SERI/TR-253-3162
DE87012277

August 1987

Direct Absorption Receiver (DAR) Systems Assessment

J. V. Anderson
W. Short
T. Wendelin
N. Weaver

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Operated for the
U.S. Department of Energy
under Contract No. DE-AC02-83CH10093

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401
(303) 231-1000

January 25, 1988

Mr. James Leonard
Sandia National Laboratories
Solar Energy Department 6220
P.O. Box 5800
Albuquerque, NM 87185

Dear Mr. Leonard:

Enclosed you will find a copy of the report, "Direct Absorption Receiver (DAR) Systems Assessment". It was prepared by the Solar Energy Research Institute under the sponsorship of the Department of Energy's Solar Thermal Technology Division.

This report describes an analysis of a new kind of receiver for solar central receiver systems. The DAR concept represents a radically new way of collecting concentrated solar energy. The energy is absorbed directly in a flowing film of blackened molten salt instead of in metal tubes. The elimination of the tubes results in a receiver that will be more efficient, lighter in weight, and considerably less expensive than conventional tube receivers. The potential reduction in the cost of energy from central receiver systems with DAR is as much as 20%. It is a concept that has generated considerable interest in the technical community and is becoming a focus of the DOE Solar Thermal Technology Program.

Much research remains to be done; this analysis is only one of many steps along the R&D path. Nonetheless, it was felt you would be interested in having this report.

Sincerely,

Walter Short

Walter Short
Thermal Systems Research

WS/rl
Enclosure

STR/wsl-22-88a

A Division of Midwest Research Institute

SERI/TR-253-3162
UC Category: 62a
DE87012277

Direct Absorption Receiver (DAR) Systems Assessment

J. V. Anderson
W. Short
T. Wendelin
N. Weaver

August 1987

Prepared under Task No. 5137.310
FTP No. 5-654

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

SERI

NOTICE

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A03

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications, which are generally available in most libraries: *Energy Research Abstracts, (ERA); Government Reports Announcements* and Index (*GRA* and I): *Scientific and Technical Abstract Reports (STAR)*: and publication, NTIS-PR-360 available from NTIS at the above address.

PREFACE

The research and development described in this document was conducted within the U.S. Department of Energy's Solar Thermal Technology Program. The goal of this program is to advance the engineering and scientific understanding of solar thermal technology and to establish the technology base from which private industry can develop solar thermal power production options for introduction into the competitive energy market.

Solar thermal technology concentrates the solar flux using tracking mirrors or lenses onto a receiver where the solar energy is absorbed as heat and converted into electricity or incorporated into products as process heat. The two primary solar thermal technologies, central receivers and distributed receivers, employ various point and line-focus optics to concentrate sunlight. Current central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single, tower-mounted receiver. Point-focus concentrators up to 17 meters in diameter track the sun in two axes and use parabolic dish mirrors or Fresnel lenses to focus radiant energy onto a receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Concentrating collector modules can be used alone or in a multimodule system. The concentrated radiant energy absorbed by the solar thermal receiver is transported to the conversion process by a circulating working fluid. Receiver temperatures range from 100°C in low-temperature troughs to over 1500°C in dish and central receiver systems.

The Solar Thermal Technology Program is directing efforts to advance and improve each system concept through solar thermal materials, components, and subsystems research and development and by testing and evaluation. These efforts are carried out with the technical direction of DOE and its network of field laboratories that works with private industry. Together they have established a comprehensive, goal-directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply. To successfully contribute to an adequate energy supply at reasonable cost, solar thermal energy must be economically competitive with a variety of other energy sources. The Solar Thermal Program has developed components and system-level performance targets as quantitative program goals. These targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and developing optimal components. These targets are being pursued vigorously to ensure a successful program.

This report describes an analysis of the potential of the direct absorption receiver (DAR); an innovative concept for central receiver systems. This concept is important to the Solar Thermal Program because it offers potential improvement in both cost and performance when compared to current receiver technology. The analysis considers the effect of these improvements on the cost and performance of the entire central receiver system. The results of this analysis show that the DAR has the potential to move the program significantly closer to attainment of the program goals for both the receiver cost and the cost of delivered energy.

In this report, the DAR concept is compared to a conventional salt-in-tube receiver as represented by the Saguaro central receiver system conceptual design (see Reference 1 of text). Although the Saguaro design is the most recent documented system design, it is expected that it will soon be supplanted by a new salt-in-tube receiver system design under development as a part of the on-going Utility Central Receiver Study (see Reference 21 of text). The new salt-in-tube receiver system is expected to show considerable improvement over the Saguaro design. Thus, the DAR advantages, relative to a conventional salt-in-tube receiver, should be reassessed when this more advanced tube design is complete.

This document was prepared under the guidance of the Division of Solar Thermal Technology of the U.S. Department of Energy.

Approved for

SOLAR ENERGY RESEARCH INSTITUTE

Lawrence M. Murphy, Manager
Thermal Systems Research Branch

Gerald C. Groff, Director
Solar Heat Research Division

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The direct absorption receiver (DAR) represents a significant departure from conventional salt-in-tube receiver technology and offers substantial promise for performance improvement and cost reduction in future generations of receivers. The DAR concept involves the absorption of concentrated solar flux directly into a film of darkened molten salt that flows over a nearly vertical plate. Since the film absorbs most or all of the flux directly, the flux limits that are associated with tubular receivers can be relaxed substantially. This high flux density allows for smaller and lighter receivers, which results in better thermal performance and lower capital costs.

This report describes the results of a detailed analysis of the effects of these factors on system performance and energy cost. In this analysis using 1984 weather data (15-minute increments) for Barstow, California, a direct comparison is made between a central receiver system with a DAR receiver and the same central receiver system with a conventional salt-in-tube receiver. The Saguaro receiver design [1] is used for the conventional receiver configuration;* the principal DAR configuration examined is a cavity. Two external DAR configurations are examined in order to assess the potential benefits of using an external design.

The base case cavity DAR configuration was developed as a part of this study by the Solar Power Engineering Company (SPECO) [2] under subcontract to SERI. The cavity configuration features a shallow, open-aperture cavity with a single, parabolic-shaped absorber plate. The working fluid, a molten draw salt doped with an optical darkener, is delivered from the receiver at 550°C for steam generation to drive a conventional Rankine-cycle turbine and electric generation system. The parabolic-shaped absorber, together with a multi-point aiming strategy, limits the peak flux on the cavity DAR to 0.9 MW/m^2 with an average flux of 0.4 MW/m^2.

In order to compare a central receiver system with a cavity DAR to a system with the conventional Saguaro receiver, the heliostat fields, towers, and all ground-based components were assumed to be identical. Hence, the only difference between the two systems was in the receiver itself. The annual energy delivered by each of the two systems was calculated by the computer model SOLERGY [3] which simulated operation of the system on the 1984 weather data for Barstow, California. All of the data input to SOLERGY was the same for each of the two systems, except for the receiver-related parameters. The thermal performance of the cavity DAR was estimated using the computer codes SHAPEFACTOR [4] and RADSOLVER [5] to predict the radiative losses, and a correlation proposed by Siebers and Kraabel [6] to predict the convective losses. The performance characteristics of the Saguaro receiver were drawn from the data published by Arizona Public Service [1].

---

*Although the Saguaro design is the most recent documented system design, it is expected that it will soon be supplanted by a new salt-in-tube receiver system design under development as a part of the on-going Utility Central Receiver Study (see Reference 21). The new salt-in-tube receiver system is expected to show considerable improvement over the Saguaro design. Thus, the DAR advantages, relative to a conventional salt-in-tube receiver, should be reassessed once this more advanced tube design is complete.

The annual energy delivered by the central receiver system with a DAR is predicted to be 16% greater than that of a system with a conventional salt-in-tube receiver, as shown in Figure S-1. This relative performance increase results from reduced DAR thermal losses (9.6%), increased absorptance of the DAR absorber (2.9%), and decreased DAR pumping power parasitics (3.7%).

The cost of a cavity DAR should be less than half (44%) that of a salt-in-tube receiver of the same size (190 MW_t). This DAR cost was obtained through a detailed category-by-category comparison with the cost of the Saguaro receiver as recently reevaluated by Raymond Kaiser Engineers [2]. When the reduction in capital costs are combined with the performance improvements of a cavity DAR, the resulting levelized energy cost (LEC) is estimated to be approximately 18% less than that of Saguaro (see Figure S-2).

Sensitivity analyses conducted using DELSOL2 [7] and other computer models show that the LEC of the cavity DAR is not very sensitive to the flux levels on the absorber for average flux levels above 0.4 MW/m^2, nor to the aiming strategy employed. However, analysis shows that annual performance is approximately directly proportional to the absorptance of the salt/plate combination. In other words, a one percent change in absorptance produces a one percent change in system performance.

Following the same procedures employed in the analysis of the cavity DAR configuration, two external DAR configurations were developed and costed (billboard receiver/north field and cylindrical receiver/surround field) for comparison with the cavity DAR and Saguaro. The annual performance of each external DAR configuration was estimated using both DELSOL and SOLERGY. As with the cavity DAR, the external DARs show both cost and performance improvement relative to Saguaro. For the billboard external DAR, the performance is expected to be 18% more per unit of heliostat area, the receiver cost 61% less, and the LEC 21% less than that of Saguaro. For the cylindrical external receiver, the values are 10%, 59%, and 18%, respectively.

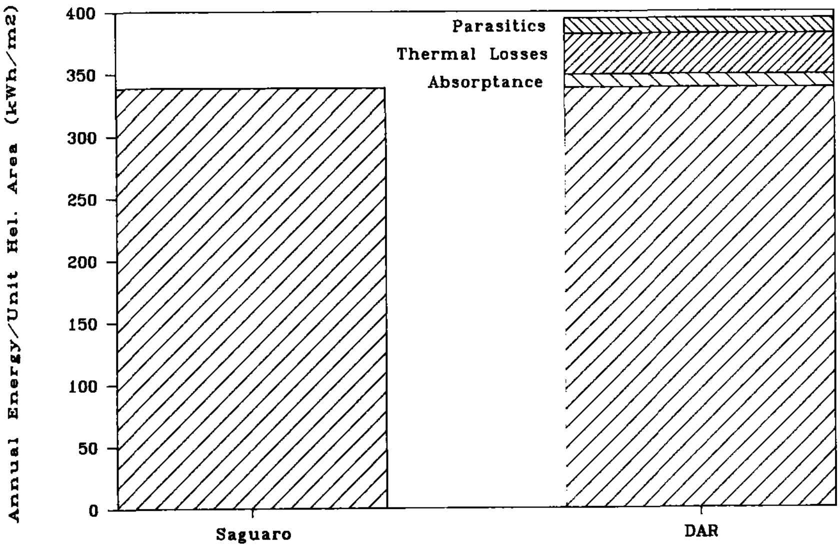


Figure S-1. DAR Performance Comparison

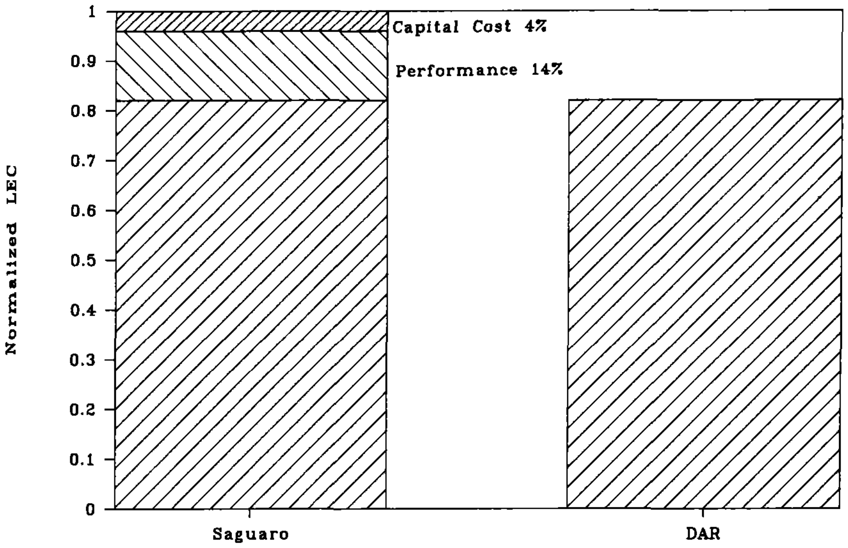


Figure S-2. DAR LEC Comparison

The small differences between the LECs of the three DAR configurations examined is well within the uncertainties of current analysis capabilities. In essence, all three appear to show equal promise for reducing the LEC of a central receiver system. The ultimate deciding criteria between the DAR configurations may not be the performance/cost issues addressed in this systems analysis study, but rather the engineering and technical issues that we were not able to fully include in our analysis, such as manifold design and startup time requirements for a cavity versus external DAR. Another possible deciding criteria may be the value of the energy produced; i.e., a utility with peak usage in the summer time will probably prefer a surround field, while a utility with peak usage in the winter time will prefer a north field of heliostats.

The DAR concept should offer other advantages relative to a salt-in-tube receiver that cannot be quantified now because of a lack of experimental data but that can be qualitatively stated. For example, fewer valves and the absence of receiver tubes in DAR should reduce operating and maintenance costs and increase availability. Also, the lower thermal mass and reduced vulnerability of DAR to the effects of thermal shock should make it less sensitive to transients and startup losses.

The cost and performance sensitivities of this study reinforced the current Solar Thermal Program emphasis on the resolution of several issues related to material properties, fluid dynamics, and design considerations. For example, the sensitivity of the results to the absorptance of the absorber suggest that we need to know more about the absorptance of doped draw salts, degradation of the salt and dopant upon exposure to air, dopant agglomeration, and fluid film stability under high flux and ambient conditions.

Of course, there exist other technical feasibility issues currently under examination by the Program that might impact the DAR cost and performance such as the control of the heat-transfer salt flow over the absorber plate. However, since these all appear to be resolvable, DAR continues to show strong promise for the advancement of receiver technology and reduction in the cost of delivered energy from a central receiver system.

ABSTRACT

The direct absorption receiver (DAR) represents a fairly significant departure from conventional salt-in-tube receiver technology and appears to offer substantial promise for future generations of receivers. The DAR concept involves absorbing the solar flux directly into a film of molten salt that flows in a thin film over a plate. Since the film absorbs most or all of the flux directly, the flux limits associated with tubular receivers can be relaxed substantially. This allows smaller and lighter receivers, which results in better thermal performance and lower capital costs. This report describes the results of an effort to analyze the effects of these factors on system performance and energy cost for both cavity and external DAR configurations. The approach taken is to directly compare a central receiver system with a DAR receiver and the same system with a salt-in-tube receiver. The results show about a 16% improvement in the thermal performance (annual energy delivered) of a cavity DAR system, while the cost estimate for the DAR indicates a reduction of over 50% in the cost of the receiver. These two effects combine to produce about an 18% reduction in the levelized cost of delivered energy when compared to a system with a conventional salt-in-tube receiver.

1.0 INTRODUCTION

1.1 Background

Historically, designs for solar flux absorbers have relied to a great extent on conventional boiler and heat exchanger technology. The typical design involves pumping a working fluid through a series of tubes arranged side-by-side to form a panel. Because the solar flux impinges on only half the tube circumference, the heating of the tubes is non-uniform, and the thermal stress tends to be high. When this is combined with the high temperatures and the cyclic nature of the solar environment, the creep and, especially the fatigue properties of the tubes, become major design criteria. In addition, the friction losses in the absorber tubes create a significant parasitic load requiring roughly half the pumping power consumed in this type of receiver.

The direct absorption receiver is a concept that has the potential to eliminate many of the problems associated with the tubes in a conventional receiver. The DAR concept involves the absorption of concentrated solar flux directly into a layer of darkened molten salt that flows in a thin film over a plate. Since the film absorbs most or all of the flux directly, the flux limits associated with tubular receivers can be relaxed substantially. This high flux density allows smaller and lighter receivers for the same power output, and results in better thermal performance and lower capital costs.

The DAR concept was considered in the early 1970s at Sandia National Laboratories, Livermore. It was not included in the early system experiments because tube receivers were perceived as requiring less development effort. SERI researchers refined the idea in the early 1980s and have revived and improved the concept [8].

Several previous system studies have been conducted to assess the overall impact of DAR in a central receiver system. In particular, Lewandowski et al. conducted an early two-phase effort in 1984 [9,10]. The two studies considered high temperature systems (900°C), and focused on electricity generation and the production of high temperature industrial process heat, respectively. The focus of work on DAR changed from high temperature applications (>900°C) to a more intermediate temperature range (550°C) in 1985. This lower temperature emphasis was created to take advantage of the potential of DAR in early electric power generation applications using existing conversion cycles [11] and the use of nitrate salts which have an extensive data base.

Several other studies in the past year have reaffirmed confidence in the direct absorption concept. Analytical studies conducted at SERI by K. Y. Wang [12] have developed improved models of the fluid dynamics and heat transfer of the working fluid film, and better predictions of the temperature distributions within both the film and the plate. Although it used carbonate salts and was designed primarily around high temperature systems, an experimental test, directed by Mark Bohn from SERI and conducted at the Advanced Components Test Facility (ACTF), demonstrated the technical feasibility of the concept [8]. Recent analysis by Craig Tyner [13] of Sandia National Laboratories, Albuquerque (SNLA), indicates that, in the long term, an external cylindrical configuration DAR in a surround field may potentially reduce the electric LEC by 26% relative to an external conventional salt-in-tube receiver in a surround field.* This reduction is attained primarily through improvements in both receiver efficiency (efficiency improvement = 14%) and capital cost (system cost reduction = 18%).

1.2 Study Approach

This report describes the results of a cost/performance comparative analysis of three DAR configurations: (1) cavity, (2) billboard external with north field, and (3) cylindrical external with surround field. The approach taken is to make a direct comparison between a central receiver system with each of the DAR configurations and the same central receiver system with a conventional cavity salt-in-tube receiver. The Saguaro receiver design is used for the conventional receiver design.

A receiver configuration was developed for the cavity DAR and several technical issues were examined, including, for example, the absorber plate stresses induced by non-uniform temperature/flux distributions. Performance-related issues, such as the optimum flux levels on the absorber, were also addressed in the development of the configuration. Detailed cost estimates based on the conceptual configuration were generated by comparison with the most recent cost estimates developed by Raymond Kaiser Engineers, Inc. for the Saguaro salt-in-tube receiver [14]. The performance and cost estimates have been combined into an estimate of the levelized cost of energy (LEC) for comparison to a similar estimate made for a conventional salt-in-tube receiver as represented by the Saguaro system.

Using the methodology developed for the cavity DAR, similar analyses were conducted for the two external DAR configurations: billboard/north field and cylindrical/surround field. The external DAR results are compared to both the cavity DAR and the Saguaro results.

In addition to defining the cost/performance benefits of the DAR concept, the system analysis activities have also identified technical issues and uncertainties that may impact system performance or cost significantly. Although each of these issues is important enough to require examination, they all appear to be resolvable. Appendix A contains a list of these issues, along with a preliminary analysis of their importance.

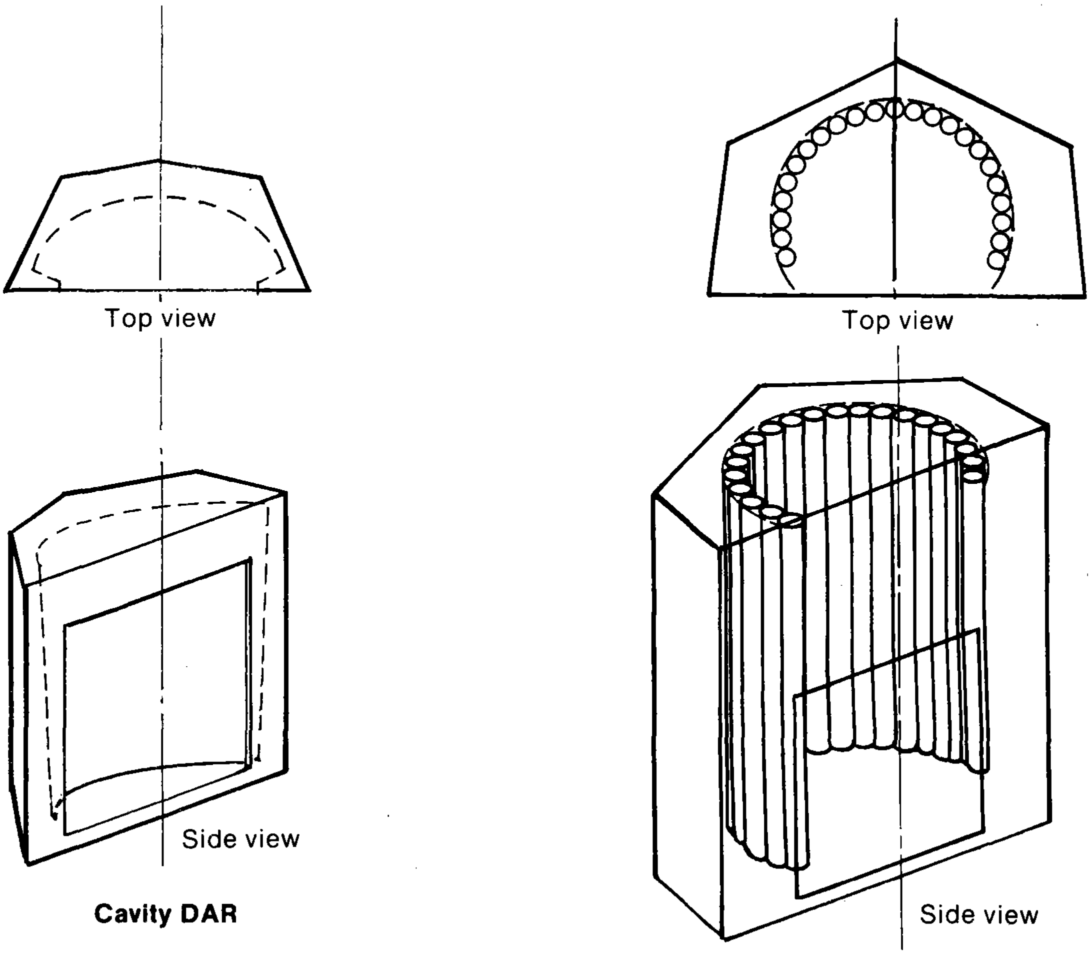
---

*Tyner predicts that the LEC improvements due to DAR will be slightly larger than that presented in the base case for this report. The discrepancy is due primarily to four factors: (1) Tyner's analysis compares an external DAR with an external tube receiver (our base case compares two cavity receivers); (2) Tyner includes greater system availability for the DAR (we include this only in our optimistic case, see Section 5.1); (3) Tyner's analysis used a reasonable approximation approach, whereas we conducted a more detailed analysis using a quarter-hour-time step simulation model; (4) Tyner compared against a conventional tube receiver operating at peak flux levels up to 0.82 MW/m^2, whereas the peak flux level of the Saguaro receiver is only 0.53 MW/m^2 (higher tube receiver flux levels tend to decrease the difference between the performances of the two systems).

2.0 CAVITY DAR CONFIGURATION

The cavity DAR configuration was developed under contract to SERI by the Solar Power Engineering Company (SPECO). Working with SERI, SPECO developed a conceptual configuration for a north-facing cavity DAR using molten draw salts (60% sodium nitrate, 40% potassium nitrate) in a 190-MW_t central receiver system to deliver energy at 550°C [2]. The configuration contains the following features.

1. Shallow cavity geometry. In the cavity configuration shown in Figure 2-1, the ratio of absorber area to aperture area is only 1.46, compared to a value of 2.28 for the Saguaro design.
2. Single-plate parabolic absorber surface. Previous DAR concepts have incorporated narrow vertical flow channels that have the potential for overheating at the channel edges. The single-plate absorber of the cavity configuration was selected because it avoids this potential problem. However, it introduces uncertainties in the ability to



Cavity DAR

Saguaro Tube Receiver
(tube sizes not to scale)

Figure 2-1. Cavity DAR and Saguaro Receiver Configurations control vertical flow rates and in the impact that flux maldistributions will have on stress and deformation in the absorber plate. The required resolution of these uncertainties was outside the scope of the configuration effort. The parabolic shape of the absorber plate was chosen to achieve a more uniform flux spread in order to minimize stress and deformation of the plate.

3. Recirculation system. A recirculating flow circuit over the absorber plate will reduce the nonlinear temperature gradients (and, consequently, the stress and deformation) over the absorber. Furthermore, the high flow rates in a recirculation system should reduce potential flow stability problems that could occur at large turn-down ratios and the sensitivity of the receiver performance to flux transients, and should increase the salt-to-plate heat-transfer coefficient. These design improvements are acquired at the expense of a small increase in capital cost, additional pumping power, an increase in control complexity, recirculation pump reliability concerns, and an increase in the average cavity temperature of about 50°C, which leads to an increase in thermal loss. (The significance of these losses is examined in Chapter 5). Although further investigation is required, these cost and performance disadvantages should be more than balanced by the system reliability advantages.

4. Multi-point aiming strategy. Using a multi-point aiming strategy, the absorber in the cavity configuration receives an average flux of 0.4 MW/m^2 and a peak flux of only 0.9 MW/m^2. This low peak flux attained through a multi-point aiming strategy will reduce stress in the absorber plate and minimize the possibility of thermo-capillary dryout. Analysis of the sensitivity of the cavity DAR to the flux levels on the absorber indicates that neither the performance nor the LEC is sensitive to average flux levels above 0.4 MW/m^2 (see Chapter 5).

5. Optical darkener dopant. There are two primary sources of optical losses of the incident radiation at the absorber. First, some portion of the radiation incident on the salt fluid surface is reflected. Second, radiation may be transmitted through the salt to the absorber plate and reflected back through the salt. Snell's law, together with a refractive index of 1.38 for a binary nitrate salt at 550°C [15], suggests that the initial reflective loss at the air/salt interface will be approximately 2%.*

   The second source of loss corresponding to two passes through the salt film and reflection off the absorber plate may be negligible if the proper optical darkener dopant is used. Experimental results developed by Drotning [16] show that absorptance in a single pass through a cobalt-oxide-doped (0.5% by weight) salt film of 0.004 m thickness can be as large as 98%. A second pass through the film, together with reflection off the absorber plate and internal reflection within the salt film at the air/film interface, should increase the absorptance within the salt/plate system to nearly 100%. Therefore, the total optical losses at the absorber are only 2-3%. For this study, an optimistic absorptance of 98% for the base case is assumed.‡ The sensitivity to this parameter is investigated in Chapter 5.

---

*Abrams [17] has shown that, at incidence angles greater than 60 degrees, reflective loss can be substantially greater than 2%. The incidence angles on a smooth surface of salt flowing over a DAR absorber plate will, in general, be significantly less than this. However, if the flowing salt is wavy or irregular, then the reflective loss may be greater.

‡Similarly, the absorptance of the Saguaro tube receiver is optimistically assumed to remain at its initial value of 0.95.

As part of the DAR configuration study, SPECO also suggested two ideas that could be applied to both DAR and conventional receivers. In the event of a power failure and subsequent loss of fluid flow, a curtain made from ceramic fibers could be lowered to shield the absorber from the direct flux. Secondly, SPECO suggested (but did not include in their configuration) a heat exchanger located at the base of the tower to separate the working fluid from the rest of the system. The advantages and disadvantages of these two concepts are discussed in Appendix A along with other technical issues.

The relatively high flux levels experienced by a cavity DAR configuration may produce significant temperature gradients in the absorber plate. A consultant to SERI employed NASTRAN, a finite element structural analysis program, to investigate whether the temperature gradients might produce unacceptable levels of stress and deformation in the single-plate absorber [18]. This analysis, which is discussed in more detail in Appendix A, indicates that it should be possible to design an absorber plate support system that will reduce stress and deformation in the absorber to an acceptable level.

3.0 COST ASSESSMENT

3.1 Non-Receiver Capital Costs

To be consistent with other systems analyses in the Solar Thermal Program, all of the capital costs for the components of the Saguaro central receiver system have been taken from the long-term goals of the Solar Thermal Program Five Year Plan [19] with the exception of the cost of the receiver/tower. These non-receiver costs are presented in Table 3-1 in terms of the original units used in the program plan and in terms of the total cost for the 190-MW_t Saguaro plant.

As will be shown in Chapter 4, the design point power provided by the base case cavity DAR system is approximately 6% higher than that of Saguaro because of the more efficient receiver (and the fact that the heliostat fields of the two systems were assumed to be identical). To account for this increase in design point power in a systematic way, the cost of transport, storage, and conversion for the cavity DAR is assumed to be 6% above those of Saguaro as also shown in Table 3-1.*

The only non-receiver cost that has been adjusted from the Saguaro values for the external DAR systems is the cost of the heliostat field. The heliostat fields of the external receiver systems have been optimized to yield a system design point performance comparable to that of Saguaro; i.e., 190 MW_t.

3.2 Receiver Capital Costs

The receiver costing methodology is based on that employed by Raymond Kaiser Engineers, Inc. in their recent reevaluation of the cost of the Saguaro salt-in-tube receiver [14]. As shown in Table 3-2, the cavity DAR costs and Saguaro costs are broken down in this method into 16 different categories and incrementally compared on a category-by-category basis. For the cavity DAR‡ this resulted in a receiver cost of only $6.5M, which is 56% less than that of the Saguaro receiver ($14.8M). The lighter DAR receiver may also result in lower tower costs, but since we had no valid way of estimating the reduction, we conservatively assumed a DAR tower cost of $3.3M as estimated in Reference 1 for the Saguaro tower. The combined cost of the receiver and tower is only approximately 6% more than the long-term cost goal ($9.3M) [19] as shown in Figure 3-1. Although this is a substantial reduction, it has a more modest impact on the overall system capital cost (10%), because, with the non-receiver costs from the long-term cost goals [19], the Saguaro receiver accounts for only approximately 15% of the total system cost of $101M.

---

*At this level of analytical detail, these small cost differences are more an artifact of the necessity of making a consistent comparison than a representation of reality. For example, the DAR transport costs might be higher than those of Saguaro as a result of the increased flow rate, but might also be reduced by the lower pressure in the receiver loop. Similarly, since the EPGS unit is buffered from the fluctuations in the receiver output by the availability of storage (roughly three hours of capacity), it could be argued that neither the DAR storage nor EPGS units would need to be increased in size.

‡The DAR costs were developed by SPECO under contract to SERI. Appendix B contains the original costing breakdown as developed by SPECO.

Table 3-1 System Capital Costs

Long-Term Cost Goals

Heliostats	$\$40/m^2$
Transport	$\$25/m^2$
Storage	$\$20/kWh_t$
Conversion	$\$350/kW_e$
BOP	$\$30/m^2$

Costs (1000s of dollars)

	Saguaro	DAR Cavity	DAR External Billboard	DAR External Cylindrical
Heliostats	\$12,351	\$12,351	\$12,073	\$12,884
Transport	7,719	8,182	7,719	7,719
Storage	13,760	14,585	13,760	13,760
Conversion	23,100	24,486	23,100	23,100
BOP	9,263	9,263	9,263	9,263
Tower	3,317	3,317	3,317	2,737
Receiver	14,812	6,545	5,810	6,057
Total*	\$101,186	\$94,475	\$90,051	\$90,626

*The total capital cost includes an additional 20% for indirect and contingency costs.

Table 3-1 shows that when the 10% reduction in system cost due to the lower cavity DAR cost is combined with the increase in the cost of the DAR transport, storage and EPGS subsystems (due to the larger capacities required for the higher DAR design point power), the total DAR system cost is only 6.4% less than that of the Saguaro plant costed at the long-term cost goals of the Program [19]. As will be shown in Chapter 5, the capital cost reduction impact on the LEC is even less than 6.4% since LEC also includes operating and maintenance costs.

As can be seen from the 16 cost categories presented in Table 3-2, three subcomponents--structure, absorber panels, and emergency curtain--have a strong cost correlation with the area of the DAR absorber. Thus, a change in absorber area to effect a change in the peak and average flux level on the absorber will have a significant cost impact on only these three subcomponents and the manifolds whose cost varies with the width of the absorber. Based on this, the actual formula used in this study to compute the DAR cost as a function of absorber size is

$$\text{Cost} = \$3.84\text{M} + \$4{,}722/\text{m}^2 \times \text{absorber area} + \$18{,}700/\text{m} \times \text{absorber width}. \qquad (1)$$

Table 3-2. Receiver Cost Breakdown
(1000s of dollars)

Subsystem	Saguaro	Cavity DAR	Billboard External DAR	Cylindrical External DAR
Structure*	$3,394	$1,278	$916	$983
Absorber*	4,247	840	601	646
Sump tanks	571	165	165	165
Manifolds‡	1,946	490	383	514
Auxiliary systems	273	273	273	273
Monorail	114	114	114	114
Fire protection	27	27	27	27
Lightening protection	230	230	230	230
Riser and downcomer	2,618	1,702	1,702	1,702
Cold salt pumps	678	422	422	422
Electrical	244	196	196	196
Instrumentation	99	50	50	50
Power and control wiring	359	215	215	215
Recirculation system	0	432	432	432
Emergency curtain*	0	98	70	75
Communications	15	15	15	15
Totals	$14,812	$6,545	$5,810	$6,057

Source: Buna, T. "DAR Component Assessment and Design Studies." Prepared for SERI by Solar Power Engineering Co., Inc. under contract XK-505115. April 1986.

*Cost varies with absorber area.

‡Cost varies with absorber width.

Thus, the cost impact of reductions in the DAR absorber size at higher flux levels is less than directly proportional to the receiver area.* As will be seen in Chapter 5, the more important effect of the higher flux levels that may be possible with a DAR receiver is that the thermal loss from the smaller receiver is reduced.

The 16 cost categories are also presented in Table 3-2 for the external billboard DAR with a north field and the external cylindrical DAR with a surround field. As in the analysis of the cost variations with absorber size, the principal cost changes relative

---

*Equation 1 contrasts with the relationship assumed by DELSOL2 and prior analyses [7,20] in which receiver cost is assumed to vary almost directly with receiver area. Each formula is designed for a different purpose. The above formula captures the change in receiver cost as the absorber area and flux levels are modified. The DELSOL2 cost relationship appears to be designed to capture the cost/absorber size relationship when the absorber size is changing with plant rated capacity; i.e., not only when the absorber size is changing, but also the fluid capacities, etc. are changing.

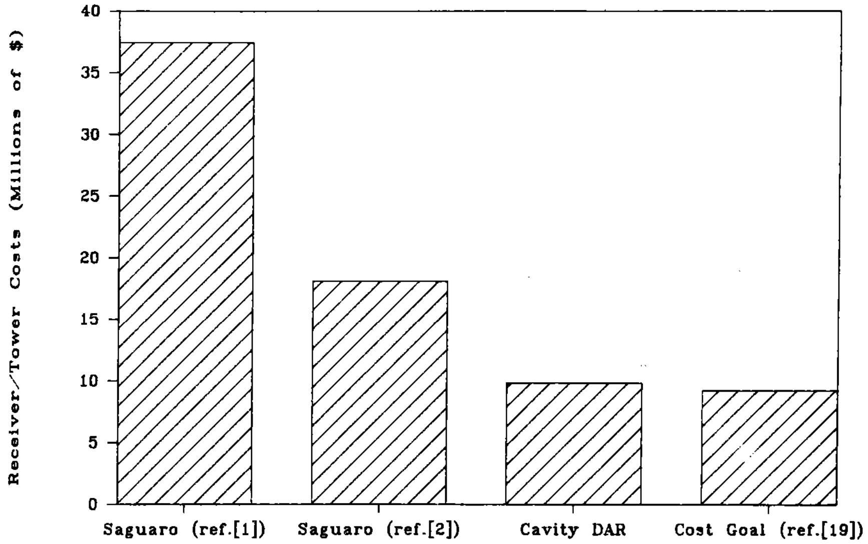


Figure 3-1. Receiver Tower Costs Relative to Goal

changes relative to the cost of the cavity DAR are in structure, absorber panels, and manifolds. For the billboard external receiver, the total receiver cost reduces to \$5.8M because of the reduction in absorber area. For the cylindrical external DAR, the receiver cost (\$6.1M) is also slightly lower than that of the cavity DAR because of its smaller absorber area, and the tower cost is lower (\$2.7M versus \$3.3M) because of the reduction in tower height that is possible with a surround field. The costs of the external receivers may be slightly exaggerated since our cost algorithm ignores the fact that external receivers will not require the inactive (non-absorber) surfaces that form the cavity of the Saguaro receiver and cavity DAR.

3.3 Operating and Maintenance Costs

In addition to the reduction in the initial system cost of a DAR receiver, it is expected that significant reductions will also occur in the operating and maintenance costs. Since DAR has no exposed receiver tubes and many fewer valves as shown in Table 3-3, SPECO has estimated that it may be 5% more reliable than the Saguaro receiver. Until more empirical data are available from system experiments, this estimate must be considered highly uncertain. Consequently, this advantage is not included in our base case assessments of DAR, although in the optimistic upper limit case for the cavity DAR, the estimated increase in reliability is assumed to improve both the performance (availability) and operating cost of DAR.

Table 3-3. Receiver Circulation System Complexity

Tubular Receiver	Cavity DAR
2000 tubes with 10,000 welds and 14,000 attachments	No tubes or welds
48 high-pressure manifolds	10 atmospheric manifolds
24 receiver drain-and-purge valves	No drain-and-purge valves
4 control valves	8 flow controllers

4.0 PERFORMANCE ASSESSMENTS

To complete the comparisons between the cavity and external DARs and the conventional salt-in-tube cavity receiver, estimates of the annual energy delivered by each of the receiver types have been developed using SOLERGY, which is an annual simulation model of the system from the heliostat field through the electric power generator. SOLERGY requires four principal inputs: (1) the heliostat field area, (2) the rate of loss of thermal energy from the receiver because of convection and reradiation, (3) the effective absorptance of the salt/plate absorber, and (4) an "Az-El" table specifying the efficiency of the heliostat field as a function of the azimuth and elevation of the sun. The code combines these inputs with the weather data over the course of the year (1984 in Barstow, California in this case) to estimate the annual energy delivered by the system.

4.1 Saguaro System Performance

The inputs for the evaluation of the Saguaro receiver were derived primarily from the the Arizona Public Service report [1]. The values of the first three inputs are shown in Table 4-1. The "Az-El" table was derived using DELSOL2 and the Saguaro heliostat characteristics listed in Table 4-2. The net annual energy delivered for Saguaro, as calculated by SOLERGY, is 96.7×10^6 kWh per year, or 313 kWh per square meter of heliostat area as shown in Table 4-3 and Figure 4-1.

4.2 Cavity DAR System Performance

The cavity DAR configuration was evaluated using the same approach and data as the Saguaro receiver with the exception that the receiver thermal loss and effective absorptance were computed as shown in Table 4-1. The thermal performance of the

Table 4-1. SOLERGY Inputs

Parameter	Saguaro	Receiver Type DAR Cavity	 DAR External Billboard	 DAR External Cylindrical
Heliostat area (1000 m^2)	309	309	302	322
Receiver thermal losses (MW_t)	20.35	8.60	8.22	8.67
Absorptance				
material	0.95	0.98	0.98	0.98
effective	0.99	0.99	0.98	0.98

Table 4-2. Heliostat Characteristics*

Area = 58.523 m^2
Panels 6 × 2
Canted at slant range
Focused based on farthest heliostat
Reflectivity = 0.92
Tracking error $\sigma_t = 1.5$ mrad
Surface error $\sigma_n = 2.0$ mrad
Tower sway error $\sigma_s = 1.7$ mrad
Total optical error‡ $\sigma_{tot} = 4.6$ mrad

*Based on Saguaro heliostat characteristics.

‡$\sigma_{tot}^2 = (\sigma_t)^2 + (2\sigma_n)^2 + (\sigma_s)^2$

Table 4-3. Annual Energy
(1000's of MWh)

	Saguaro	DAR Cavity	DAR External Billboard	DAR External Cylindrical
Gross energy	129	141	141	140
Parasitics	32.4	28.8	28.6	28.6
Net energy	97	113	112	111
Heliostat area (1000 m^2)	309	309	302	322
Energy/heliostat area (kWh/m^2)	313	364	369	345

cavity DAR was estimated using the computer codes SHAPEFACTOR [4] and RADSOLVER [5] to predict the radiative loss, and a correlation proposed by Siebers and Kraabel [6] to predict the convective loss.*

For the cavity DAR configuration, the net annual energy delivered as calculated by SOLERGY is 112.5×10^6 kWh, or 364 kWh/m^2. As shown by Figure 4-1 and Table 4-3, this is 16% more than that delivered by the conventional salt-in-tube receiver of

---

*RADSOLVER and SHAPEFACTOR underestimate the radiative losses from the Saguaro tube receiver since they do not account for the increase in tube temperature at those points along the tubes that are normal to the incoming flux. Since the original Saguaro receiver loss estimates did account for this effect, they were used in this analysis.

Saguaro. This relative performance increase results from increased absorptance (2.9%), reduced thermal losses from the smaller DAR (9.6%), and decreased pumping power parasitics (3.7%).

The reduction in parasitics is due to the elimination of absorber tubes in DAR. About half of the cold salt pumping power requirement in the Saguaro receiver was associated with the head loss in the absorber tubes. On this basis the required parasitic pumping power may be reduced from 2700 kW to 1300 kW.

An examination of the gross (i.e., before accounting for parasitics) annual energy (Table 4-3) produced by the cavity DAR and Saguaro systems provides additional insights into the relative performance advantages of the DAR system. The cavity DAR system produces 9.4% more gross electricity than does the Saguaro system. Of this, 2.3% is due to the greater material absorptance of the DAR.* The remaining 7.1% is due to the reduction in convective and radiation losses from the receiver. This 9.4% annual improvement is greater than the design point improvement in gross power of approximately 6%, because at off-design conditions, the receiver thermal loss constitutes a larger fraction of the total system output.

4.3 External DAR System Performance

To compare the DAR concept as an external receiver with Saguaro, DELSOL2 was used to optimize the field layout (and the number of heliostats) to achieve the same design point power level (190 MW_e) as the Saguaro system. The DELSOL2 simulations also provided optimum receiver dimensions and flux levels from which the receiver thermal

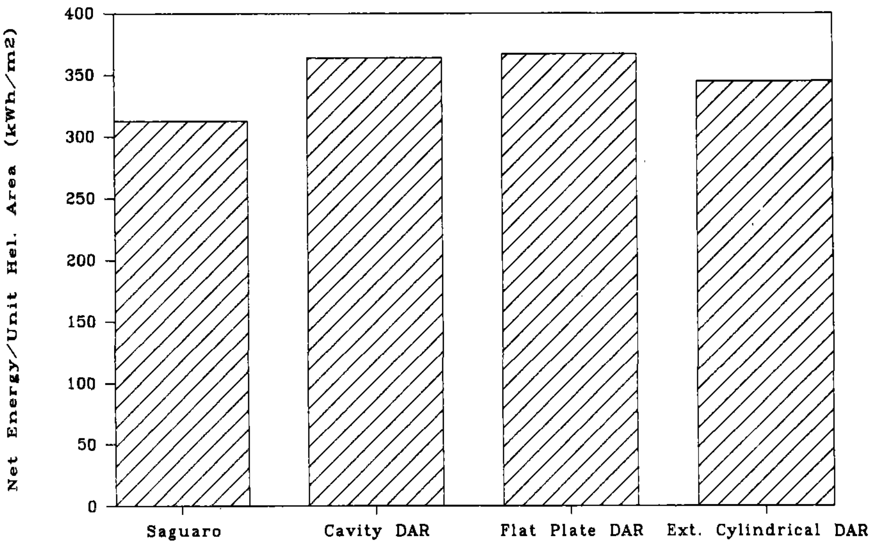


Figure 4-1. Annual Energy Per Unit Heliostat Area

---

*The 2.3% performance improvement due to the greater DAR material absorptance was determined as the performance difference between the base case cavity DAR and a cavity DAR with the same material absorptance as Saguaro (i.e., 0.95).

losses shown in Table 4-1 were calculated. Re-radiation losses from the absorber were calculated with a gray body radiation model assuming an emissivity of 0.98. Convection losses were based on correlations developed by Siebers [6]. The receiver thermal losses were input to SOLERGY along with the other input parameters shown in Table 4-1 and the "Az-EL" tables from DELSOL2 to estimate the annual performance of the external DAR systems. The net annual energy delivered by the external billboard DAR system as calculated by SOLERGY is 16% greater than that of Saguaro (18% more than Saguaro per unit of heliostat area), while that delivered by the external cylindrical DAR system is 15% greater than that of Saguaro (10% more than Saguaro per unit of heliostat area) as shown by Table 4-3.

Compared to the cavity DAR system, the external billboard DAR system delivers essentially the same net annual energy, but approximately 2% more energy per unit of heliostat area. This increase in efficiency will be apparent in the lower levelized energy cost of the billboard external receiver to be presented in the next section. The external cylindrical DAR delivers only 1% less net annual energy than the cavity DAR, but 5% less per unit of heliostat area.

5.0 LEC AND SENSITIVITY RESULTS

This chapter combines the cost and performance results presented in the two previous sections to calculate an LEC for the Saguaro plant and the DAR configurations. This section also examines the cost/performance sensitivities of both the cavity and external DAR configurations to several of the study parameters. To calculate the LEC, the electric utility economic parameters (Table 5-1) and the LEC methodology of the Solar Thermal Program Five Year Plan [19] were used.

5.1 Cavity Direct Absorption Receiver

The LEC of the base case cavity DAR configuration with an average flux of 0.4 MW/m^2, an absorber absorptance of 0.98, and recirculating flow circuit is 7.6¢/kWh. This is approximately 18% less than the 9.3¢/kWh LEC for the Saguaro system as shown in Table 5-1. This reduction in LEC is attributable to both the reduced cost (4%) and increased efficiency (14%) of a cavity DAR as shown in Figure 5-1.

The base case results for the cavity DAR have been prepared conservatively based on the best data available. From a more optimistic viewpoint, there are several improvements in performance and cost that may be possible, but which were not included in the base case results because of the difficulty in assessing their magnitude. For example, based on their survey of the required components and their engineering judgment, SPECO estimated that DAR may be approximately 5% more reliable than a conventional salt-in-tube receiver.

Table 5-1. Levelized Energy Costs

Financial Parameters*

Real discount rate	0.0315
Fixed charge rate	0.0593
Construction time adjustment factor	1.0318

Cost and Energy Data

	Saguaro	DAR Cavity	DAR External Billboard	DAR External Cylindrical
Heliostat area (1000m^2)	309	309	302	322
Capital cost ($1000s)	101,186	94,475	90,051	90,626
Net annual energy (10^6 kWh)	97	113	112	111
LEC‡ (¢/kWh)	9.3	7.6	7.4	7.6
LEC normalized to Saguaro	1.00	0.82	0.79	0.82

*Source: Solar Thermal Program Five-Year Plan.

‡Assumes annual O&M costs of $9/m^2. (See Reference 19 of text.)

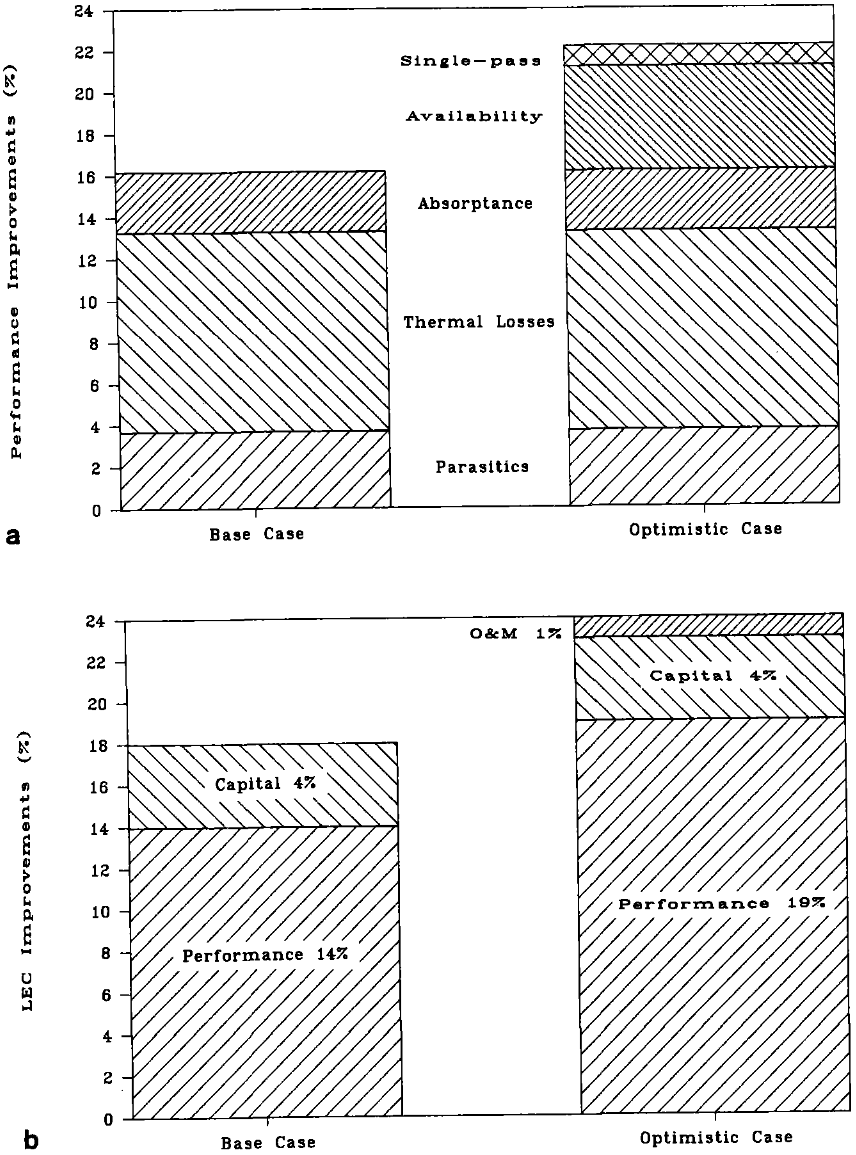
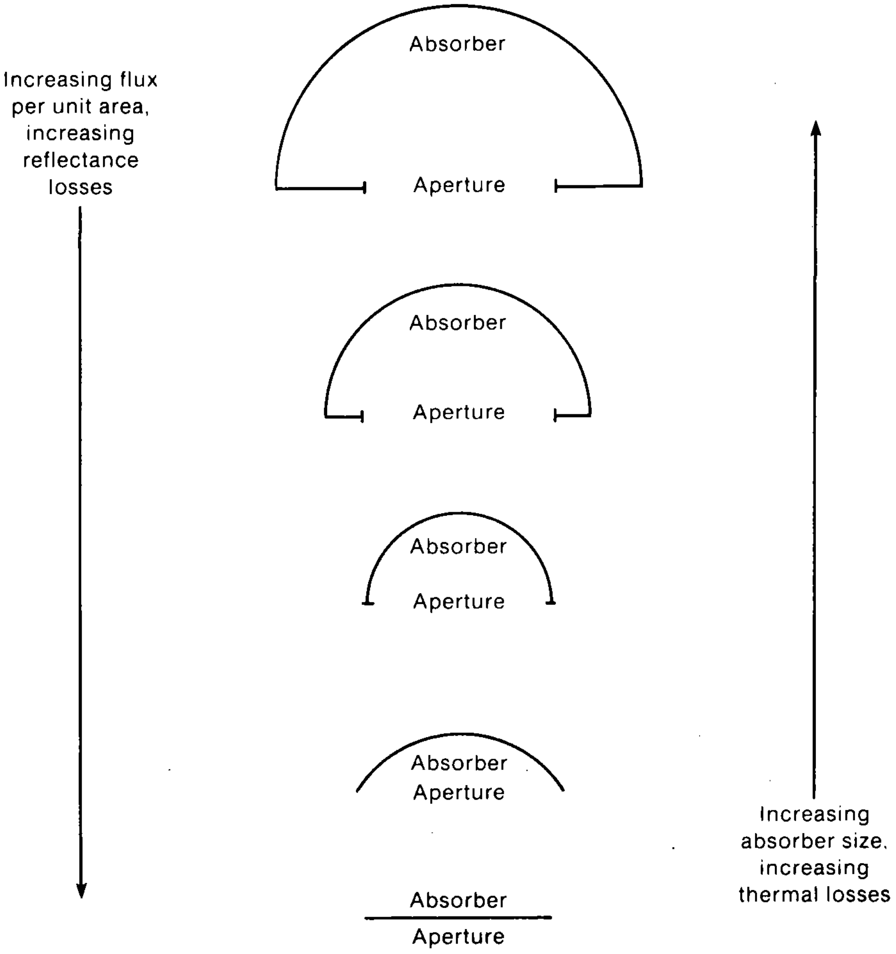


Figure 5-1. Cavity DAR vs. Salt-in-Tube

As also shown in Figure 5-1, a more optimistic case has been constructed by assuming that this increase in reliability/availability can be attained even without the recirculation flow system. For this optimistic case, the LEC of the cavity DAR may be reduced below that of the conventional salt-in-tube receiver system by as much as 24%, with 19% due to performance improvements relative to Saguaro and 5% due to cost improvements. The increase in the performance improvements includes both increased availability (5%) and lower thermal losses in the absence of the recirculation system (1.2%). The cost improvement increase is due to lower operating and maintenance costs and the absence of the recirculation system. The sensitivity of the annual performance and LEC of the cavity DAR to flux levels, aiming strategy, recirculation, salt/plate absorptance, and response to transients was also examined.

Flux levels. The average flux level for the cavity was varied by changing the distance from the aperture to the absorber, as shown in Figure 5-2. Because the reflected beams from the heliostats converge at the aperture and diverge immediately behind the



Optimum aperture size varies only slightly with the absorber size and peak flux levels.

Figure 5-2. Cavity DAR Absorber Size Adjustments

aperture, the average flux levels are the highest in the aperture plane and decrease as the radiation proceeds back into the cavity. The maximum average flux levels are reached in the limiting case where the absorber becomes a flat surface in the aperture plane.

As noted in Figure 5-2, the cavity aperture size was optimized for each flux level in this study. This involved trading off the thermal and reflective losses against the spillage (the flux lost around the edges of the aperture). Because the tower height and field size were not varied, the aperture size did not vary significantly from case to case.

The performance of the cavity at various flux levels was primarily determined by the behavior of the losses. The emissive losses from a cavity are primarily a function of the temperature of the surfaces behind the aperture and the size of the aperture. Because the absorber temperatures are the same in all cases and the aperture size is nearly constant, the emission losses vary only slightly with increasing flux levels. By contrast, the convection losses are strongly driven by the amount of hot surface area, and decrease monotonically with the decreasing receiver size. The reflective losses are strongly dependent on the depth of the cavity and the probability of a reflected ray striking another surface before being lost through the aperture. Thus, as the flux levels increase, the cavity gets shallower and the reflective losses increase.

Figure 5-3 illustrates the performance sensitivity of a cavity DAR to the average flux levels on the absorber surface for two different sets of heliostats. The lower curve, which corresponds to the heliostats of the Saguaro system (see Table 4-2), shows only a slight increase in performance as the average flux level is increased from 0.3 MW/m^2 to 0.6 MW/m^2. The upper curve of Figure 5-3 assumes that the heliostats are the same size but more accurate with a total optical error of $\sigma_{tot} = 2.1$ mrad and a mirror reflectance of 0.89 (compare to the values in Table 4-2). As in the case of the Saguaro heliostats, performance is not very sensitive to the average flux level over a wide range from the base case value of 0.4 MW/m^2 to the highest average flux level examined for the more accurate heliostats, corresponding to a flat billboard absorber at the aperture.

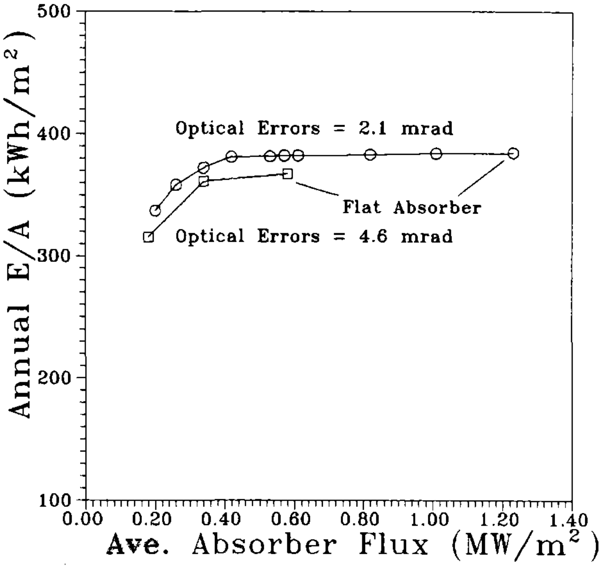


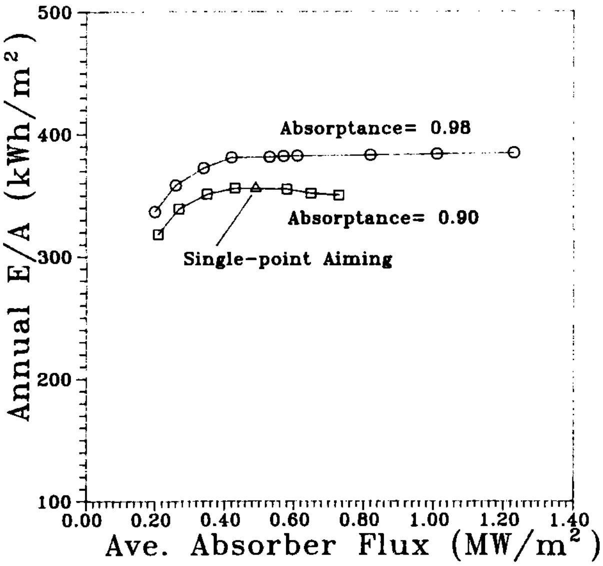
Figure 5-3. Cavity DAR Performance vs. Average Flux

Figure 5-3 shows that variations in the optical qualities of the heliostats do not impact the relative sensitivity of system performance to the average flux level on the receiver; i.e., both curves of Figure 5-3 increase monotonically as thermal losses are reduced with decreasing absorber area. However, the absorptance of the absorber/salt combination can impact the shape of these curves. If the receiver absorptance is decreased from the base case value of 0.98 to 0.90, then reflectance loss may begin to dominate and the performance-versus-flux curve eventually turns over as shown in Figure 5-4 for the more accurate heliostats. At an absorptance of 0.90, the optimum* average flux level appears to be in the vicinity of 0.6 MW/m^2 (1.7 MW/m^2 peak flux), although there is little sensitivity to the average flux level between 0.3 MW/m^2 and 0.7 MW/m^2.

Flux level variations achieved by modifying the absorber area impact the system LEC through both performance and system cost variations. However, as shown in Figure 5-5, the absorber cost variations (calculated as a function of absorber size using Equation 1) are not large enough, even when combined with the modest performance sensitivity, to produce significant sensitivity in the LEC to the average flux level. Although the LEC continues to decrease slightly as the limiting billboard case is approached (average flux of 0.58 MW/m^2), within a reasonable range of average flux levels between 0.35 MW/m^2 and 0.58 MW/m^2, the LEC varies by less than 2%.

---

*The optimum was actually determined by examining the levelized energy cost as a function of flux level.



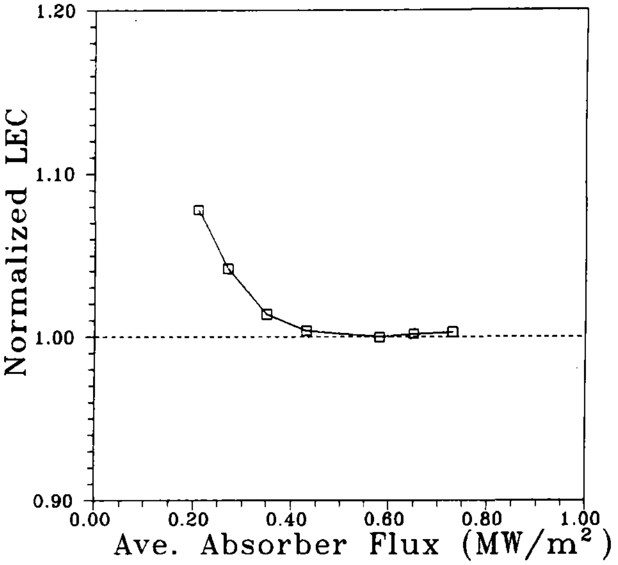


Figure 5-4. Cavity DAR Performance vs. Average Flux and Absorptance

Figure 5-5. Normalized Energy Cost-Cavity DAR

Although the flux sensitivity results presented here are fairly general, the optimum flux level may be sensitive to other system parameters that were not investigated, such as the overall system size and the operating temperature.

Aiming strategy. In the most sophisticated DELSOL2 aiming strategy, close-in heliostats with relatively little beam spread are aimed at peripheral points while distant heliostats with larger beam spread are aimed at the center of the aperture. On the assumption that the DAR absorber could withstand an increase in peak flux, a single-point aiming strategy was examined to determine if it would decrease the absorber and aperture sizes and, therefore, improve the cavity DAR cost and performance. Analysis of such a strategy indicates that it will not result in a smaller aperture.* Consequently, the single-point aiming strategy yields no significant change in the energy delivered by the receiver or the LEC. This is illustrated for a single case (average flux = 0.48 MW/m^2; absorptance = 0.90) in Figure 5-4.

Absorptance of the salt/plate. Although based on empirical results obtained by Drotning, the salt/plate absorptance of 0.98 employed in the base case analyses is a fairly optimistic value. Figure 5-6 shows that the annual energy delivered by a cavity DAR is sensitive to this absorptance value. An 8% decrease in the absorptance from 0.98 to 0.90

---

*The distant heliostats still require the same aperture size to avoid increasing the spillage. Furthermore, the spillage from the close-in heliostats is not significantly reduced since their aimpoints are not spread out very much in the DELSOL2 smart aiming strategy.

produces a 7% decrease in the annual energy delivered per unit heliostat area. The sensitivity of delivered energy to material absorptance is reduced by the cavity effect and the resulting effective absorptance. As a result of this performance sensitivity to absorptance, the LEC is also quite sensitive, as shown in Figure 5-7. Over a reasonable range of uncertainty in the absorptance (0.90 to 0.98), the LEC also varies by 7%.

Recirculation impact. The base case cavity configuration included a recirculation flow system to reduce temperature gradients (and, thus, stress) in the absorber plate, and to reduce potential flow stability problems and sensitivity to transients through increased flow rates. One of the drawbacks to the recirculation flow scheme is that it increases the average temperature of the salt/absorber plate by about 50°C, thereby producing increased thermal loss. However, analysis indicates that these additional losses represent only 1.2% of the net energy delivered by the system, and that the combination of increased losses, together with the cost of the recirculation system, yields an increase in the LEC of only 1.4%. This LEC calculation ignores the potential for increased receiver reliability that might be expected because of the recirculation flow and the reduced absorber plate temperature gradients that it produces. Conversely, the recirculation system may have reliability problems of its own. On the whole, however, it is expected that recirculation will provide an increase in system reliability, which, if accurately accounted for, would produce an LEC with the recirculation scheme less than that without recirculation.

Transient and startup losses. Energy and startup time transients for DAR are not well known at this time. However, the low thermal inertia of DAR and its reduced

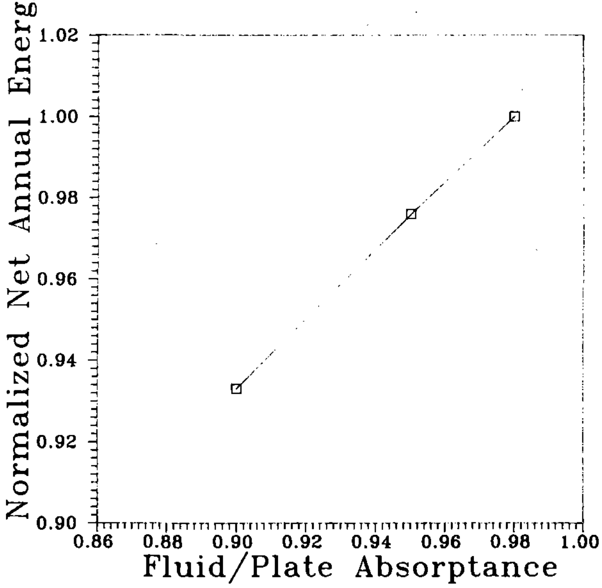


Figure 5-6. Normalized Annual Energy vs. Absorptance — Cavity DAR

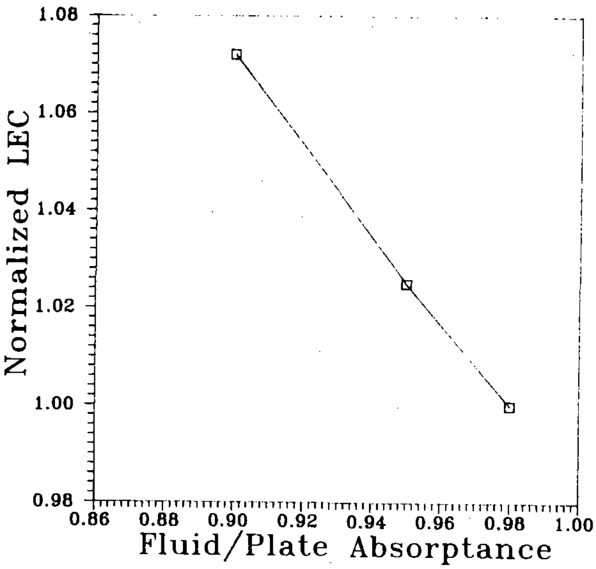


Figure 5-7. LEC vs. Absorber Absorptance - Cavity DAR

vulnerability to thermal shock suggest that it may be capable of starting up in as little time as 15 minutes [2]. Ordinarily, the startup time of a conventional salt-in-tube receiver could be expected to be longer than that of DAR because of the larger thermal mass and increased vulnerability to thermal shock of a tube receiver. However, the Saguaro receiver design includes doors on the receiver for retention of heat during non-operating periods. Thus, it is expected that the two receiver types will experience approximately the same energy and time requirements for startup. The sensitivity of performance to the startup requirements is shown in Figures 5-8 and 5-9.

5.2 External Direct Absorption Receiver

The LEC of the external billboard DAR with a north field was shown by the last point (average flux = 0.58 MW/m^2) in Figure 5-5 to be approximately 97% of that of the base case cavity DAR (average flux = 0.4 MW/m^2). Most of this small difference can be attributed to the reduced cost of an external billboard DAR relative to the larger absorber plate required by the cavity DAR configuration. Relative to the Saguaro system with a cavity salt-in-tube receiver, the LEC of the billboard external DAR system is reduced by approximately 21%.

The cost ($91M) and performance ($111.2 \times 10^6$ kWh/year) of the 190-MW$_t$ central receiver system with external cylindrical DAR and a surround field yield a levelized energy cost for this system of 7.6¢/kWh, approximately the same as that of the cavity DAR and 18% less than that of a conventional salt-in-tube cavity receiver. This reduction in LEC compared to the Saguaro system is attributable to both the reduced cost (9%) and increased efficiency (9%) relative to the conventional receiver.

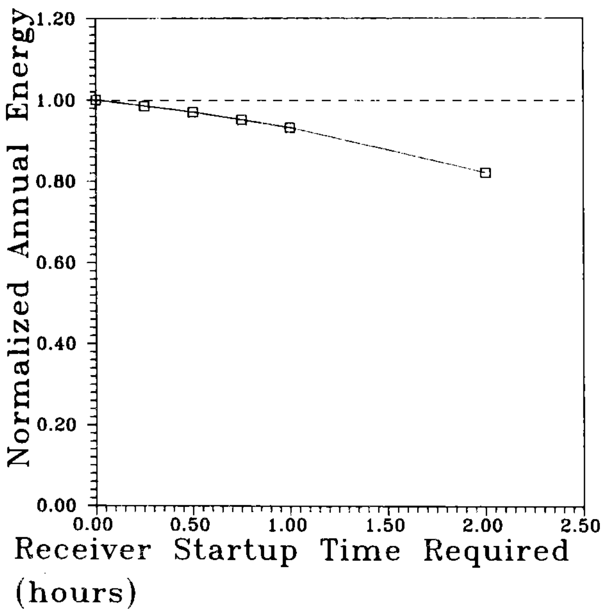


Figure 5-8. DAR Sensitivity to Startup Time Delay

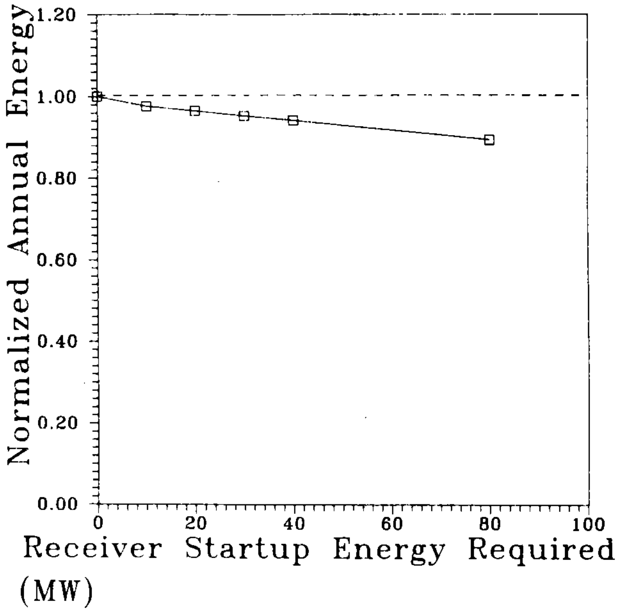


Figure 5-9. DAR Sensitivity to Startup Energy Delay

For the external cylindrical DAR configuration, the sensitivity of the annual energy delivered per unit heliostat area to the average flux level is presented in Figure 5-10. The average fluxes for the external/surround receiver were varied by changing the size of the cylinder. Since the heliostats are aimed at the centerline of the cylinder, increasing the diameter will decrease the flux level. The cylinder height is influential because the aiming strategy for external/surround receivers involves aiming the heliostats with smaller images above and below the midpoint of the centerline. Thus, as the cylinder becomes taller, the images can be spread out vertically and the average fluxes decrease.

Since both the emission and convection losses vary directly with the amount of hot absorber area, they decrease with increasing average flux. On the other hand, the reflected losses vary only slightly since the absorptance of the surface was held constant and the radiation incident on the absorber was nearly constant. However, as the average flux increases, the cylinder dimensions get smaller. When the size of the cylinder becomes smaller than the size of the reflected beams from the heliostat field, there is a marked increase in the spillage. Figure 5-10 demonstrates that the combination of these factors produces a fairly sharp maximum in the annual performance at about 0.60 MW/m^2.

The normalized LEC values for the external/surround receivers as a function of the average absorber flux are given in Figure 5-11. As with the cavities, the LEC results for the external receivers track the loss values and form a minimum at an average flux of about 0.6 MW/m^2 (peak flux = 1.4 MW/m^2). Beyond this value, the LEC begins to rise dramatically because of the decrease in performance.

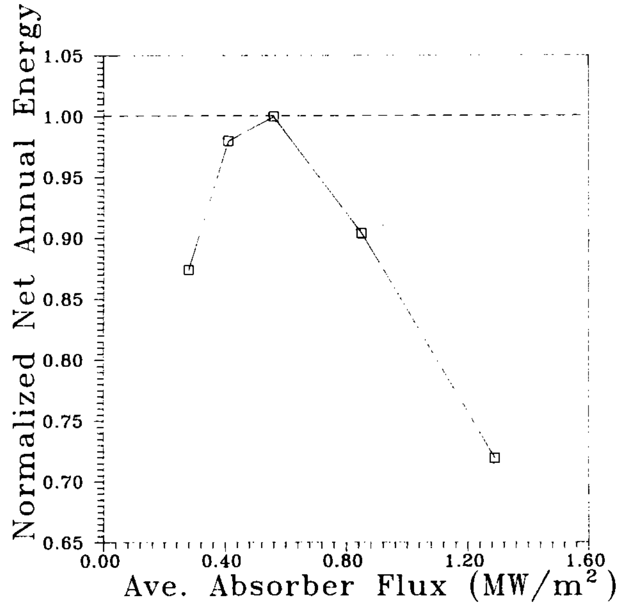


Figure 5-10. Cylindrical DAR Performance vs. Average Flux

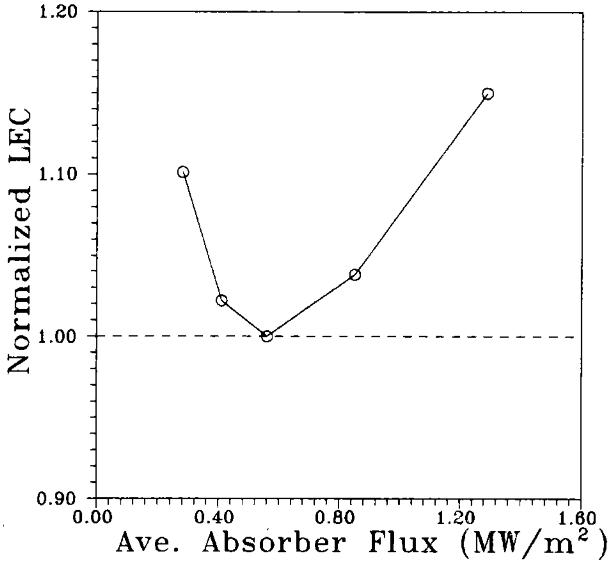


Figure 5-11. Normalized Levelized Energy Cost - Cylindrical DAR

Since the flux level at which this minimum occurs is dependent on the heliostat image size, the optimum average flux will depend on the optical quality of the heliostats. In particular, larger errors would drive the optimum flux level to smaller average flux values. The results shown in Figures 5-10 and 5-11 were generated for the heliostats with total optical errors of 4.6 mrad (sigma) listed in Table 4-2.

Explicit analyses of the sensitivity of performance and LEC to recirculation flow, aiming strategy, and the time required for startup and transients were not conducted for the external DARs since they are expected to show approximately the same sensitivity to these factors as the cavity DAR. The sensitivity to absorber material absorptance might be slightly larger than that of the cavity DAR since the effective absorptance is equal to the material absorptance.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The direct absorption receiver concept has the potential to significantly improve both the cost and performance of a central receiver system. In direct comparison with a conventional salt-in-tube receiver, as represented by the Saguaro design, a cavity DAR could reduce the receiver cost to less than half (44%) and increase the annual energy delivered by 16%, yielding, by a combined effect, an 18% reduction in LEC. The receiver cost reduction results from the decrease in absorber area size that is possible at the higher flux levels that can be tolerated by DAR and by the absence of the expensive tubing and many of the welds and valves required by a tube receiver. The performance increase is achieved through reduced thermal losses from the smaller receiver (9.6%), increased absorptance of the doped salt (2.9%), and a reduction in parasitic pumping power (3.7%).

Similar improvements in system cost, performance, and LEC may be attainable with an external DAR. A billboard external DAR with a north field may, by virtue of its smaller absorber area, improve the system cost and performance slightly more, resulting in an LEC 21% less than that of the Saguaro system. A cylindrical external DAR combined with a surround field has the potential to produce an LEC 18% less than that of Saguaro. (Additional advantages might occur to the cylindrical external DAR were one to consider the value to a summer-peaking utility of the larger amount of energy supplied in the summer by a surround field.)

The small differences between the predicted LEC's of the three baseline DAR systems are not by themselves significant enough to indicate a preference for one DAR configuration over another, especially given the assumptions that were required by the analysis in the absence of experimental data. Furthermore, sensitivity analyses on the major performance parameters do not show one configuration to be clearly superior. Thus, the selection between DAR configurations will probably depend on engineering issues and the resolution of technical uncertainties such as startup time requirements, the influence of manifold design on flow patterns, wind shear effects and flow stability.

Several sensitivity issues have been examined as a part of the systems analysis of the DAR concept. In general, both the cavity and external DAR configurations show approximately the same sensitivities to the parameters/assumptions examined. Both configurations are expected to show the greatest sensitivity to the absorptance of the absorber plate/salt combination. A decrease in the salt/plate absorptance from the base case value of 0.98 to 0.90 yields a similar fractional decrease in the performance of both the cavity and external DAR configurations. Neither is very sensitive to the aiming strategy employed or the presence of a recirculation system.

In general, the results show that for cavity receivers there is a strong incentive to increase the average flux levels up to some "threshold" level, generally near 0.4 to 0.6 MW/m^2, but little incentive to increase the fluxes beyond that level. Overall, the value of this "threshold" flux level is largely insensitive to the range of parameters studied here.

The external receivers show similar sensitivity to the flux for low flux levels. However, at some flux level the dimensions of the absorber become nearly the same size as the reflected beam from the heliostat field, and the spillage losses cause an abrupt decrease in the performance above that point. Average flux levels of about 0.6 MW/m^2 produced the best results for the range of parameters tested and for the heliostats used.

There are two additional characteristics of the DAR concept that have the potential to reduce the cost of energy even further below the estimates. SPECO estimates that the substantial reduction in the number and complexity of components, and the absence of flow tubes in DAR should increase the reliability of the receiver by 5%. Secondly, the reduced mass of DAR may yield less sensitivity to flux transients and a quicker startup time. These two potential DAR advantages have not been included in this analysis because of the uncertainty associated with their estimation; however, a 5% increase in reliability/availability could, by itself, reduce the delivered energy cost another 5%. These significant potential DAR advantages warrant further quantification and analysis.

The sensitivity analyses of this study reinforce the current Solar Thermal Program emphasis on the resolution of several issues related to materials, fluid dynamics/heat transfer, and design considerations. From a preliminary analysis, all such issues appear to be resolvable.

The economic importance of improved receiver technology, and DAR in particular, will increase as improvements in heliostat technology reduce the cost of heliostats. Current work on the DAR concept should position it to carry an important role in future systems.

6.2 Recommendations

The results of this systems analysis suggest that since the direct absorption receiver concept has significant potential to reduce the delivered energy cost of a central receiver system, research and development activities on this concept should be given a high priority. Immediate activities should address the fluid dynamics, materials, and optical issues of draw salts, dopants, and the absorber plate under high fluxes. More specifically, since this systems analysis has shown that the absorptance of the salt/dopant/plate combination may be a critical determinant of the DAR system performance, further investigation of the absorptance and reliability of cobalt oxide darkener in a draw salt is recommended. This will require measurements of both the absorptivity and falling-film thickness of the doped salt.

The systems analysis results presented in this report are current best estimates of the potential of the DAR concept to improve the cost of energy delivered by a central receiver system. However, these estimates can be improved in the future through three primary systems analysis activities.

1. Compare with other advanced salt-in-tube receivers. On-going analyses by Sandia National Laboratories, Livermore [19] and others [21] suggest that it may be possible to improve the delivered energy costs from conventional salt-in-tube receivers through increases in the flux levels on the receiver. Once these results are documented, the advantages of the DAR concept relative to these advanced tube receivers should be reassessed.

2. Incorporate new data on the DAR concept. Currently, there are several on-going and planned experiments to evaluate the optical, thermal, and flow stability properties of molten nitrate salts and dopants in exposed flow. As the results of these experiments become available and as more data are acquired on the cost and operational advantages of DAR such as pumping power requirements, reliability, and transient response, the systems analysis should be updated.

3. Examine promising alternate DAR configurations. In addition to the three DAR configurations investigated in this analysis, there are other configurations with potential promise. For example, an internal-film receiver with free flow of the heat-transfer fluid over the interior or non-illuminated side of an absorber plate may

enjoy additional advantages such as the absence of potential wind blowoff problems, elimination of optical dopants, and the use of a selective surface absorber plate to reduce emissive losses. Such innovative approaches merit continued evaluation in search of ideas which may further reduce the capital cost of receivers and increase the performance and operational reliability of solar thermal central receiver systems.

REFERENCES

1. Preliminary Design of a Solar Central Receiver for a Site Specific Repowering Application (Saguaro Power Plant), September 1983, Cooperative Agreement DE-FC03-82sf11675-4, Arizona Public Service.

2. Buna, T., April 1986, DAR Component Assessment and Design Studies, Prepared for the Solar Energy Research Institute by Solar Power Engineering Co., Inc., under contract XK-505115.

3. Stoddard, M. C.; S. E. Faas; C. S. Chaing; and J. Dirks, SOLERGY - A Code for Predicting Annual Energy Production from Solar Central Receivers, Livermore, CA: Sandia National Laboratories, SAND 86-8068.

4. Emery, A. F., October 1980, Instructional Manual for the Program "SHAPEFACTOR", SAND80-8027, Sandia National Laboratories.

5. Abrams, M., October 1980, RADSOLVER - A Computer Program for Calculating Spectrally Dependent Radiative Heat Transfer in Solar Cavity Receivers, SAND81-8248, Sandia National Laboratories.

6. Siebers, D. L. and J. S. Kraabel, April 1984, Estimating Convective Energy Losses from Solar Central Receivers, SAND84-8717, Sandia National Laboratories.

7. Dellin, T. A. et al., August 1981, A User's Manual for DELSOL2: A Computer Code for Calculating the Optical Performance and Optimal System Design for Solar Thermal Central Receiver Plants, SAND81-8237, Sandia National Laboratories.

8. Bohn, M. S. et al., January 1986, Direct Absorption Receiver Experiments and Concept Feasibility, SERI/TR-252-2884, Golden, CO: Solar Energy Research Institute.

9. Lewandowski, A. et al., July 1984, Direct Absorption Receiver System Study, Phase 1, SERI/SP-253-2438, Golden, CO: Solar Energy Research Institute.

10. Lewandowski, A. et al., December 1984, Direct Absorption Receiver System Study, Phase 2, SERI/SP-253-2592, Golden, CO: Solar Energy Research Institute.

11. Personal communication with L. M. Murphy. See also Anderson, J. V.; L. M. Murphy; and D. Simms, August 1985, "Medium Temperature (560°C) Application of Direct Absorption Receivers," SERI Letter Report to DOE.

12. Wang, K. Y. and R. J. Copeland, Heat Transfer in a Solar Radiation Absorbing Molten Salt Film Flowing Over an Insulated Substrate, ASME, 84-WA/Sol-22.

13. Tyner, C. E. and T. R. Tracy, "The Feasibility and Potential of a Direct Absorption Receiver in Nitrate Salt Solar Power System," Proceedings of the 1987 ASME-JSME Solar Energy Conference, Honolulu, Hawaii, March, 1987.

14. Personal communication with Raymond Kaiser Engineers, Inc., Oakland, CA, to Tom R. Tracey.

15. Bloom, H. and D. C. Rhodes, 1956, "Molten Salt Mixtures, Part 2. The Refractive Index of Molten Nitrate Mixtures and Their Molar Refractivities," Journal of Physical Chemistry, Vol. 60, pp 791-3.

16. Drotning, W. D., 1976, Solar Absorption Properties of a High Temperature Direct-Absorbing Heat Transfer Fluid, SAND-76-9104-c, Albuquerque, NM: Sandia National Laboratories.

17. Abrams, M., "The Effective Absorptance of a Semi-Transparent Layer on a Diffuse, Opaque Substrate," Paper No. 76-HT-4 presented at the ASME-AIChE Heat Transfer Conference, St. Louis, MO, August 9-11, 1976. See also Abrams, M., September 1975, The Solar Absorptance of a Semi-Transparent Layer on an Opaque Substrate, SAND75-8041, Livermore, CA: Sandia National Laboratories.

18. Schaeffer, H. G., 1979, MSC NASTRAN PRIMER - Static and Normal Mode Analysis: A Study of Computerized Technology, Mount Vernon, NH: Schaeffer Analysis, Inc.

19. U.S. Department of Energy, Office of Conservation and Renewable Energy, September 1986, National Solar Thermal Technology Program - Five Year Research and Development Plan 1986-1990, DOE/CE-0160.

20. Personal communication with Bruce Kistler, April 1986, and as found in "Receivers Design and Performance Analysis," presented at the Solar Central Receiver Technology Workshop, Pleasanton, CA, April 22-24, 1986.

21. Utility Coordination Board Meeting for the Utility Central Receiver Study at San Ramon, CA. March 27, 1987.

APPENDIX A

Technical Issues

Several engineering/design issues arose during the development of a viable cavity DAR configuration and the subsequent systems analysis of that configuration. Some of the issues were examined briefly during the course of this effort, while others warrant further analysis. At this time all appear to be manageable.

1. Stress levels in the absorber. Thermal stress in the single curved thin metal sheet absorber panel was identified in the SPECO study as a potential problem for the cavity DAR configuration. Under SERI direction, Sallis* investigated the possibility that nonlinear temperature distributions on the absorber plate could lead to large thermal stresses that could warp or buckle the plate unacceptably. Using NASTRAN, a finite-element structural analysis program, and predicted two-dimensional temperature distributions in the absorber plate, Sallis examined both one- and two-dimensional stress distributions in an attempt to bound both the magnitude of the stresses and the expected deflections in the plate. The plate support system proposed by SPECO and one other promising, but more idealized, configuration were evaluated by Sallis. For both configurations the two-dimensional temperature distribution analysis indicates significantly more stress in the absorber plate than does the simplified analysis of a one-dimensional temperature distribution. Nevertheless, both analyses indicate that it should be possible to alleviate any thermal stress problems that might occur in a single plate absorber for a cavity DAR. The two support systems examined were:

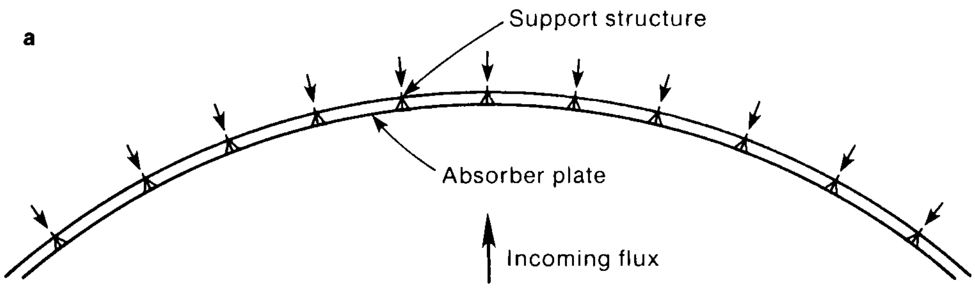
   o SPECO support system. In SPECO's configuration the absorber plate is held to a one-dimensional parabolic shape by an array of flexible supports that allow only in-plane expansion as shown in Figure A-1.a. Such a support system is predicted to lead to extremely large in-plane stresses (>15,000 psi). In reality, these stresses will probably be reduced by low amplitude, local and structural, non-damaging buckling of the absorber plate between supports; a possibility that Sallis's original model was not meant to capture. The analysis of this configuration yields an upper limit on the stresses in a highly constrained absorber plate.

   o Free shape support system. A second support system for the cavity DAR absorber was considered by Sallis to find an upper limit on the deflection that will occur in a less constrained, low stress, absorber support system. In this support system only the ends of the absorber plate are held fixed along their vertical edges (see Figure A-1.b), and the shape of the absorber plate deflects from an ideal parabolic shape to relieve the in-plane stress. It appears that the in-plane stress can be reduced by an order of magnitude, while over the entire absorber height of 13 m, maximum deflections of only 0.12 m or less occur at the bottom center of the absorber surface.

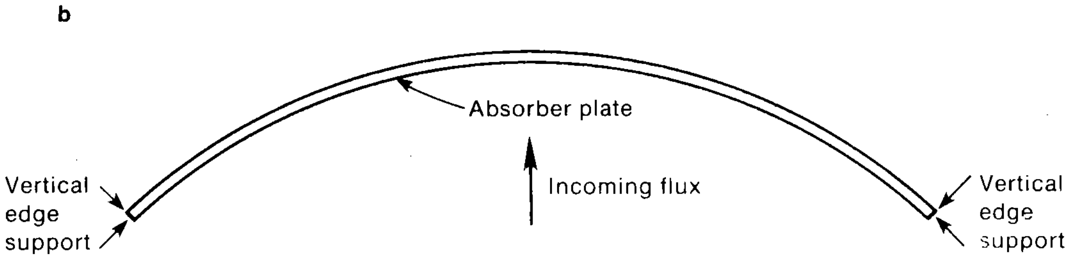
   Sallis points out that even if the concept of a single absorber plate proves infeasible due to thermal stress, there exist several other promising alternatives; for example, side-by-side vertical plates connected by some kind of expansion joint, or horizontal strips that overlap in the fashion of roofing shingles.

---

*Personal communication with D.V. Sallis, June 30, 1986, at a presentation made at SERI.



SPECO fixed-shaped absorber plate



Free-form absorber plate

Figure A-1. Absorber Plate Attachment

2. Fluid dynamics/heat-transfer concerns. There are several concerns about the fundamentals of film flow and heat transfer that need better resolution.

    - The heat-transfer mechanisms within the salt/absorber system require further investigation. A model is currently being developed at SERI and calibrated with SERI experimental results that will allow more accurate predictions of absorber plate temperature distributions and the resulting thermal stresses and deflections. Tests planned for later this year at SERI will also attempt to establish a better estimate of the plate-to-salt convection coefficient.*

    - We need to understand better the impacts of external factors on the salt film stability; e.g., local hot spots, deformations of the plate, wind, contamination of the salt and or the plate.

    - We need a better understanding of the effect of tilt angles on salt flow, and of the transition from film flow to "free fall."

---

*Tyner, C. E. and Carasso, M. "Direct Absorption Receiver R&D Plan: Task Summary." Joint SERI/SNLA task plan, Sep. 1986.

3. Materials concerns. Although at the intermediate design temperature of 550°C the materials problems are not severe, there remain several areas in which current understanding is incomplete.

   - We need more data on the salt/dopant/plate absorptance and its potential for degradation over time.
   - We need more data on the potential for agglomeration of dopants. Early tests at Sandia showed some agglomeration of cobalt oxide, the most promising dopant, under stagnant conditions (e.g., in storage tanks) on a time scale of hours. This trend might be controlled by agitation in the storage tanks, or by introduction of a segregated two-loop design employing a heat exchanger at the base of the tower as suggested by SPECO (see Chapter 2).
   - We need data on the initial cost of the salt dopant and the requirement for periodic regeneration or replacement.
   - We need the rates of NO_3 salt degradation in air and estimates of the cost of in-line regeneration or periodic replacement of the salt.
   - We need better estimates of the capacity of the DAR concept to handle large average fluxes and high peak-to-average flux ratios.
   - The capability of existing pumps to recirculate over the molten salt temperature range needs to be investigated.

4. Design considerations. In addition to the research-type issues described above, there are also some areas in which we need a better design approach.

   - A better method of flow introduction onto the absorber plate needs to be identified. The weir approach, which has been used in all the experimental work to date, appears to be very sensitive to maladjustments and external influences (e.g., wind-induced tower sway). Some work will have to be done to define the relative advantages and disadvantages of other methods for introducing the flow, such as manifolds along the top edge of the absorber plate. The problem is complicated by the thermal expansion of the absorber plate.
   - If the vertical flow channels are not to be used, then control of flow rates along vertical sections of the plate becomes an issue. The single plate absorber configuration allows horizontal movement of the fluid between various control sections and will probably decrease accuracy of flow rate control. Several possibilities exist:
   - The obvious possibility is some new arrangement for forming flow channels (a method of horizontal containment) on the absorber plate that does not develop local hot spots (as the knife-edges used in the ACTF tests appear to have). If the technique for forming the flow channels also included some allowance for differential expansion of the plate, then it might relieve some of the concerns about thermal stresses as well.
   - Another possibility is a recirculation scheme in which the flow rate is uniform across the plate, and the temperature of a particular vertical section of the plate is controlled by the temperature of the inlet fluid to that section. This plan has the advantage of allowing the single absorber plate, but would require a somewhat more sophisticated control system and might aggravate the thermal stress/deformation situation.

   As part of the DAR design study, SPECO also suggested two ideas that could be applied to both DAR and conventional receivers.

1. Dual flow loops. A heat exchanger located at the base of the tower can be used to separate the working fluid from the rest of the system.

   Advantages. For DAR this will minimize the amount of dopant required, ameliorate potential problems associated with agglomeration of dopant in stagnant flow sections, and reduce the salt fluid replacement requirements should the salt degrade with exposure to air. For all receivers, the use of a "U-tube" arrangement for the downcomer and riser will reduce the hydraulic head and the associated pumping power requirements.

   Disadvantages. A decrease in system efficiency will result from the drop in temperature through the heat exchanger. The total system cost will increase with the additional cost of the high-temperature, high-pressure heat exchanger.

   This dual-loop configuration was not included in our analysis of DAR.

2. Ceramic-fiber curtain. A curtain made from ceramic fibers could protect the absorber in the event of a power failure. Typically, this protection has been provided by a 2-3 minute supply of salt positioned to flow by gravity across the absorber.

   Advantages. The curtain will eliminate the weight and concomittant structural requirements associated with supporting a heavy (25,000 lb) salt tank at the top of the tower. It might also serve to diffuse the energy from the warm-up heliostats in the morning.

   Disadvantages. The technology is undemonstrated in the context of solar thermal receivers, although the product is available commercially.*

---

*For example, Nextel 312 is manufactured from a ceramic fiber by 3M Company to withstand temperatures of 2600°F on a continuous basis as a furnace curtain.

APPENDIX B

Comparative Cost Analysis Summary

	Saguaro		DAR (same rating)	
Subsystem	Description	Cost, $	Description	Cost, $
Structure	Very large and heavy (1,208,000 lb)	3,393,700	Much smaller and lighter (640,000 lb)	1,278,200
	Large and complex door ($ 553,300)		No door	
Absorber Panels	8190 ft^2 projected area; 25,730 ft^2 tube area	4,247,200	5700 ft^2 wall area	839,800
	2016 1.5-in. dia. tubes, 70 ft long ea.		No tubes	
	- approx. 10,000 welds - 14,000 attachments - 48 manifolds (drill 2016 holes)		-1/8 in. sheet -342 supports	
	High pressure (235 psi)		Vented	
	Creep/fatigue is a risk to receiver life		Operates in the elastic regime	
Sump Tanks	Cold surge tank pressurized to 600 psig. - Carbon steel	571,100	Cold surge tank vented -Stainless, 25% of Saguaro volume	164,700
	Hot surge tank vented, Stainless steel		Same as Saguaro, except 25% volume	
Manifolds	Lines -44 drain & purge valves -4 control valves	1,945,900	No drain and purge valves	489,700
			10 flow controllers - Much simpler than valves: No stem seal No positive shutoff No valve body	
	Residence time 150 secs. at full load, 750 secs. at 20% load		Residence time 4 secs. at full load	
	Manifold at 235 psig.		Manifold at very low pressure	

Comparative Cost Analysis Summary (continued)

	Saguaro		DAR (same rating)	
Subsystem	Description	Cost, $	Description	Cost $
Auxiliary Systems	Mainly pneumatics	273,200	Same estimate	273,200
Monorail	Needed to remove panels	113,900	Not needed	0
Fire Protection	Receiver	21,400	Same estimate	21,400
Lightning Protection		17,000	Same estimate	17,000
Riser and Downcomer	Riser: 1150 psig. - Expansion joints Downcomer: - Expansion joints	2,617,600	Riser: 610 psig. - No expansion joints (Reduced length by factor of 2; No bends or fittings reduced welds) Downcomer: - No expansion joints (Reduced length by a factor of 3)	1,702,200
Cold Salt Pumps	High head rise, high power - Head = 1505 ft - 2700 kW - Multi-stage with bearings in salt (reliability problem) - High pressure isolation valves - 3-50% pumps for redundancy - Cost of power @ $2000/kW$_e$ = $5.4M	677,800	Significantly reduced head rise and power - Head = 700 ft - 1300 kW - Cantilever pump with no bearings or seals in salt - No isolation valves - Built-in spares - Cost of power @ $2000/kW$_e$ = 2.6M (Delta = -2,800,000)	422,100
Electrical		243,500	About 40 less valves to wire - power - position indicators	196,400

Comparative Cost Analysis Summary (concluded)

	Saguaro		DAR (same rating)	
Subsystem	Description	Cost, $	Description	Cost $
Fire Protection	Circulation & drain system	5200	Same estimate	5200
Instrumentation	Large number of temperature measurements needed for control About 40 more valve positions	98,600		49,600
Power and control wiring	Cold pumps: 2700 kW	358,900	Cold Pumps: 1300 KW	215,400
Lightning Protection		212,400	Same estimate	212,400
Recirculation system	Not needed		100 kW Stainless pump 100 ft of 10-in. dia Schedule 10 pipe Wiring and Controls Installation	431,500
Emergency Curtain	Not required		Ceramic Fiber Cloth or equivalent Installation	98,400
	Totals:	$14,811,900		$6,545,400 (56% Saving)

Source: Buna, T. "DAR Component Assessment and Design Studies." Prepared for SERI by Solar Power Engineering Co., Inc. under contract XK-505115. April 1986.

DAR SYSTEMS ASSESSMENT

SELECTED DISTRIBUTION LIST

Acurex Solar Corporation
485 Clyde Ave.
Mt. View, CA 94042
Mr. Don Duffy

Arizona Public Service Company
P.O. Box 21666
Phoenix, AZ 85036
Mr. Eric Weber

Babcock and Wilcox
91 Stirling Ave.
Barberton, OH 44203
Mr. Paul Elsbree

Barber-Nichols Engineering Co.
6325 W. 55th Ave.
Arvada, CO 80002
Mr. Robert Barber

Battelle Pacific NW Laboratory
P.O. Box 999
Richland, WA 99352
Dr. Ben Johnson
Dr. Kevin Drost
Mr. Tom A. Williams

Bechtel Corporation
P.O. Box 3965
San Francisco, CA 94119
Mr. Pascal DeLaquil

Black and Veatch Consulting Engineers
1500 Meadow Lake Parkway
Kansas City, MO 64114
Dr. Charles Grosskreutz

Brumleve, Mr. Tom
Consultant
1512 N. Gate Road
Walnut Creek, CA 94598

Department of Energy/ALO
P.O. Box 1500
Albuquerque, NM 87115
Mr. Dean Graves
Mr. Joe Weisiger
Mr. Nyles Lackey

Department of Energy/HQ
Forrestal Building
1000 Independence Ave., SW
Washington, DC 20585
Dr. H. Coleman
Mr. S. Gronich
Mr. C. Mangold
Mr. M. Scheve
Mr. Frank Wilkins

Department of Energy/SAN
1333 Broadway
Oakland, CA 94536
Mr. Robert Hughey
Mr. William Lambert

Department of Energy/SAO
1617 Cole Blvd.
Golden, CO 80401
Dr. Paul Kearns

Electric Power Research Institute
P.O. Box 10412
Palo Alto, CA 94303
Mr. Donald Augenstein

England, Dr. Christopher
Consultant
Engineering Research Group
138 West Pomona Ave.
Morrovia, CA 91016

Entech, Incorporated
P.O. Box 612246
DFW Airport, TX 75261
Mr. Walter Hesse

Foster Wheeler Solar Development Corp.
12 Peach Tree Hill Road
Livingston, NJ 07070
Mr. Robert J. Zoschak

Gas Research Institute
8600 West Bryn Mawr Ave.
Chicago, IL 60631
Mr. Keith Davidson

Georgia Institute of Technology
Atlanta, GA 30332
Dr. Tom Brown

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109
Mr. William Owen

LaJet Energy Company
P.O. Box 3599
Abilene, TX 79604
Mr. Monte McGlaum

Lawrence Berkeley Laboratory
Building 90-2024,
University of California
1 Cyclotron Road
Berkeley, CA 94720
Dr. Arlon Hunt

Luz Engineering Corp.
15720 Ventura Blvd.
Suite 504
Encino, CA 91436
Dr. David Kearney

Martin Marietta
P.O. Box 179
Denver, CO 80201
Mr. Tom Tracey

McDonnell Douglas Astronautics
Company
5301 Bolsa Ave.
Huntington Beach, CA 92647
Mr. Jim Rogan

NASA Lewis Research Center
21000 Brookpark Road
Cleveland, OH 44135
Dr. Dennis Flood

NASA-Johnson Space Center
NASA Road One - EPS
Houston, TX 77058
Mr. William Simon

National Bureau of Standards
Building 221, Room 252
Gaithersburg, MD 20899
Mr. Joseph Richmond

New Mexico State University
Physical Sciences Lab
P.O. Box 3548
Las Cruces, NM 88003
Mr. James McCrary

Olin Corporation
315 Knotter Drive
Cheshire, CT 06410-0586
Mr. Jack Rickly

Pacific Gas and Electric Company
3400 Crow Canyon Rd.
San Ramon, CA 94583
Mr. Gerry Braun
Mr. Joe Iannucci

Sandia National Laboratories
Solar Department 8453
Livermore, CA 94550
Mr. A Skinrood

Sandia National Laboratories
Solar Energy Department 6220
P.O. Box 5800
Albuquerque, NM 87185
Mr. John Otts
Mr. James Leonard
Dr. Donald Schuler
Mr. Craig Tyner

Science Applications, Inc.
10401 Rosselle Street
San Diego, CA 92121
Dr. Barry Butler

Solar Energy Industries Association
1717 Massachusetts Ave. NW No. 503
Washington, DC 20036
Mr. Carlo La Porta
Mr. Scott Sklar

Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401
Mr. B. P. Gupta
Dr. L. J. Shannon

Solar Kinetics, Inc.
P.O. Box 47045
Dallas, TX 75247
Mr. Gus Hutchison

University of Illinois
Dept. of Mechanical and Industrial
Engineering
1206 W. Green Street
Urbana, IL 61801
Dr. Art Clausing

Document Control Page

1. SERI Report No. SERI/TR-253-3162

2. NTIS Accession No.

3. Recipient's Accession No.

4. Title and Subtitle
Direct Absorption Receiver (DAR) Systems Assessment

5. Publication Date
August 1987

6.

7. Author(s) J. V. Anderson, W. Short, T. Wendelin, N. Weaver

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

10. Project/Task/Work Unit No.
5137.31

11. Contract (C) or Grant (G) No.
(C)
(G)

12. Sponsoring Organization Name and Address

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

The direct absorption receiver (DAR) represents a fairly significant departure from conventional salt-in-tube receiver technology and appears to offer substantial promise for future generations of receivers. The DAR concept involves absorbing the solar flux directly into a film of molten salt that flows in a thin film over a plate. Since the film absorbs most or all of the flux directly, the flux limits associated with tubular receivers can be relaxed substantially. This allows smaller and lighter receivers, which results in better thermal performance and lower capital costs. This report describes the results of an effort to anlayze the effects of these factors on system performance and energy cost for both cavity type and external DAR configurations. The approach taken is to directly compare a central system with a DAR receiver and the same system with a salt-in-tube receiver. The results show about a 16% improvement in the thermal performance (annual energy delivered) of a cavity DAR system, while the cost estimate for the DAR indicates a reduction of over 50% in the cost of the receiver. These two effects combine to produce about an 18% reduction in the levelized cost of delivered energy when compared to a system with a conventional salt-in-tube receiver.

17. Document Analysis
a. Descriptors
Absorption, solar flux, molten salt, receiver, thermal performance

b. Identifiers/Open-Ended Terms

c. UC Categories
62a

18. Availability Statement
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

19. No. of Pages
48

20. Price
A03

Form No. 0069 (3-25-82)

The Feasibility and Potential of a Direct Absorption Receiver in a Nitrate Salt Solar Power System

Craig E. Tyner
Central Receiver Technology Division
Sandia National Laboratories
Albuquerque, New Mexico 87185

and

Thomas R. Tracey
Consultant
Denver, Colorado

ABSTRACT

The Direct Absorption Receiver (DAR) concept was proposed in the mid 1970's as an alternative advanced receiver concept to simplify and decrease the cost of central receiver systems. Rather than flowing through tubes exposed to the concentrated solar flux, the heat-absorbing fluid (a blackened molten nitrate salt) flows in a thin film down a basically flat, vertical panel and absorbs the flux directly. Potential advantages of the DAR include a substantially simplified design, improved thermal performance, increased reliability and operating life, and decreased operating costs. High flux capability also results in decreased receiver size and capital costs. The cost savings and improved performance can result in reductions in levelized energy costs of 17% (near-term) to 26% (long-term). Perhaps more importantly in the near-term, lifetime considerations and the simplicity of design could decrease the perceived risks associated with construction of a commercial central receiver system.

A number of technological uncertainties affecting DAR feasibility require resolution before the concept can be considered a commercial alternative, however. Among these are the stability of the flowing salt film in high, non-uniform fluxes and in wind; the stability and performance of blackening agents; effects of long term, high temperature exposure of the salt to the atmosphere; and the optical and thermal efficiency of the absorbing film. Current research and development plans to address these issues are discussed.

INTRODUCTION

The challenge to develop economically viable solar power systems has become greater with the elimination of tax credits and reduced oil prices. Therefore we must explore more innovative ways of solving the many problems ahead. For example, the receiver subsystem of a central receiver (CR) system is critical to success of the plant. It is subject to very high flux levels with complex distributions that change rapidly due to clouds. A conventional salt-in-tube receiver is limited to a peak flux level of about 0.85 MW/m^2, resulting in a relatively large receiver that increases both the receiver cost and thermal losses. High metal temperatures and cyclic thermal stresses result in combinations of creep and fatigue that make absorber tube life prediction very difficult. Although molten salt-in-tube receivers have been successfully tested at the 5 megawatt thermal (MW_t) level at the Central Receiver Test Facility (CRTF) in three U. S. programs and in France, cost and lifetime issues may affect potential future uses.

In this paper, we describe a promising alternative to the tube receiver, the Direct Absorption Receiver (DAR), and discuss its potential design and cost advantages and its development requirements, including current status and future plans.

CONCEPT DESCRIPTION

The molten nitrate salt Direct Absorption Receiver concept is an alternative to other receiver configurations (such as tube receivers using water/steam, liquid sodium, or molten salt as the heat absorbing fluid) for Solar Central Receiver systems. The DAR concept was originally investigated in the 1970's by Sandia National Laboratories Livermore (SNLL) (1,2). In this concept, molten nitrate salt (commercial "draw salt", 60% sodium nitrate and 40% potassium nitrate) flows down a vertical (or nearly vertical) panel, directly absorbing the concentrated solar flux focused on the plate by the collector field. Figure 1 shows the original external DAR configuration conceived by Brumleve (2).

Inlet and outlet salt temperatures are the same as those of tube receivers (about 285°C and 565°C respectively). The salt flow properties are very much like those of ambient temperature water, except for better surface wetting characteristics (a function of viscosity, surface tension, and contact angle). The salt film thickness is a few millimeters; typical salt

---

This work was supported by the U.S. Department of Energy (U.S. DOE) under Contract DE-AC04-76DP00789.

velocities are on the order of meters per second. Because the salt is transparent to much of the solar spectrum, it must be sufficiently blackened (typically with micron-sized cobalt oxide particles) to enhance direct absorption of most of the solar energy. Unlike tube receivers, in which the amount of solar flux that can be absorbed is limited by heat transfer rates through the tube walls and by stresses induced in the tubes by uneven heating and diurnal cycling, the flux absorption capability of the DAR (demonstrated on a small scale by Brumleve (2) at levels up to 6 MW/m^2) probably far exceeds the flux capabilities of practical heliostat fields. The same concept could be used in a cavity receiver as well as in external receiver configurations.

POTENTIAL ADVANTAGES

Because of its unique design, the DAR offers a number of significant potential advantages over fluid-in-tube receivers.

- **<u>Simplicity and Reliability</u>**. The design and construction of a DAR are much simpler than for a tube receiver. The Saguaro 190 MW_t tube receiver design (3), for example, has over 2000 tubes, 10000 tube welds, 14000 welded attachments, 48 manifolds, 44 drain and purge valves, and 4 control valves. A complex trace heating system is required for the valves and manifolds. (The failure of any one of the valves or trace heaters could prevent the receiver from being operated.) The DAR, in contrast, has no tubes (or their associated welds) and no drain and purge valves. Flow controllers can reside in the flow manifolds and hence do not require stem seals or valve bodies. Because riser and downcomer piping are open to the atmosphere at the receiver, accommodation of thermal expansion may be simplified. Finally, because the salt is heated in a single pass with a residence time of seconds (as opposed to multiple passes and a residence time of minutes for a tube design), control during solar transients is greatly simplified.

- **<u>Improved Efficiency</u>**. Elimination of maximum allowable flux constraints results directly in decreased receiver size (when compared to a tube receiver), with resulting decreases in capital cost and thermal losses. Thermal losses are also lower because surface temperatures of the salt are lower than the corresponding metal surface temperatures in a tube receiver. In addition, the low thermal mass of the receiver can mean lower losses during start-up and transients. Figure 2 summarizes many of the factors contributing to improved performance of the DAR. The figure should be considered illustrative only; it is not intended to represent any actual day. (Tube receiver outages, for example, would be expected infrequently, but would probably be of much longer duration.)

- **<u>Extended Life</u>**. Tube receiver life is limited by stresses induced during thermal cycling of the tubes. Although receivers are nominally designed for a 30 year life, no extended-life field testing has been completed to verify designs. Tubes at the Solar One pilot plant (4) have already shown fatigue-related failures. These failures represent a major risk factor in CR system designs. The DAR design essentially eliminates this problem. In addition, because metal substrate temperatures in a DAR are somewhat lower than those of a tube receiver, corrosion rates may be lower.

- **<u>Decreased Operations & Maintenance (O & M) Costs</u>**. Because over half of the cold salt pumping power requirements for a tube receiver are used to overcome tube flow resistance, <u>total</u> plant parasitic power requirements for a DAR system can be reduced by about 10% compared to a tube receiver. The decreased pump head also means that simple constant-speed cantilevered pumps with no bearings or seals in salt can probably be used for a DAR. The concern for receiver tube leaks is also eliminated, and the potential for piping leaks is reduced due to lower operating pressure. Periodic repainting of receiver tubes will not be required to maintain high solar absorptivity (as has been the case with the Solar One tube receiver), although some maintenance of the blackener may be required. The potential for repair or replacement of tubes and valves will also be significantly reduced.

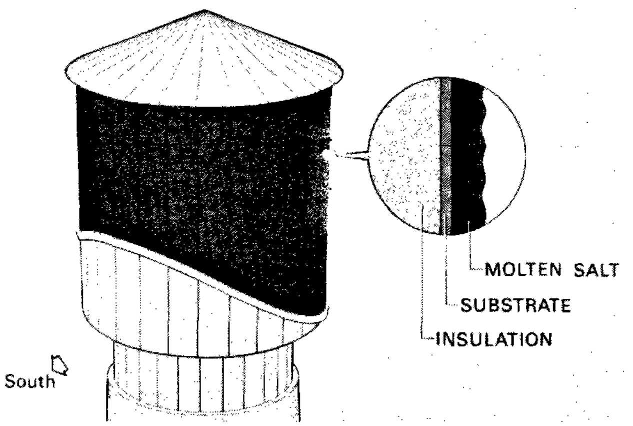


Fig. 1. External Direct Absorption Receiver (2). (In this example, the active area of the heat absorbing surface is reduced on the south-facing panels due to lower flux levels.)

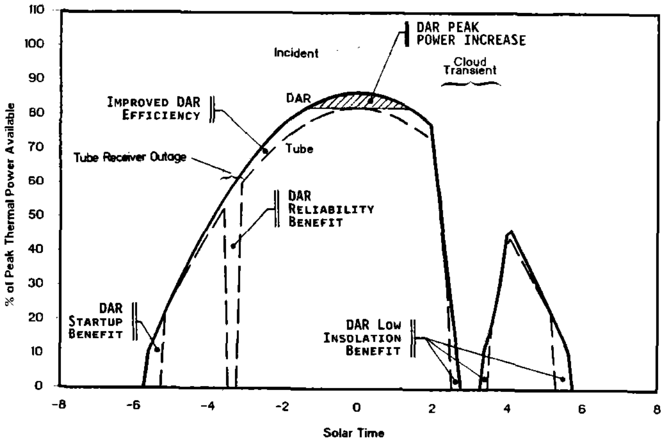


Fig. 2. Comparison of DAR and Tube Receiver Efficiency and Operational Factors Showing Effects on Delivered Thermal Power. (See explanatory notes in text.)

Although the DAR concept received considerable attention in the late 1970's, including several experimental studies (2), it was eventually shelved for several reasons. First, compared to more well-understood technologies such as tube receivers using water/steam, liquid sodium, or molten salt, the DAR was perceived to have a higher development risk because of a number of technological questions. Uncertainties included the stability of a flowing salt film under high solar fluxes; long term salt and blackener stability when exposed to solar flux and air; and effects of wind and natural convection on film stability and thermal losses. Secondly, in the 1970's the cost of receivers was considered to be a minor fraction of total system cost. As a result, the total system savings, even with major receiver cost reductions, were not thought to be high enough to justify DAR development at that stage of the central receiver program.

Evolution of solar central receiver technology since that time has caused both of these conditions to change. Although there are still technological uncertainties relating to the DAR, recent experimental work by the Solar Energy Research Institute (SERI) with a small molten carbonate salt DAR panel (5) has been encouraging. But more importantly, field experience with both a water/steam receiver (Solar One) and salt-in-tube receivers has shown them to be more complex, less reliable, and more costly than originally anticipated. With this complexity, estimates of receiver costs have substantially increased over the years. This fact, coupled with major heliostat technology advances and cost declines, has left the receiver as the solar CR component where the most significant system cost savings can be achieved.

COST COMPARISONS

Anticipated DAR cost savings arise from two major areas: 1) substantially lower costs (capital and O & M) for the receiver and some supporting components, and 2) improved system efficiency. Both near- and long-term effects of various receiver advances on levelized energy cost (LEC) are summarized in Figures 3 and 4. In these figures, direct capital costs are from SNLL system improvement studies (6,7) (near-term, "current technology") and the DOE Solar Thermal Five-Year Research and Development Plan (8) (long-term goals). Basic cost categories shown in the figures include the heliostat field (FIELD), the receiver and associated components (RECEIVER), the storage system (STORAGE), the electric power generation system (EPGS), miscellaneous and balance of plant (MISC), and operations and maintenance expenses (O & M). (As discussed below, non-receiver component costs generally remain fixed in these figures; because of differences in efficiency, the levelized energy costs of the these components do, however, vary.)

The base case used for comparison here is the 100 megawatt electric (MW_e) external molten salt-in-tube receiver system defined in the SNLL studies (6). "Low flux" parameters, 0.82 MW/m^2 peak flux, 0.46 MW/m^2 average flux, were used for the base case tube and DAR low-flux examples. (The low-flux DAR is shown only for comparison purposes. Lack of flux constraints will in all likelihood lead to a high flux DAR design.) "High flux" parameters for both a generic high flux tube receiver and the DAR are defined here as the SNLL sodium receiver parameters (i.e., 1.70 MW/m^2 peak flux, 0.79 MW/m^2 average flux), even though this is conservative for the DAR (since collector fields can provide average flux levels over 1 MW/m^2 for external or shallow cavity receivers). The high flux receiver refers to an as-yet-undeveloped and untested salt-in-tube receiver using, for example, modified 9Cr-1Mo steel for the tube material. (The high thermal conductivity and low coefficient of thermal expansion of this material would permit higher flux levels than the Alloy 800 or 300-series stainless steels currently specified for tube receivers.)

DAR capital cost savings assume that the receiver capital costs can be <u>halved</u> over those of a tube receiver of the same absorber area (A recent SPECO study (9) has estimated that the savings may actually be greater than half.) and that receiver cost savings can be scaled as the absorber area to the 0.8 power (a typical relationship for costing conventional heat exchangers). Receiver material and fabrication costs per unit area for the high flux tube receiver are assumed to be the same as those of the base case tube receiver (although welding and fabrication costs for an alloy such as modified 9Cr-1Mo steel may ultimately be higher), but the absorber area effects on cost are scaled to the 0.8 power as for the DAR. Because the DAR has significantly decreased pumping requirements, a fractional cost savings for the cold salt pump is also taken for that system; that savings is, however, small. EPGS costs for the DAR have been increased to account for the increase in plant peak power output (~6%, as shown on Figure 2). This is a conservative

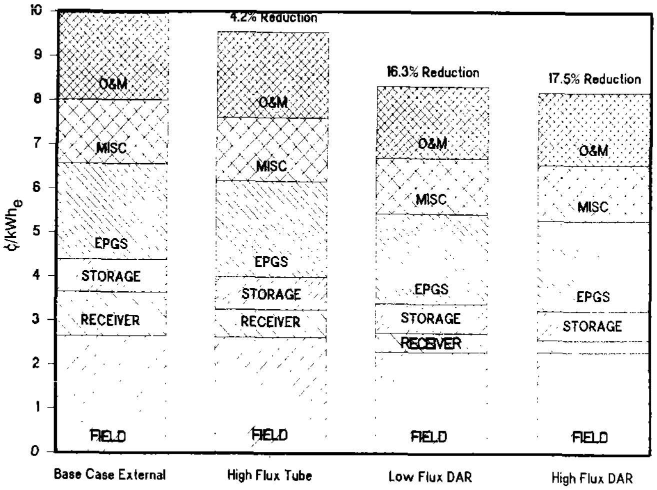


Fig. 3. Near-Term Levelized Energy Cost Comparisons

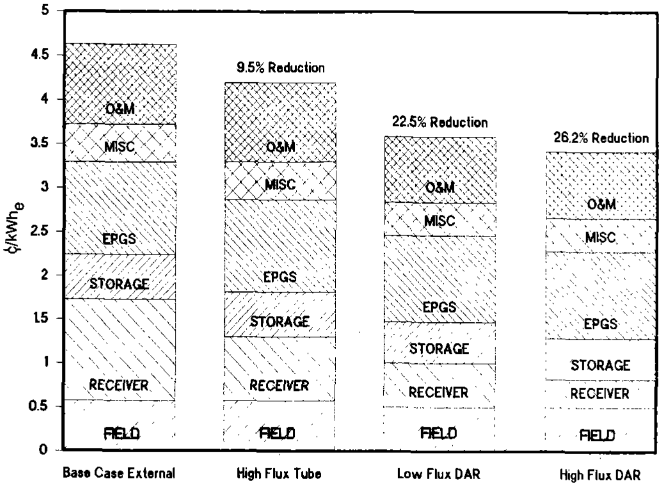


Fig. 4. Long-Term Levelized Energy Cost Comparisons

estimation of the DAR savings, since that additional peak power could probably be accommodated with judicious management of existing storage.

The net effect of near-term system capital cost savings for the DAR is 4% (low flux) to 6% (high flux) compared to the base case. The near-term capital cost savings for the high flux tube receiver (4%) is solely due to the decrease in receiver area at high flux. In the long term, these savings are 12 to 18% for the DAR and 11% for the high flux tube receiver.

In both the near- and long-term, annual operations and maintenance costs for the DAR have been assumed to be 5% lower than for tube receiver systems because of the simplicity of components, lower temperatures and pressures, and other reasons described previously. While salt and dopant maintenance requirements (e.g., contaminant removal, maintaining dopant suspension, etc.) will probably be higher for DAR systems, these increased costs are expected to be small because of the simple regeneration procedures. The effect of the assumed DAR O & M cost savings amounts to a 1% decrease in LEC.

Because the LEC is the ratio of total annualized cost to net electricity produced, improvements in system performance and annual efficiency directly affect LEC's. For the high flux tube receiver, the efficiency improvement is simply that of decreasing thermal losses because of smaller size. This was estimated by using thermal efficiency and spillage values of the SNLL sodium external receiver design (6). Because higher spillage and lower thermal losses nearly offset, this results in a 0.8% annual efficiency increase for the high flux tube receiver over the base case receiver.

The DAR at high flux also reaps this benefit, as well as a number of others, all relating to its unique design. Some of these are well defined and can be estimated reasonably accurately. First, the thermal losses will be less because for a specified salt outlet temperature, the average temperature driving both convective and radiative losses will be lower (since there is no tube wall temperature gradient). Assuming the average DAR surface temperature is 65°C lower than that of a tube receiver (10) (a reasonably conservative estimate), convective losses will be reduced by 14% and radiative losses by 31%. The net effect of this and the area reduction for the high flux DAR is an annual efficiency increase of over 6% (i.e., a 6% increase in gross electric output, and an even larger increase in net power since parasitic power requirements do not change). Improvements resulting from high absorptivity can also be estimated. Experimental evidence has shown a salt film reflectivity of 5% or less for blackened Hitec salt and undoped carbonate salts. If this holds for the blackened draw salt (as all evidence currently suggests), the DAR will have an absorptivity (relatively constant over time) of 95% or higher. While the initial absorptivity of a tube receiver will be about 94%, that absorptivity will decrease with time until the receiver is repainted. Assuming an average absorptivity of 91.5% (typical of Solar One), the DAR offers an efficiency increase of 3.5%. Finally, parasitic electric pumping power savings (because of the lack of tube resistance) have been estimated (9) to be 1400 kW for a Saguaro-sized receiver. Scaling to 100 MW_e, that amounts to a 10% savings on total system parasitics, giving a 3.6% increase in net annual power production.

Several more-difficult-to-estimate potential savings for the DAR relate to operational features including lower thermal inertia and higher turndown ratios (both of which could decrease start-up times and allow increased operation during periods of intermittent or low insolation). Using SNLL SOLERGY code parameter study results (7) with an estimated 50% decrease in energy loss for both inadequate insolation periods and receiver start up results in a combined improvement of 1% in annual energy. Finally, because of the simplicity of design, it is reasonable to assume that there will be decreased outages, both scheduled (e.g., receiver painting) and unscheduled. Assuming 5 fewer outage days per year results in an annual net energy improvement of 1.3%. Although the quantitative measure of these savings cannot be confirmed without more detailed design and operating data, these estimates represent an attempt to quantify some of the unique advantages of the DAR. Since their contribution to improving LEC is less than 2.5%, they could have been totally neglected without changing any of the conclusions drawn below.

The total increase in annual energy for improved DAR performance amounts to about 14% for both the low and high flux cases (versus less than 1% for the high flux tube receiver). Combined with the saving in capital cost discussed above, the total potential reduction in "near-term" LEC for the DAR ranges from 16.3% to 17.5%, depending on flux levels. The corresponding reduction in LEC for the high flux tube receiver is 4.2%.

For "long-term" technology, the same calculations have been made assuming the same receiver efficiencies (and thus improvements in annual energy), and using DOE long-term cost goals for all components except the receiver. Because the lower long-term costs make the receiver a larger fraction of the total system, the relative savings are greater. Reductions in LEC for the DAR range between 22.5 and 26.1%, while the corresponding high flux tube receiver reductions are 9.5%. A comparison of the receiver fraction of the LEC for the two receivers shows that <u>only the DAR</u> is capable of meeting long-term DOE receiver cost goals ($\$25/m^2$ of collector surface for a DAR vs. $\$50/m^2$ for the high flux tube receiver vs. the goal of $\$30/m^2$).

These calculations show the DAR to have a 14 to 18% potential for cost saving over the high flux tube receiver. This benefit is due in large part to the unique advantages in efficiency of the DAR.

DAR DEVELOPMENT ISSUES AND STATUS

A number of technological uncertainties affecting DAR feasibility require resolution before the concept can be considered a commercial alternative. These issues and their current status are summarized in Table 1. Key among these issues are the demonstration of thermal/hydraulic stability of the fluid film over all operating conditions, including substrate imperfections; the optical, physical, and chemical effects of doped salt exposure to air; and mechanical and hydraulic design to provide a controlled mass flow rate per unit width in order to control the salt temperature. As the technology develops, we need to reevaluate the economics to determine the degree to which the potential of the DAR described in this paper can be achieved.

A research and development plan to study the DAR has been initiated jointly by SERI and Sandia. The plan is intended to assess the technical feasibility of the DAR over the next three years by addressing the issues in Table 1 through the following tasks:

- <u>Systems and conceptual design studies of a commercial direct absorption receiver</u>. This task is required to guide experimental work and provide

TABLE 1. DAR DEVELOPMENT ISSUES AND STATUS

Issues	Status
1. Thermal/Hydraulic Stability	
▪ Stable flow regimes, turndown ratios. ▪ Surface tension and thermocapillary effects.	Analyses based on data in the literature show the flow will be stable. Small scale tests by SNLL and SERI have shown stable flow over limited conditions.
▪ Possible recirculation requirements.	Preliminary design has been done to keep the mass flow nearly constant down to 20 percent power if required for film stability.
▪ Mass flow variation control.	Upper manifold design is critical. Conceptual designs and testing begun.
▪ Interaction of film thickness, velocity, flux gradients, and flux density.	Testing done by SNLL with very high flux levels and gradients showed no problems.
▪ Air/film/plate heat transfer.	Reasonably predictable from literature. Not critical when dopant is used.
▪ Panel surface effects [material (including meshes), roughness, warpage, tilt angles, joints, welds].	Very little work has been done in this important area. It *has a high priority in future testing.*
▪ Surface waves.	Very little data available at this time.
▪ Wind effects on stability.	An air jet on the salt tests by Brumleve of up to 60 mph did not show instability. This is particularly important for the external receiver.
2. Panel Design Considerations	
▪ Panel design (thermal stresses, distortions).	Conceptual design complete. Large non-linear gradients near edges are a potential problem. Sensitivity of film stability to distortions is a key factor in the design.
▪ Transient effects.	Start up and cloud transients cause complex gradients. Detailed analysis and solar testing planned.
▪ Effects on flow stability. ▪ Panel joints and salt containment. ▪ Structural support. ▪ Insulation.	Stresses must be kept low, either with thin panels or a segmented surface. The structural support must provide minimum friction. Imperfections in the resultant surface may cause instabilities. In the segmented design the salt, which is very wetting, must be kept out of the insulation.
▪ External vs. cavity configurations.	The choice between external and cavity receivers could depend on the results of wind effects; more likely it will be determined by plant economics. Most utilities are summer peakers, which would favor a surround field (best supported by an external receiver).
3. Salt and Dopant Chemistry and Optical Properties	
▪ Salt contamination and degradation in air.	Very slow reactions with CO_2 and water expected. Treatment process available. Rates and economic impacts need to be determined.
▪ Film absorptivity (as function of temperature and dopant concentration, surface film conditions, angle of incidence, and time).	Work done by Drotning (11) measured absorptivity as a function of dopant concentrations and film thickness. More *data needed on surface reflections and effects of angle of* incidence.
▪ Dopant optical properties and stability (settling, agglomeration, chemical stability).	Work done by Drotning showed some settling problems. Additional work in progress.
▪ Dopant erosion effects.	Sub-micron particles at low concentrations are not expected to be a major problem.
4. Commercial Design	
▪ Costs. ▪ Integration with tower and other systems. ▪ Annual energy estimates.	The analyses presented in this paper show the potential. We need to reassess the commercial design as the technology evolves.

realistic cost estimates for assessing the economic potential of the DAR. Once preliminary experimental work has been concluded, a conceptual design effort by industry will be initiated.

- Material studies of salt and dopant properties. This task will address salt and dopant optical properties, including surface reflectivity, dopant absorptivity, and emissivity; salt degradation in air and regeneration; homogeneous dopants; and dopant agglomeration, erosion, corrosion, settling, and chemistry.

- Small DAR panel tests in a simulated solar flux. These tests will use the existing SERI 15cm wide by 60cm long panel (previously used for carbonate salt DAR tests (5)), refurbished for nitrate salt testing. Simulated solar fluxes up to 0.7 MW/m^2 will be achieved from radiant heat panels. The tests will address film stability at various flux levels and flux gradient conditions; panel surface, material (including advanced concepts such as metal meshes or screens), and joining effects; and wind effects. In addition, continuous salt flow tests (utilizing an existing direct contact heat exchanger loop) will provide realistic, accelerated salt and dopant life testing in a controlled DAR-like environment.

- Large flow tests using ambient temperature salt-like fluid. These tests, conducted with water or water/glycol mixtures, will address flow stability, wind effects, and flow distribution. Collection manifold and panel designs will be evaluated on a scale sufficient to allow extrapolation to full scale DAR designs.

- 2 MW panel research experiment. This experiment is designed to test a large panel (~1 m by 4 m) at high flux (up to 3.0 MW/m^2 peak flux) and high flux gradients in an actual solar environment. This test will also provide data on wind effects, control, thermal inertia effects, and actual panel configurations (relevant to cavity and/or external designs) and flow manifold designs. The test will use a stand-alone loop on the 49 m level of the CRTF tower as illustrated in Figure 5.

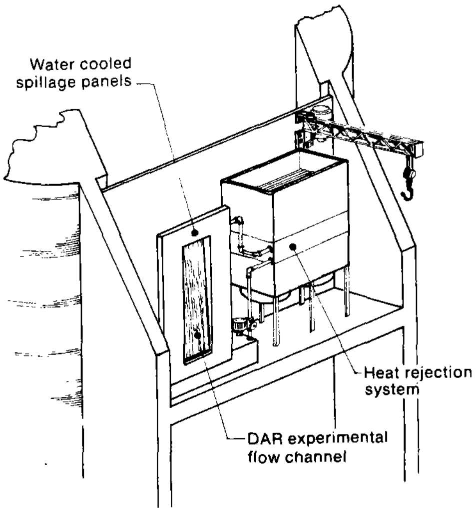


Fig. 5. DAR Panel Research Experiment at the CRTF.

SUMMARY

The DAR offers a number of potentially significant advantages over conventional tube receivers in solar central receiver power systems. These include improved efficiency and reliability and decreased cost and complexity. Perhaps most importantly, the DAR may decrease the perceived risks (relating to tube life in the solar environment) associated with conventional tube receivers. To achieve this potential, technological uncertainties associated with the DAR must be addressed. Most important among these uncertainties is stability of the flowing salt film in high, non-uniform fluxes and in wind. A joint Sandia/SERI research and development program is underway to establish the technical feasibility of the direct absorption receiver.

REFERENCES

1. A. C. Skinrood, T. D. Brumleve, C. T. Schafer, C. T. Yokomizo, C. M. Leonard, Jr., Status Report on a High Temperature Solar Energy System, Sandia National Laboratories Report SAND74-8017, Livermore, CA, 9/74.

2. T. D. Brumleve, Status Report on the Direct Absorption Receiver, Sandia National Laboratories Report SAND78-8702, Livermore, CA, 7/78.

3. E. R. Weber, Advanced Conceptual Design for Solar Repowering of the Saguaro Power Plant, Arizona Public Service Company, DOE/SF 11570-2, 4/82.

4. L. G. Radosevich, Final Report on the Experimental Test and Evaluation Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant, Sandia National Laboratories Report SAND85-8015, Livermore, CA, 9/85.

5. M. S. Bohn, H. J. Green, G. Yeagle, J. Siebarth, O. D. Asbell, C. T. Brown, Direct Absorption Receiver Experiments and Concept Feasibility, Solar Energy Research Institute Report SERI/TR-252-2884, Golden, CO, 2/86.

6. P. K. Falcone, "Central Receiver System Improvement Studies, Overview and Principal Results," Presented at Solar Central Receiver Technology Workshop, Livermore, CA, 4/86.

7. M. C. Stoddard, "Annual Energy for Solar Central Receiver Power Plants," Presented at Solar Central Receiver Technology Workshop, Livermore, CA, 4/86.

8. National Solar Thermal Technology Program: Five Year Research and Development Plan 1986-1990, Solar Thermal Technology Division, U. S. Department of Energy, 12/85.

9. Solar Power Engineering Co., Inc., DAR Component Assessment and Design Guide, Final Report, Morrison, CO, 4/86.

10. B. L. Kistler, SNLL, personal communication, 5/86.

11. W. D. Drotning, "Optical Properties of Solar Absorbing Oxide Particles Suspended in a Molten Salt Heat Transfer Fluid," Solar Energy, 20 (1978).