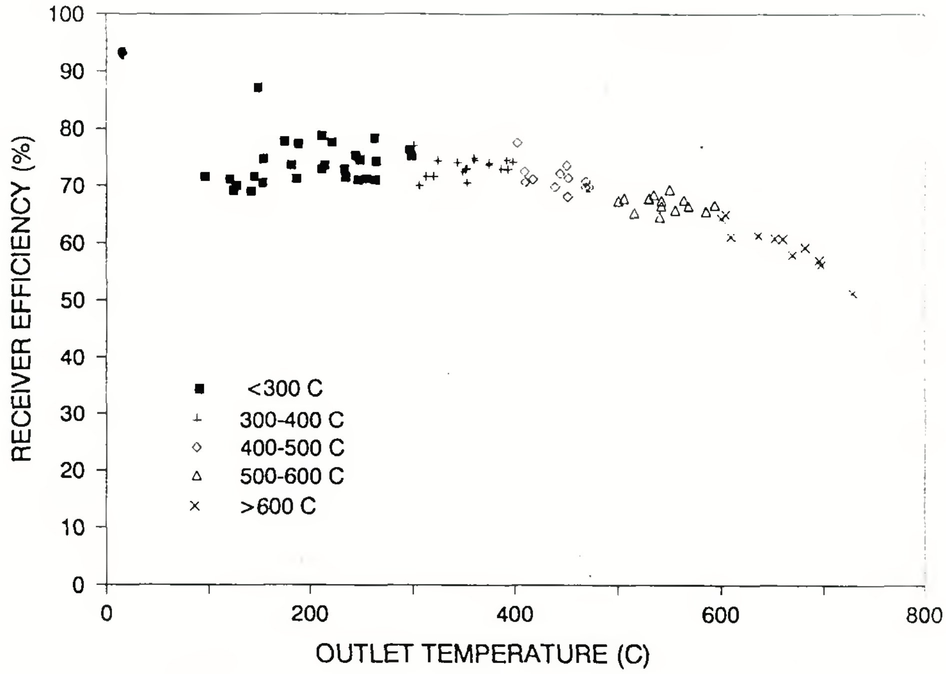

Fig. 5. Ceramic foam absorber receiver efficiency vs outlet air temperature.

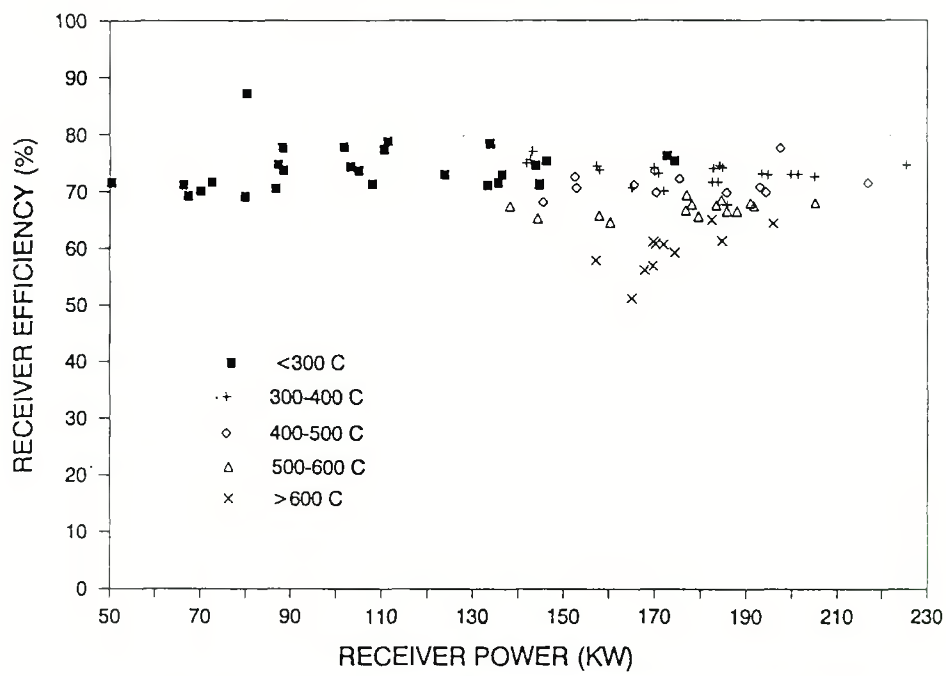

Fig. 6. Ceramic foam absorber receiver efficiency vs receiver power.

5 and 6 plot absorber efficiency versus outlet air temperature and absorber power, respectively. The lower than expected values were attributed largely to a higher than optimum optical density exacerbated by a thick coating of Pyromark paint. A second foam absorber is presently being designed using the lessons learned from this test series, a more characterization tests from the solar furnace. This second absorber is scheduled for testing in Almeria in 1991. Other candidate absorber materials are also being characterized in solar furnaces at Sandia and New Mexico State University. Interactions with Bechtel National have influenced our choice of materials for this optical and thermal characterization. Bechtel, as a member of the PHOEBUS consortium, has a commercial interest in this technology.

Analytical modeling of absorbers has benefitted from efforts aimed at chemical applications. Reference [10] describes the model presently being used at Sandia. Here the absorber is modeled as a one-dimensional, planar, radiatively participating medium. To account for spatial variations in incident solar flux and/or mass inflow, a suitable number of one-dimensional, but independent, steady-state solutions are obtained. The model incorporates solar and infrared radiation using a two-band, two-flux radiation technique with empirically determined effective properties for the absorber (including absorptivity, emissivity and specularity, conduction within the absorber, and convection between the air and the absorber). A comparison of predicted and measured temperatures is given in reference [11] and it suggests that the multiple one-dimensional modeling approach is valid.

3. Reflux receiver technology

Primarily because of the lower capital costs involved, distributed, modular, parabolic dish concentrator/converter systems have a nearer term potential for commercialization than the larger, capital-intensive central receiver systems.

Of the many conversion devices considered for dish-electric systems, the Stirling engine, mainly because of its exceptionally high thermodynamic efficiency, has the most potential for producing low-cost energy from the sun [12,13]. A high point of dish-Stirling development centered around the technology developed by United Stirling of Sweden and the Jet Propulsion Laboratory (JPL). The potential of the technology for high efficiency was demonstrated by Advanco Corp. and McDonnell Douglas Corp. [14–17].

The Advanco and McDonnell Douglas United Stirling modules utilized directly illuminated heater-head tube receivers. The inherent difficulties of dealing with concentrated sunlight and the need to contain a high-pressure working fluid make the design of tube receivers difficult and result in compromises in engine and receiver performance and life. In addition, the tube receiver requires highly accurate concentrators to produce reasonably uniform incident solar flux distributions.

The difficulties associated with non-uniform high-intensity solar flux, the desire to reduce optical requirements of dish concentrators (to reduce cost), and the promise of hybrid systems (the use of a fossil fuel in addition to solar) have led to concepts that use an intermediate heat transfer fluid. Currently the reflux receiver is

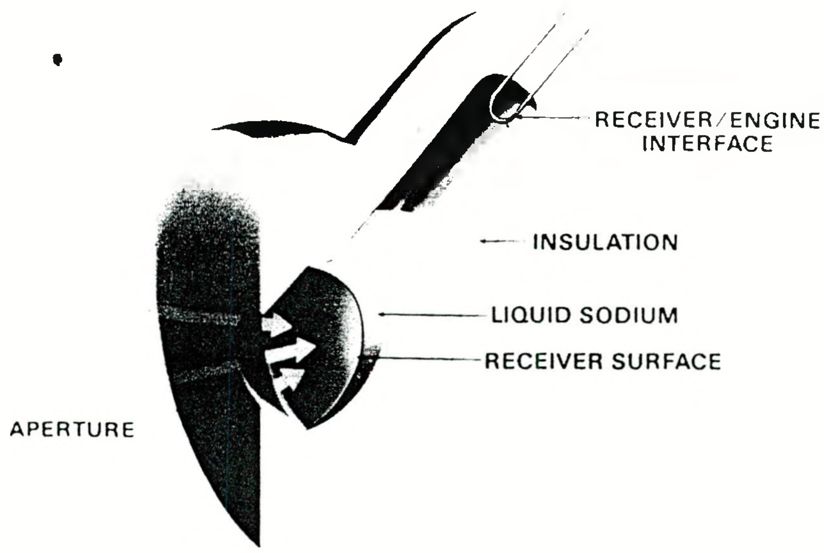

Fig. 7. Schematic of a reflux pool-boiler receiver: A pool of liquid metal bathes the absorber. Nucleate boiling occurs at the absorber/liquid metal interface.

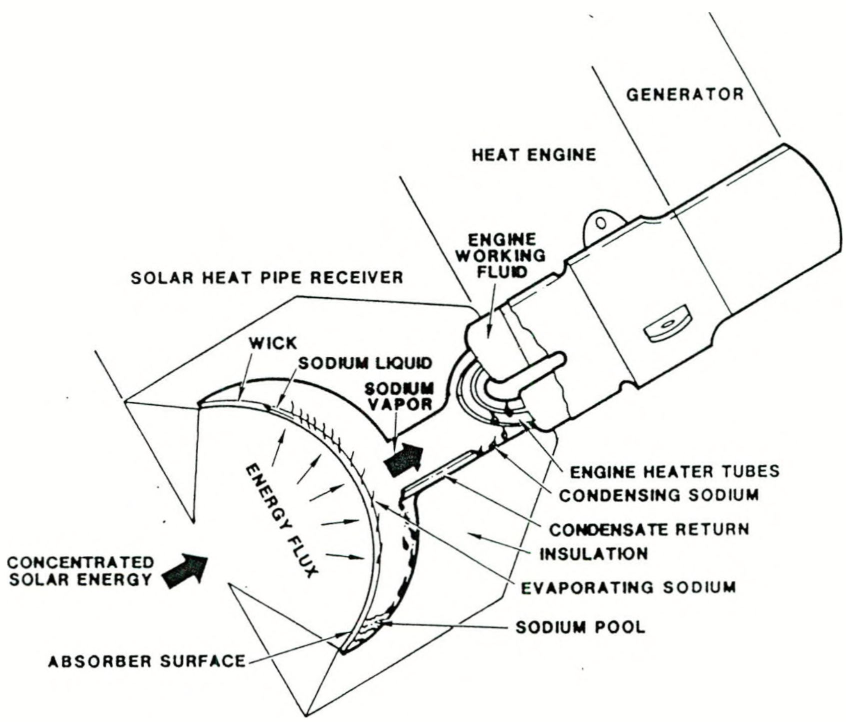

Fig. 8. Schematic of a reflux heat-pipe receiver: Capillary forces in a wick pump liquid metal across the absorber surface where it evaporates.

receiving the most development attention and appears to have the potential to improve on the performance and life of tube receiver dish-Stirling modules, while reducing the overall system cost and making overall system design and hybridization significantly easier.

In the reflux receiver sodium and/or potassium is used as an intermediate heat transfer fluid between the heater tubes of a Stirling engine and a solar absorber. The liquid metal is contained within an evacuated vessel and vaporized from the backside of a spherical solar absorber surface by solar energy. The vapor then flows to the Stirling engine's heater tubes where it condenses, releasing its latent heat. The liquid is passively returned to the backside of the solar absorber by gravity (refluxing) since the engine is always located above the receiver.

Distribution of the liquid metal to the backside of the solar absorber is a key design issue for reflux receivers and can be accomplished by one of two fundamental methods; pool boilers and heat pipes. In the reflux pool-boiler receiver, fig. 7, liquid return is assured by an inventory sufficient to submerge the absorber in all orientations. Boiling heat transfer occurs at the absorber/liquid metal interface. Because of the submerged absorber requirement, the pool-boiler is generally limited to use with an azimuth-elevation drive dish. In the reflux heat-pipe receiver, fig. 8, liquid metal is distributed across the absorber by capillary forces in a wick, and, under some situations, gravity. Evaporative heat transfer occurs at the liquid metal/vapor interface.

Comma?

3.1. Pool-boiler reflux receivers

Because of the wetting properties of liquid metals, the establishment of stable nucleate boiling and the possibility of film boiling and entrainment have been the primary concerns for this receiver concept. Bench testing showed that stable nucleate boiling could be initiated and maintained if artificial nucleation sites were located on the backside of the absorber [18]. At Sandia, a 75-kW$_t$ sodium reflux receiver was tested and characterized on a Test Bed Concentrator (TBC). Fig. 9 shows this receiver prior to its being insulated. A cold-water gas-gap calorimeter was used to simulate a Stirling engine. The receiver efficiency was about 90% when operated at full power at 800°C. Stable boiling was achieved by the addition of 35 equally spaced electric-discharge-machined (EDM) cavities in the absorber wetted surface. High incipient boiling superheats following cloud transients were observed in this system. The problem was effectively eliminated by the addition of a small amount of xenon gas [19]. This successful test proved that a reflux pool-boiler receiver can operate in transient solar conditions and demonstrated the efficiency potential of reflux receivers.

Through an interagency agreement between DOE and NASA, Sandia is working with NASA Lewis Research Center (LeRC) to develop 25-kW$_e$ Advanced Stirling Conversion Systems (ASCS) based on free-piston Stirling and reflux receiver technology [20–24]. In October 1986, NASA placed contracts with Mechanical Technology Inc. (MTI) and Stirling Technology Corp. (STC) for the conceptual design of two ASCSs.

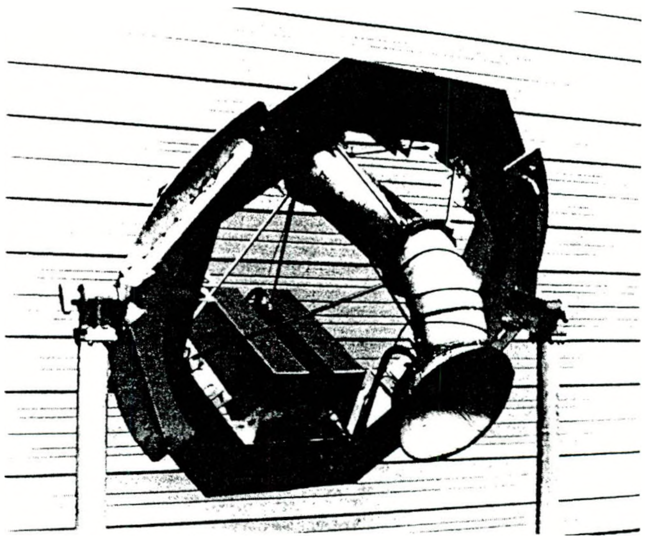

Fig. 9. Photograph of the Sandia reflux pool-boiler prior to being insulated.

The STC conceptual design for the ASCS used the reflux pool-boiler receiver concept. Sanders Associates and Saaski Technologies, Inc. were also involved in the receiver design. Because of concerns for corrosion and thermal stresses in the engine's heater head, the engine operating temperature for both ASCS designs was derated to 700°C from 800°C. As a consequence of this decision, potassium, which has a higher vapor pressure than sodium, was selected as the intermediate heat-transfer fluid in the STC conceptual design. The pool-boiler receiver has been developed into a preliminary design by STC under a new cost-shared contract. NaK-78 was selected as the heat-transfer fluid because its low melting point, −12°C, precludes the need for heat trace in all but the coldest climates. Bench tests at Thermacore with NaK, sintered powder artificial cavities, and inert gases demonstrated stable boiling, good transient response characteristics, and isothermal operation [25].

3.2. Heat-pipe reflux receivers

Stirling Thermal Motors (STM) was one of the first to recognize the advantages of heat pipes for interfacing a variety of heat sources with Stirling engines. In 1985 STM teamed with Advanco Corp. and, with support from the DOE and the Gas Research Institute (GRI), developed a preliminary design of a hybrid reflux heat-pipe solar receiver for the STM4–120 kinematic Stirling engine. Currently STM is under contract to Sandia to fabricate two heat-pipe receivers. The initial design featured a shallow spherical absorber (designed to result in a nearly uniform incident solar flux distribution), a composite screen wick, and vacuum support provided by coarse 8-mesh screen sandwiched between the front and aft spherical sections. This arrangement has the benefit of holding the screen wick firmly to the absorber. The composite wick in the design was made of four layers of 55-mesh S.S. screen sandwiched between the absorber and two layers of 325-mesh S.S. screen. In this type of arterial wick, the 325-mesh screen provides high capillary pumping pressure and the 55-mesh wick provides high permeability [26,27].

Detailed stress analysis of the STM receiver performed at Sandia indicated a problem during cold start-up due to relative and constrained movement of the front and aft domes. In addition, an analysis of the composite wick indicated little safety factor in the design assuming no refluxing of sodium to the absorber. Concerns about the tolerance to boiling in the composite wick led to bench tests at Sandia, which demonstrated that the wick design was unsuitable.

As a result of the above findings, the original design has changed substantially. The modifications resulted in removing the coarse 8-mesh screen, reducing the absorber diameter and radius of curvature, and changing from the composite screen wick design to a pedestal-type arterial wick, also based on screens. Attachment of the screen wick to the absorber is a challenge. Experiments with brazes have shown promise, but no definite approach has been developed. Encouraging results were also obtained by first sintering the screens to a flat sheet of stainless steel and then hydroforming it into the final spherical shape. Unfortunately, voids in the screens tend to be closed during hydroforming, and low wick permeability results.

As a part of the Sandia/STM development effort, a computer model has been developed for calculating the pressure distribution in a wick structure for given flux profiles and wick properties [28]. Although wick properties can be determined using generalized models, these models often have large errors, and they are poor at predicting the properties of mechanically formed wicks. To better quantify wick properties, techniques have been developed for directly measuring the flow characteristics of formed spherical wick structures [29]. These techniques, along with the computer model, allow potential wick designs to be screened before full-scale on-sun testing is attempted.

The heat-pipe receiver conceptual design developed by Thermacore, Inc. and Sanders Associates under subcontract to MTI for the ASCS program features a sintered nickel powder wick that incorporates circumferential and radial arteries to facilitate the distribution of liquid sodium to the hemispherical solar absorber [21]. Under a new contract through a DOE/NASA interagency agreement, Cummins Engine Co. is cost sharing the development of a preliminary design for an ~~SES~~ ASCS based on the MTI conceptual design. Thermacore and Northern Research are involved in the preliminary design with Cummins. A photograph of a Thermacore receiver, which is being applied at a reduced scale in a 4-kW_e free-piston dish-Stirling project internally funded by Cummins, is shown in fig. 10. Testing of two heat-pipe receivers on a LaJet Energy Co. LEC460B faceted stretched-membrane dish in Abilene, Texas, has demonstrated both the promise and the challenges of the technology. Both receivers failed before attaining full power. The first failure appeared to be mainly the result of a flux "hot spot". Peak flux intensities on the order of 120 W/cm^2 were diagnosed with the Sandia Video Flux Mapper and the Sandia-developed flux distribution computer program CIRCE2. The second failure appears to have resulted from poor adherence of the wick to the absorber. Both

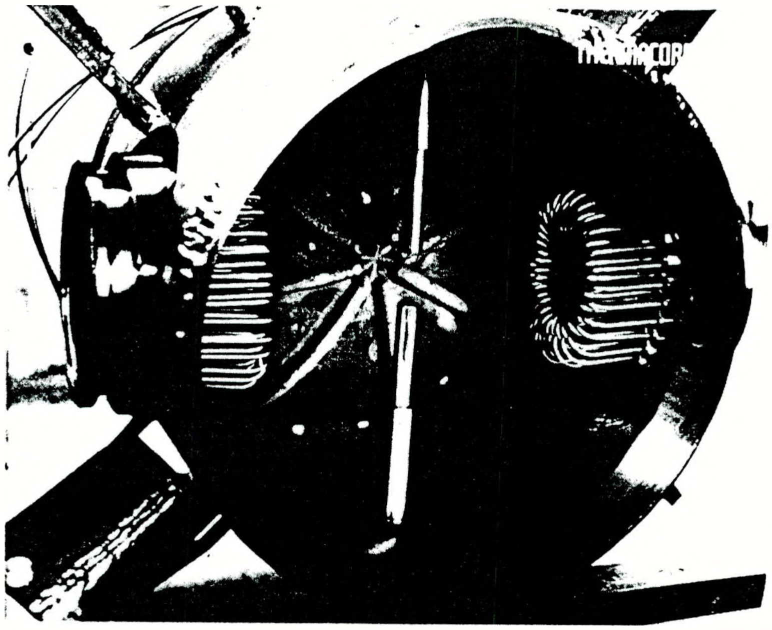

Fig. 10. Photograph of the sodium side of the Cummins/Thermacore heat-pipe receiver. Eight radial arteries fed by a circumferential artery are used to increase sodium liquid flow capacity to a sintered nickel-powder distribution wick. The two opposed free-piston Stirling engine heater tubes and thermowells can also be seen in the photograph.

causes appear to be solvable, but emphasize the importance of careful wick design and fabrication, and the severe characteristics of concentrated solar flux.

A comprehensive review of dish-Stirling receiver design history, status and trends is given in reference [30].

4. Future plans

4.1. Central receivers

The program faces an important decision point with respect to central receiver development. It would appear that the next logical step for this technology would be the building of a power plant in the 10- to 30-MW_e size range. This would be a very resource-intensive undertaking, requiring more financial resources than the program presently can depend on. Building this next power plant will probably be a joint effort and, possibly, an international one. The course of the U.S. central receiver program will strongly depend upon whether such a joint effort (or efforts) is begun, when it is begun, and whether the technology of choice is either salt- or air-based.

4.2. Distributed receivers

(1) Heat-pipe receivers: Currently, reflux heat-pipe receiver hardware being developed by Cummins/Thermacore, DLR/University of Stuttgart, Sandia, and STM is close to on-sun demonstration. Establishment of the capability for operating over the entire range of solar transients can be expected to happen soon – perhaps by more than one design. At Sandia we plan to demonstrate a screen-wick heat-pipe-receiver design on a TBC in 1990. Establishment of low-cost, manufacturable designs and comparisons of sintered powder and screen wicks can be expected to be issues in the near future.

(2) Pool-boiler receivers: Reflux pool-boiler receiver technology has been demonstrated at the 75-kW_t scale at Sandia. Future pool-boiler activities at Sandia involved refining fabrication techniques and investigating alternate methods of promoting boiling stability including laser-drilled pits and sintered or hot-pressed porous structures. Evaluation of NaK as a heat-transfer fluid with various boiling surfaces and with and without xenon are also planned. The objective is to evaluate materials and methods for a next-generation receiver. Bench-scale tests to assess long-term boiling stability and materials compatibility are also planned. Similar design activities at STC and Thermacore will occur during the up-coming detailed design phase of the ASCS program.

Acknowledgements

Although many have participated in the recent development efforts described here, there have been a number of key personnel who have been responsible for a large measure of what has been accomplished. For central receivers, James Chavez, Gregory Kolb, Chauncey Matthews, and Earl Rush of Sandia and Mark Bohn of SERI are in this group. The principal reflux receiver developers are Richard Diver, Douglas Adkins, Charles Andraka, James Moreno, Timothy Moss, and Scott Rawlinson of Sandia and Richard Shaltens of NASA/LeRC. Much of the work was done under contracts or in cooperation with U.S. industry. Although few individual names are mentioned in the text, the contributions and relevant participation of industrial partners have been noted where appropriate.

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