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PERFORMANCE AND COSTS OF PARABOLIC DISH SOLAR THERMAL SYSTEMS FOR SELECTED PROCESS APPLICATIONS*

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ABSTRACT

The performance and cost characteristics of parabolic dish solar thermal systems are determined for a wide range of thermal applications encompassing the supply of solar-derived heat from low to high temperatures. Recent case studies of selected process applications are used to delineate the influence of site-specific application requirements. Selected applications include provision of thermal energy for enhanced oil recovery operations, borax ore processing, and production of furfural/ethanol from biomass. Cost and performance characteristics are based on parabolic dish development program objectives as supported by findings from recent experimental activities. The thermal transport piping network needed to transport energy from the parabolic dish collectors to the application site is predicated on the use of automated factory fabrication and semi-automated field installation methods to achieve low costs. Energy costs associated with the parabolic dish solar heat supply system are determined by using economic parameters deemed to be appropriate for process applications by the Solar Thermal Program Cost Goals Committee. The feasibility of solar systems is assessed in the context of alternate conventional fossil fuel systems and uncertainties in fuel price escalation rates.

Functionally, parabolic dish solar thermal systems can satisfy a wide range of process heat applications. This solar-derived heat can be supplied from low to high temperatures. In this present study, the temperature range considered extends from 316°C(600°F) to 510°C(950°F). The inherent modularity of dish systems enables them to be useful for small to large plant sizes (the range covered in the present study was limited to 3 to 150 MW_t) and their high optical/thermal performance leads to minimum land use. Each dish concentrator focuses sunlight into a focal-point-mounted cavity receiver where energy is transferred to the transport fluid. The outlet fluid temperature level is controlled by the fluid flow rate through the receiver. The heated fluid is then transported in a piping network to the user site. The transport of this thermal energy from dispersed dish collectors to a user site is a critical item in the overall cost effectiveness of a solar-derived process heat application.

Early studies (Powell et al (1), Turner (2), Caputo (3)) considered conventional labor-intensive methods of constructing the field piping network. A recent study comparing various solar thermal systems for Industrial Process Heat (IPH) applications (Eicker et al, (4)) was also based on using conventional pipe assembly methods. These techniques and the associated relatively expensive piping networks are considered to be applicable to initial market entry conditions where volume production methods are not yet implemented.

The large-scale penetration of solar thermal systems is predicated on achievement of low costs through mass production of solar plant components such as mirrored concentrators and heliostats. When analyzing these systems, it is consistent to consider the use of mass production and automated methods for fabricating and assembling the thermal transport piping network. These techniques result in major cost reductions over conventional labor intensive methods.

These cost-reducing techniques can include such items as automated factory welding, the use of special labor-saving weld fittings, and pre-fabricated pipe supports to reduce field assembly labor. These labor-saving approaches can also be extended to factory installation of pipe insulation, which avoids the high cost of manually applying insulation in the field. These so-called nonconventional or non-traditional assembly

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techniques have been studied by the Jet Propulsion Laboratory (JPL), Ford Aerospace and Communications Corp. (FACC), Science Applications, Inc. (SAI), and the Solar Energy Research Institute (SERI) (Biddle et al (5), Polzien et al (6), Liers (7) Hooker, (8)).

In this paper, selected process heat applications that use parabolic dish collectors covering a wide range of operating temperatures and plant sizes are described. Then, parametric studies of the cost and performance characteristics of thermal transport piping networks typical of the above applications are presented. These low-cost, mass-production transport costs are combined with other component subsystem costs associated with the solar process heat systems to determine an overall energy cost. Finally, the feasibility of these solar systems to provide process heat is considered in the context of alternate conventional fossil fuel systems and uncertainties in fuel price escalation rates.

SOLAR-DERIVED PROCESS HEAT APPLICATIONS

In this section, recent IPH case studies (Liers and Young (9), Polizen et al (6), Gupta and Edwards (10), Sommerlad et al (11)) are examined to delineate a representative set of applications for solar-derived heat and the influence of site-specific application requirements. The selection of representative applications is based essentially on the existence of a good national market potential for that particular application, a good annual insolation at the application site and/or a poor local supply of fossil fuels; and other favorable requirements, such as process temperatures which are compatible with temperatures that can be supplied by solar systems, ease of integrating the solar system into the IPH plant, availability of suitable space within the plant, and existing plant layout. Selected applications include provision of solar-derived energy for enhanced oil recovery operations, stripper well operations, borax ore processing, and the production of furfural/ethanol from biomass. Most of these selected case studies are synthesized and tabulated in Table 1.

Enhanced Oil Recovery (EOR) was projected to constitute a major portion of the near-term IPH potential market in the Multi-Year Program Plan of the Solar Thermal Energy Systems Program (1981). EOR has a very

Table 1

Typical IPH Application Case Studies

Enhanced Oil Recovery
275°C Saturated Steam -- EXXON/FACC[a]
427°C Syltherm 800/Fossil - Fuel Superheater -- SAI[b]
Production of Furfural/Ethanol
232°C Therminol T-55 177°C Steam -- SAI[b]
Borax Ore Proccesing
232°C Therminol T-55 185°C Sat. Steam -- SAI[b]
Stripper Well Emulsion Pumping and Heat Treatment
427°C Dow Chem Fluid B/Organic Rankine Engine -- SAI[b]
Wallboard Drying
482°C Air at Atmospheric Pressure -- SAI[b]
Process Steam for Oil Refinery
270°C Sat. Steam/Fossil Fuel Superheater (370°C) -- Foster Wheeler[c]

[a]Polzien et al (6)
[b]Liers and Young (9)
[c]Sommerlad (11)

large potential market, a vigorous implementation of which can help bolster the nation's energy independence (Gupta and Edwards (10)). In an EOR application study (Polzien et al (6)), the IPH plant size chosen was 5.4 MW_t. This plant consisted of 72 concentrators, each having a diameter of 12 meters. The transport medium/process interface of this EOR application is greatly simplified by using saturated steam as the transport as well as the process medium. The vapor pressure of the 275°C (527°F) saturated steam is low enough so that schedule 40 carbon steel pipes can be used.

Petroleum refining appears to be another promising solar IPH application for reasons similar to the EOR application. In the crude distillation tower, a large amount of solar-derived steam could be introduced to heat the crude oil to 290°-350°C (550°-660°F) and to suppress its boiling point through the reduction of its partial pressure (McKetta and Hoffman (12)).

A system study (Sommerlad et al (11)) addressed the incorporation of a 43 MW_t solar IPH (solar fraction 21%) system into a new refinery design for the Provident Energy Co. at Mobile, Arizona. For petroleum refineries whose IPH requirements range between 10-30 MW_t at temperatures between 370°-540°C (700°-1000°F), the annual process heat consumption is close to 10^{18} Joules (10^{15} BTU), which is quite sizable (Iannucci (13)). However, the constancy requirement of the process heat supply in the petroleum refinery process is much more stringent than in the EOR application, and further study would have to be made to address this problem more thoroughly.

Another very promising IPH application is the pumping and thermal separation (heat treatment) of oil-bearing emulsion. A particular approach (Liers and Young (9)) involves a package with one 6-meter dish, all skid-mounted for mobility, that would be used in the Mobile Spencer Oil Field at Yukon, Arizona. With some modifications, if need be, this modular emulsion pumping and heater-treater package, which is particularly compatible with remote and rugged terrain, could conceivably be used to displace some of the propane engine pumps throughout the stripper wells in the U.S. The total number of these domestic wells is in the hundreds of thousands. Intrinsically, this application has a very limited energy transport system.

There is an interesting system testing project being pursued by JPL, with Applied Concepts Corp. as the system integrator. This IPH system utilizes a Power Kinetics, Inc. (PKI) Fresnel concentrator to provide process steam at about 4 atm to two autoclaves for curing masonry blocks at the Capitol Concrete Products, Topeka, Kansas. When steam is not needed, as during the weekend or during public holidays, the plant will preheat the boiler feed water for subsequent use. Following a successful performance verification test with a parallel system at Sandia Laboratories, Albuquerque, in October 1981, the IPH system became operational in November 1981. The PKI collector is shown mounted on an elevated platform in Figure 1.

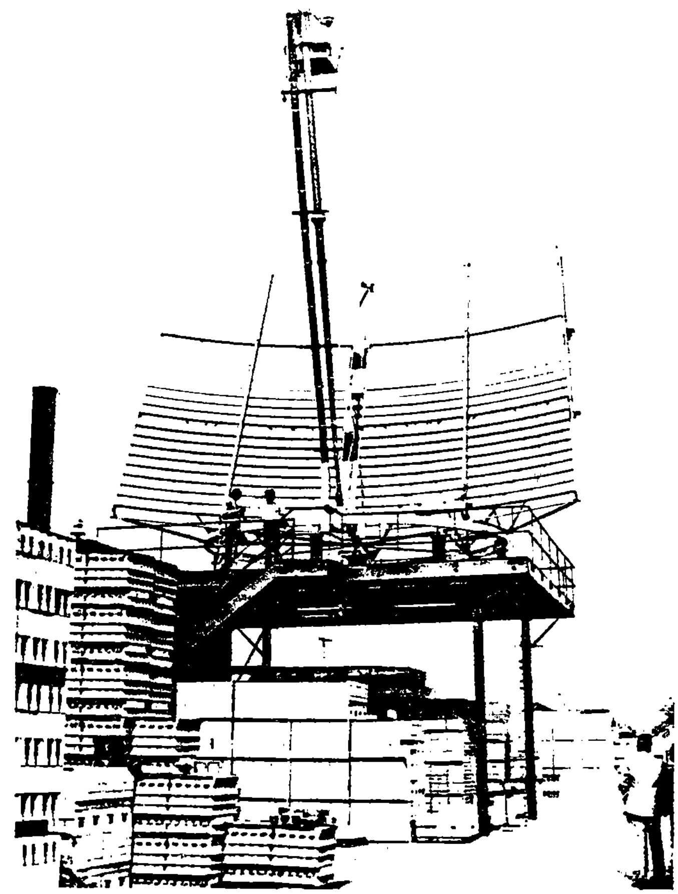

Figure 1. A Power Kinetics, Incorporated (PKI) Collector Installed at Capitol Concrete Products, a Masonry Block Producer in Topeka, Kansas.

All of the IPH applications detailed in Table 1 and the system testing project discussed above involve the introduction of solar-derived heat into existing, mature industrial technologies. There are also some other IPH application concepts being proposed, particularly in regard to chemical production and biomass processing (Gregg et al (14) and Reed (15)). Since these concepts are generally in an earlier stage of technological maturity and appear to have minimum transport system requirements, they are not treated in the present paper. However, it is emphasized that these technically more advanced applications could represent a significant market for solar-derived heat.

Some general considerations that apply to all specific cases can be inferred from the above discussion of various case studies of IPH applications. In each IPH market sector, there are several parameters or factors that are of primary importance for potential penetration by solar thermal energy, whether they are new designs or retrofits. These parameters for each market sector include process temperature, IPH plant size, annual process heat consumption, geographic location, land availability and terrain, plant layout, constancy requirement of the process heat supply, process heat-load characteristics, and the transport medium-process interface, among others. The plant layout, land availability, and terrain are all important parameters for either new designs or retrofits, but they will be even more crucial for solar IPH retrofit. In some cases, these restrictive factors might impose an upper bound on the IPH solar fraction. These parameters also appear to be so case-specific that they preclude a general quantification.

Excluding these case-specific parameters, a general numerical survey of the U.S. IPH usage distributions in regard to the process temperature, IPH plant size, and the annual process heat consumption has been made; and a comprehensive, quantitative compilation of these data for each industry sector has been published (Iannucci (13)). The overall annual process heat consumption in a particular industrial sector determines the upper bound of the potential solar IPH penetration therein. The process temperature determines the quality of heat supplied and imposes requirements on the concentrator and energy transport system.

In the initial stages of implementation, it is advantageous first to introduce small quantities of solar energy so that system checkout and operation can be accomplished with minimal disruption, risk, and cost. This will allow for further expansion upon obtaining a satisfactory initial return on performance and cost. The likely initial conservatism of the end users and the projected subsequent expansion can be readily accommodated by the parabolic dish system, due to its modularity. This modularity allows expansion by simply adding dish modules and is also advantageous when considering land availability, terrain, and retrofit into existing plant layouts. The dish modules can be located on odd-shaped parcels of land where the primary requirement on the terrain is the avoidance of topological features that block insolation.

COST AND PERFORMANCE OF THERMAL TRANSPORT

In all the solar thermal process heat applications discussed above, the thermal transport system costs and performance play a pivotal role in determining the economic feasibilty of the application. Cost and performance data have been generated for the fluids listed in Table 2. The pipe size and insulation thickness for each pipe segment in the overall network is optimized by means of a Lagrangian multiplier technique to yield a minimum overall pipe network cost. Details of this optimization methodology can be found in other references (Turner (2) Caputo (3) Biddle et al (5)).

TABLE 2

TRANSPORT FLUID PARAMETERS

Fluid	Hot Pipe Supply Fluid Temperature	Cold Pipe Return Fluid Temperature	Operating Pressure (MPa)	Operating Pressure (Psia)	Fluid Cost ($/kg)
Steam/Water	316°C (600°F)	204°C (400°F)	5.5	800	0.02
Therminol T-66	316°C (600°F)	204°C (400°F)	1.0	150	4.16
Steam/Water	510°C (950°F)	288°C (550°F)	10.3	1500	0.02
Draw Salt	510°C (950°F)	288°C (550°F)	1.0	150	0.33

Plant sizes from 3 to 150 MW_t are studied. The 11-meter-diameter dishes were arranged in a rectangular grid pattern with an aspect ratio (N/S to E/W spacing) of 0.71 to reduce annual shading effects. The packing factor of the field is held at a constant value of 0.35 for this study. Previous studies have used dish field layouts in which all dishes were arranged in parallel as shown in Figure 2(a) (Biddle et al (5) and Fujita et al (16)). This current study uses an arrangement shown in Figure 2(b) that has four dishes in series instead of a single dish. The reduced piping length required by this arrangement is reflected in lower costs and lower transport losses.

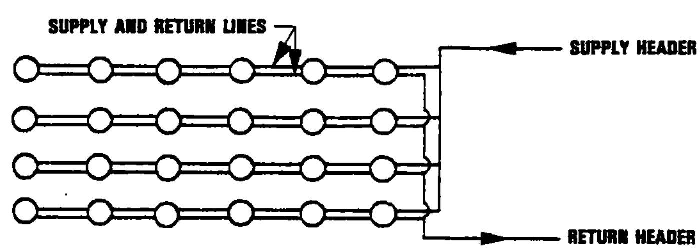

Figure 2(a). Single Dish Arrangement

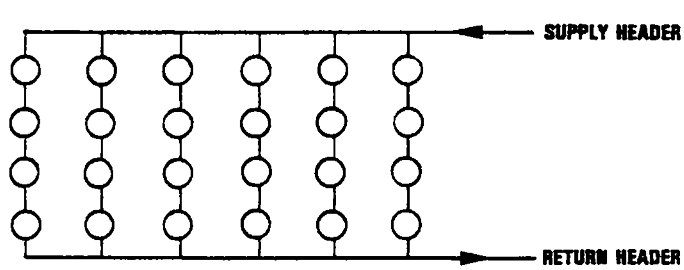

Figure 2(b). Four Dishes in Series

Typical field layouts used for this study are shown in Figures 3(a) and 3(b) for a 3MW_t and a 30 MW_t field respectively. The pipe optimization methodology uses cost models for installed piping and insulation. The installed pipe cost model reflects non-conventional factory assembly techniques, such as the use of automated welding in a factory, mass production environment, prefabricated pipe supports and special weld fittings (Biddle et al (5), Daksla (17)). The installed insulation model also assumes that pipe insulation is installed in a factory wherever possible (Daksla (17)). Using the field layouts and installed pipe and insulation cost models as inputs to the pipe optimization methodology/computer program, minimized direct costs and corresponding pipe sizes and insulation thicknesses for the thermal transport network were obtained.

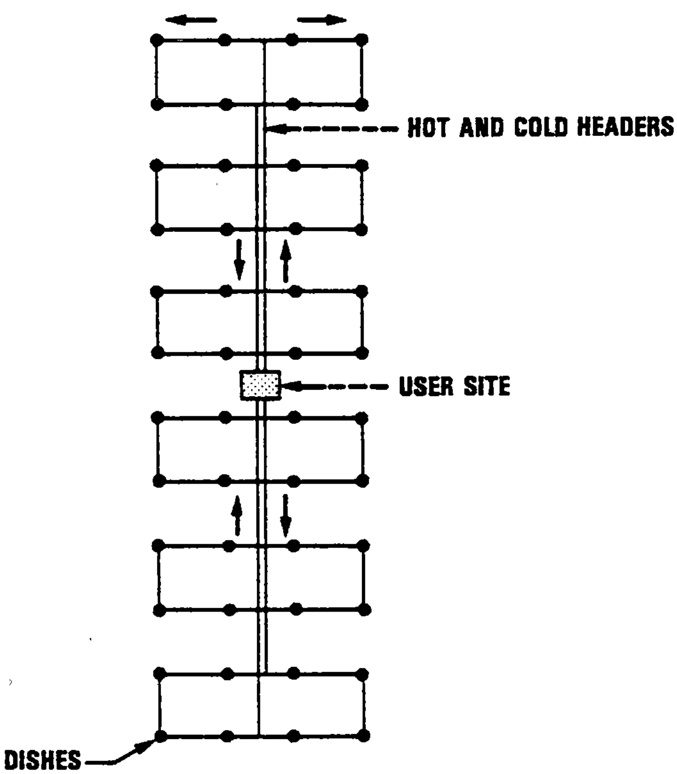

Figure 3(a). 3 MW_t Dish Field Layout, 4 Dishes in Series

The minimized direct cost includes the installed pipe cost, the installed insulation cost, and the cost of the fluid required to fill the pipe network. The chosen pipe sizes are the commercially available sizes closest to the theoretical optimums. The direct cost does not include the insulated pipe going from the field up to the dish receiver and returning to the field (riser/downcomer piping). This is because the

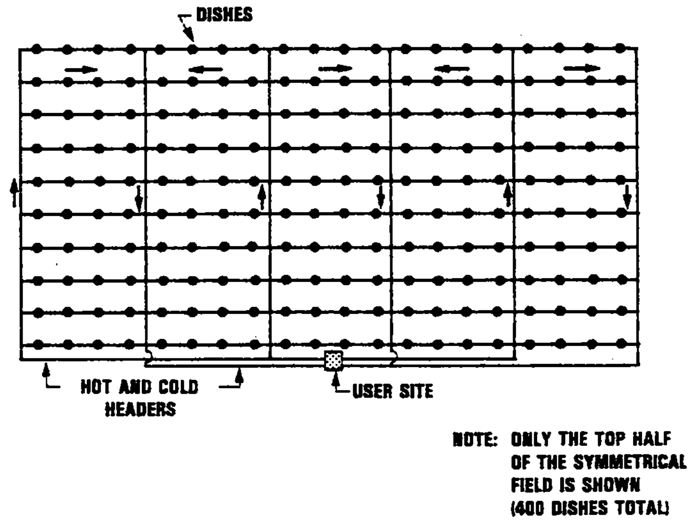

Figure 3(b). 30 MW_t Dish Field Layout, 4 Dishes in Series

riser/downcomer piping will be mass produced as an integral part of the dish assembly and will be costed separately with the dish.

The direct costs for the four transport fluids are shown in Figure 4 as a function of thermal transport capacity or plant size. For all fluids, these results show that direct cost is not a strong function of plant size. For medium temperature steam and Therminol, the direct cost increases by about 20% as the plant size increases from 3 to 150 MW_t. It can also be seen that 316°C steam and Therminol have very similar costs over the range of plant sizes from 3 to 150 MW_t. At the 510°C temperature level, the draw salt gives consistently lower

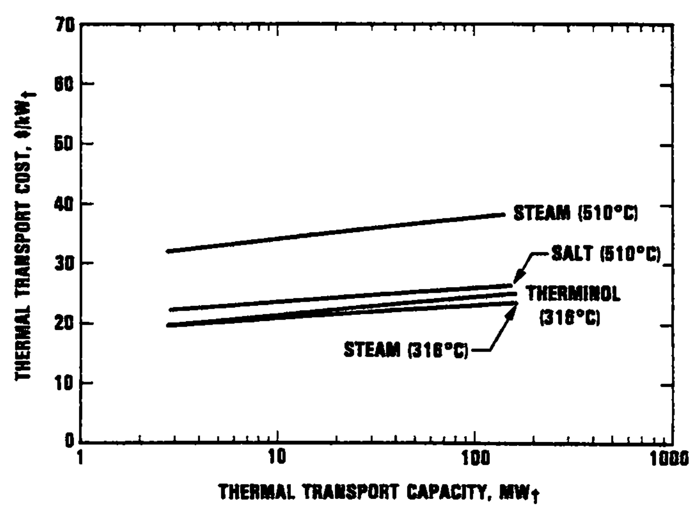

Figure 4. Transport System Cost Comparison of Different Transport Fluids

direct costs than the 510°C steam. This is due in part to the fact that the high pressure/high temperature steam requires schedule 80 pipe, while the lower-pressure draw salt only needs schedule 40 pipe; and in part to the fact that the steam transport requires a larger diameter pipe.

Transport losses of the optimized transport network are shown in Figure 5 for all fluids. The transport losses include both thermal and pumping losses from the network. Steam and Therminol at 316°C have approximately the same transport loss over the full range of plant sizes examined. Steam and draw salt at 510°C exhibit 70% and 60% higher losses respectively than the 316°C fluids over the range of plant sizes covered.

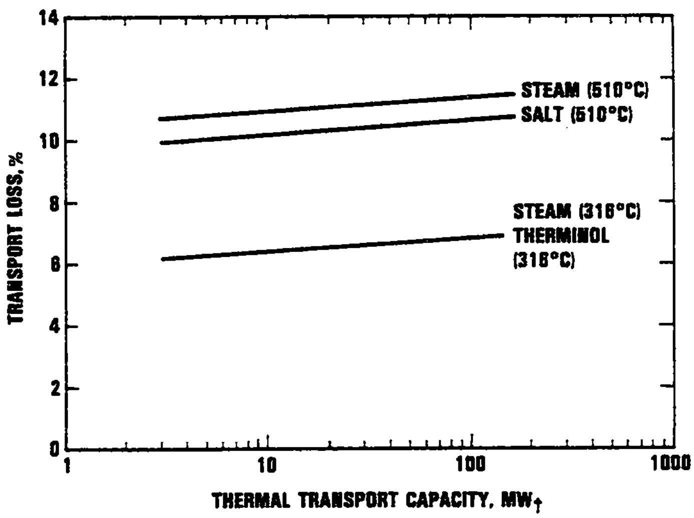

Figure 5. Transport System Loss Comparison of Different Transport Fluids

Results for both direct costs and transport losses for 4 dishes in series as presented in this paper can be compared to the results for single-dish layouts from a previous paper (Fujita et al (16)). The trends for both cases are very similar, but the four-dish-in-series arrangement reduces transport direct costs by approximately 15% over the plant size range of 3 to 150 MW_t for both steam and oil at 316°C and by about 25% for steam and draw salt at 510°C. The transport loss (including both pumping and thermal loss) shows a decrease of approximately 15% for the arrangement with four dishes in series when compared to the single-dish configuration (Fujita et al (16)).

The control strategy for four dishes in series appears to offer advantages. Because control valves are relatively expensive, use of a single-control valve for a cluster of dishes is usually the more cost-effective arrangement. The optimal number of dishes to be controlled by a single valve depends on site-specific requirements, such as the desired reliability of energy from the solar system. For the series arrangement, a temperature sensor can be located downstream of the last dish in series, while the control valve is located in the coolest line upstream of the first dish. In the event that any dish in the series string fails to function properly, the temperature output from the series string will tend to drop. The sensor will signal the control valve to decrease the flow rate through the string and thereby maintain the desired temperature. Thus, for the series arrangement, it will not be necessary to shut down the entire string in the event of a single dish malfunction. Note that there is no danger of over-heating because the sensor is subjected to the highest temperature in the string.

SYSTEM CHARACTERISTICS AND ENERGY COSTS

In the previous section, a set of thermal transport piping networks that cover the temperature and size range of the selected applications (Table 1) was characterized in terms of cost and performance. In this section, this key transport subsystem is combined with other parabolic dish components to form a set of IPH supply systems that can meet the selected applications. The energy costs associated with these parabolic dish IPH supply systems are then determined and compared with the conventional alternative of using petroleum-based fuels.

The major subsystems/components in costing a parabolic dish IPH system are the concentrator, receiver, thermal transport, and balance-of-plant (BOP). The BOP category includes items such as site preparation, plant controls, and indirect costs that include architect and engineering fees as well as construction management fees. Except for thermal transport, which is based on series-piping arrangements presented in this paper, the cost of the dish IPH plant is determined by using component costs development in an earlier study directed toward dish electric plants (Rosenberg and Revere (18)).

Capital costs for four parabolic dish IPH plants corresponding to the four transport systems of the previous section are presented in Figure 6. A breakdown of costs is shown so that the relative contribution

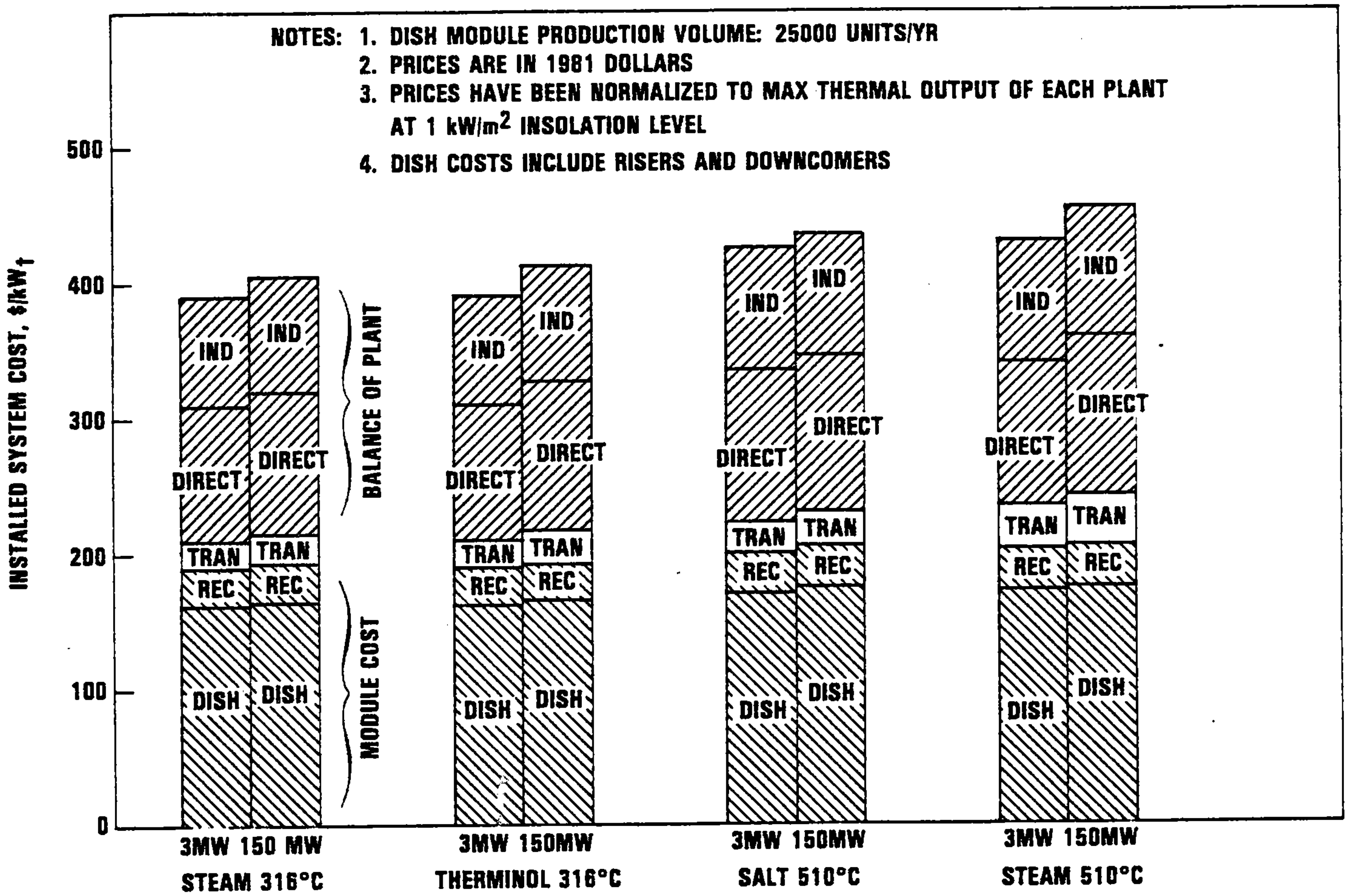

Figure 6. Installed System Cost for Parabolic Dish IPH Plants

of major costs items can be discerned. The module, consisting of the dish concentrator and receiver along with risers and downcomers, and the BOP items are the two large contributors of comparable magnitude whose sum comprises the bulk of the cost. The transport system costs are nominally ≤ 10% of the total system capital costs. These relatively small transport costs are predicated on use of efficient series piping layouts and the implementation of automated factory fabrication and semi-automated field assembly as described in the previous section.

A comparison of capital costs normalized to rated plant output power as presented in Figure 6 reflects efficiency variations as well as cost differences among the systems. For a given rated output, a less efficient system will require a greater number of modules and an associated increase in thermal transport piping requirements. This will result in higher normalized capital costs. Because higher temperature systems that employ draw salt or steam at 510°C have higher receiver and transport losses, they generally have higher unit capital costs as compared to the more efficient lower-temperature systems of 316°C. This trend is evident in Figure 6.

Comparisons from Figure 6 indicate that steam has a slight cost advantage compared to Therminol at 316°C. This results mainly from the added cost of spill ditches in the BOP category for Therminol. For the higher temperature 510°C systems, spill ditch costs are also added to the BOP category for molten draw salt. Even with these added costs, the smaller pipe sizes for molten salt as compared to those for steam provide a slight advantage. Generally, the differences among the optional systems are not large. Thus, it is expected that site-specific considerations would play a major role in selection of the most appropriate system.

The dish module costs in Figure 6 are based on a nominal production volume of 25,000 units/year, which is considered to be appropriate for the 1990 plant startup date considered in the present study. This production volume is the baseline used in the earlier study (Rosenberg and Revere, (18)) from which component costs for this paper are derived. The component costs used were $123/m^2$ for the dish concentrator (including risers and downcomers) and $21/m^2$ for the receiver. There costs represent values which were updated to reflect 1981 base year dollars as used herein.

Capital costs are dependent on production volume as shown in Figure 7. If a production volume of only 5000 units/year were achieved instead of the baseline of 25,000 units/year, capital costs normalized to plant output power would increase by about 20%. If a high market penetration corresponding to 100,000 units/year were achieved, the normalized costs would decrease by approximately 10%. As seen from Figure 7, module (dish plus receiver) costs are quite sensitive to production volume, whereas BOP costs are relatively insensitive. The indirect costs, which are in the BOP category, are primarily responsible for variations in BOP costs. These indirect costs are usually estimated as a fixed percent of total costs and therefore reflect variations in module costs with changes in level of production volume.

Energy costs for the four parabolic dish IPH systems are presented in Figure 8 as a function of module production volume. Each system is represented by a strip whose lower and upper bounds correspond to a 3 MW_t and a 150 MW_t plant size, respectively. If economically justified, it is anticipated that a primary use for solar IPH systems will be the displacement of petroleum-based fuels, which are subject to volatile price escalations. Thus, energy costs corresponding to petroleum-based fuels as represented by #2 Diesel oil are presented on Figure 8 for comparison with the solar IPH systems. The fuel escalation rates used in this study were assumed to be constant from the 1980

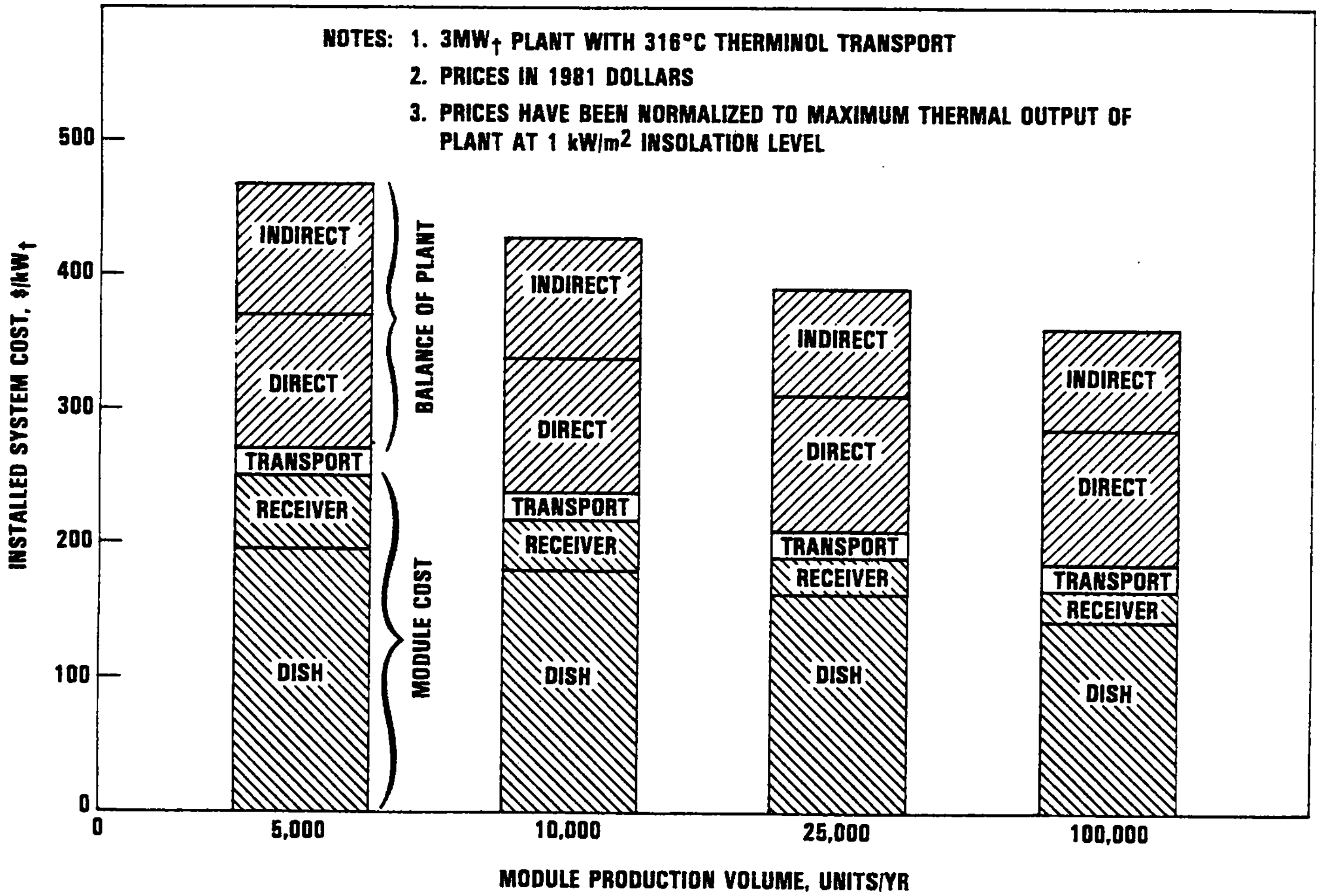

Figure 7. Effects of Production Volume on Installed System Costs for Parabolic Dish IPH Plants

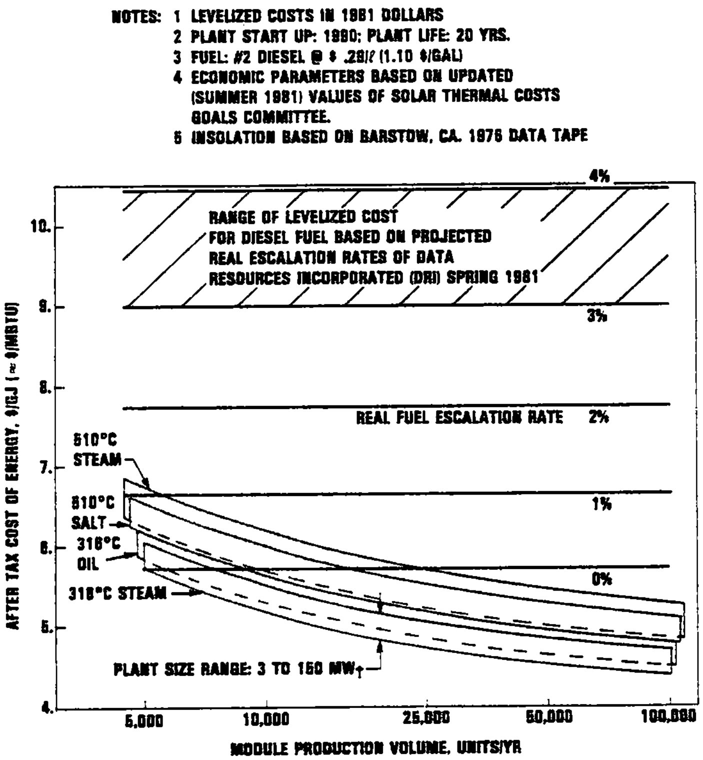

Figure 8. Energy Cost Comparison of Solar Parabolic Dish IPH Plants With Petroleum-Based Fuels

base year. According to econometric projections (Data Resources Inc. (19)), real fuel escalation rates (i.e., escalation over and above inflation) are expected to be in the range of 3% to 4%. As shown in Figure 8, levelized fuel energy costs in this projected range of real escalations is approximately twice that of parabolic dish IPH plants. Even if the real fuel escalation rate is zero, solar systems generally have lower energy costs for the baseline production volume of 25,000 units/year. Also note that these costs are conservative because they are based on 100% fuel combustion efficiency.

The comparison in Figure 8 is based on locating the solar plant in the Southwest sunbelt region as reflected by use of insolation data for Barstow, CA, which is considered to be representative of the sunbelt. An earlier study (Latta et al (20)) compared solar thermal electric plants in widely different insolations. From this study, it is determined that energy costs for solar IPH plants will be approximately doubled for a plant located in the poor insolation region of the Northeast as compared to the Southwest. With this doubling, Figure 8 shows that solar plants will have comparable energy costs to fossil fuels. This indicates that solar IPH systems are potentially viable options, even in poor insolation regions.

In determining the energy costs on an after-tax basis for solar plants and the conventional alternative of using fossil fuels, standard discounted cash flow procedures that are essentially the same as those adopted by the Solar Thermal Cost Goals Committee have been employed. Economic parameters recommended by the committee are used because they generally conform with economic projections (Data Resources Inc. (19)). It is believed that these recommended values represent reasonable projections within the range of uncertainty. Using their economic parameters, the committee established goals of about 8 to 10 $/GJ (when expressed in 1981 dollars after taxes to a firm in a competitive industry) for solar thermal IPH systems in the 1990 time frame. These costs overlap the projected energy costs for fossil fuels shown in Figure 8.

For the present study, the economic parameters established by the committee were updated to reflect the current, more favorable, depreciation policies. The sum-of-the-years-digits depreciation method is used along with a 5-year tax life, a cost of capital of 20% and a tax credit of 25%. The effective income tax rate is 48%, and "other" taxes and insurance are assumed to be 2% of the present value of the capital investment. The long-term rate of general inflation is 6%, and the escalation rate for capital costs is also taken to be 6%. The escalation rate for operating and maintenance costs is 7%. The plant Operating & Maintenance (O&M) cost in the first year is 2% of the initial capital investment, and the nominal escalation rate for these costs is 7% (i.e., 1% above inflation).

The basic procedure for determining levelized energy costs was established for use in analyzing power plants for electric utility service (Doane et al (21)). Although this procedure was developed to determine the required energy cost that a utility must charge, it can be shown that this procedure is easily adapted to the determination of after-tax energy costs for a solar system owned and operated by an industrial concern that is unable to flow increased energy costs through to consumers. Conversion to an after-tax basis involves multiplication by the factor $(1-\tau)$, where τ is the effective income tax rate.

It is noted that fuel energy costs are computed on an after-tax basis so that solar and fuel options can be compared on a consistent basis. The fuel energy costs are optimistic in the sense that losses encountered in converting fuel to heat have been disregarded. However, some of the solar systems may lose energy in the process of transferring heat to the application, and these application specific losses at the interface with the application are not taken into account. Both the fuel-to-heat losses of the fossil fuel system and the interface losses between the solar system and application are considered to be sufficiently small that overall trends will not be affected.

Additionally, when considering the annual performance of a solar IPH power plant, the daily heat investment required to bring cool components up to operating temperature must be considered. This is particularly important for systems that use thermal piping networks. Using the findings of a previous study (Fujita et al (16)), these losses, which constitute about 3% of the energy passing through the transport network, are taken into consideration when determining the system energy costs shown in Figure 8. Also, blocking and shading losses that correspond to the selected field arrangement and dish spacing are taken into account.

CONCLUSIONS

The primary conclusion is that parabolic dish IPH systems have the potential to economically displace at least a portion of petroleum based fuels that are used in wide-ranging process applications. This is contingent upon successful completion of the technological development activities underway for parabolic dish systems. The size of the potential solar market, which depends strongly on site-specific factors, cannot be estimated without conducting detailed market analysis studies. The potential shown by this study is believed to be sufficient to justify such further studies.

Three key factors support this conclusion. First, in sunbelt regions, dish system levelized energy-costs predicated on successfully accomplishing developmental objectives are lower than levelized energy costs associated with using petroleum-based fuels, even if prices of the fuel stay constant in real terms for the next 30 years. If petroleum based fuels increase in price at a real fuel escalation rate of 3 to 4% (Data Resources Inc. (19)) solar levelized-energy-costs are found to be substantially lower by about a factor of two. With this fuel escalation rate, solar and fuel levelized-energy-costs are found to be comparable even in poor insolation regions.

Second, fuel prices are subject to rapid price escalations that must be considered when comparing the use of petroleum-based fuels with other options. When the costs of the options are comparable, as is the case for the present solar versus fuel comparison, the uncertainty in fuel prices can become a dominant factor that tends to favor the solar option.

Third, the modularity of parabolic dish systems eases implementation. A small number of dish modules can be installed initially and checked out with minimal risks in terms of disruption of plant operations and capital investments. The system size can then be increased by adding modules. Furthermore, modules can be located on odd-shaped parcels of land close to application sites that are at various locations within an industrial plant complex. This is particularly advantageous when considering the retrofitting of existing plants.

An important conclusion is that the employment of efficient series piping networks, along with automated factory fabrication of network components and semi-automated field assembly methods, can potentially reduce transport costs to the point where they constitute a relatively small fraction of system costs (of the order of 10%). Thus, the use of piping network systems is not considered to be an obstacle that would limit wide-scale implementation of modular parabolic dish IPH systems.

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