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ASCUAS: A Solar Central Receiver Utilizing a Solid Thermal Carrier

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ASCUAS: A SOLAR CENTRAL RECEIVER UTILIZING A SOLID THERMAL CARRIER

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ABSTRACT

This report documents the preliminary examination of the use of solid carriers, e.g., pebbles or sand, as both a working fluid and storage medium for high temperature ($T \geq 600C$) solar receivers. Advantages of such a scheme include direct absorption of the incident radiation, direct heat transfer, use of the working fluid as a storage medium, and ease of hybridizing with a fossil-fired system. Key parameters and materials concerns for solar as well as for commercial fossil-fired sand or pebble heaters are identified and discussed. Commercial experience in the fuels and chemical industries attests to the technical and economic viability of this concept, while also defining the most significant materials issue: breaking of the thermal carrier. Subsequent analysis indicates that the problem may be mitigated by careful selection/development of carrier material and processing. Future R&D directions are briefly discussed.

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*Worked performed while an A.S.E.E. summer fellow at Sandia National Laboratories, Livermore, California.

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The authors are indebted to T. D. Brumleve and S. E. Faas for discussions of their earlier work in sand absorption and storage schemes, to M. J. Fish for discussions of her experience in pebble heaters and fluidized beds, to V. Prantil for the thermal shock resistance calculations used in this study, to M. D. Skibo for the thermal shock resistance experiments described in this study, and to J. E. Shelby for various experimental consultations. Helpful comments and encouragement were received from G. W. Anderson, C. T. Yokomizo, W. G. Wilson, and R. L. Rinne. The authors are especially indebted to Chris Loschi of the University of Lowell, Lowell, Massachusetts, for the latest versions of Tables 1 and 6 used in this study.

INTRODUCTION

Studies conducted at Sandia National Laboratories have identified solid heat transfer media, e.g., pebbles or sand, as an attractive "working fluid" for high temperature ($T \gtrsim 600C$) solar applications. This concept has been named ASCUAS from the Spanish word ascuas which means "hot solids from a fire." ASCUAS is a logical extension of earlier studies of direct absorption by falling sand [1] and of sand as a thermal storage media [2,3] as well as commercial experience with fossil-fired pebble or sand heaters [4-10]. ASCUAS offers numerous advantages over gaseous working fluids, including direct absorption of the incident radiation, direct heat transfer, use of the working fluid as a storage medium, and ease of hybridizing with a fossil-fired system.

Potential high temperature applications include advanced storage systems for superheated steam receivers [3]; working fluid and storage for many industrial process heat applications including the highly energy intensive fuels and chamical industries [11,13]; and use for high temperature gas turbines (Brayton cycle) [14].

Present High Temperature Receiver (HTR) Designs

Currently, many HTR designs employ a gaseous working fluid confined in superalloy [15,16] or ceramic receiver tubes [17,18] within cavity-type receivers. Depending on the application, the hot gas may then drive a process at the tower-top (e.g., receiver reactor) or be brought down to a ground-level process through an insulated pipe known as a "downcomer."

The use of a gaseous working fluid, and the resultant need to confine it at high temperature, imposes technical requirements which translate into cost penalties. The relatively poor heat transfer properties of the working fluid limit the acceptable average flux on the reactor tubes to $\simeq 100\text{kw/m}^2$ [15-18]. Such a low flux implies large heat transfer areas and, hence, large receiver cavities. The lifetime of the receiver tubes subjected to the one-sided heating and thermal cycling characteristic of some solar HTRs is an area of significant concern. Some of these "solar effects" may be mitigated by the use of near isotropic reradiant heating of the receiver tubes from the receiver walls [16]. Reradiant heating incurs additional design penalties: a larger cavity, and the need to operate the receiver at a higher temperature and, hence, a lower efficiency [15]. A third concern arises in using the hot gas. Economic and process considerations often dictate a hybrid process, i.e., using solar during favorable insolation and a fossil-fired system at other times. In the case of a receiver-reactor this is usually accomplished by having a second ground based reactor, with resulting additional costs. In the case of ground-based processing, this requires a rather complicated and costly insulated high-alloy downcomer.

ASCUAS

Figure 1 shows a hypothetical ASCUAS system. Except for the means of heating the carrier, this system looks very similar to the fossil-fired systems described in reference 4. Bucket elevators, or a pneumatic lift, transport the cold sand to the top of a 100 m tower. The sand is then dropped, and falls freely past a windowless aperture in the side of the receiver cavity. The sand absorbs the incident insolation directly, and is heated to approximately 1000°C before passing through the cavity, down a refractory chute, and into a hot sand bunker which provides both buffering and storage. (Varying insolation and possible non-uniformities in particle heating

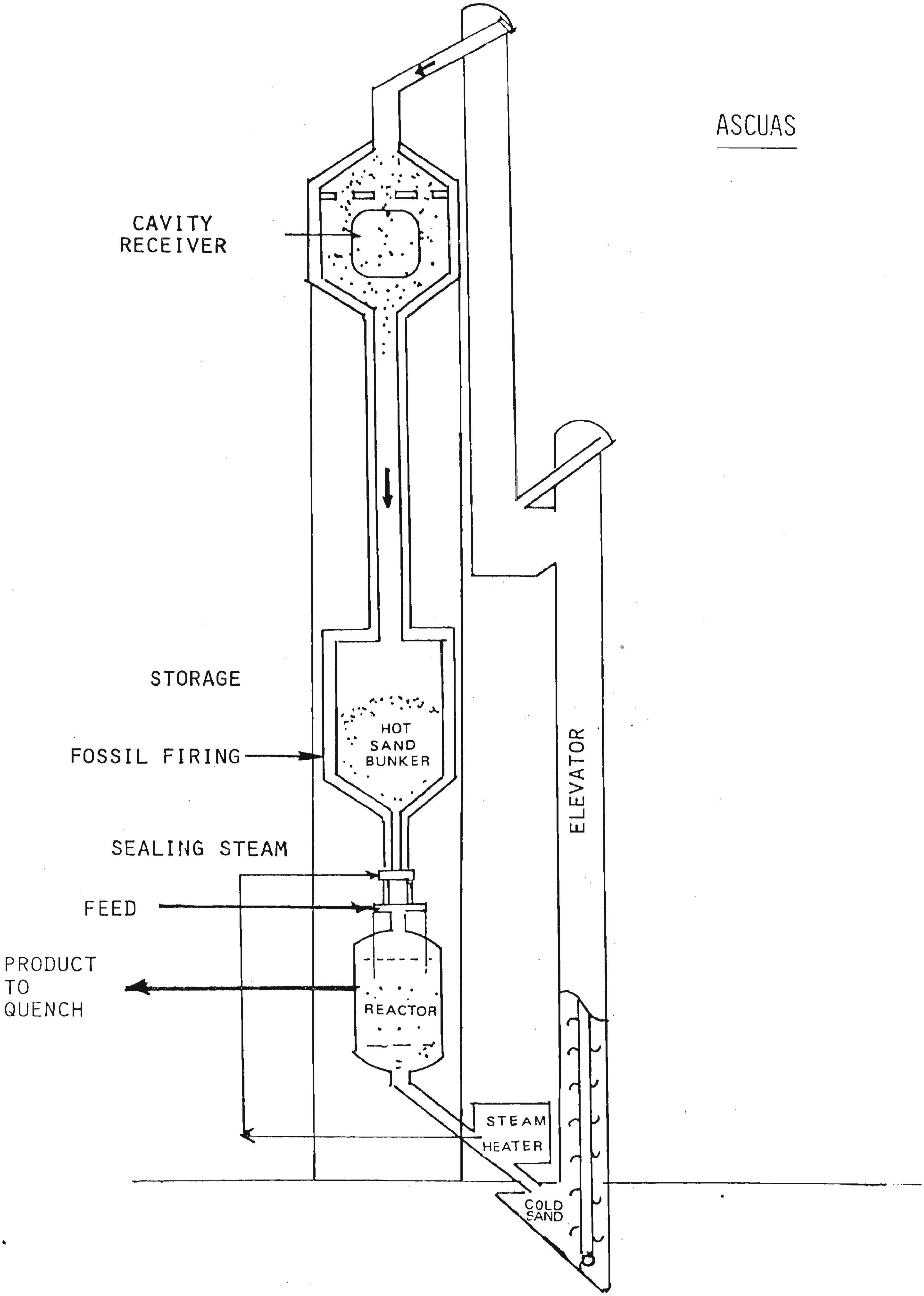

FIGURE 1. A Possible ASCUAS Design

may be accommodated by fossil heating within the storage bunker.) Hot sand is released from the bottom of the sand bunker, passes through a steam seal, and enters the reactor where it comes into direct contact with the reactants. After leaving the reactor, the warm sand is used to generate steam, then passes to the cold sand hopper and the whole process begins again. Representative temperatures and times at the various stages of the sand heater may be found in Figure 2, which gives a hypothetical time-temperature profile for a sand particle used in ethylene production.

Direct absorption and the good heat transfer characteristics of a solid carrier result in a smaller, cooler, more efficient cavity design. A windowless receiver can be used if the sand is not too fine. Containment of the "working fluid" is simplified to the extent that no receiver tubes are required, and the downcomer can be a simple refractory chute with a structural exoskeleton--without the need for expensive leak-tight high-temperature tubing. Heat exchange is direct, eliminating costly heat exchangers and any flux limitations that might arise from the use of an intermediate working fluid or heat exchanger. Both storage and hybridization are naturally incorporated by

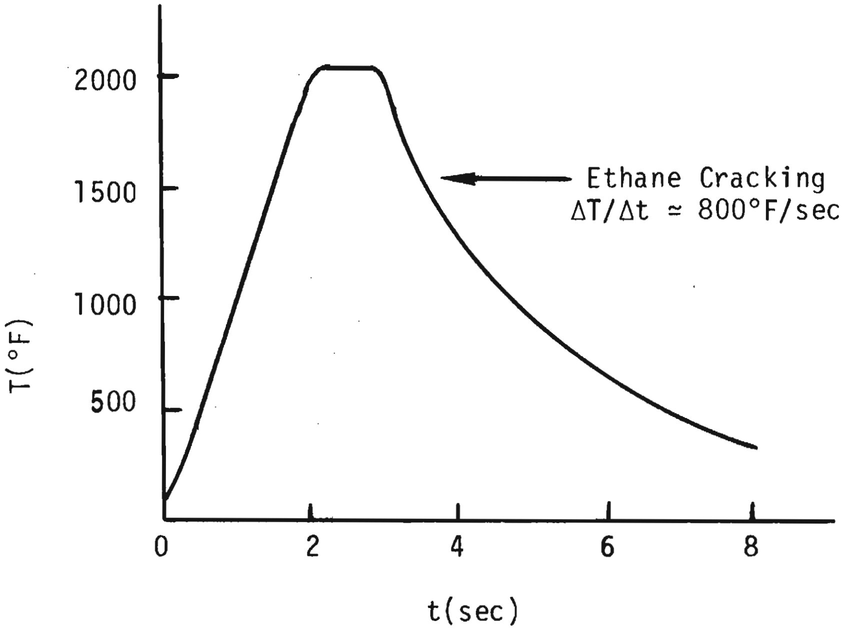

FIGURE 2. Hypothetical Time-Temperature Profile for a Sand Particle Used in Ethylene Production.

providing for a large hot sand bunker with supplemental fossil firing. Finally, mechanical cyclones (not shown in Fig. 1) are used to remove the sand from the product stream and, hence, the working fluid does not dilute the energy content of the product stream.

Some Design Considerations

As noted earlier, except for the means of heating the carrier, the hypothetical ASCUAS system is very similar to commercial fossil-fired pebble or sand heater designs. Therefore, because of this similarity and the time constraints of the study, we limited ourselves to a brief look at possible carrier materials, the required mass flow rate, time for the particle temperature to equilibrate with the incident radiation field, and the availability and cost of suitable particle conveyors. These considerations, and the resulting conclusions, are summarized below.

The ideal solid carrier would be inert; have a high melting or sublimation temperature; have a low thermal expansion coefficient; have a high thermal conductivity, specific heat, and solar absorptivity; have excellent resistance to thermal shock and to abrasion, and be relatively inexpensive (to minimize inventory and make-up costs) [7]. Table 1 summarizes the physical properties of a number of candidate materials. Of these, Al_2O_3 and crystalline SiO_2 (sand) have actually been used as solid carriers, whereas the other materials promise increased resistance to thermal shock and may extend the operating temperature range. The ideal material and fabrication process have yet to be identified and may or may not be listed in Table 1. However, for concreteness, the subsequent analysis assumes the use of SiC.

	Al_2O_3	Xtal SiO_2	Fused SiO_2	SiC	Si_3N_4
Coefficient of Thermal Expansion ($°C^{-1}$)	9.0×10^{-6}	32.2×10^{-6} (b)	0.5×10^{-6}	5.8×10^{-6}	2.4×10^{-6}
Thermal Conductivity (W/cm-°c)	0.06	0.042 (b)	0.045	0.225	0.0588
Breaking Tensile Strength (psi)	34×10^3	7×10^3 (c)	10×10^3	25×10^3	16×10^3
Young's Modulus (psi)	55×10^6	49×10^6 (c)	12×10^6	47×10^6 (d)	31×10^6 (e)
Poisson's Ratio	0.37	0.17 (c)	0.19	0.18 (d)	0.25 (f)

TABLE 1

Physical properties of some candidate ASCUAS materials. (Wherever possible, physical properties are tabulated at 1000°C; otherwise values are averages over the smallest available temperature range including 1000°C. Values are from Reference 19a unless otherwise indicated in parentheses, e.g., (b) means value is from Ref. 19b.)

Knowing the specific heat of SiC, and assuming that the carrier enters the reactor at a temperature of 900°C and exits at a temperature of 600°C, it is a simple matter to calculate the required mass flow rate for a hypothetical 50 MW_t receiver. The calculated mass flow rate, $\dot{m}$, is approximately 490 tons/hr and it is well within the 1100 tons/hr routinely handled by commercially available belt and bucket conveyors [20]. Such conveyors can handle abrasive materials, and can operate at temperatures up to 148°C; hence, the handling of "cold" SiC poses no particular problems. Each conveyor is limited to a height of ≈50 m, and so a 100 m tower would require cascading two such conveyors at a total estimated capital cost of $200,000 [21]. The horsepower (HP) needed to start up the conveyors is given by

$$HP = h\dot{m}/550, \tag{1}$$

where h=height in feet and $\dot{m}$=mass flow rate in tons/hr [20]. Hence, the required "startup" power for lifting 490 tons/hr a distance of 320 feet is approximately 290 HP (210 kW_e or ~640 kW_t). The steady-state power consumption is expected to be even less, and, hence, the parasitic losses due to carrier transport are small compared with the 50 MW_t rating of the receiver.

Storage volumes are estimated from the receiver rating, the desired hours of storage, and an assumed effective density of SiC sand of ≃ 1600 kg/m^3 vs. 3200 kg/m^3 for bulk SiC. For a 50 MW_t receiver, and for 15 hours of storage, we require 7400 tons of SiC sand in a storage volume of 4200 m^3 (i.e., a cube 16 m on a side). The product of the density (ρ) and the specific heat (C_p) provides another measure of the compactness of storage. This number is 0.46†, 0.45, 0.68, 0.29 cal/cm^3-°C for SiC, caloria, molten nitrate salt, and molten Na respectively [22]. (Caloria, molten nitrate salt, and molten Na are the more common materials considered for thermal storage at lower temperatures.)

Finally, we wish to consider the coupling of the incident radiation to the particle. In the case of the proposed ASCUAS system, the radiation field couples directly to a large number of particles falling through the cavity (Fig. 3a). However, this is an extremely complex problem, and is one of the areas singled out for future studies. In actuality, we examined the less desirable case of a single SiC particle falling through an ideal cavity (ε=1) and heated by reradiation from the cavity walls (Figure 3b). In this case

$$\varepsilon\sigma(T_o{}^4-T^4)S = C_p\rho V dT/dt , \tag{2}$$

where ε=emissivity of SiC; σ=the Stefan-Boltzman constant; T_o,T=the average temperature of the cavity wall and the particle respectively; C_p,ρ=the specific

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†Based on effective density of 1.6 gm/cm^3 for SiC sand.

heat and density of SiC; S, V= the surface area and volume of the particle and t is the time the particle spends in the radiation field. For SiC spheres of radius r, this reduces to

$$dT/dt = 4.446 \times 10^{-12} (T_0^4 - T^4)/r , \tag{3}$$

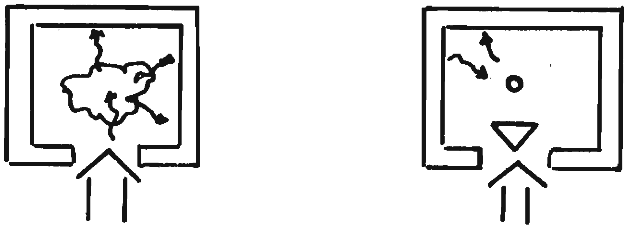
with r given in cm and T in °K. Integrating eq. (3), we find that the time τ for a particle temperature to rise from an initial value T_i to a final value T_f is given by

$$\frac{\tau}{r} = (8.89 \times 10^{-12} T_0^3)^{-1} \{\frac{1}{2} \ln[(T_f+T_0)(T_0-T_i)/(T_i+T_0)(T_0-T_f)] + \tan^{-1} (T_f/T_0) - \tan^{-1} (T_i/T_0)\} . \tag{4}$$

Assuming T_i = 25C (298K), T_f = 950C (1223K) and T_0 = 1090C (1366K) we find that

$$\tau/r = 77 \text{ sec/cm} . \tag{5}$$

Hence, for coarse sand ($r \simeq 0.023$ cm) it only takes 1.8 sec to heat the particle whereas it takes approximately 30 sec to heat a pebble of $r \simeq 0.5$ cm. Since a particle will fall a distance of approximately 9m in 1.8 sec, it is quite conceivable to heat coarse SiC sand while free falling through a cavity. Heating of larger pebbles, however, will require a somewhat more complicated receiver design in which the residence time of the particle in the cavity is significantly increased.



"Real"
(A)

"Solvable"
(B)

FIGURE 3. Coupling of the radiation field to particles falling through the cavity. (A) Real case: direct coupling of incident radiation to a large number of falling particles. (B) Simplified case: single falling particle is heated by reradiation from cavity walls.

A more comprehensive treatment is needed to address the direct coupling of the radiation field to a particle bed of finite thickness in which the particle sizes exhibit some distribution about a mean size. Complications include the relative amounts of direct vs. reradiative heating, one sided heating, non-uniform heating of particles of varying sizes, and partial "shadowing" of particles by other particles. Although such calculations will be critical to optimizing the receiver design, we feel that any significant departures from ideality could be accomodated by supplementary fossil-firing of the hot sand bunker which provides buffering and storage for the system.

Commercial Experience [4-10]

As noted in the previous section, a preliminary examination of several key design criteria revealed no significant technical or economic stumbling blocks. This "cautious optimism" is strongly reinforced by the limited commercial experience with fossil-fired pebble or sand heaters. Table 2 briefly summarizes the commercial ventures employing solid heat transfer media. Pebble heaters were developed in the early 1950s by Phillips Petroleum [6] and were an outgrowth of early work by Socony-Vacuum Oil [4]. Lurgi-Ruhrgas had a pilot plant sandcracker as early as 1938 [10], and opened five sandcracker ethylene production plants in the 1960s [23, 10b] (see Table 3). Three of the Lurgi plants were closed after several years of operation due to economic considerations arising from "dusting" or break-up of the sand. However, two plants, dating from 1964 to 1968, are still operating. Lurgi is currently involved in using sand, coke and spent shale as heat carriers for oil shale retorting [24] (Rio Blanco Project). In a similar vein, Tosco will be using ceramic balls as the heat carrier in both their coal pyrolysis (TOSCOAL) and oil shale retorting (Colony Project) programs. (DOE has said it will issue $1.1 billion in Federal loan guarantees to Tosco for their shale oil project [26].) Thus solid carriers are being used in some of this country's largest synfuels projects.*

PRODUCT	HEAT CARRIER	FIRMS
Ethylene	Pebbles, Sand	Socony-Vacuum Oil Phillips Petroleum Lurgi
Coal Retorting	Ceramic Balls (Toscoal)	Tosco
Oil Shale Retorting	Ceramic Balls (Tosco-II) Sand, Coke, Spent Shale (L/R)	Tosco Gulf Oil/Std Oil Ind Getty-Oil

TABLE 2

Summary of commercial ventures employing solid heat transfer media

YEAR	PLANT
1960	2 commercial plants started Dormagen, FR6 Leuna, CDR, 100 T/D, (naptha), closed 1964
1964	Macruzen, Chiba, Japan 120 T/d, closed 1971
1964	Rosario, Argentina 70 T/D (naptha), still operating
1968	Lan Chow, China 125 T/D (crude oil), still operating

TABLE 3

Recent Lurgi plant ethylene production plants using sandcracking technology [23,10b]

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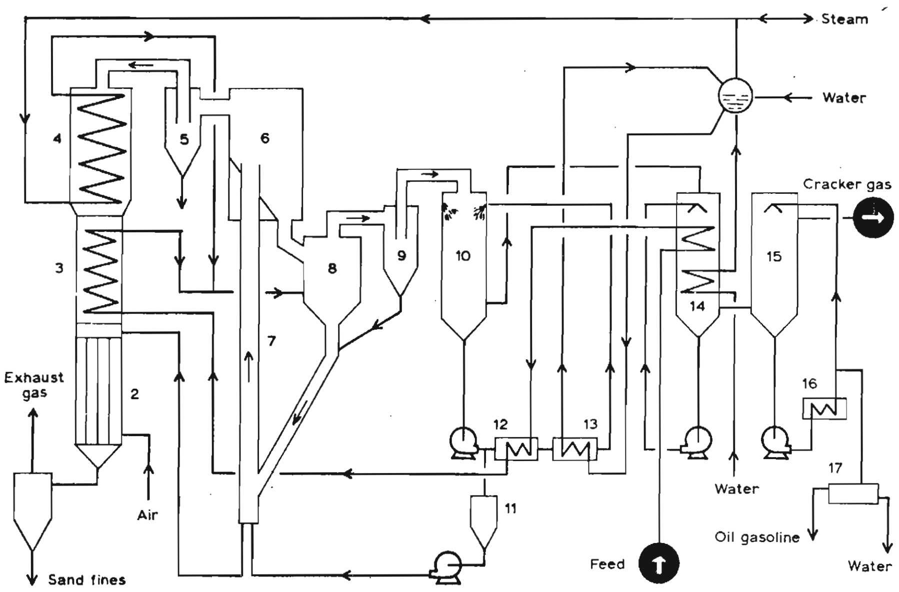
*Shale retorting is being studied using both direct and indirect combustion to provide the necessary heat. Indirect combustion may help control the problem of nitrogen contamination of the output. Nitrogen is a poison for current refinery catalysts. The occurrence of high levels of organic nitrogen in raw shale oil limits its use in existing refineries and has led to study of its use as a chemical feedstock [25].

The majority of commercial plants have used Al_2O_3 pebbles, local sand, or coke pebbles as the heat carrier. The use of a solid carrier did not adversely effect either the product quality or yield, nor did it present significant abrasion problems [23]. The only significant difficulty encountered was the break-up (attrition or dusting) of the heat carriers [27]. Approximately 3 to 4 percent of the sand is lost per cycle [10a]. In the case of pebble heaters, the effect of this problem was lessened, but not eliminated, by replacing the bucket elevators used to transport the particles with pneumatic lifters. The significance of this problem is attested by the numerous cyclones that appear in flowsheets of the various processes (e.g., Figure 4) and the fact that the economics of dusting and the resulting "makeup" costs led to the closing of three Lurgi sandcracking plants even though these plants were using local, and presumably inexpensive, sand. (In the next section we explore the possibility that alternate carrier materials or processing may then further reduce the dusting problem.)

Figure 4a shows a flow sheet of a rather typical sandcracking plant [10c]. Note the similarity to the proposed ASCUAS design, with the heated sand being fed to a sand bunker, then to a reactor, and back to the heater. Also, note the cyclones for removing the sand fines. The process flow of both the sand and pebble heaters naturally results in a vertical structure (Figure 4b) which may be reasonably integrated with the solar receiver tower.

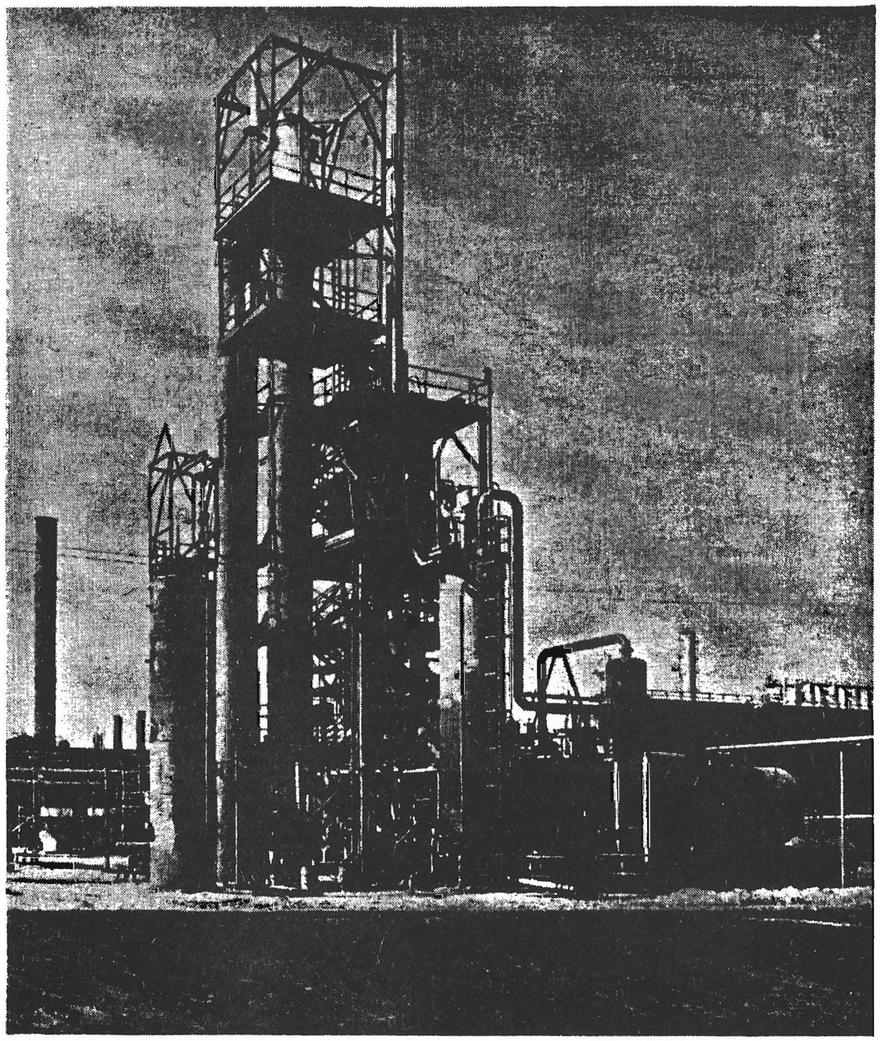
In summary, extended experience with commercial scale sand and pebble heaters attests to the technical and economic feasibility of such heaters. The only significant problem encountered in commercial applications was one of particle breakage or dusting. In a solar application, we can also benefit from the potential for direct absorption and simplified storage and hybridization which a solid carrier offers.



1. Multiple cyclone; 2. Air preheater; 3. Feed superheater; 4. Steam superheater; 5. Cyclone; 6. Sand bunker; 7. Sand lift; 8. Reactor; 9. Sand cyclone; 10. First washer/cooler; 11. Container for rejected heavy oil; 12. Feed vaporiser; 13. Waste heat boiler; 14. Second washer/cooler; 15. Third washer/cooler; 16. Recycle cooler; 17. Oil-water separator.

FIGURE 4a: The Lurgi-Ruhrgas sand cracker (from Ref 10c, courtesy of Ernest Benn Limited).

FIGURE 4b: The Phillips pebble heater (from Ref 10c, courtesy of Ernest Benn Limited).



Materials Consideration

A. Dusting:

A simple example will serve to illustrate the magnitude of "makeup" costs and the large economic leverage in reducing the dusting rate. Table 4 lists the approximate cost per unit pound of some candidate materials. Assuming a 50 MW_t receiver and a reported makeup rate of 3% sand per cycle, we find that the makeup costs for a silica sand carrier is $\simeq$ \$50 x 10^6/yr. This is to be compared against an estimated capital cost of \$8.5 x 10^6 [16] for a "conventional" 50 MW_t high temperature gas cavity, support structure, riser and downcomer. We need a significant (approximately 100 fold) reduction in the dusting rate if we are to use any of the materials in Table 4.

Material	Price
"SiC"	\$0.9/#
Al Oxide	0.5
Silica Sand	0.2
Molten Salt(b)	0.15

TABLE 4

Typical costs(a) for some candidate materials [28]

a) With the exception of molten salt, the price estimates do not include any discounts for large volume purchases.

b) Molten nitrate salts are frequently used as a working fluid and storage medium in intermediate temperature receivers, and have been included for the sake of comparison.

Abrasion and impacts in handling are important mechanisms contributing to solid fracture. The other major mechanism is thermal shock. Rapid and repeated thermal excursions over a wide temperature range may induce fracture. Ceramics, in particular, show relatively poor thermal shock resistance. The chosen solid carrier must be able to withstand the excursions.

For either sand or pebbles, the resistance will be dependent on the solid history, through grain structure, imbedded impurities, initial strains, etc. It is not possible here to explore this complex subject. Instead, we shall attempt a tentative ranking of possible ceramic in terms of simple, albeit not definitive, models of shock analysis. The analysis utilizes the critical stress theory of Crandall and Ging [29] and assumes a homogeneous isotropic sphere which is heated symmetrically about its center. Failure of the particle occurs when the thermally induced tensile stress at a point exceeds the strength of the body. In this theory, the temperature difference (ΔT) which will cause failure is given by

$$\Delta T = \frac{2.5\ S_T\ (1-\nu)\ (1+2/\beta)}{\alpha E}\ , \tag{6}$$

where S_T = breaking tensile strength, α = coefficient of thermal expansion, E = Young's modulus, ν = Poisson's ratio, and

$$\beta = rh/k\ , \tag{7}$$

where β = Biot's modulus, r = the radius of the particle, k = thermal conductivity, and h = the heat transfer coefficient between the particle and the surrounding medium. Crandall and Ging's test of their model [29] is summarized in Table 5. The calculated and experimental failure temperatures for heating in both salt and air are in reasonable agreement. However, the measured failure temperatures for cooling in salt are significantly lower than the calculated values.

SPHERE DIAM. (IN)	1	1 1/4	1 1/2	2	3
Heating in salt (calculated)	736	648	559	448	352
Heating in salt (experimental)	722	600	575	540	500
Heating in air (calculated)	x	1442	1400	1135	1032
Heating in air (experimental)	x	1344	1228	1117	950
Cooling in salt (calculated)	736	648	559	448	352
Cooling in salt (experimental)	250	230	x	x	x

TABLE 5

Experimental and Calculated Failure Temperatures (°C) [from Ref. 29, courtesy of the Journal of the American Ceramics Society]

Table 6 summarizes the calculated thermal shock values (ΔT) for 0.1 cm radius pebbles of candidate ASCUAS materials subjected to two different heat transfer rates. These heat transfer coefficients are representatives of water and air quenches [30], and bracket the value (0.2 w/cm^2-°C) of h estimated for ethylene production on the basis of a 350C temperature drop in 0.8 sec [31]. As may readily be seen, a number of materials yield much higher ΔTs than either Al_2O_3 or SiO_2 or than is required by the process. (The extremely low thermal expansion coefficient of vitreous silica makes this material a particularly attractive candidate for temperatures below the onset of devitrification, i.e., $\leq$1000C.) Figure 5 suggests that this calculated increase in ΔT may indeed be significant, since the transition from a fracture-free to a fractured regime occurs over a relatively narrow range of temperatures.

MATERIAL	ΔT_{calc} (°C) H = 0.6 W/cm^2°C	ΔT_{calc} (°C) H = 0.019 W/cm^2°C
Al_2O_3	310	(6,920)
SiO_2 (crystalline)	22	416
SiO_2 (fused)	(8,620)	(170,000)
SiC	1,600	(44,800)
Si_3N_4	1,190	(25,400)

TABLE 6

Ranking of the thermal shock resistance of candidate ASCUAS materials. Calculation assumes 0.1 cm radius pebbles subjected to a 1000 C shock. (Parenthesis indicate that the temperature difference, ΔT, which would cause failure exceeds the melting point of the material.)

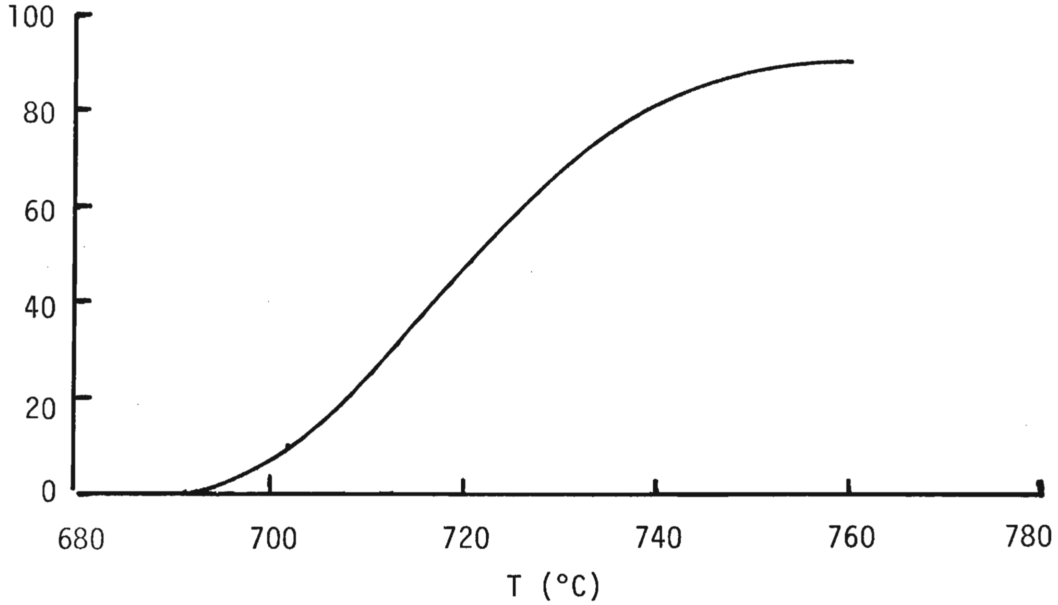


FIGURE 5. Percent of 1" diameter ceramic (Al_2O_3) balls fracturing upon heating in HiTec salt. (Figure redrawn from Ref. 29 by permission of the Journal of the American Ceramics Society.)

These predictions suggest that to the extent that the dusting is due to thermal shock, we may be able to reduce significantly the extent of dusting by a careful choice of carrier material and fabrication technology. To test these ideas, we have initiated a simple set of screening experiments in which SiC, Al_2O_3, and sand (all ≃ 200 μm in maximum dimension) are water-quenched from 1000 C. After quenching, the particles are collected by means of filtering and/or centrifugation. A portion of the sample is withdrawn for characterization, and the remainder is again heated and quenched, for a total of 5 to 10 cycles. Optical and electron microscopy are used to provide information on particle and fracture morphology, and laser particle sizing is used to provide particle size distributions as a function of particle history. These measurements are currently in progress.

B. Sintering [32]:

Another possible problem not mentioned in available literature* is the potential for particle sintering arising from the small particle sizes and high operating temperatures characteristic of sand heaters. As discussed in Kingery [32], sintering can occur by a variety of mechanisms, e.g., viscous or plastic flow, surface or grain boundary diffusion, evaporation, and condensation, etc. In spite of the variety and complexity of these mechanisms, we can make a few simple generalizations about sintering. Sintering can occur significantly below (e.g., at ~ 1/2) the melting temperature and occurs

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*Breakage of 0.5" diameter magnesia pebbles at operating temperatures of 4000F resulted in excessive fines and sintering of portions of the bed of the Sunflower Ordinance Works in Lawrence, Kansas, in 1953 [7]. However, these temperatures are <u>much</u> higher than contemplated in the current study.

more readily for small particles and at high pressures. The functional dependence on temperature is a strong function of the sintering mechanism. However, the temporal dependence for many mechanisms is of the form t^{α} ($1/5 \lesssim \alpha \lesssim 1/3$). The fact that α is significantly less than 1 means that the sintering effectively "slows down" at long times. This means that relatively short time (days to month) laboratory and field tests should allow us to assess the sintering potential of any proposed schemes.

Any potential sintering problem can be further reduced by minimizing dusting (i.e., the production of smaller, more easily sintered particles) and by designing the reactor and storage beds to be self draining and to have active flow at all times, thereby preventing the accumulation of fines at dead spots and their subsequent agglomeration.

CONCLUSIONS

The use of solid thermal carriers offer a number of advantages over gaseous working fluids, including direct absorption of the incident radiation, direct heat transfer, use of the working fluid as a storage medium, and ease of hybridizing with a fossil-fired system. Commercial experience with fossil-fired pebble and sand heaters appears to attest to the technical and economic feasibility of such a concept. The only significant problem encountered in commercial applications was one of particle breakage or dusting. This problem was of sufficient magnitude as to make the economics marginal but not unattractive. Appropriate materials selection and processing may further reduce the extent of dusting and its associated economic penalty. Furthermore, solid carriers offer even more advantages for solar applications than for fossil-fired applications in which the solid-carrier serves only to provide direct heat transfer. These additional advantages include direct absorption, use of working fluid as a storage media, and ease of hybridization.

Though encouraging, this study must be regarded as preliminary. Future studies are needed in the areas of systems analysis, materials R&D, engineering design, and ultimately hardware testing. Industry input should be solicited and a preconceptual ASCUAS facility should be designed, costed, and compared with other high temperature solar receivers. This design process will require detailed knowledge on expected cavity performance, coupling with the incident radiation field, transport and storage of heat carriers, etc. Accurate modeling of the coupling of the solid-carrier to the radiation field is particularly important since this aspect is unique to solar applications and cannot be "validated" by previous commercial experience. Improvements in the lifetime of the solid carriers can have major impact on the overall economics of this technology. Likely causes of carrier failure should be pursued with commercial operators (possible joint program emphasizing materials analysis) and in prototype experiments and should be part of a materials R&D effort aimed at identifying or developing an optimal carrier material and fabrication technique. Finally, all this has to come together into the design, construction, and analysis of laboratory and field-sized solid carrier receivers.

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