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REQUIREMENTS FOR HIGH-TEMPERATURE AIR-COOLED CENTRAL RECEIVERS

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ABSTRACT

The design of solar thermal central receivers will be shaped by the end user's need for energy. This paper identifies the requirements for receivers supplying heat for industrial processes or electric power generation in the temperature range 540°-1000°C and evaluates the effects of the requirements on air-cooled central receivers. Potential IPH applications are identified as large baseload users that are located some distance from the receiver. In the electric power application, the receiver must supply heat to a pressurized gas power cycle. The difficulty in providing cost-effective thermal transport and thermal storage for air-cooled receivers is a critical problem.

INTRODUCTION

Recent research and development of solar thermal central receivers has focused on providing heat for electric power production or industrial processes at temperatures below 540°C (1000°F). In determining the direction of future research for higher temperature applications it is useful to identify the needs of the end users and to assess the demands they will place on the receiver. In this paper, we identify the end use requirements between 540° and 1000°C (1000° and 2000°F) and determine their implications for air-cooled central receivers.

There are two approaches to providing high-temperature air with central receivers. One is to heat the air in the receiver, and the other is to use another working fluid in the receiver and transfer the heat to the air through a heat exchanger. Air-cooled central receivers have been evaluated previously at PNL (1), Sandia (2), and SERI (3). Instead of repeating or critiquing the results of these studies, we analyze what the application of high-temperature receivers (high-temperature air receivers in particular) might be, and then see what requirements these uses will place on the solar thermal system. The user can then discern whether high-temperature air receivers are appropriate for these tasks. This paper will, therefore, define the uses and requirements of high-temperature receivers and then determine whether receivers using air as the working fluid can meet these needs.

The potential applications of high-temperature (540°-1100°C, 1000°-2000°F) solar thermal receivers share several characteristics that dictate the attributes the receiver must possess. In this temperature range, industrial process heat (IPH) applications tend to be large baseload plants, while electric power generation covers peaking, intermediate, and baseload users. The IPH users will often be distant from the receiver. The receiver for electric power applications will probably need to be interfaced with a pressurized gas cycle.

INDUSTRIAL PROCESS HEAT

Industrial process heat is a potentially large application for high-temperature central receivers. Approximately 4 quads (4.2×10^{12} MJ or 4×10^{15} Btu) of IPH between the temperatures of 400° and 1100°C (750° and 2000°F) is consumed annually. Almost all of this high-quality energy is consumed in facilities with demands of greater than 10 MW_t, and 75% of it is consumed by facilities requiring greater than 30 MW_t (see Fig. 1).

The following major industries consume almost all of this energy: petroleum refining, inorganic chemicals, ceramics, pulp and paper, and glass. Petroleum refining alone accounts for roughly 65% of the total identified uses (5). All of these industries operate essentially 24 h/day, 365 days/yr.

These large baseload industries require solar thermal systems large enough to provide a significant portion of the load. For example, the median size for refineries is 19,000 m^3/day (120,000 bbl/day) of crude oil (half the crude oil in the United States is processed in smaller refineries, half in larger); a median-sized refinery requires approximately 980 MW_t (80×10^9 Btu/day). In a high insolation site, an area of roughly 12.9 km^2 (5 mi^2) would be needed to supply half of a refinery's annual heat requirements (6). It is unlikely that large, vacant areas will be available near refineries. Indeed, for a typical refinery located in Houston, the required transport distance may be 16 to 48 km (10 to 30 mi). While the problem is most dramatic in oil refineries, which are the largest users in both annual industry requirement and actual plant size, similar problems are expected in all industries. A plant that would supply 50% of the annual load of a 10 MW_t user would require an area of roughly 27.1 ha (67 acres). Generally, large industries are located in or near population centers; hence the problem becomes clear.

A final consideration is that most high-temperature processes exhaust air at modest temperatures. This high-temperature gas is normally used to preheat the air being fed to the fuel burner. A receiver that replaces a fossil fuel burner should be able to accept preheated air. Otherwise, the receiver

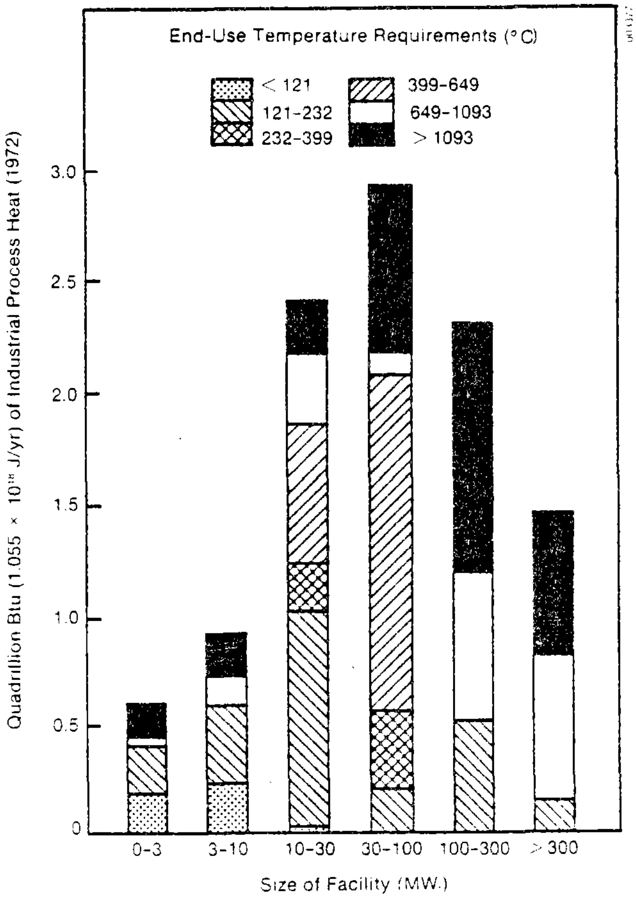

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Figure 1. Distribution of Process Heat Used at Facilities by Size and Temperature

must be sized to supply more heat than the furnace it replaces, raising the effective price of solar energy.

The distant nature and size of the application puts several requirements on the solar system. A baseload application is best served by a solar system that can supply energy in a continuous manner through the use of thermal storage. The addition of thermal storage will always raise the cost of heat delivered to the user. However, if the price of solar energy without storage is equal to or greater than the cost of conventional fuels, then a solar system would probably not be installed anyway. When solar energy is less expensive than the conventional alternative, it is in the user's interest to maximize his savings by replacing as much fuel as possible. The first step is to provide a solar field size that can produce energy equal to the baseload demand. This approach produces a solar capacity factor (CF) of 0.2 to 0.3, depending on the site (which is roughly equal to a reduction in fuel consumption of 20%-30%). More displacement of fuel entails either use of storage or the dumping of some collected heat. While the price of delivered energy will be higher with storage than without, the difference is small for many proposed storage systems. Figure 2 shows that for one specific system, the addition of up to 15 h of storage raises the cost of delivered energy only 3%. As long as the price of solar energy with storage is lower than the price of fuel, the addition of extra heliostats and storage is advantageous.

Figure 3 (7) illustrates the effect of adding storage to an IPH system for a given ratio of the cost of solar energy to conventional fuel and for a given cost of storage. In this figure the IPH system produces 290°C (550°F) saturated steam. A molten-nitrate-salt receiver is used with molten-salt storage for short-term buffering and air/rock storage for storage over 6 h. The figure shows that if solar energy is 10% less expensive than fuel, 15 h of storage is the optimum. The optimum remains at 15 h (CF = 0.75) until the cost of solar energy is lowered to 50% of the cost of fuel. This broad, flat optimum curve shows the transition from diurnal to long-duration storage. Diurnal storage is valuable because it is used often (daily). Long-term storage is worth much less to the user because it is used much less frequently. For any reasonably priced storage system where solar energy is the low-cost alternative, a baseload system (CF = 0.75) will return maximum savings to the user. Therefore, a desirable characteristic for any proposed receiver would be the ability to interface with a low-cost storage system.

The large energy requirements (10 MW_t and up) of the potential users dictate that the energy must be produced in a readily transportable form. Studies of the smallest repowering systems indicate that energy transport distances are about 600 m (2000 ft). Thus, for anything but the smallest systems, a liquid heat-transfer loop will be the preferred choice. At very short distances, transportation of hot air may be possible. As distance increases, fluids with greater energy density are required to overcome problems with parasitic power and capital cost. For intermediate distances (up to 50 km [30 mi]) molten salts are preferable. At very long distances, thermochemical transport may be the preferred alternative, but no promising system has been identified (8).

ELECTRIC POWER

The second potential market for high-temperature receivers is electric power generation. Electric power generation accounts for approximately 22 quads (23.2×10^{12} MJ or 22×10^{15} Btu) of primary energy consumption per year. The electric power market can be categorized into peak, intermediate, and baseload requirements, which are 10%, 30%, and 60%, respectively, for a typical utility. Current central receiver programs are targeted at providing systems with roughly 3 h of storage (CF = 0.4) to displace expensive oil and natural gas for the peak and intermediate loads. However, only 20%-30% of the market is served by intermediate and peak loads.

Storage with electrical generation is more advantageous than with IPH. When thermal energy is stored before its use in the power generation equipment, the power cycle and generation equipment are used more efficiently. For example, a plant with a CF of 0.5 (6 h of storage and a solar multiple of 2) can produce

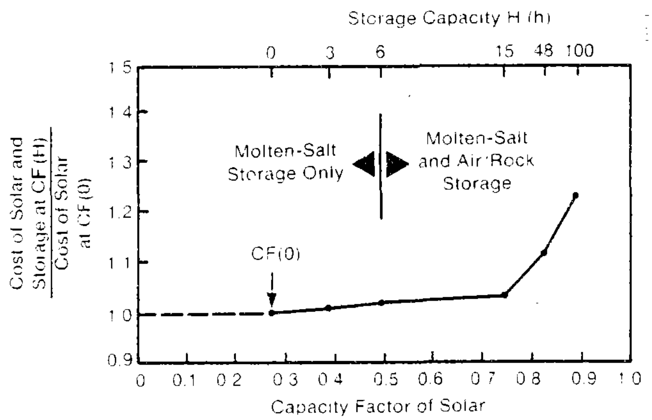

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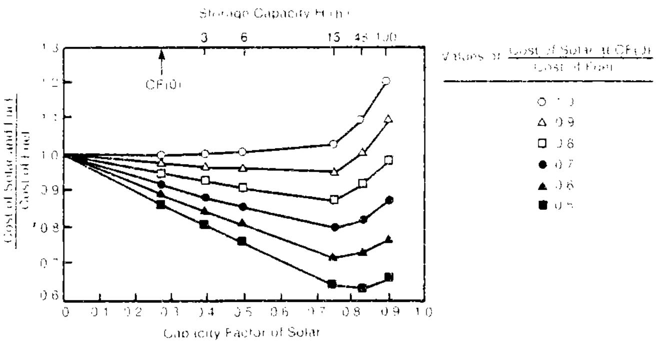
Figure 2. Ratios of Delivered Heat Costs as a Function of Storage Capacity, Not Including Backup Fuel Costs (Baseload IPH Plant)



Source: Ref. 7.

Figure 3. Ratios of Delivered Heat Costs as a Function of Storage Capacity, Including Backup Fuel Costs (Baseload IPH Plant)

twice as much energy per day as a plant without storage (CF = 0.25), without requiring additional investment in power cycle or generators. For an efficient, cost-effective storage such as draw salt, which is a 50/50 mixture of $NaNO_3$ and KNO_3 (Fig. 4), the addition of storage can reduce the cost of power by up to 18%. However, if storage is expensive or inefficient, it may have little effect on the price of electricity (as in water/steam or sodium receiver systems), or it may increase the cost of electricity (as in air/Brayton systems).

Even if the addition of storage has no effect on or slightly raises the cost of electricity, the same arguments that show the need for diurnal storage in the IPH case apply here as well. The bulk of the market consists of baseload users. If solar energy is less expensive than the alternatives, storage will allow the utility to maximize its savings. (If solar energy is not less expensive than fuel, there will be no energy to store.) For these reasons, receivers must be coupled with efficient, reasonably priced, high efficiency, diurnal (approximately 15 h) storage. Note that good storage will almost triple the potential market for an effective solar thermal system, by allowing solar energy to compete for the baseload market.

The choice of the power cycle affects the efficiency of the high-temperature central receiver. The power cycle of prime interest is the Brayton cycle, in which a gas is compressed, heated, and expanded in a turbine to produce work. In this cycle heat must be added to a high-pressure gas either by heating the gas in the receiver or by heating a different fluid in the receiver and transferring the heat to the gas. The gas cycle would be either an advanced Brayton or a Brayton/Rankine combined cycle. If the advanced Brayton engine is used, energy storage before the engine would be desirable, as such engines are relatively expensive. If a combined cycle is used, the investment in the Brayton part of the system is less. Therefore, much of the advantage of using storage could be retained by placing a current storage system such as draw salt between the Brayton and Rankine engines (10). Of course, the potential advantages of high-temperature storage in front of the Brayton would be greater.

The different types of high-temperature receivers offer various improvements in energy costs. Molten-nitrate-salt receivers are the best of the current receivers. The design receiver efficiency of a nitrate-salt receiver operating at an average temperature of 425°C (peak temperature 565°C [1050°F]) is 90%. It is unlikely that a receiver that can operate at a peak temperature of 1100°C will be more efficient. The efficiency of a steam Rankine cycle operating at a throttle temperature of 540°C (1000°F) is approximately 39% (11). An advanced Brayton cycle operating at a peak temperature of 1115°C (2040°F) has an efficiency of 49.5% (12), representing a relative increase in efficiency of 27% compared with the Rankine cycle. Therefore, if the cost and collection efficiency at 1100°C are equal to that of a nitrate-salt system operating at 540°C, the maximum reduction in busbar energy cost (BBEC) cost is 21%. Thus, the potential for BBEC cost reductions is real, but the receiver requirements are strict. Receivers that are substantially more expensive or have substantially lower efficiencies would negate the advantage. The receiver in a draw salt system accounts for 23% of the capital investment. Doubling the receiver cost would eliminate all potential gains of high-temperature operation. A decrease of 25% in receiver and transportation efficiency would likewise remove all advantages. For a combination of the two effects, the allowable changes in each would be less. Clearly the potential for improvement in BBEC exists, but receiver costs and efficiencies must be near those of present generation systems.

SUMMARY OF USER REQUIREMENTS

Potential IPH and utility users of high-temperature central receivers have a common characteristic: they both have large baseload demands. IPH users may often be located far from the potential solar field locations. High-temperature electric power generation systems will probably use pressurized gas cycles.

If solar energy is less expensive than fossil fuels, then users in both the IPH and power sectors will want diurnal storage. Even though thermal storage always increases the delivered price of IPH, it allows replacement of a more expensive fuel. In electrical applications, thermal storage allows even more effective utilization of the nonsolar portion of the plant. For these reasons, receivers that can accommodate efficient, low-cost storage will be greatly preferred.

Because of the large size of IPH plants, the receiver will often be located between several hundred yards and 30 miles away from the actual processing plant. For this reason, low-cost and efficient transportation of energy will be required. This means transporting sensible heat by means of a liquid medium (probably a molten salt). Additionally, receivers for either IPH or electric power applications that are unable to utilize a preheated coolant input to the receiver will be at a serious disadvantage, because they must supply more heat than other systems.

Any receiver built for power generation must be able to deliver heat to a pressurized gas (Brayton) cycle because only gas cycles can take advantage of these high temperatures. Finally, reductions in BBEC of up to 21% are possible, but receiver costs and efficiencies similar to those of a nitrate-salt receiver will be required.

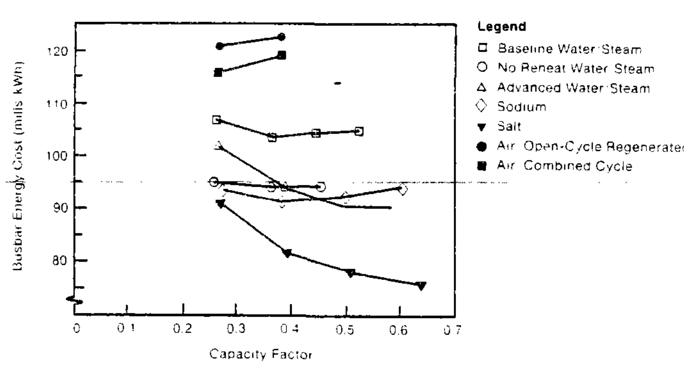


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Figure 4. Solar Central Receiver Busbar Electricity Cost as a Function of Capacity Factor for Nitrate Salt, Sodium, Water/Steam, and Air Heat Transport Technologies. Storage capacity was optimized for each solar multiple. Plotted points are roughly 0, 3, 6, and 9 hours of storage.

IMPLICATIONS FOR AIR RECEIVERS

These criteria have significant implications for air-cooled receivers. Most important for IPH systems is the distance between the receiver and the user. Transport of thermal energy in hot air can be extremely expensive. Second, air receiver systems do not interface well with any storage system designed to date, especially when the requirement is for pressurized air.

Due to its low density, hot air is prohibitively expensive to transport over any appreciable distance. The cost of transporting a fixed amount of heat at temperatures between 550° and 1100°C is insensitive to the delivery temperature but decreases with increasing pressure. The costs are insensitive to delivery temperature because the increasing thickness of insulation in higher temperature applications is offset by the smaller pipe diameter (due to the reduced mass flow rate required to deliver an equal amount of energy). Transportation costs are inversely proportional to delivery pressure up to 10 atm because at higher pressures the gas density is greater, and smaller volumetric flow rates are required. Table 1 presents piping costs for internally insulated pipes as a function of pressure. The pipes are designed to deliver 50 MW_t of hot air. If this hot air is produced by a solar system operating without storage, this corresponds to approximately 110,000 MWh/yr (375,000 MBtu/yr). Knowing the cost per foot and the amount of energy delivered per year, we can calculate the levelized cost of transporting a gigajoule (GJ) of energy a given distance; we can also calculate the transport distance which will raise the cost by $1/GJ. For comparison, the study from which these numbers are taken (2) estimates the cost of energy at the tower base of a molten-salt receiver at $12/GJ and at the base of an air-cooled metal tube receiver as $19/GJ.

The important point is that unless the receiver is mounted next to the process, the cost of moving the air will be unacceptable. In large systems, approximately 1000 m of piping will be required just to move the energy from a receiver located in the center of a heliostat field. Even the relatively short runs found in the repowering studies showed receivers located 600 meters or more from the process. In most air receiver applications, the cost of energy delivered to the user would be at least twice the cost of energy at the base of the tower.

A second problem with air receivers is storage. No inexpensive high-temperature (>550°C) storage system has been developed for air receivers. Also, storage systems proposed for air/Brayton applications (which require pressurized air) are so costly that their use lowers the BBEC of electricity. Most concepts have used various sensible heat storage media in large, pressurized vessels that are too expensive to warrant further consideration. Other investigators have proposed atmospheric pressure storage with air-to-air heat exchangers to allow production of pressurized air from storage. These have floundered on the high cost of air-to-air heat exchangers. A latent heat design (13) depended on the costly removal of heat from the storage media. The economics of an atmospheric-pressure, high-temperature storage system are uncertain because no one has attempted to design one. However, such a system would probably be considerably more cost effective than a pressurized system.

Table 1. Piping Costs as a Function of Pressure

Pressure (atm)	Pipe Diameter (ft)	Pipe Diameter (m)	Pipe Cost ($/m)	($/GJ)/m	m/($1/GJ)
1	9.0	2.74	3,500	0.027	37
5	4.7	1.42	2,100	0.017	59
10	3.8	1.17	1,900	0.015	67

Inlet to compressor 1 atm, 20°C
Power 50 MW
Air outlet temperature 815°C (1500°F)

Source: Ref. 2.

In summary, it appears difficult to match high-temperature air receivers to high-temperature IPH applications. First, the price of transporting energy is clearly exorbitant for all but the few small applications where the receiver could be located very close to the process. Second, no inexpensive storage has been identified for air receivers, even though the market exists for solar energy with storage if solar energy was a viable option.

The power cycles that would be used with high-temperature receivers are all gas-powered cycles (Brayton). However, an efficient, inexpensive storage system would be desired before the engine to reduce the stresses caused by temperature cycling and to increase engine utilization. Additionally, the majority of the electricity is consumed for baseload requirements (requiring storage). Also, none of the storage systems for pressurized air were cost effective.

Finally, the cost and efficiency of the high temperature air receiver must be close to that of a molten-nitrate-salt receiver. A recent report by Sandia (2) showed that heat produced as pressurized hot air in an air-based receiver was 60%-90% more expensive than heat produced by a nitrate-salt receiver. The potential for a 21% improvement in cycle efficiency cannot compensate for such an increase in the cost of heat energy.

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