CONF-900444--9

An Economic Analysis of a Quad-Panel Direct Absorption Receiver for a Commercial-Scale Central Receiver Power Plant*

SAND--89-2955C

DE90 005959

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Abstract

The Direct Absorption Receiver (DAR) concept was proposed in the mid-1970s as an alternative advanced receiver concept to simplify and reduce the cost of solar central receiver systems. Rather than flowing through tubes exposed to the concentrated solar flux, the heat absorbing fluid (molten nitrate salt) would flow in a thin film down a flat, nearly vertical panel and absorb the flux directly. Potential advantages of the DAR over conventional tubular designs include a substantially simplified design, improved thermal performance, increased reliability and operating life, as well as reduced capital and operating costs. However, before commercial-scale designs can be realized, a method for controlling droplet ejection from the panel must be developed. In this paper, we present a new DAR design, which has the potential to control these droplets. The design employs four flat panels that are sloped backwards 5 degrees, wind spoilers, and air curtains. A systems analysis is presented indicating that the levelized-energy cost of the quad geometry should be very similar to cylindrical geometry that was originally proposed for the DAR concept.

*This work is supported by the Department of Energy under contract DE-AC04-76DP00789.

1.0 Introduction

The Direct Absorption Receiver (DAR) concept was proposed in the mid-1970s as an alternative advanced receiver concept to simplify and reduce the cost of central receiver systems [1,2]. Rather than flowing through tubes exposed to the concentrated solar flux, the heat absorbing fluid (molten nitrate salt) would flow in a thin film down a flat, nearly vertical panel and absorb the flux directly. Potential advantages of the DAR include a substantially simplified design, improved thermal performance, increased reliability and operating life, as well as reduced capital and operating costs.

Sandia National Laboratories (SNL) and the Solar Energy Research Institute (SERI) began development of the DAR in the mid 1980s. Several small-scale proof-of-concept tests were conducted by both organizations during 1986-1988 [3,4,5]. The results from these tests were generally favorable and have paved the way for a much larger Panel Research Experiment, rated at 3 MW_t, to be conducted at the Central Receiver Test Facility in 1990 [6]. In parallel with these tests, SNL and SERI have performed systems analyses [7,8,9] to better understand the performance and cost advantages of the commercial-scale DAR power plant (>190 MW_t) over a conventional salt-in-tube plant. These analyses indicated that a DAR power plant should be able to achieve a 15-20% reduction in the levelized electrical energy cost (LEC) produced by the plant.

A thorough study was also conducted by Foster Wheeler Corporation and SNL to define the design details and cost of a commercial-scale DAR rated at 320 MW_t [10]. The design consisted of a thin, continuous, cylindrical shell. This shell is pretensioned vertically to eliminate potentially damaging compressive stresses and to help absorb wind loading. The shell is also compressively loaded from the inside, through a rigid subpanel and a layer of dense fiber insulation, to provide vibration dampening and horizontal pretensioning of the shell. This receiver is illustrated in Figure 1 and the features of the design, in vertical cross-section, are displayed in Figure 2.

Though water and salt flow test results [3,4,5] to date have been generally encouraging, the stability of the molten salt flowing down the panel is a problem that needs to be resolved before a commercial-scale design can be realized. The fluid instability is in the form of waves that develop in the falling film. The waves grow in size as they flow down the panel. Eventually, droplets begin to be ejected from the wave tips after traveling approximately 4 meters down the panel, and the ejection rate steadily increases at greater flow lengths. This problem is exacerbated by the effects of external winds, which tend to strip the wave tips and droplets away from the vicinity of the panel [4,5,11]. This will pose a problem for a commercial-scale receiver since the panels are typically greater than 10 meters long and are exposed to high winds at the top of the tower. While a small amount of fluid loss from the receiver is not a problem, it is desirable to reduce loss to a minimum to reduce the impact on the surrounding environment and on the cost and performance of the system.

Water flow tests at Sandia have indicated that fluid loss from the panel can be minimized by sloping back the panel 5 to 10 degrees from vertical and shielding it from the wind [4,6]. The commercial-scale receiver depicted in Figures 1 and 2 does not possess these mitigating features, and modifying it so that it does would be complicated. In this paper we discuss an alternative concept for a commercial design containing features that will minimize the fluid loss, and we compare the cost and performance of this new concept with a cylindrical receiver similar to one studied by Foster Wheeler.

2.0 Quad-Panel DAR

One concept that appears to be feasible is a receiver composed of four separate flat panels tilted back 5 to 10 degrees. The heliostats surround the receiver-tower, and each 90° sector is aimed at the facing receiver panel, which is also spaced 90° apart. This receiver is illustrated in Figure 3. Wind spoilers protrude near the edges of each of the four panels, and wind curtains are located within the spoiler structures. The wind curtains blow ambient air in a direction transverse to the salt flow. The wind curtain flow pattern and the theory of its operation are presented in Figure 4. The spoiler structure is insulated to prevent solar-flux spillage from damaging it.

Four panels with a surround heliostat field were chosen over a single panel employing a north field in order to reduce the panel dimensions. For example, a 470-MW_t quad-plate receiver would consist of four panels each measuring 13 x 13 meters, whereas a single-paneled DAR would require a panel measuring 24 x 24 meters. Since droplet ejection rate increases with panel length, reducing the length will help mitigate the ejection problem. In addition, the performance of commercially available air curtains improves as the flow length of the air is reduced.

A schematic of the commercial quad-panel DAR is shown in Figure 5. The design is based, in part, on the study conducted by Foster Wheeler. The design for accommodating structural and thermal stresses is very similar to the design being used in the ongoing panel research experiment (PRE) at the Central Receiver Test Facility in Albuquerque, New Mexico. The panel is fixed at the bottom and tensioned with the air cylinders on the other three sides. A load of 100 lb per linear inch would be required on the sides and 600 lb/in on the top (the panel would be fixed at the bottom). However, unlike the PRE where many air cylinders are used, the quad-panel design only uses four cylinders per side, but larger air cylinders, for the tensioning system. The quad-panel DAR has five inlet distribution manifolds per panel. Depending on the flux distribution and extent to which a graduated manifold works, these may be adequate (see Section 3). The wind spoiler would help reduce wind velocities near the panel and the air curtain would work as described above.

The quad-panel DAR is currently only a concept, and detailed analyses of the panel stresses, optimum wind spoiler size, and some design details have not yet been performed.

We studied the cost and performance of the quad-panel DAR power plant and then compared these results to a cylindrical DAR of the same size. This was done to determine if the quad approach could achieve the same LEC as the cylinder. The DELSOL3 code [12] was used to size the DAR systems and the SOLERGY code [13] was used to analyze annual performance. We selected a commercial-size plant with a receiver rated at 470 MW_t, a 100 MW_e turbine, and a solar multiple of 1.8.[1] Selection of this size allowed us to use much of the subsystem cost information presented in a recent utility study [14], which investigated a salt-in-tube plant of the same size. Since we were interested in understanding differences in LEC, given changes in the receiver design only, both DAR plants employed the same number of heliostats. This approach is consistent with previous studies that compared DARs with salt-in-tube plants [7,8,9].

Comparison of Performance

A comparison of the subsystem annual efficiencies for the quad DAR and cylindrical DAR is presented in Table 1. It can be seen that the quad DAR is predicted to have a lower field and receiver efficiency but a higher availability. The reasons for these differences are explained in the following paragraphs.

The quad DAR has a lower field efficiency than the cylindrical DAR because flux spillage losses are greater. Flux spillage occurs around the edges of the absorber panels and on the wind spoilers. Unlike for the cylinder, the width of the receiver target for the quad design, as viewed from the heliostats, is not constant along a given concentric ring surrounding the receiver tower. This width is reduced by the cosine of the incidence angle of the heliostat beam. (Incidence angle is measured between a vector normal to the receiver panel and a vector pointing at the heliostat from the receiver.) Spillage is therefore greater for the quad receiver, as compared with the cylinder, because heliostats with large incidence angles will have a smaller target and thus spill more of their beams.

The quad DAR has a lower receiver efficiency than the cylindrical model because radiation and convection losses are higher. Since the quad receiver has more surface area, it will have greater thermal losses. Using the DELSOL3 code, we

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[1] Solar multiple is defined as the thermal power produced by the receiver divided by the thermal power required by the turbine. For solar multiples greater than unity, excess energy is sent to thermal storage for later use.

calculated the optimum dimensions for the cylinder to be 13 m tall by 13 m in diameter; this equates to a total area of 531 m^2. With the code we also determined the quad should consist of four panels, each measuring 13 m wide by 13 m tall, a total area of 676 m^2.[2] Though the receiver area is somewhat larger for the quad, it is still one-half the area of the salt-in-tube receiver analyzed in the utility study [14]. Tubed receivers are larger in order to reduce the peak flux below 0.8 MW/m^2 to mitigate tube stresses. In the DAR designs studied here, lack of a flux constraint [2] permitted us to raise the the peak flux to 2.7 MW/m^2. At the design point, losses from the cylindrical receiver are estimated to be 9.2 MW from radiation and 2.4 MW from convection. For the quad, losses are 11.6 MW from radiation and 3.0 MW from convection.

A significant advantage of the quad-panel DAR is that it can operate with one of the receiver panels down for maintenance. This is not possible with the cylindrical receiver and is the reason the availability of the quad is higher. The availability improvement to 93.7% for the quad, versus 90% for the cylinder, was calculated by the following procedure:

1. The 90% value for the cylindrical DAR is a typical value chosen for central receiver plants [14]. Experience from Solar One suggests that it is obtainable [15].

2. Receiver outages typically cause one-half of plant outages. This insight is based on the analysis of 3 years of data from Solar One [16]. If receiver outages could be totally eliminated, plant availability would therefore be 95%.

3. When a quad receiver experiences a problem, only one of the panels should typically be affected. Analysis of Solar One data [16] indicated that the vast majority of receiver problems were local faults at individual panels (e.g., panel leakage, warpage, process sensors, panel valves, etc.) and failures simultaneously affecting more than one panel (i.e., common mode failures) were insignificant.

4. When a quad panel is unavailable, on the average the receiver will still retain 75% of its energy collection capability. Seventy-five percent of the availability improvement from 90% to 95% (see 2) is 93.7%.

As indicated in Table 1, the annual-efficiency products of the cylinder and quad DARs are similar. The availability advantage of the quad is therefore counterbalanced by its lower field and receiver efficiencies.

Cost Comparison

A comparison of the subsystem costs is presented in Table 2.

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[2]The 13-m dimension is dictated by the image size for the outermost heliostats. We have assumed stretched-membrane heliostats are employed with focal length equal to slant range.

Substitution of the parameters defined above into the LEC equation produces the values displayed in Table 2. It can be seen that the LECs for the quad and cylindrical concepts are essentially the same.

3.0 Future Experimental Studies

We recommend that two sets of experiments be performed, beyond those planned for the PRE [6], to help resolve uncertainties in our analysis of the quad-panel DAR concept. They would encompass

1. Evaluation of wind spoiler and wind curtain effectiveness,

2. Construction and demonstration of an inlet manifold.

These experiments are discussed in the following paragraphs.

The wind spoilers depicted in Figure 3 should significantly reduce the stripping of fluid from the panels caused by tangential winds. However, their effectiveness during a variety of windy conditions, as well as their optimum geometry, will have to be determined by experiment. These experiments may show that wind spoilers alone may be effective enough to negate the need for an air curtain. If spoilers alone do not solve the problem, then experiments with a wind curtain will be necessary.

Wind curtains are commercially available that are capable of preventing 20-mph winds from entering an opening as large as 6.1 meters across [17]. We believe it would be possible to employ opposing units to protect each of the four panels from external winds (see Figure 4). Besides controlling droplet ejection, the curtain could also significantly reduce the convective losses from the panel. We performed preliminary calculations that indicate reduction in convective losses by one-half would compensate for the cost of buying and running the curtain. (The total cost of the curtains for all four panels would be approximately $400,000 and operation of them would use 0.54 MW of electrical power). However, even if the curtain did not reduce convective losses, the LEC for the quad-panel DAR would only increase from 0.076 to 0.077 $/kw-hr.

Experiments are necessary to understand the effect the air curtain has on a) the stability of the salt flowing down the panel, b) controlling droplet ejection, and c) convective losses. Determination of the penetration speeds of external winds as a function of curtain velocities is also needed. The height of a commercial-scale receiver tower is 200 m. At that elevation the median external wind speed is approximately 20 mph [18]. If a wind curtain is designed to protect against 20 mph winds we need to understand curtain and receiver performance

Except for the receiver, all subsystem and operating and maintenance costs were taken from the utility study [14]. The receiver costs were estimated from information presented in Foster Wheeler's design study [10].

The cost estimate of the quad-panel DAR was conducted using the cylindrical DAR as a base line. Individual component costs from the Foster Wheeler design study were identified--some component costs were based on actual materials purchased for the panel research experiment at the CRTF. Then costs were all scaled to the 470-MW_t receiver. The estimated cost for the quad-panel DAR is $14.6 million (this does not include the cost of the tower, pumps, heat trace, etc.). The cost of the quad DAR is approximately 14.5% more than a cylindrical DAR, which costs $12.8 million. (In comparison the salt-in-tube receiver costs $17.3 million, 35% more than the cylindrical DAR.) A comparison of the cylindrical and quad DAR cost estimates is shown in Table 3. The reason for the higher shop fabrication costs on the quad is the machine work that is necessary on the panels for the tensioning system attachment, although the sub-panels and lugs for the quad are less expensive. The air cylinders and all the necessary supports and linkages, plus the additional material, make the sub-contracted fabrication more expensive on the quad. The wind spoilers and additional trace heat increase the cost for auxiliary equipment. The field erection costs for the quad are also greater because the panels are too large to be shipped as sub-assemblies and because of the additional work required to assemble the tensioning systems. In general, it is fair to say that the quad-panel DAR is a more complex receiver, and this is reflected in the cost.

<u>Comparison of Levelized-Energy-Costs</u>

The levelized-energy costs of the DAR systems, in constant real dollars, were calculated from the following equation:

$$LEC = \frac{\text{Annualized Capital Costs + Annual O \& M Costs}}{\text{Annual Energy}}$$

where,

$$\text{Annualized capital costs} = FCR*DC*(1+INDC)*(1+AFUDC)$$

and,

FCR = fixed charge rate (0.105 from [14]),
DC = total direct costs (from Table 2),
INDC = indirect charges, specified as a fraction of the total direct costs (0.225 from [14]),
AFUDC = allowed funds during construction to cover interest charges, expressed as a fraction of the total capital costs (0.1 from [14]),
O&M = annual operating and maintenance costs (from Table 2),
Ann E = net annual electricity delivered to the grid (from Table 1).

when wind speeds exceed that level. Since many studies have shown that water at room temperature behaves similarly to hot molten salt [4,5], we anticipate performing these experiments with water.

Due to flux gradients that traverse the width of DAR panels, the salt flow rate along the width must vary in proportion to flux in order to obtain a uniform salt-outlet temperature. For a cylindrical receiver, these flux/flow gradients can vary by a factor of 3 around the circumference [19]. For a quad-paneled receiver, the DELSOL3 code predicts these gradients can reach a factor of 10. Varying the flow across the width can be accomplished by installing several flow-control valves and/or by increasing the hole sizes across the inlet manifold in proportion to the required flow out of it (holes can be seen in Figure 1). Use of flow control valves was the straightforward solution to varying the flow around the cylinder, since the flux gradient was relatively minor and only a few valves were needed. Flow-control valves could also be used on the quad DAR, but six times the number of valves required by the cylinder might be needed due to the higher flux gradient and because there are four instead of one receiver panels. Use of flow-control valves alone would increase the cost and cause unnecessary reliability problems. In an effort to reduce the number of required valves, we will build and test a manifold to determine the best combination of valves and graduation of hole sizes.

4.0 Conclusions

The cost and performance of a quad-panel DAR are predicted to be similar to the cylindrical concept. Disadvantages of the quad-panel concept due to lower receiver and field efficiencies and higher costs are compensated for by an anticipated improvement in receiver availability. The quad concept should therefore retain the same 15-20% reduction in LEC over the salt-in-tube receiver that was originally predicted for the cylindrical DAR. Experiments, beyond those planned for the PRE, are needed to establish wind spoiler and wind curtain performance, as well as inlet manifold design. If results of these experiments are successful, the feasibility of a commercial-scale DAR concept will be demonstrated. The next step after concept demonstration would be to scale up to commercial size. This is likely to be conducted in stages, e.g., 40 MW_t, 120 MW_t, 470 MW_t.

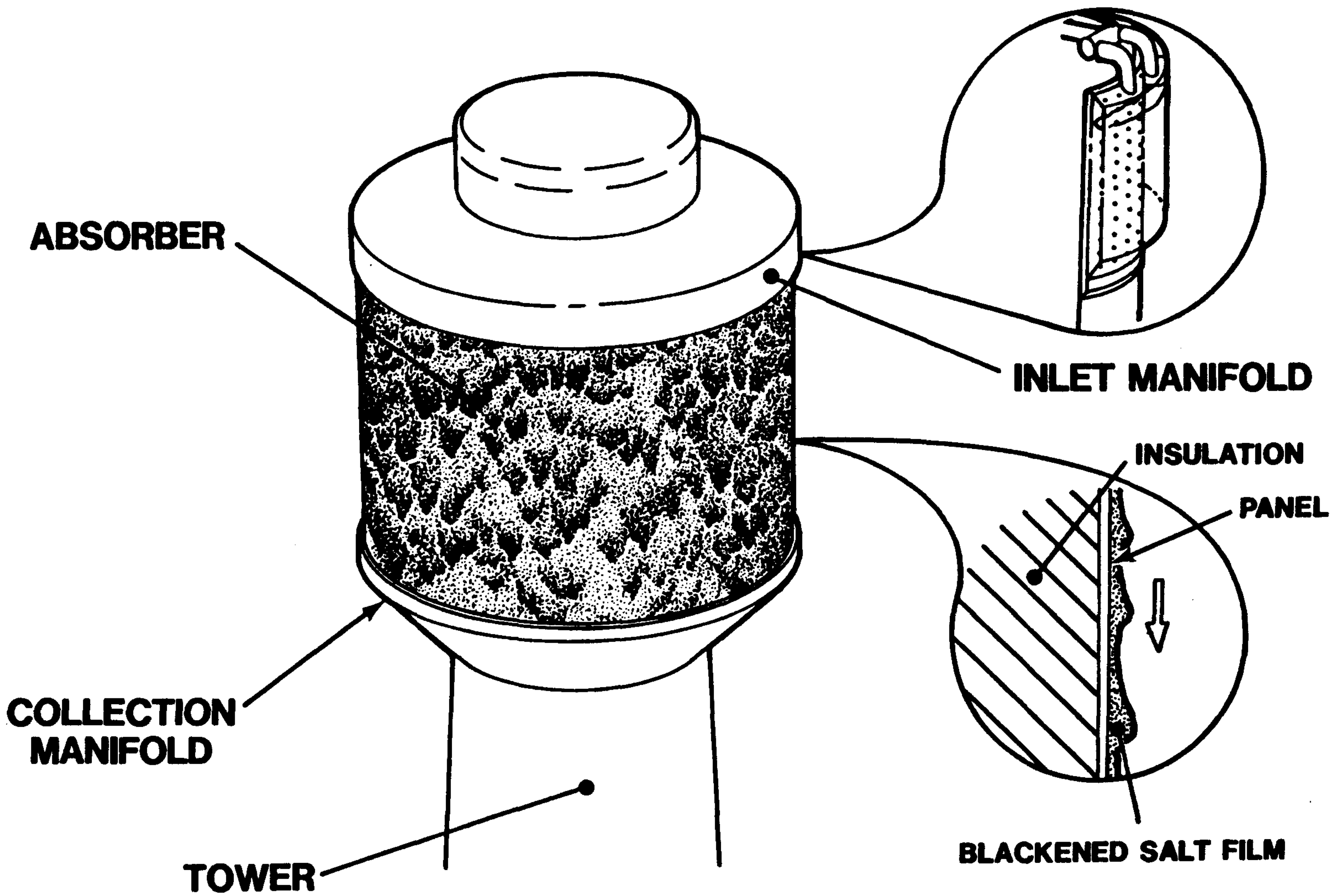

Figure 1 Artists Concept of a Commercial-Scale DAR with a Cylindrical Configuration

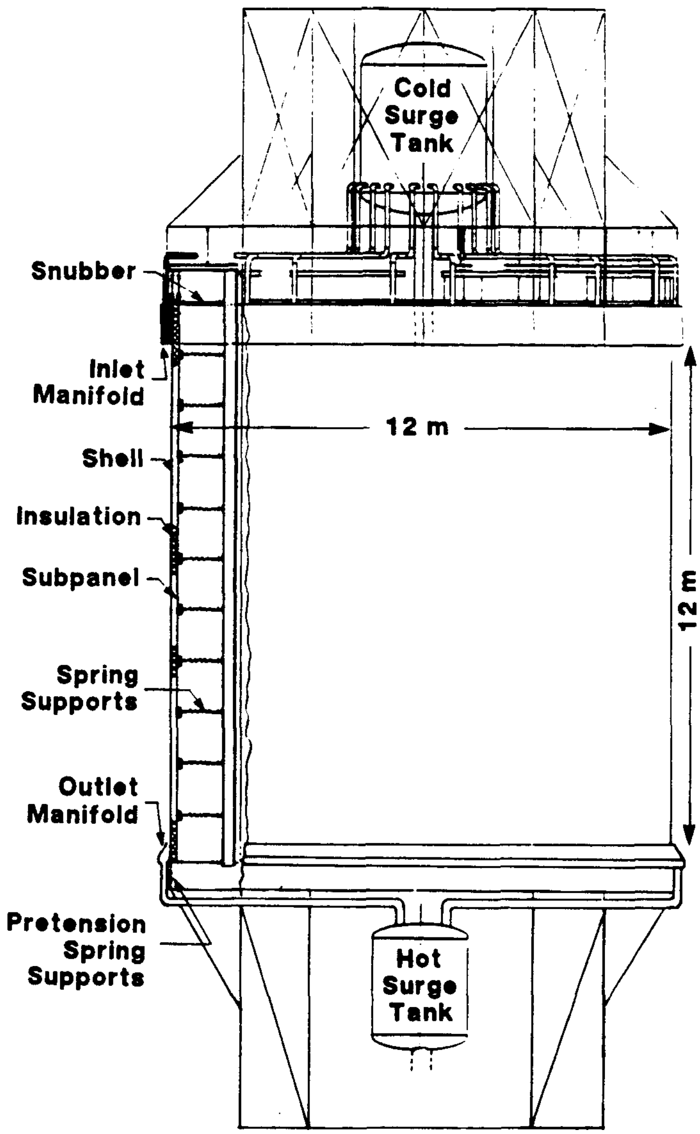

Figure 2 Design Details of the Cylindrical DAR

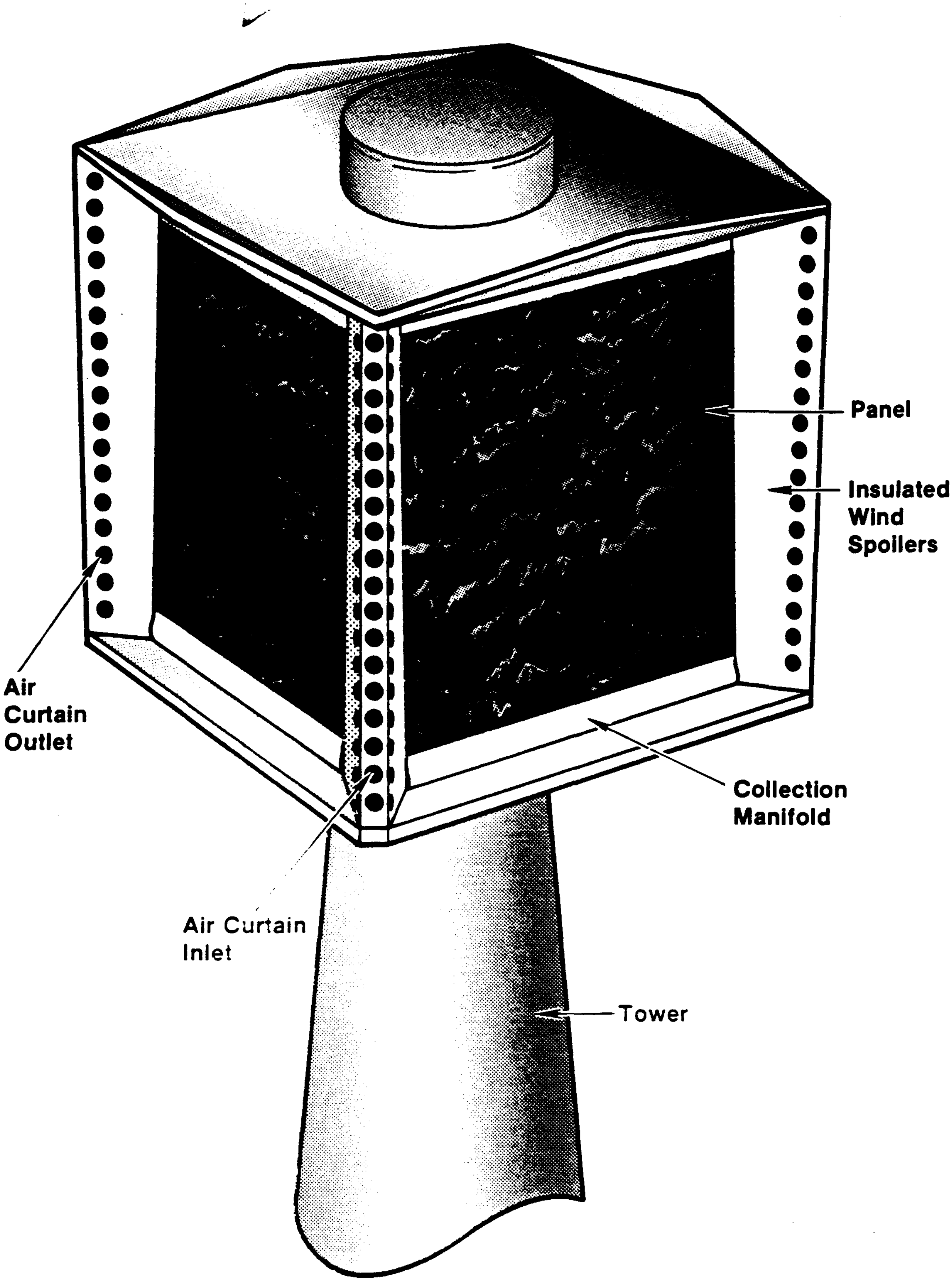

Figure 3 Artists Concept of a Quad-Plate DAR. Receiver panels are oriented in the NE, SE, SW, and NW directions.

Top View

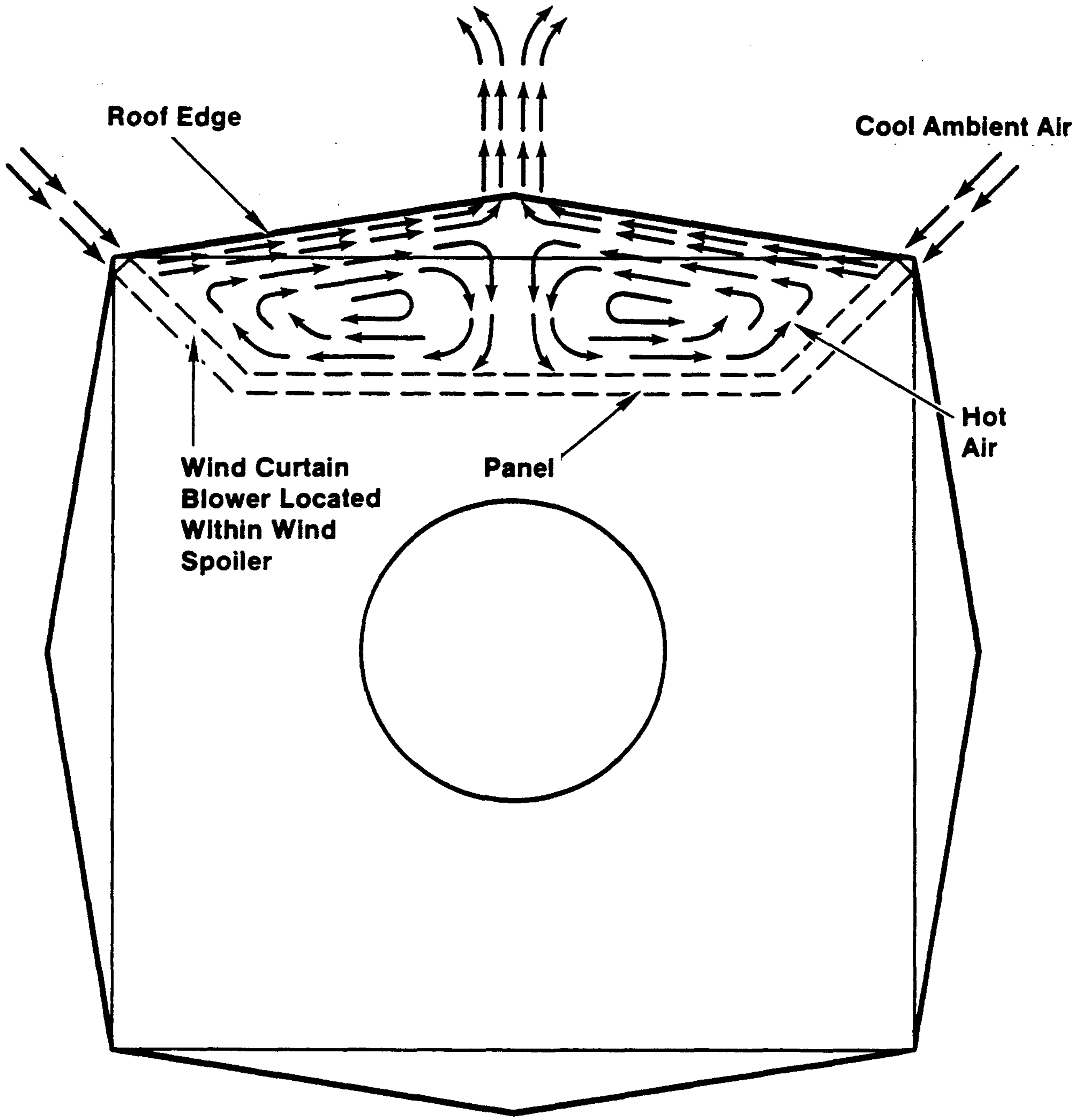

Figure 4 Top view of one of the four DAR panels showing the wind curtain flow field. The wind-curtain air flowing within the outer loop induces the inner-loop flow field. The direction of the inner-loop flow field tends to push ejected salt droplets back towards the panel. This concept was proposed by Paul Klimas of Sandia National Laboratories.

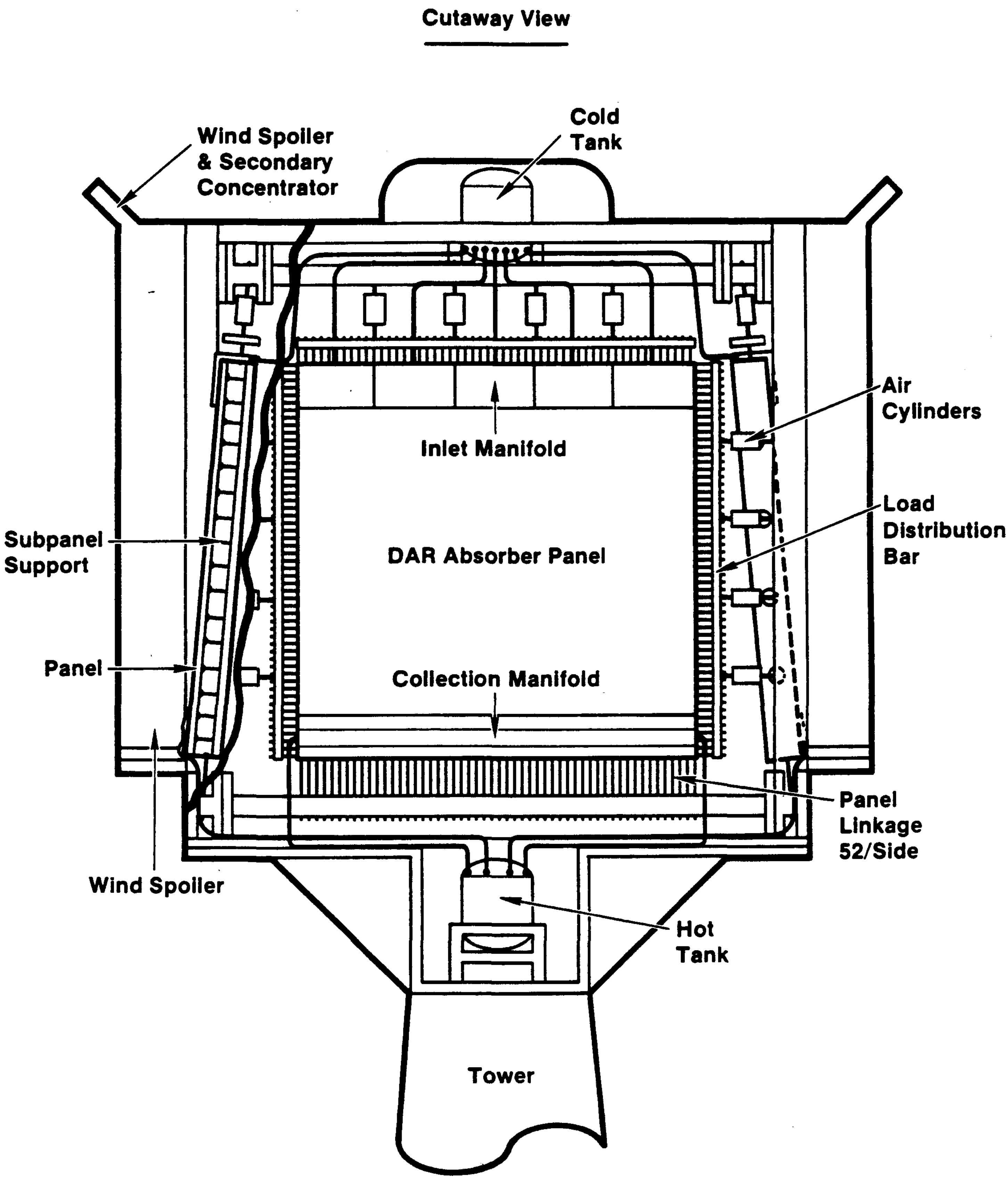

Figure 5 Design Details of the Quad-Panel DAR

Table 1

Annual efficiency comparison of cylindrical and quad-panel DAR power plants. Both plants employ 100 MW_e turbines, receivers rated at approximately 470 MW_t, and have a solar multiple equal to 1.8.

Annual Efficiency Elements	Cylindrical DAR	Quad-Panel DAR
Field	0.565	0.554
Receiver	0.911	0.904 *
Storage	0.991	0.991
Power Conversion	0.412	0.412
Parasitics	0.880	0.880 *
Availability	0.900	0.937
Efficiency Product	0.166	0.169
Total Heliostat Area (m^2)	885000	885000
Annual Energy (MWh_e)	418000	426000

* These efficiencies do not include the effects of the air curtain. See Section 3.

Table 2

Cost comparison of cylindrical and quad panel DAR power plants. All subsystem costs except for the receiver were taken from the USDOE utility study [12]. The utility study considered a salt-in-tube power plant of approximately the same size as the DAR plants studied here.

Cost Elements	Cylindrical DAR	Quad-Panel DAR
Land/Improvements	4.3	4.3
Heliostats ($80/m^2)	70.8	70.8
Receiver *	27.9	30.1 **
Storage	21.9	21.9
Power Conversion	68.5	68.5
Master Control	2.0	2.0
Total Direct Costs	195 $M	198 $M
Annual Operating and Maintenance	4.5 $M	4.5 $M
Levelized-Energy Cost ($/kw-hr)	0.077	0.076

* Receiver system includes receiver panels, surge tanks, tower, tower piping, pump, valves, and heat trace.

** Receiver system cost does not include cost of air curtain. See Section 3.

*** All system costs contain the same contingency factors used in the utility study.

Table 3

Comparison of Costs for Cylindrical and Quad-Panel DARs

Cost Category	Cost (10^3\$)	
	Cylinder	Quad
Shop Fabrication	1,826	1,930
Sub-Contracted Fabrication	1,205	1,943
Auxiliary Equipment	1,450	1,567
Engineering & Home Office Cost	2,927	2,927
Field Erection	2,279	2,758
Subtotal	9,687	11,125
Contingency @15%	1,453	1,669
G&A @ 7%	678	779
Fee @ 8%	775	890
Subtotal	12,593	14,643
Blackener	180	180
Total	12,773	14,634

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