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A Comparison of the Performance/Economics of Thermochemical and Sensible Energy Transport for Distributed Receiver Solar Thermal Systems

James F. Muir

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A COMPARISON OF THE PERFORMANCE/ECONOMICS OF THERMOCHEMICAL
AND SENSIBLE ENERGY TRANSPORT FOR DISTRIBUTED
RECEIVER SOLAR THERMAL SYSTEMS

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ABSTRACT

A major challenge facing the development of distributed receiver solar systems is the efficient transport of high-temperature thermal energy from the collectors to the point of use. As receiver temperatures increase, conventional sensible energy transport methods become less attractive because of increased heat losses and insulation costs. A promising alternative that is particularly attractive for the high temperatures characteristic of paraboloidal dishes and the extensive piping associated with large collector fields is the concept of thermochemical energy transport. Estimates of the performance and economics of four sensible and two thermochemical transport systems for a dish collector field are compared at four delivery temperatures ranging from 400 to 815°C. The sensible working fluids are Syltherm 800, NaK, Li-Na-K carbonate salt eutectic, and steam. The thermochemical systems are carbon dioxide reforming of methane and dissociation of sulfur trioxide. On the basis of levelized energy cost, there is no clear choice between sensible and thermochemical energy transport at 400°C. At higher output temperatures, thermochemical transport is more cost-effective and is the only viable choice at temperatures above ~700°C. The thermochemical system based on the carbon-dioxide reforming of methane has the best performance and lowest costs at temperatures >400°C and appears closest to meeting the DOE Solar Thermal Technology Program long-term IPH goal of 3 ¢/kWh_{th} (9 \$/MBtu_{th}) LEC.

ACKNOWLEDGEMENT

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SOLAR THERMAL TECHNOLOGY FOREWORD

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

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

The Solar Thermal Technology Program is directing efforts to advance and improve promising system concepts through the research and development of solar thermal materials, components, and subsystems, and the testing and performance evaluation of subsystems and systems. These efforts are carried out through the technical direction of DOE and its network of national laboratories who work with private industry. Together they have established a comprehensive, goal directed program to improve performance and provide technically proven options for eventual incorporation into the nation's energy supply.

To be successful in contributing to an adequate national energy supply at reasonable cost, solar thermal energy must eventually be economically competitive with a variety of other energy sources. Components and system-level performance targets have been developed as quantitative program goals. The performance targets are used in planning research and development activities, measuring progress, assessing alternative technology options, and making optimal component developments. These targets will be pursued vigorously to insure a successful program.

One of the challenges in the program is to develop efficient, economical energy transport systems suitable for high-temperature solar thermal distributed receiver applications. As receiver temperatures increase, conventional sensible energy transport methods become less desirable because of increased heat losses and insulation costs. A

promising alternative that is particularly attractive for the high temperatures characteristic of parabolic dishes and the extensive piping associated with large collector fields is the concept of thermochemical energy transport. It is based on the conversion of energy from thermal to chemical form in the receiver, reduction of stream temperatures to near ambient for transport, and conversion from chemical back to thermal energy at the use point. The principal advantage offered by thermochemical systems is low thermal loss transport at near ambient temperatures. This report compares the performance and economics of representative sensible and thermochemical energy transport systems for a dish solar thermal system operating at high temperatures.

EXECUTIVE SUMMARY

A major challenge facing the development of distributed receiver solar systems is the efficient transport of high-temperature thermal energy from the collectors to the point of use. As receiver temperatures increase, conventional sensible (SEN) energy transport methods become less attractive because of increased heat losses and insulation costs. A promising alternative that is particularly attractive for the high temperatures characteristic of paraboloidal dishes and the extensive piping associated with large collector fields is the concept of thermochemical (TC) energy transport. The principal advantage offered by TC systems is low thermal loss transport at near ambient temperatures.

Performance and cost estimates have been generated for SEN and TC energy transport systems for a collector field consisting of 690 12-m diameter dishes and producing ~ 40 MW_{th} of high-temperature thermal power. Four SEN and two TC energy transport systems are defined to carry energy from the dishes to an end-use point at the edge of the field. The SEN working fluids are an oil, Syltherm 800; a liquid metal, NaK; a molten salt, Li-Na-K carbonate eutectic; and a gas, steam. The TC systems are reversible, catalytic, all-gas chemical reactions: carbon dioxide reforming of methane and dissociation of sulfur trioxide. Thermal energy is delivered at four output temperatures ranging from 400 to 815°C. Four transport systems, the two TC candidates and the two most appropriate SEN systems, are evaluated at each of the four output temperatures.

Concentrator, receiver and transport system performance estimates are based on insolation conditions representative of the Southwest (average annual insolation of 2696 kWh/m²-y), assuming the systems are operating 10 h/d for 311 d/y. Concentrator efficiency is assumed the same, 85%, for all systems and operating conditions, while receiver efficiency varies from 76 to 96% as a function of receiver temperature. Transport system performance is determined by estimating thermal losses both while the system is operating and during nighttime and shutdown periods.

Installed capital costs of components common to all systems, concentrators, sensible type receiver elements (housing, insulation, heat exchanger, and supports), and balance of plant, since they do not affect relative comparisons among the SEN and TC transport systems, are assumed to be the values cited as long-term goals for IPH in the U.S. Department of Energy National Solar Thermal Technology Program: Five Year Research and Development Plan, 1985-1989. Transport system capital costs, however, are estimated in considerable detail using a "bottoms-up" methodology and assuming that many large solar thermal dish systems have been constructed and operated. These are combined with estimates of annual energy output, using accepted methodology for comparing energy production alternatives, to yield levelized energy costs (LECs). These range from approximately 3 to 11 ¢/kWh_{th} depending on the transport system and output temperature.

Within the context of the assumptions and methodology employed in the analysis, the major conclusions are

1. At 400°C, despite some performance and cost differences, the levelized energy costs of the two SEN and two TC transport systems are about the same.
2. At higher output temperatures, TC transport is more cost-effective and is the only viable option at delivery temperatures above ~700°C.
3. The CO₂/CH₄ system has better performance and lower costs than the SO₃ system at all output temperatures.
4. The CO₂/CH₄ TC system is the most cost-effective transport system at all temperatures and appears closest to meeting the STT Program long-term IPH goal of 3 ¢/kWh_{th} (9 \$/MBtu_{th}) levelized energy cost.
5. The steam system exhibits the poorest performance and highest costs of all transport systems at the three highest temperatures. The use of an all gaseous system for high temperature sensible energy transport, therefore, is not cost-effective.

6. The high capital and parasitic costs required to heat trace the carbonate salt system illustrate the severe economic penalty that will be associated with any transport system that needs to be heat traced.

Certain aspects of the SEN and TC transport systems that bear on the comparisons, but are not explicitly included in the analysis, are 1) the effect of the corrosive nature of the carbonate salt and SO_3 fluids on the performance and costs of these systems, 2) the likelihood that the SO_3 system will have to be heat traced (to $\sim 65^\circ\text{C}$) to prevent SO_3 condensation, 3) the effects of side reactions in the CO_2/CH_4 system that have the potential for water and carbon generation, 4) the likelihood that off-design (low insolation) operation will cause a much greater reduction in the performance of SEN transport systems than in that of TC systems because increased thermal losses in the former, as a result of lower flow rates, consume an even greater fraction of the absorbed energy than in design operation, and 5) the potential of TC transport systems for more rapid start-up each morning since nighttime thermal losses that need to be made up are much smaller than SEN system losses.

Items 1, 2, 4 and 5 will tend to drive the comparisons further in the directions already evident and reinforce the conclusions cited above. Item 3, on the other hand, could potentially have a detrimental effect on the most promising candidate, the CO_2/CH_4 TC transport system. Consequently, it must be addressed and resolved as part of any program to develop this system further.

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INTRODUCTION

Point focus distributed receiver solar systems utilize paraboloidal dish concentrators with receivers mounted at their focal points. A dish thermal system consists of a field of these collectors in which thermal energy is transported by a working fluid that absorbs energy in the receivers. The fluid then passes through a piping network to a central conversion device where it releases the energy either to a heat engine for electrical power generation or to a heat exchanger for use as industrial process heat. Because of the large energy flux concentrations possible with paraboloidal dishes, they are ideally suited for applications requiring high delivery temperature, $>400^{\circ}\text{C}$.

Potential applications utilizing high temperature thermal energy occur almost exclusively in two areas: electric power generation and industrial process heat (IPH). In 1984, the United States consumed more than 76 quads (80×10^9 GJ) of energy, 87% of which came from fossil fuels (oil, gas and coal), approximately 5% from nuclear plants, and the remaining 8% from renewable sources. Of this total energy consumption, approximately 34% (~26 quads) was used to produce electricity and about 30% (including 36% of the electricity generated) was used by the industrial sector. Roughly half of this industrial consumption (~12 quads) was used for process heat. The remainder was split between end-use losses (~6 quads) and the use of various fuels as feedstocks for the manufacture of non-energy materials (~5 quads)[1].¹

Most of the electricity produced in the U.S. is generated in steam plants using fossil fuels and high speed turbines. Steam Rankine cycle (SRC) turbines currently used by the utility industry range in size from less than one to several hundred MW_e . Standard utility practice limits SRC turbine inlet temperatures to $\sim 400^{\circ}\text{C}$ for the smallest units, $\sim 510^{\circ}\text{C}$ for an 80 MW_e size, and $\sim 565^{\circ}\text{C}$ for the larger turbines. Organic Rankine cycle (ORC) turbines have come into use during the last two decades, but the

1. Numbers in brackets designate references cited in this report.

majority of these operate at turbine inlet temperatures below 320°C because most organic working fluids are not stable above this temperature. One notable exception to this is toluene which, because of its stability at higher temperatures, has enabled ORC units to operate at a peak cycle temperature of 400°C. Combined cycle power plants use a Brayton cycle gas turbine as a topping cycle with a SRC to achieve improved performance through a higher peak cycle temperature. Brayton cycle turbines typically operate at peak temperatures more than 500°C higher than possible with conventional SRC units (upwards of 1100°C)[2]. All of the SRC systems, the toluene ORC, and the combined cycle plants are viable applications for solar thermal dish systems.

The situation for industrial process heat applications is much more complex. Surveys of the industrial consumption of thermal energy [3,4,5] show that there is a great variety of IPH applications. They differ in the type of process, facility size, manner by which heat is delivered to the process (i.e., heat delivery mode), delivery temperature, facility capacity factor, fuel, and fuel cost. Industrial energy consumption as a function of process temperature, facility size, and number of facilities, assuming average plant sizes and 100% capacity factor, is illustrated in Figure 1 [3].

More energy, 67%, is consumed at temperatures above 400°C than below and mostly by facilities of sizes between 30 and 300 MW_{th}. However, because the larger facilities tend to use energy at higher temperatures, energy delivered at temperatures >400°C is consumed by only 20% of the facilities. Further categorization of industrial energy consumption by process, heat delivery mode, and fuel reveals that much of the highest temperature energy, >1100°C, is delivered at temperatures ranging from 1400 to 2200°C and is provided by electric heating [4,5]. Application of solar thermal technology, either as a direct replacement for electric heating or for supplying very high-temperature energy, would require major process modifications and significant advances in solar hardware design [4]. Thus, the most likely IPH applications for solar thermal dish systems

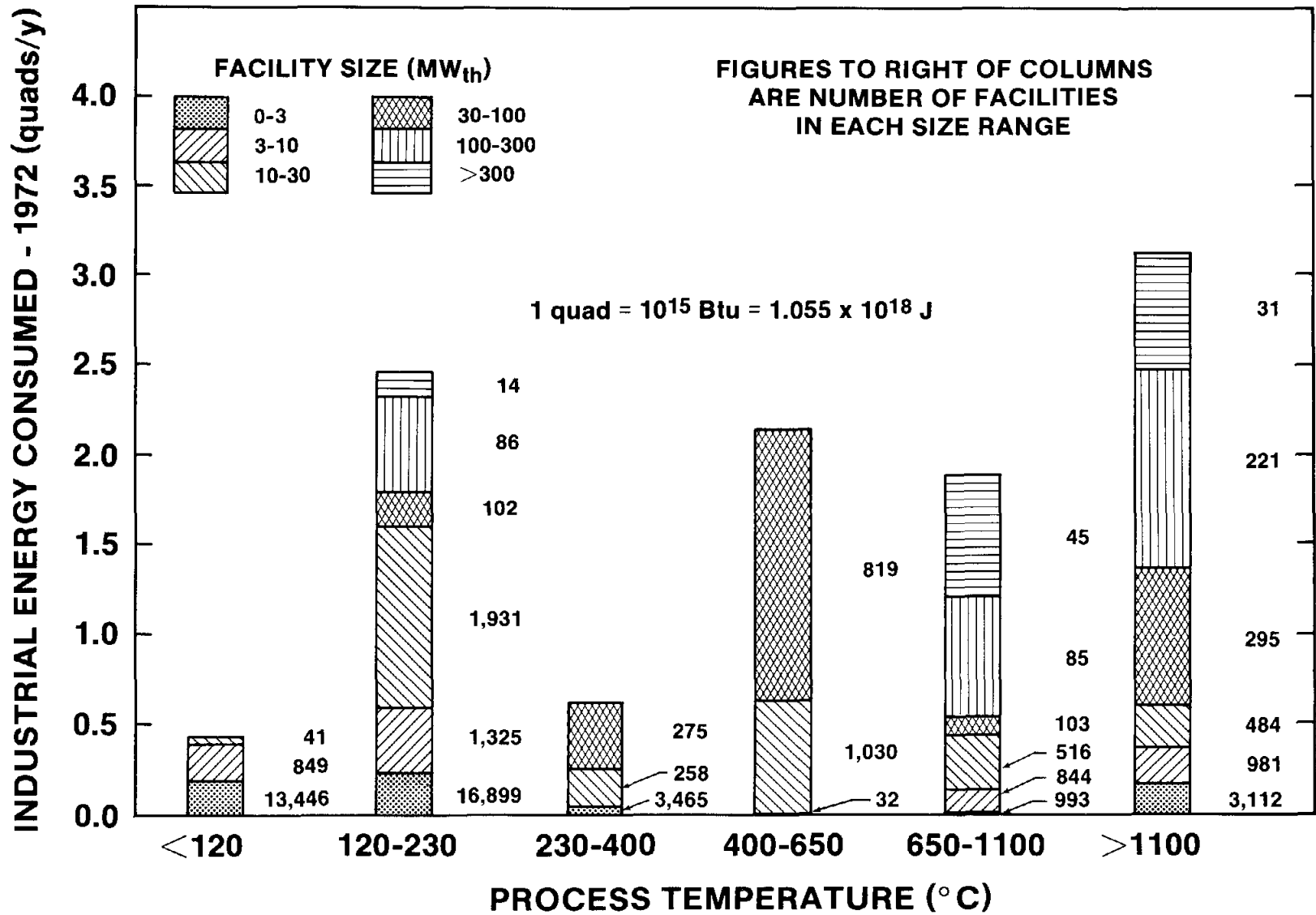


Figure 1 - Industrial energy consumption in 1972 [3].

are those industries requiring process heat in the 400 to 1100°C temperature range. These industries use about 38% of the total IPH energy consumption (e.g., ~4 1/2 of the 12 quads used in 1984).

The extent to which solar thermal dish systems will actually be applied in these areas hinges on the costs of solar produced energy becoming competitive with conventionally generated energy costs. Thus, the marketplace will make the final decisions as to what technology will be used, and when and where it will be applied. The value of solar thermal-generated electricity and IPH, therefore, is determined by the cost of electricity and IPH produced from conventional fuels and equipment.

The cost of electricity from conventional fossil and nuclear power plants varies with the fuel (coal, oil, gas, nuclear), the type of plant (baseload, intermediate-load, peaking), and plant location and ownership (utility and grid characteristics). Lower-bound estimates of the future cost of electricity, based on intermediate-load coal-fired power plants, are presented by the U.S. Department of Energy in its National Solar Thermal Technology Program: Five Year Research and Development Plan 1986-1990 [6]. For a capacity factor range of 0.4 to 0.5, the levelized energy cost (LEC) varies from approximately 5 to 8 ¢/kWh_e.

IPH energy costs are a function of all of the parameters cited above. Future IPH costs from conventional technologies have been estimated by Brown et al. [5] for 17 combinations of fuel (coal, oil, gas, and electricity), heat delivery mode (boiler, combustion furnace, and electric furnace), and delivery temperature (~120-2200°C). Levelized energy costs were computed using 1984 dollars levelized in real terms and based on a 1995 plant start-up and an annual capacity factor of 0.5. For the baseline designs having temperatures in the 400-1100°C range, the LECs vary from roughly 2 to 5 ¢/kWh_{th}.

The efficient transport of high-temperature thermal energy represents a major technical challenge that must be overcome if dish thermal systems are to be cost-effective. Conventional SEN energy transport suffers several disadvantages with regard to high temperature applications: 1) Since the

extensive piping network required must operate at high temperatures, all pipes, valves, etc. must be well insulated. 2) Special piping materials (e.g. stainless steels, Inconel) will be needed to handle the more exotic high temperature working fluids such as liquid metals and molten salts. 3) In some cases it will be necessary to heat-trace the piping to prevent solidification of the working fluid during periods of nonoperation. 4) Operating heat losses can be quite large resulting in significant reductions in delivered energy. 5) Nonoperating heat losses occurring overnight and during shutdowns can also be large, and the lost energy must be replaced as the system is brought up to operating temperatures upon start-up.

TC energy transport is a promising alternative for low-loss energy transport for dish thermal systems. It is based on the conversion of energy from thermal to chemical form for transport and then back to thermal energy at the use point. This is accomplished through the use of reversible chemical reactions: 1) to convert thermal energy absorbed in endothermic reactors located in the receivers to chemical form for transport, and 2) to convert this back to thermal energy in an exothermic reactor in the central conversion unit. Recuperators between the supply and return lines at each end of the system (adjacent to the reactors) utilize the sensible energy in the products to heat the reactants, minimizing sensible energy losses from the system and reducing the stream temperatures to near ambient for transport. The characteristic of near-ambient stream temperatures is the principal advantage offered by TC transport. It results in minimal transport heat losses and, because little or no insulation is required, reduced piping costs. A further consequence is that transport system efficiency is essentially independent of system size or transport distance [7].

This report compares the performance and economics of representative sensible and thermochemical energy transport systems for a dish solar thermal system operating at high temperatures. The analysis focuses more on providing meaningful relative comparisons among the systems studied than on absolute evaluations vis-a-vis other energy production systems or delivered energy costs.

BACKGROUND

The transport of thermal energy as sensible heat is an old and proven technology. Common heat transfer fluids include liquids (water, oils) for low and medium temperature applications, and gases (steam, He) for medium and high temperatures. Higher energy density fluids currently being explored for use at high temperatures include liquid metals (Na, NaK and Li), molten salt mixtures (alkali nitrates and carbonates), and particle seeded liquids and gases. Equipment to utilize these fluids for solar applications is under development.

Thermochemical energy transport, on the other hand, is a relatively new concept. Two of the earliest applications of the technology involved long distance transport of high temperature energy from nuclear reactors. The West German project, Nukleare Fernenergie (NFE), based on the steam reforming of methane followed by methanation of the syngas, operated the EVA/ADAM pilot plant successfully in closed-loop mode for several years [8]. A screening study of high temperature energy transport options by Oak Ridge National Laboratory evaluated three types of sensible fluids (organics, liquid metals, and molten salts) and six thermochemical systems. Performance/economics comparisons of three of these, 2 SEN (steam and a molten nitrate/nitrite salt) and one TC (steam/methane reforming/methanation), revealed that for the operating conditions selected, the H₂O/CH₄ TC transport system was the least expensive for distances greater than about 32 km [9].

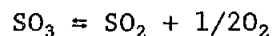
Interest in thermochemical energy transport and storage for central and distributed receiver solar systems prompted a number of investigations beginning in the mid 1970s. These included screening studies of reversible chemical reactions to identify viable candidates for solar applications [10,11], receiver/ reactor design studies [12,13], and performance and cost analyses of storage and transport systems employing specific chemical reactions [14-18]. Several of the TC transport performance/cost analyses

are reviewed by Schredder [18] and Fox [19], and a recent comprehensive review of the literature pertinent to the use of TC energy transport in solar energy systems has been prepared by Fish [7].

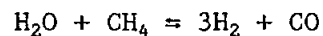
Chemical reactions suitable for solar TC transport applications should have as many of the following characteristics as possible: 1) complete reversibility, 2) catalytic in both directions to insure that reactions will occur only in the reactors and not in the recuperators or pipelines, 3) no side reactions in either direction, 4) constituents all gaseous at ambient temperature and system pressure (i.e., no condensibles) to avoid the need for insulation and heat-tracing of the piping system, 5) high energy density, 6) non-toxic, non-corrosive constituents, and 7) low-cost chemicals [7].

The reaction screening studies identified four reactions as suitable candidates for solar applications:

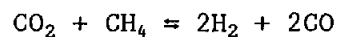
1. sulfur trioxide dissociation:



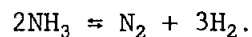
2. steam reforming of methane:



3. carbon-dioxide reforming of methane:



4. ammonia dissociation:



The characteristics, advantages, and disadvantages of these reactions are discussed in detail by Fox [19] and Fish [7].

Performance and cost estimates from two studies comparing SEN and TC transport [14,15] and three analyses of TC transport systems only [16-18], are summarized in Tables 1 and 2. The systems vary in size from 1 to 454 MW_{th} (thermal power output), and output temperatures range from 315 to

Table 1 - Sensible Energy Transport*

Investigator	System	Working Fluid	Thermal Output		Concentrator	Receiver/HX	Piping Network	Transport System**		Combined Collection & Transport System***		O&M	Levelized Energy Cost (LEC)***	
			Energy (MW _t)	Temp. (°C)	No.	Cost (\$/m ²)	Cost (\$/m ²)	Cost (\$/m ²)	Efficiency (%)	Cost (\$/m ² , \$/kW _t)	Efficiency (%)	Cost (\$/kW _t)	Cost (\$/m ² - y)	Cost (¢/kWh _t)
Caputo (14) 1975 \$	150 MW _e 11 m Dishes, 95 m ²	Hot Water	454	315	8686	134.3	5.9	28.7	92	28,752.2	69	307	—	—
		Steam/Water	377	430	[7659] ^a	134.3	7.8	34.2	90	34,266.0	66	340	—	—
		NaK He	380 419	540 540	[8365] ^a 10,000	134.3 134.3	10.9 18.1	90.6 85.5	85 71	90,619.0 85,519.4	59 50	493 540	— —	— —
Nix (15) ^b	1 MW _t 11 m Dishes	Steam	1	400	[25] ^a	115	11	—	—	—	—	799	109	19
		Draw Salt (NaNO ₃ :KNO ₃ 60:40, wt)	1	400	[25] ^a	115	11	—	—	—	82	1677	122	27

* No storage. Costs include installation.

** Transport system is piping network only. Collector includes concentrator and receiver.

*** No BOP costs included.

\$/m² Based on total concentrator area.

\$/kW_t Based on thermal output (delivered energy) from transport system.

— Items not reported in reference.

[] Quantities estimated by author.

^a Estimates based on efficiencies and power levels given in reference.

^b Some component costs based on estimates in 1978 \$, basis for others not given.

Table 2 - Thermochemical Energy Transport*

Investigator	System	Chemical System	Thermal Output		Concentrator	Receiver/Endo. Reactor/ Recuperator			Piping Network	Exo. Reactor/ Recuperator	Transport system**		Combined Collection & Transport System***	
			Energy (MW _t)	Temp. (°C)		No.	Cost (\$/m ²)	Cost (\$/m ²)			Cost (\$/m ²)	Cost (\$/m ²)	Efficiency (%)	Cost (\$/m ² , \$/kW _t)
Caputo (14) 1975 \$	150 MW _e 11 m Dishes 95 m ²	H ₂ O/CH ₄ ^a	376	540	7580	134.3	20.1 ^b	17.4	2.9 ^c	98	40,477.4 ^d	65	335	
Williams (16) 1974 \$	10 MW _e 11 m Dishes	H ₂ O/CH ₄ SO ₃ ^e NH ₃ ^f CH ₃ OH ^g	27.8 27.8 27.8 27.8	— — — —	512 512 512 512	— — — —	— — — —	11.3 ^h 10.9 11.1 11.0	— — — —	— — — —	11.3,19.7 ^h 10.9,19.0 11.1,19.5 11.0,19.3	— — — —	— — — —	
Smith (17) 1980 \$	10 MW _e 11 m Dishes	SO ₃	27.7	527	720	—	38 ⁱ	86	31 ⁱ	77	180,444 ^k	—	—	
Nix (15) ^l	1 MW _t 11 m Dishes	CO ₂ /CH ₄ ^m SO ₃	1 1	400 400	[25] ⁿ [25]	115 115	21 21	— —	— —	— —	— —	79.6 85.0	1680 5803	
Schredder (18) 1980 \$	30 MW _t [11 m Dishes]	SO ₃ - L ^o SO ₃ - H ^o H ₂ O/CH ₄ CO ₂ /CH ₄	30 30 30 30	427 621 427 427	[668] ^p [730] [668] [707]	— — — —	22 ^q 28 24 22	— — — —	11 ^q 13 12 12	95 93 96 92	75,159 ^{q,r} 92,212 83,175 76,171	— — — —	— — — —	

* No storage. Costs include installation.

** Transport system includes piping plus endothermic and exothermic reactors and recuperators.

*** No BOP costs included.

\$/m² Based on total concentrator area.

\$/kW_t Based on thermal output (delivered energy) from transport system.

— These items not included in reference.

[] These items estimated by author.

^a Steam reforming of methane.

^b Includes 17.2 \$/m² for the receiver/reactor plus 2.9 \$/m² for catalyst. No recuperator cost given.

^c Cost of catalyst only. No recuperator or reactor costs given.

^d Includes everything but concentrator.

^e Dissociation of sulfur trioxide.

^f Dissociation of ammonia.

^g Dissociation of methanol: CH₃OH ↔ CO + 2H₂.

^h From minimum in δ = 0.6 curves of \$/kW_t vs. pressure. Installed pipe cost plus running cost of pumping power required.

ⁱ Average of range (20-55) given in reference.

^j Staged exo. reactor with intercoolers plus recuperator.

^k Includes 25 \$/m² for compressor.

^l Some component costs based on estimates in 1978 \$, basis for others not given. O&M and LEC values for these two systems are: CO₂/CH₄: 133 (\$/m² - y) and 28 (¢/kW_t); SO₃: 244 (\$/m² - y) and 70 (¢/kW_t).

^m Carbon dioxide reforming of methane.

ⁿ Estimates based on efficiencies and power levels given in ref.

^o SO₃ - L: "Low-temperature SO₃ - SO₂ system," SO₃ - H: "High-temperature SO₃ - SO₂ system."

^p Estimates based on assuming 11 m dishes which provide 50 kW_t per dish to supply solar energy input, Q, to systems.

^q Costs based on use of metal components. Avg. values used when range given in ref. Use of advanced ceramic components estimated to reduce costs by factors of 2.5-5.

^r Total installed costs do not include organic Rankine heat recovery equipment reported in ref.

621°C. Unfortunately, there are significant differences in the performance and cost assumptions and methodologies employed and in the amount of detail presented in the various references. Consequently, comparisons of the results from different studies are difficult to interpret and of questionable value. Nevertheless, the results do serve to illustrate that estimated costs can vary over a wide range, particularly for TC transport, and that further study is needed to evaluate the cost-effectiveness of TC transport for solar applications. A comparison of the SEN and TC results from the two studies that treated both systems indicate the following:

1. At an output temperature of 400°C, SEN transport costs range from about the same to much less than those of TC transport, and CO_2/CH_4 is more cost-effective than SO_3 [15].
2. At 540°C, TC transport using $\text{H}_2\text{O}/\text{CH}_4$ is more efficient and less expensive than SEN transport using either NaK or He [14].

TRANSPORT SYSTEMS

System Definition

The present analysis assumes a collector field of 690 12-m diameter dishes with the end use point located at the edge of the field as shown in Figure 2. The dish spacing and piping layout are based on those employed at the Solar Total Energy Project (STEP) at Shenandoah, Georgia [20]. Thermal energy is delivered to the user at one of four output temperatures: 400, 540, 675, and 815°C. The power output for a direct normal insolation of 867 W/m² ranges from approximately 34 to 47 MW_{th} depending on the output temperature and transport fluid. Two TC and two SEN energy transport systems are evaluated at each output temperature as indicated in Table 3. The TC systems considered are carbon dioxide reforming of methane, CO₂/CH₄ (CH₄), and dissociation of sulfur trioxide, SO₃ (SO₃). The SEN working fluids include an oil, Syltherm 800 (SYL), a liquid metal, NaK (NAK), a molten salt, Li-Na-K carbonate eutectic (CS), and an all-gas system, steam (STM).

Table 3 - Transport Systems

	<u>Output Temperature - T_o (°C)</u>			
	<u>400</u>	<u>540</u>	<u>675</u>	<u>815</u>
Thermochemical:	CH ₄	CH ₄	CH ₄	CH ₄
	SO ₃	SO ₃	SO ₃	SO ₃
Sensible:	SYL	STM	STM	STM
	NAK	NAK	NAK	CS

Operating pressures are assumed to be near ambient for SYL, NAK, and CS, 54.4 atm for STM, 20 atm for CH₄, and 5 atm for SO₃.

The collector and transport systems for both SEN and TC energy transport are shown schematically in Figure 3. The collectors are assumed to include the concentrator and a cavity receiver that, for the SEN systems, contains a conventional heat exchanger (HX). The TC receivers,

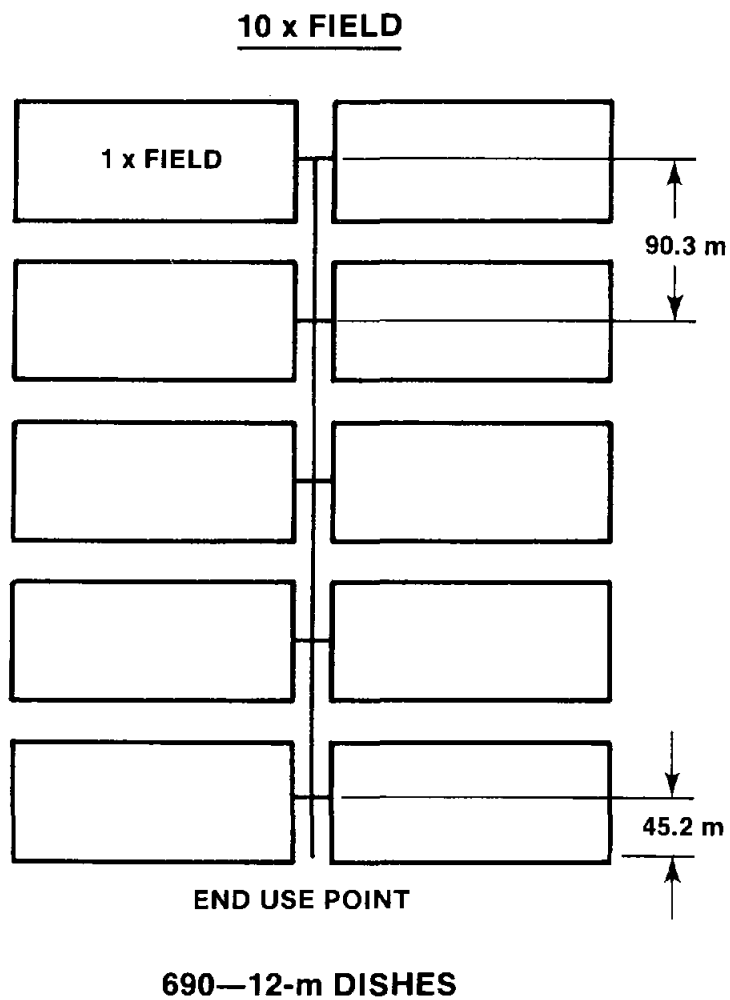
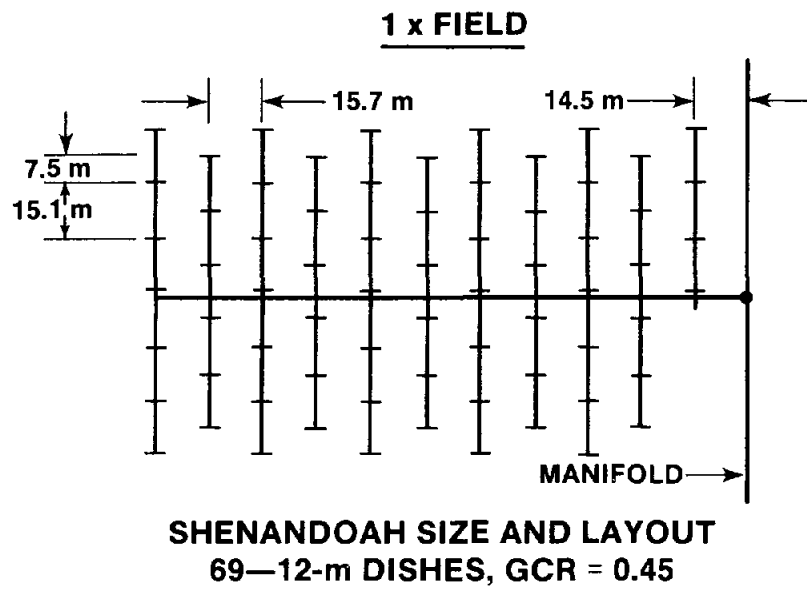
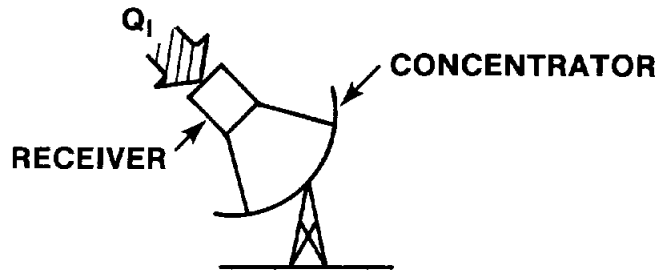


Figure 2 - Collector field layout.

COLLECTOR



TRANSPORT SYSTEMS

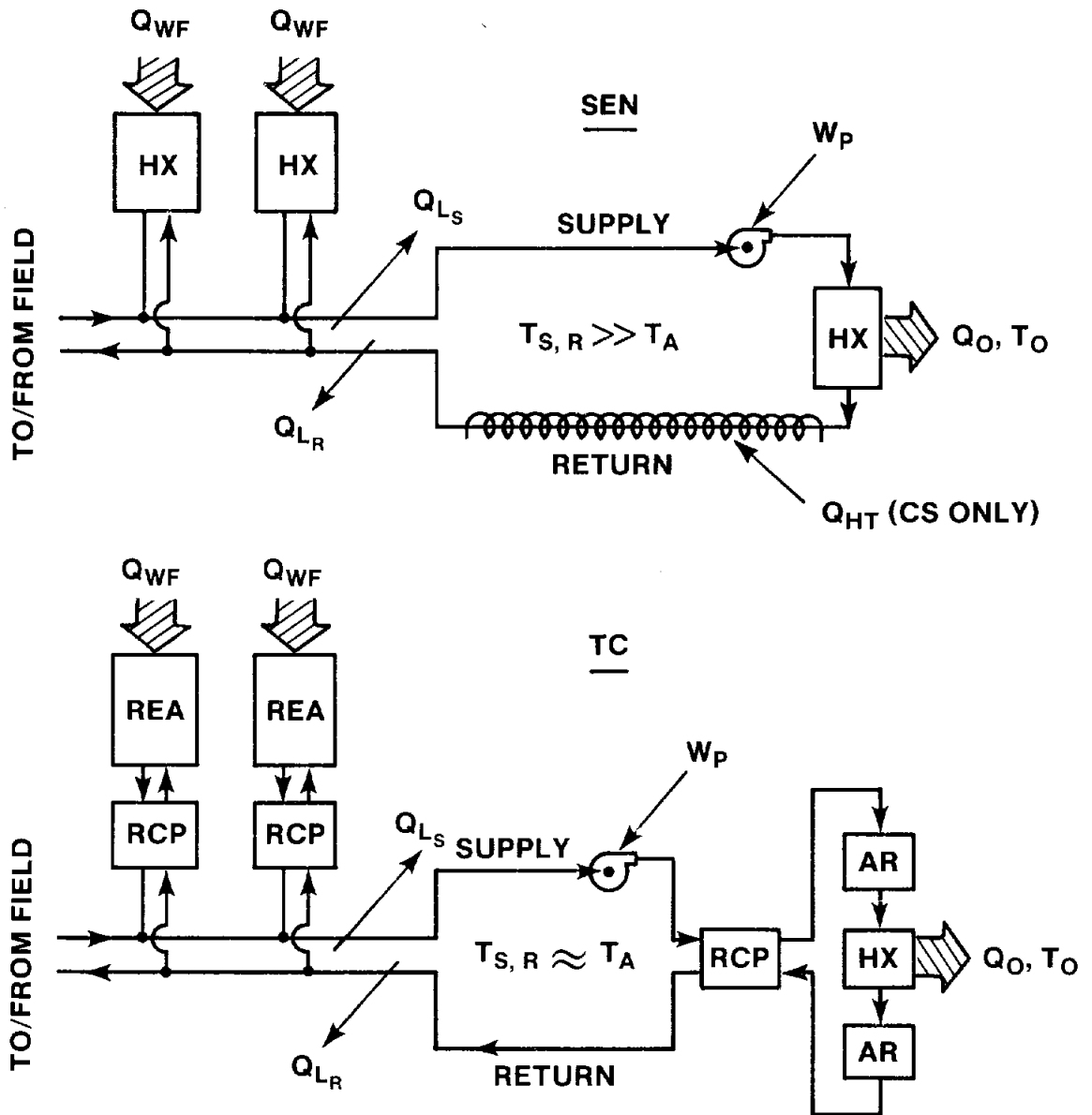


Figure 3 - Collector/transport system schematics.

however, contain an endothermic reactor (REA) and a recuperator (RCP) between the reactant and product streams. The receiver housing, insulation, supports, etc., are considered to be part of the collector, while the reactor and recuperator are included in the transport system.

The transport systems consist of all piping (including risers and downcomers), insulation, pumps or blowers, valves, controls, the working fluid, and conversion equipment at the use point. The CS system also includes heat tracing, which is required to prevent freezing of the carbonate salt eutectic overnight and during shutdowns. For SEN transport, the conversion equipment consists of a conventional heat exchanger, but for TC transport, it includes a recuperator and an exothermic reactor (shown schematically as a staged unit consisting of adiabatic reactors (AR) with intercoolers (HX)). The other major difference between the two transport concepts is that the pipeline temperatures will be much higher than ambient for the SEN systems but close to ambient temperature for the TC systems. Thus, insulation is required on the SEN pipelines but not on the TC lines, to keep piping heat losses (Q_{L_S} and Q_{L_R} for the supply and return lines, respectively) to reasonable levels.

Pipe Network Optimization

The extensive piping network required for a distributed receiver solar thermal system represents a significant fraction of the cost of the transport system, especially for SEN energy transport. Optimization of such networks is essential for efficient, economical transport of high temperature thermal energy. Caputo [14] used an optimization scheme based on first minimizing installed pipe costs (subject to the constraint of constant pumping power) and then minimizing insulation costs to achieve an acceptable heat loss. Williams [16] used a similar procedure for minimizing installed pipe costs but subject to the constraint that the total pressure drop be constant. Barnhart [21] developed a model for determining the optimum combinations of pipe diameter and insulation thickness that minimize the network annualized system-resultant cost.

Hostetler and Iannucci [22], on the other hand, present a methodology involving a coupled optimization of pipe diameter and insulation thickness that minimizes the overall solar system levelized energy cost.

The present analysis utilizes a network optimization scheme that selects pipe diameters and insulation thicknesses based on minimizing pipeline heat losses and pump work [23]. The model treats both daytime steady-state operating heat losses and nighttime transient losses. The optimum insulation thickness for each pipe size is determined first by minimizing the sum of the heat losses and an energy cost of installed insulation. The latter is determined by relating the volumetric cost of insulation to the value of thermal energy, including the time-value of money. The optimum pipe/insulation size is then chosen by minimizing the daily heat and pumping losses. A comparison of this energy loss minimization procedure with the ETRANS cost minimization model developed by Barnhart [21] indicates that it yields similar pipe sizes and total field losses and slightly greater insulation volume (~20%) for a representative dish field piping network [24].

All piping networks are insulated except that for the CH₄ TC transport system. In all cases, the flow velocities, pressure drops, and insulation amounts determined by the optimization model were checked against accepted design practice and experience gained at the STEP facility, Shenandoah, Georgia. When necessary, pipe diameters and insulation thicknesses were adjusted accordingly.

PERFORMANCE ANALYSIS

Operating Conditions

Insolation assumptions are based on representative conditions for the Southwest. The daily average direct normal insolation, \bar{I}_{dn} , is assumed to be 867 W/m². System down periods due to low insolation were estimated using the daily direct normal solar radiation data for Albuquerque, New Mexico, for the years 1957 and 1958 [25]. The numbers of one, two, and three-day periods during which the insolation did not exceed 3 kWh/m² were 18, 11, and 2, respectively (averaged over the 2 years). Added to these were shutdowns for maintenance of two 1- and 3-day periods per year, making a total of 54 d/y (5650 h/y including overnights) during which the system is assumed to be shutdown. This leaves a total of 311 days per year during which the system is considered to be operating 10 h/d. Multiplying by \bar{I}_{dn} yields an annual average insolation of 2696 kWh/m²-y.

Performance Estimates

Based on the assumed value of \bar{I}_{dn} , a 12-m dish intercepts solar energy at a rate of 98 kW. The corresponding rate for the whole collector field is

$$Q_I = \bar{I}_{dn} A_{CON} N_{CON} = 67.7 \text{ MW.} \quad (1)$$

The energy absorbed by the transport system working fluid in the receiver, Q_{WF} , is lower as a result of concentrator and receiver losses, Q_{LCON} and Q_{LREC} , while the thermal output delivered at the use point, Q_o , is further reduced by the transport system losses, Q_{LTRN} .

Concentrator performance was estimated by assuming a representative value for the concentrator efficiency,

$$\eta_{\text{CON}} = Q_{\text{REC}}/Q_{\text{I}} = (Q_{\text{I}} - Q_{\text{LCON}})/Q_{\text{I}} = 85\% \quad (2)$$

The thermal loss from the receiver, Q_{LREC} , is the sum of the conductive, convective and radiative losses. Receiver efficiency,

$$\eta_{\text{REC}} = Q_{\text{WF}}/Q_{\text{REC}} = (Q_{\text{REC}} - Q_{\text{LREC}})/Q_{\text{REC}}, \quad (3)$$

therefore, is strongly dependent on the receiver aperture area, A_{REC} , and cavity temperature, T_{REC} , but is only weakly dependent on ambient temperature, T_{A} , especially for high receiver temperatures.

A concentration ratio ($\text{CR} = A_{\text{CON}}/A_{\text{REC}}$) of 1500 is assumed and receiver temperatures for the SEN systems, as determined from the piping network analyses, are 427, 565, 704, and 871°C at output temperatures of 400, 540, 675, and 815°C, respectively. The TC receiver temperatures are assumed equal to the endothermic reaction temperatures. The latter are defined to be relatively high in order to achieve a high degree of energy conversion in the TC systems with the constraint that the exothermic temperatures are determined by the delivery temperatures (in the present analysis they are assumed equal to the four delivery temperatures). A larger endothermic-exothermic temperature difference means a greater difference between the extents of reaction at the two ends and hence more energy transported per pass of the gas mixture through the system. The endothermic reaction temperatures are 927°C for $T_{\text{o}} = 400$ & 540°C and 1127°C for $T_{\text{o}} = 675$ and 815°C. The resulting receiver efficiencies, shown in Figure 4, illustrate the performance penalty experienced by the TC receivers as a result of these higher temperatures.

Thermal losses from the transport system occur mainly from the piping network because of the large volume of working fluid contained therein and the large surface area available for heat transfer. The SEN heat

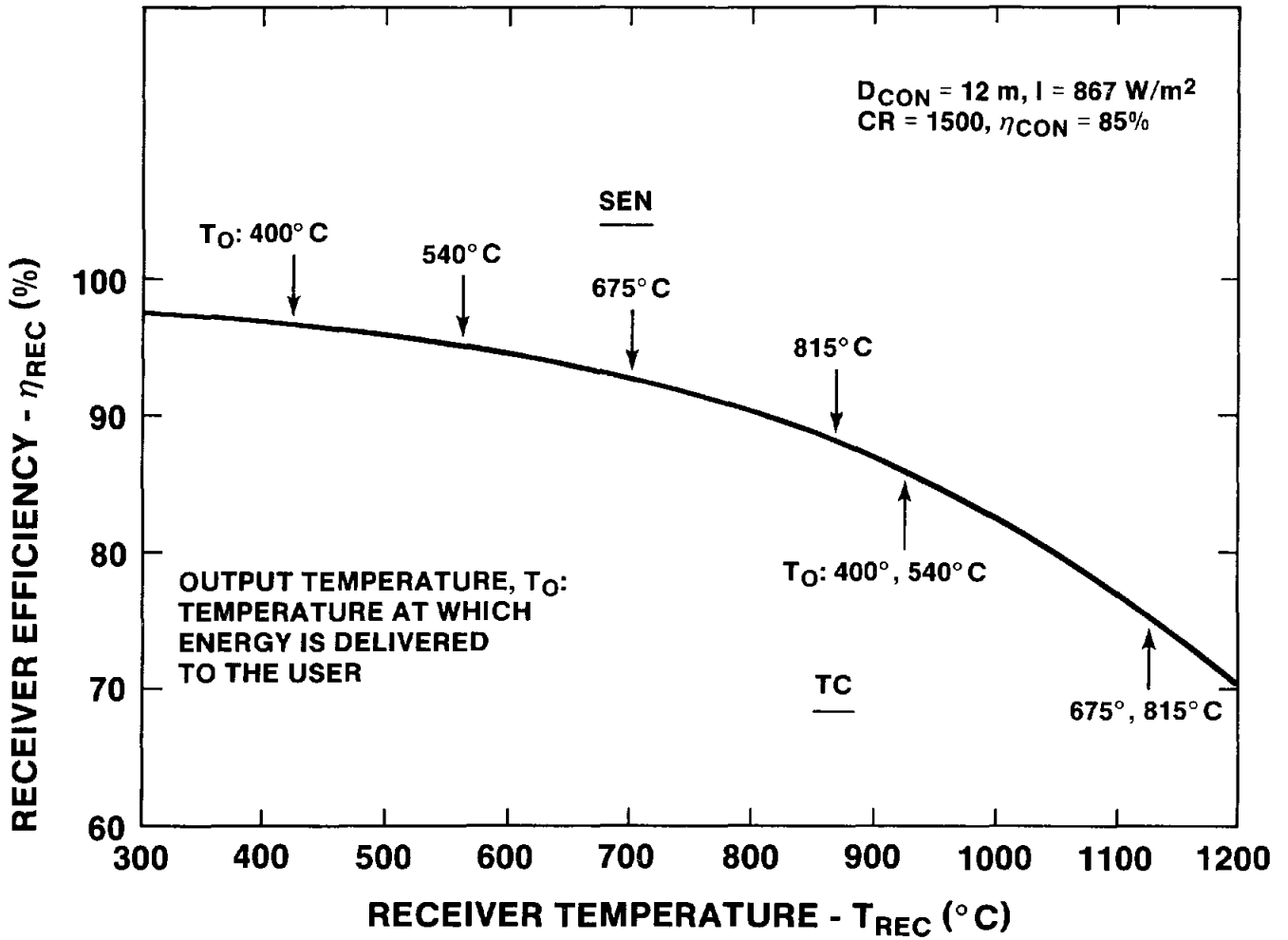


Figure 4 - Receiver efficiency.

exchangers and TC reactor/recuperator units in the receivers and the SEN and TC components at the use point are assumed to be well enough insulated that their losses are negligible relative to the piping losses.

The total transport system thermal loss, $Q_{L_{TRN}}$, is the sum of the daytime operating losses, Q_{L_S} and Q_{L_R} , and the transient shutdown losses, Q_{L_N} (nighttime and other shutdowns). Estimates of these losses for the SEN transport systems were based on results from the piping network optimization calculations [23]. Daytime operating losses, computed using a steady-state pipe heat transfer model, were increased by factors of approximately 2 and 1 1/2, for the supply and return lines respectively, to account for approximations made in the model and for actual losses encountered in real operating systems (e.g., through pipe supports and valves). Multiplying by the operating time per year gives the annual operating losses for the SEN transport systems.

Fluid temperatures at the receiver inlet and outlet for the SEN systems were determined using these steady-state heat loss rates and assuming: 1) the fluid enters the use point HX at the specified output temperature, and 2) its temperature drops 139°C in passing through the HX. The resulting temperature rise across the receiver, ΔT_{REC} , together with Q_{WF} and fluid properties, determined the SEN working fluid flow rates.

Transient shutdown losses for the SEN systems were estimated using a simple lumped thermal capacitance model applied to each pipe segment independently. The working fluid was assumed to be stagnant with an initially uniform temperature equal to the average of the supply and return line temperatures. The pipe wall and a portion of the insulation (based on energy content) were assumed to have the same temperature as the fluid and make up the lumped thermal capacitance [23]. Once again, to account for experience with operating systems in the field, the thermal conductances used in the transient loss estimates were taken as twice the computed values, effectively doubling the heat loss rates. Estimates were made for shutdown periods of 14, 38, 62, and 86 hours, corresponding to overnight

and overnight plus 1, 2, and 3 days, respectively. The results were summed first over all pipe segments in the network for each shutdown and then over the number of all shutdown periods per year to obtain the total annual transient heat loss.

Transient losses for the CS sensible system, which employs heat tracing to maintain a temperature of at least 400°C during shutdowns, were determined by either the length of the shutdown period (as above for the other SEN systems) or the time required for the average temperature to fall to 400°C, whichever occurred first. Heat lost from 400°C to ambient during shutdowns defines the heat trace energy required, Q_{HT} , which is treated as a parasitic loss.

Operating losses for the TC transport systems were estimated with the aid of an initial version of the CLEA single-loop, TC transport steady-state performance model [7]. The model assumes equilibrium chemistry and provides energy and mass flows and state properties around the system. The minimum temperature difference between the streams in the recuperators is assumed to be 25°C. As the gases flow through the piping network, their temperatures are assumed to decrease to ambient (25°C) in the CH₄ system and to 121°C in the SO₃ system. The latter is achieved by insulating the SO₃ network and is necessary to prevent condensation of SO₃ in the lines. The TC steady state operating losses, therefore, are simply the decreases in sensible energy that occur as the gas mixtures, which enter the pipelines from the recuperators at temperatures ranging from 50-134°C for CH₄ and 146-178°C for SO₃, cool to the values given above as they pass through the network. Multiplying by 3110 hours of operation per year gives the annual operating losses for the TC systems.

Transient shutdown losses differed considerably between the two TC systems. Since the CH₄ pipelines are uninsulated and the gases leave the recuperators at lower temperatures, it is assumed that the small amounts of sensible energy involved are lost soon after the gases enter the lines. Gas temperatures in the lines, therefore, are assumed close to ambient throughout a large portion of the network. Consequently, the transient losses are negligible for the CH₄ system. The SO₃ shutdown losses, on the

other hand, are estimated in the same manner as those for the SEN systems. The simple lumped thermal capacitance transient model is applied for each shutdown period using doubled thermal conductances and assuming the initial average gas temperature to be 121°C. Summing over the number of shutdown periods per year gives the annual transient heat loss.

Parasitic losses considered are pump work, W_p , for all systems and heat trace energy, Q_{HT} , for the CS SEN transport system. Estimates of annual pump work are based on pressure drops calculated using the Colebrook relation for friction factor (as a function of Reynolds number, pipe diameter, and surface roughness - assuming $\epsilon = 46 \mu\text{m}$ for new commercial steel pipe) [26]. The incompressible and compressible steady flow work relations were used where applicable, assuming a pump efficiency of 60% and an annual operating time of 3110 h. The annual heat trace energy required for the CS system is calculated using the steady-state heat loss model for a constant fluid temperature of 400°C, using doubled thermal conductances, summing over pipe segments, and multiplying by the total shutdown time per year (5650 h).

Estimated values of the various performance parameters described above (and used in the calculations) are tabulated in Appendix A for all systems and operating conditions.

Performance Results

The relative magnitudes of the concentrator, receiver, and transport system annual losses, and the resulting overall system annual output energies, are illustrated in Figure 5 for the various systems and delivery temperatures. At 400°C the total losses for all four systems are about the same, but the distributions among the components are different. The TC system losses are dominated by the collector losses (due in part to the higher receiver temperatures) while the collector and transport losses for the SEN systems are about the same. As output temperature increases, the total SEN losses increase more rapidly than the TC losses and become dominated by the transport losses. The output energies, Q_o , show

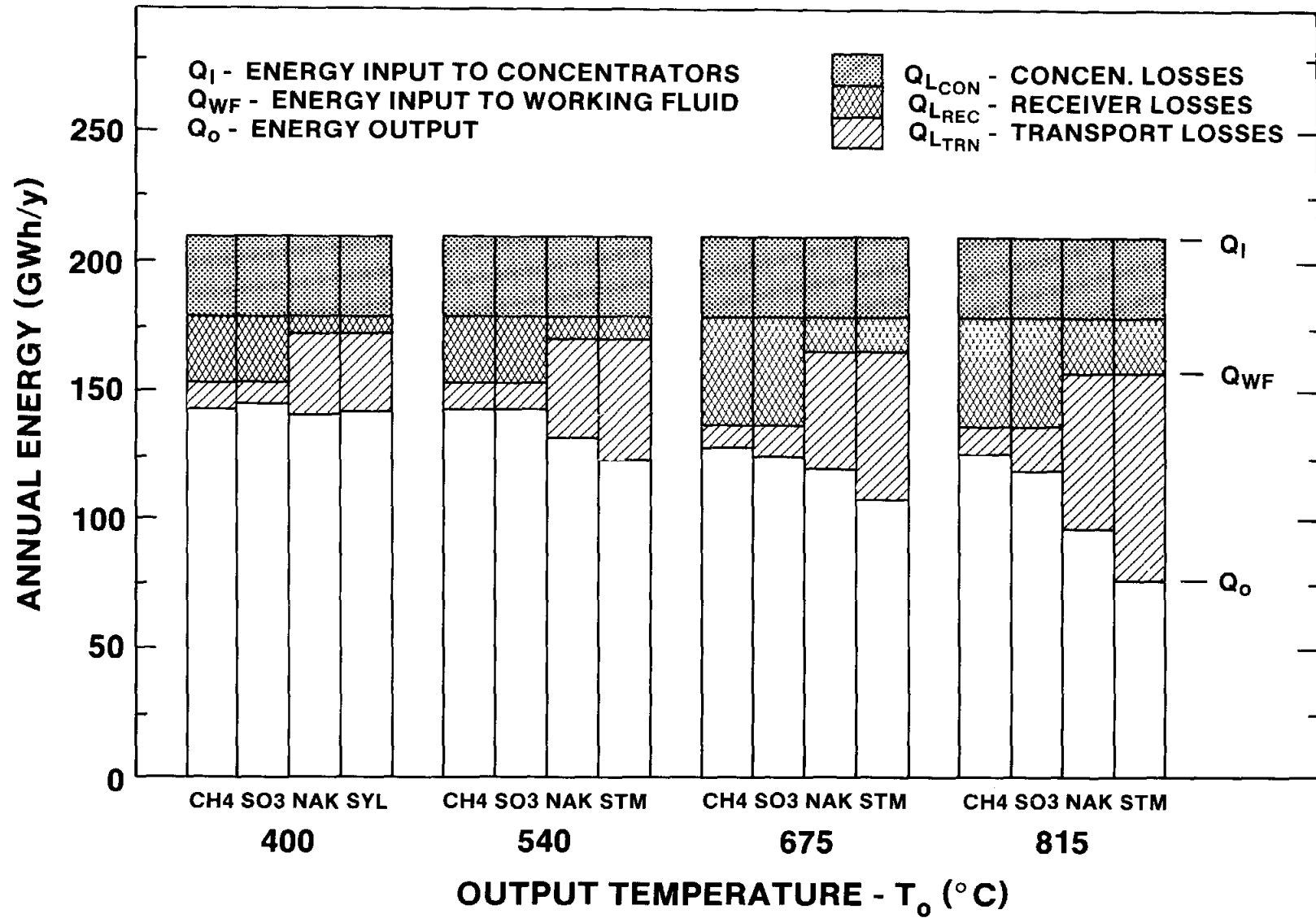


Figure 5 - Annual energy input, component thermal losses, and overall system output.

corresponding decreases as T_o increases, with the SEN transport values becoming significantly less than those for TC transport. The SEN transport losses are much greater than the TC transport losses, by factors of from about 3 at 400°C to roughly 5 at higher temperatures. Above 400°C, the CH4 TC system exhibits the lowest losses (transport and overall) and hence the highest output of all systems considered.

The performance of the transport systems can be measured in terms of a first law efficiency defined as [7]

$$\eta_{\text{TRN}} = \frac{Q_{\text{WF}} - Q_{\text{L,TRN}} - r(W_{\text{P}} + Q_{\text{HT}})}{Q_{\text{WF}}} \quad (4)$$

Parasitic energy for pumping and heat tracing is treated as a thermal loss. Since this energy is assumed to be supplied electrically, its thermal energy equivalence is $r(W_{\text{P}} + Q_{\text{HT}})$ where r , the thermal-to-electric energy ratio, is assumed to be 3. Annual efficiencies based on this definition are presented in Figure 6.

An examination of these efficiencies yields the following observations:

1. The CH4 TC energy transport system has the highest efficiency at all output temperatures by a margin that increases with output temperature.
2. By comparison, the performance of the S03 TC system is rather poor - its efficiency ranges from 18 to 37 percentage points below that of the CH4 system. This is due primarily to the much lower energy conversion in the endothermic reactor (by a factor of 3.5 - 4.4) that necessitates higher flow rates and causes the S03 pump work to be 6-7 times that for CH4.
3. The NAK liquid metal system exhibits the best performance of the SEN systems at 540 and 675°C (it is comparable to Syltherm at 400°C), and its efficiency is from 3 to 7 percentage points higher than that of the S03 TC system.

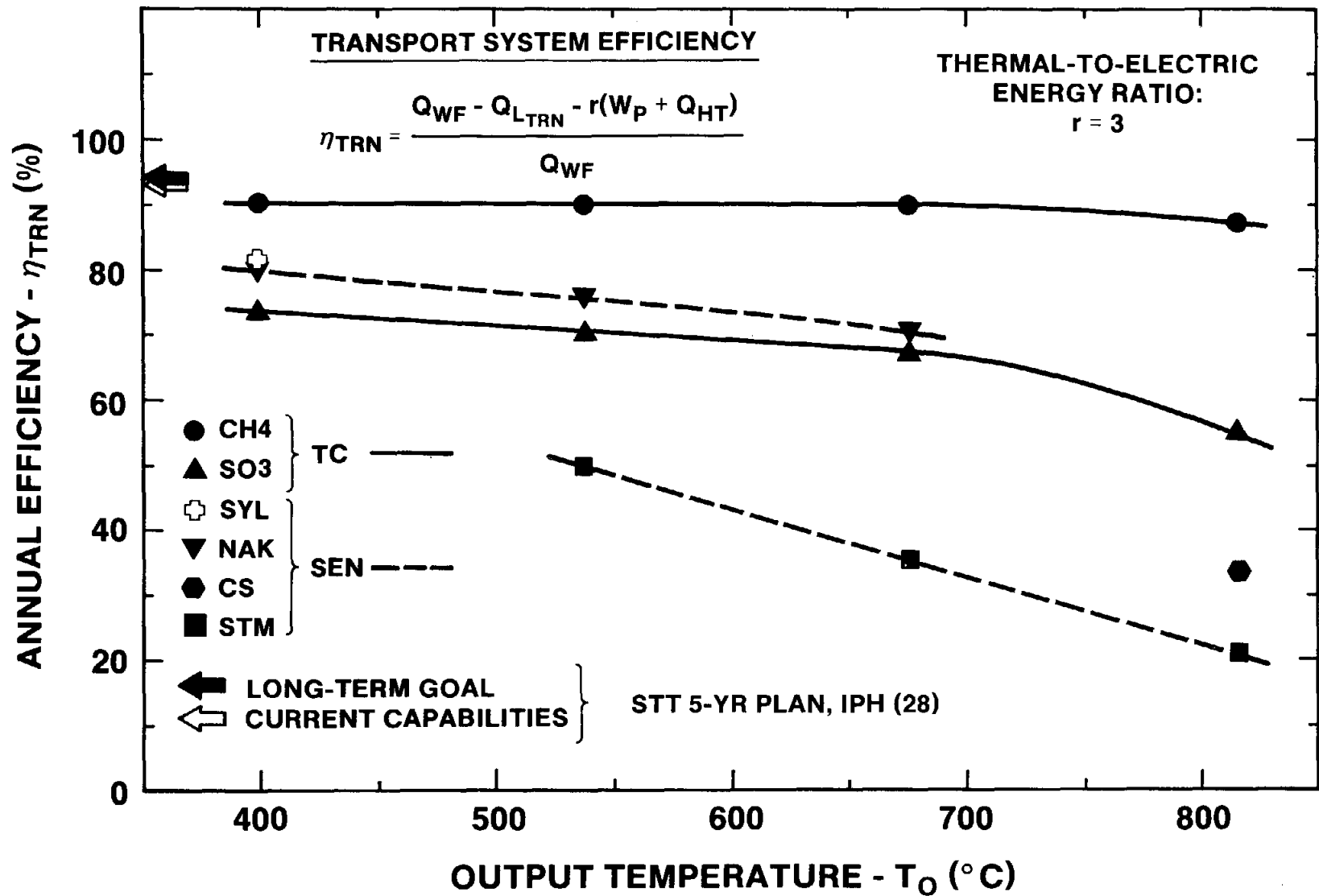


Figure 6 - Annual transport system efficiency.

4. The performance of the steam system, the poorest of all by far, clearly illustrates the futility of using an all gaseous system for high temperature SEN energy transport. This is primarily a consequence of the very high volume flow rates and the attendant high pump work required. The latter is 11 and 14 times that for the NAK system at 540 and 675°C, respectively, and over 50 times that for CS at 815°C.

5. The low efficiency of the CS transport system, on the other hand, demonstrates the severe performance penalty incurred when heat tracing is required. The heat trace energy is more than 50 times the pump work for this system.

The performance of the overall collector/transport systems, as measured by their annual efficiencies, defined as

$$\eta_{C/T} = \frac{Q_I - Q_{L_{CON}} - Q_{L_{REC}} - Q_{L_{TRN}} - r(W_P + Q_{HT})}{Q_I}, \quad (5)$$

is shown in Figure 7. The trends exhibited here are generally similar to those of the transport system efficiencies in Figure 6. The most notable difference is the reduction in the TC efficiencies relative to the SEN values as a result of the higher TC receiver temperatures and hence lower receiver efficiencies.

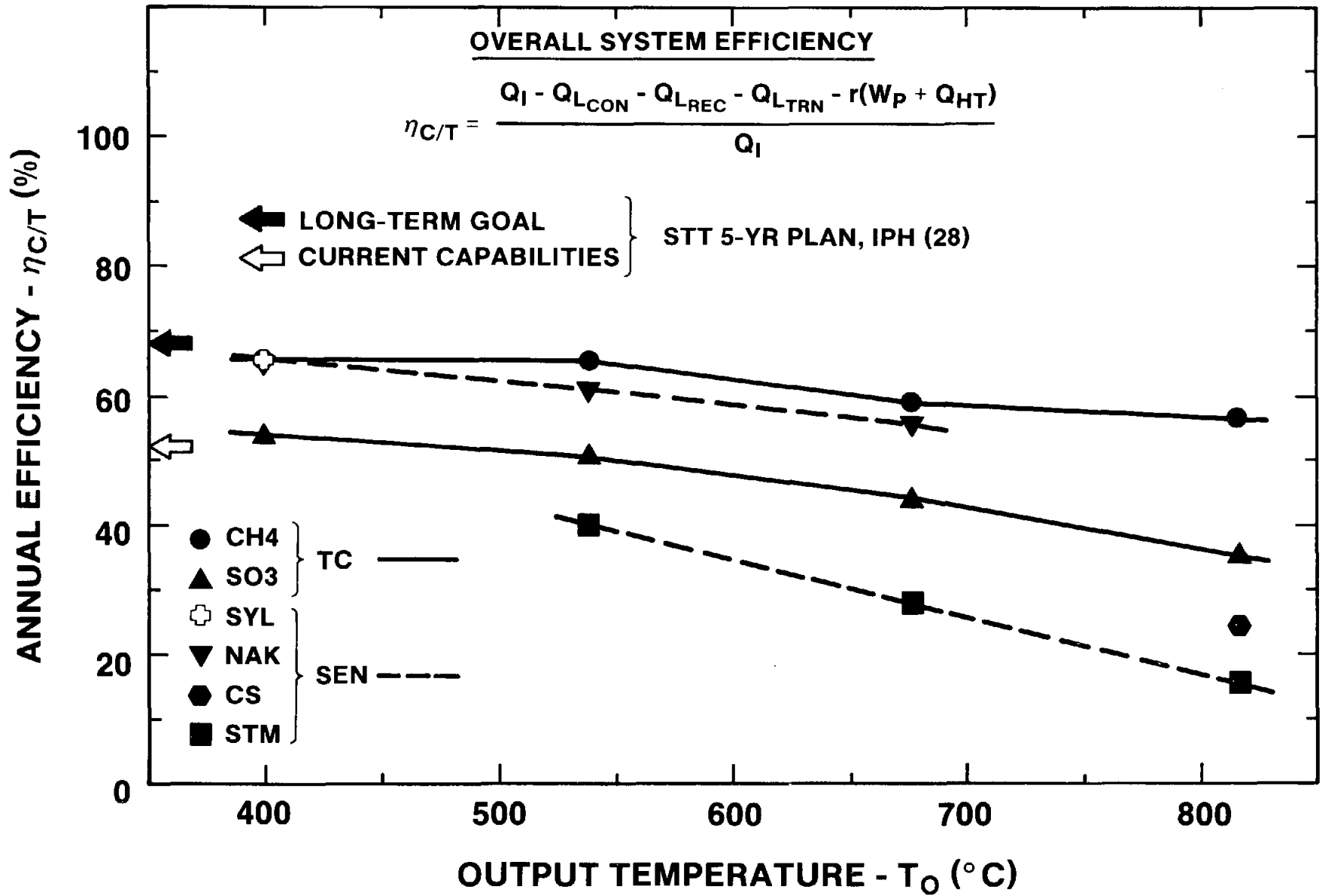


Figure 7 - Annual overall collector/transport system efficiency.

ECONOMIC ANALYSIS

A convenient and accepted method for comparing and evaluating the economic attractiveness of alternative energy production technologies is the required revenue approach developed by Doane et al. [27]. It is based on determining the required revenue per unit of energy output that will exactly recover the full costs of purchasing, installing, and operating the system over its lifetime. To apply this method, it is necessary to estimate the installed capital costs and annual operating and maintenance (O&M) costs for each of the collector/transport systems examined.

Installed Capital Costs

Consistent with the primary objective of comparing the economics of SEN and TC energy transport alternatives, transport system costs were estimated in considerable detail. The costs of other components, because they do not affect the relative comparisons, were selected on the basis of being reasonable and the same for all systems. Thus, installed capital costs for the concentrators, sensible-type receivers (including the housing, insulation, a heat exchanger, and the supports), and balance of plant were assumed to be the values cited as long term goals for IPH in the U.S. DOE National Solar Thermal Technology Program: Five Year Research and Development Plan, 1985-1989 [28]. For paraboloidal dish systems and process heat applications the long-term goals are (1984\$):

Concentrators	140 \$/m ²
Receivers (SEN)	30 \$/m ²
Balance of Plant (BOP)	50 \$/m ²

The transport systems consist of the following: the endothermic reactor and recuperator in each of the TC receivers; the piping network, which includes a riser and downcomer (including flex hoses), a control valve, and two manual valves for each collector, a manual valve for each of the ten 1X collector fields, special bellows seals for all valves in the

NAK and CS systems, all of the remaining pipe and fittings, and insulation (for all but the CH₄ system); a pump or blower; energy conversion equipment at the use point; heat tracing (for the CS system); and electrical controls.

A "bottoms-up" methodology was used to estimate transport system installed costs based on 1984 Means mechanical cost data [29]. The estimates are based on three important assumptions: 1) Large solar thermal dish systems such as this have already been constructed and operated, i.e., it is not a prototype facility and a base of construction and operating experience exists. 2) Large systems involve many replicated parts. 3) A solar experienced contractor will be used, one that has installed 10 or more similar facilities.

Piping costs are a function of pipe size and material and are quoted as dollars per unit length of pipe. The total length of pipe in the 10X collector field, from the receivers to the end-use point, and including both supply and return lines, is more than 44.7 km (23 km in just the risers and downcomers). Pipe size and material depend upon the working fluid, the temperature and pressure, and the allowable pressure drop (i.e., pump work). Pipe diameters were selected using the energy loss minimization procedure described above. Pipe wall thickness schedules and materials selected are schedule 40 carbon steel for SYL; sch. 10 304 stainless steel for NAK, SO₃, and CH₄; sch. 80 304 stainless steel for STM; and sch. 10 Inconel 600 for CS. Installed pipe costs were estimated to be the material cost plus 15 percent for fittings and 40 percent for installation (except CS for which installation costs are 45 percent).

Pipe insulation costs depend on material, thickness, and length of pipe. Insulation materials selected, as a function of output temperature, are fiberglass at 400°C, calcium silicate at 540 and 675°C, and Kaowool at 815°C. Insulation thicknesses were determined using the pipe optimization procedure as described previously. Installed insulation costs were estimated to be the material cost for the total pipe length plus 15 percent for insulation of fittings and 50 percent for installation.

Other components in the SEN transport systems and many in the TC systems are standard items, and estimating their costs was reasonably straight forward. The same is not true, however, for the endothermic and exothermic reactor/heat-exchanger units in the TC systems. The endothermic reactors and recuperators in particular, since they are mounted in the receivers, will be considerably different from conventional designs used in the chemical process industry. Thus, there is very little cost data available relevant to these units. The exothermic reactors and heat exchangers, on the other hand, should be very similar to commercial units for which a cost data base is available. Component sizes and materials requirements were determined based on mass and energy flows, system pressures, materials compatibility concerns, and for the reactors, catalyst characteristics. Component costs were subsequently obtained through telephone conversations with industrial suppliers and manufacturer's representatives. Based on this information, endothermic reactor/recuperator installed costs were estimated to be \$2k per receiver (in addition to the basic receiver cost of 30 \$/m² discussed above). The exothermic reactors and heat exchangers in the central conversion unit of each TC system were estimated to cost \$220k installed. These TC endothermic and exothermic reactor/heat-exchanger costs have the greatest uncertainty of all of the estimated SEN and TC component costs.

Ranges in the estimated costs of the various transport system components are presented in Table 4. Estimated installed capital costs for all system components are tabulated in Appendix A for all sixteen systems considered.

Balance of plant, concentrator, receiver and transport system capital costs are summarized in Figure 8. At $T_0 = 400^\circ\text{C}$, the CH₄ and SYL transport costs are essentially the same and the lowest of the four, and all transport costs are less than the collector costs. At higher output temperatures, TC transport costs are consistently less than those for SEN transport, with the difference increasing with increasing temperature. The STM transport costs are highest at the higher temperatures and also greater than the collector costs. The CH₄ TC transport system has the lowest

Table 4 - Transport Systems Component
Cost Estimates (1984\$)

<u>Component</u>	<u>No. of Units</u>	<u>Ranges of Installed Cost (k\$)</u>
Piping	--	672 (CH4)- 7,531 (STM)
Insulation	--	1,054 (SO3)- 7,455 (STM)
Flex Hoses	4 per collector (\$200 ea)	552
Control Valves	1 per collector (\$1,200 ea)	828
Bellows Seals (NAK & CS)	3 per collector (\$507 ea)	1,050
Heat Trace System (CS) (incl. 5 MW substation)	--	4,756
Pump/Blower	1 per system	45 (SYL)- 750 (STM)
Endo. Reactor/ Recuperator (CH4, SO3)	1 per collector (\$2,000 ea)	1,380*
Central Conversion Unit:		
- SEN (HX)	1 per system	80 (SYL, NAK)- 300 (STM)
- TC (AR/HX's)	1 per system	220*
Electrical Controls	--	80 (SYL) - 600 (STM)
Working Fluid Charge	to fill system	0.1 (STM) - 1,500 (NAK)

*Includes cost of catalyst, estimated to be \$20 per kg.

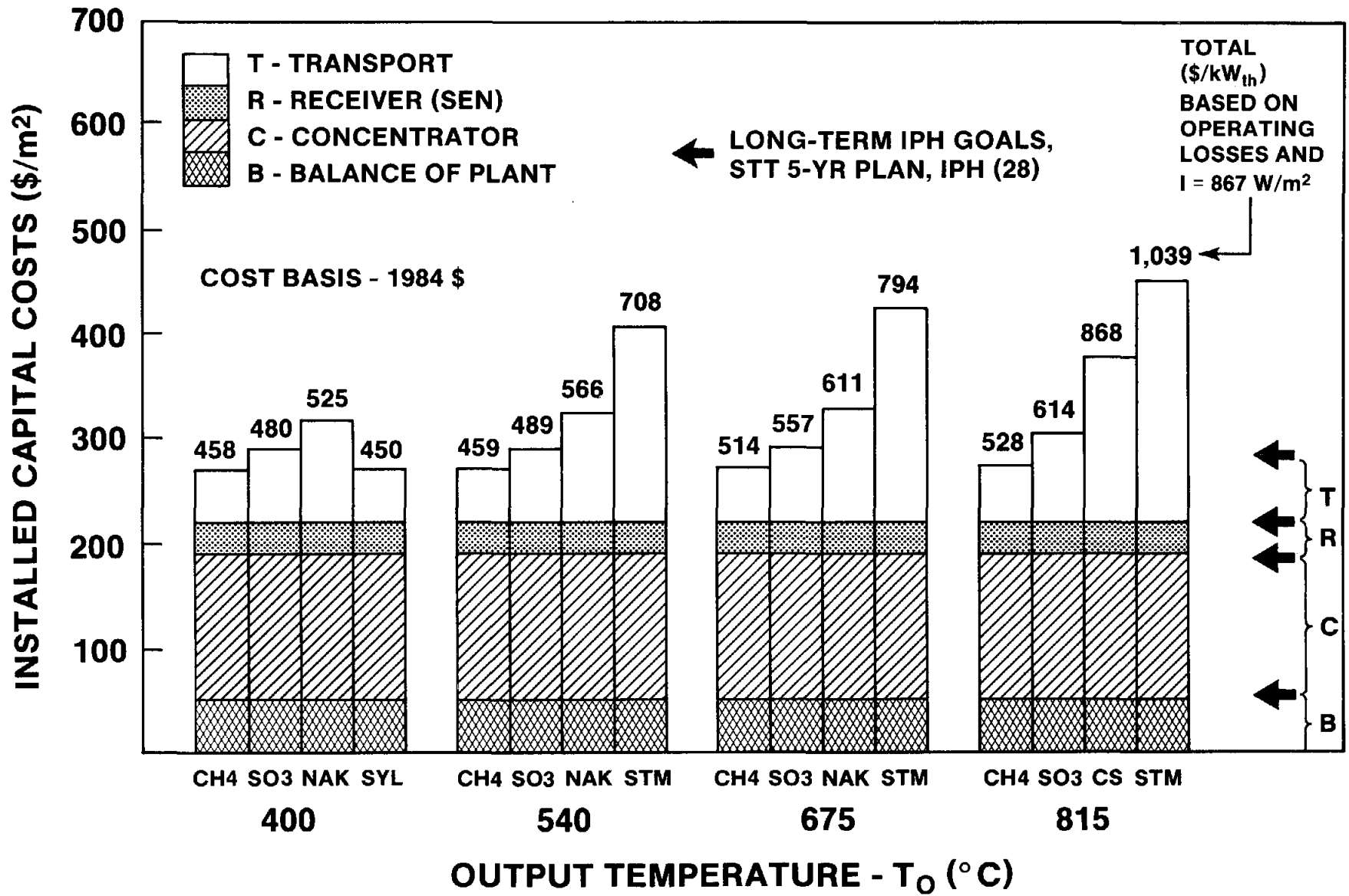


Figure 8 - Concentrator, receiver and transport system installed capital costs.

capital costs at all output temperatures above 400°C. All but the STM and CS systems appear to have a chance of meeting the long-term goal (IPH) of 65 \$/m² cited in the STT Five Year Plan [28].

Annual O&M Costs

Annual operating and maintenance (O&M) costs are comprised of materials, labor, and parasitic power costs. Materials costs include catalyst replacement (assuming a three year cycle and reduced cost due to recovery of precious metals and large quantity production), make-up chemicals and heat transfer fluids, water treatment, and spare parts and seals. Labor costs include repair and calibration of instrumentation, and insulation and heat trace system repair. Pumping and heat trace energy is valued at 6 ¢/kWh_e. Except for the pumping and heat trace energy requirements, which were computed as part of the transport system performance analyses, estimates of the collector and transport system O&M costs are based to a great extent on experience gained with the STEP dish system (SEN energy transport, T_o = 400°C) at Shenandoah and a number of other IPH systems (trough collectors) that have been operating for several years.

Collector O&M costs were estimated to be \$250,000 per year. This is applied to all systems and hence does not affect relative comparisons among the transport systems. Ranges in the estimated transport system O&M costs are given in Table 5. A detailed tabulation of estimated O&M costs is given in Appendix A for all systems analyzed.

Again, as with the capital cost estimates, 1) it is assumed that many systems of this size have been built previously and are operating reliably, and 2) the greatest uncertainties are in the O&M costs estimated for the TC transport systems, in particular the materials costs. This is due largely to unanswered questions concerning the catalysts: Which catalysts are best suited for the type of cyclic operation characteristic of solar applications? How much catalyst is required? What will the bulk price be for the quantities of catalyst needed for a large system? How often will

Table 5 - Transport Systems Annual O&M
Cost Estimates (1984\$)

	<u>(k\$/y)</u>
Materials	10(STM) - 90(STM)
Labor	120(SYL,NAK,STM) - 250(CS)
Parasitics:	
Pumping	17(CS) - 976(STM)
Heat Trace	888(CS)

the catalyst have to be replaced? What procedures, if any, can be employed to regenerate the catalyst in situ when the system is not operating (nighttime, shutdowns)?

Collector and transport system annual O&M costs are summarized in Figure 9. A striking feature of this comparison is the excessive parasitic costs for the SO₃, STM, and CS transport systems. For SO₃ and STM this is due to the high pump work, while for CS it is due to the high heat trace energy. The CH₄, NAK, and SYL costs are all lower by a factor of 2 or more, with the costs for CH₄ and NAK being essentially the same at the three lower output temperatures. Only the O&M costs for these three systems are anywhere near the STT long term goal.

Levelized Energy Costs

The required revenue approach of Doane et al. [27] computes a levelized energy cost (LEC) that is the quotient of the annual system-resultant cost divided by the expected annual output from an energy production system. The annual system-resultant cost is an amount which, if collected in revenues each year for the energy produced, constitutes a revenue distribution with exactly the same present value as the summed present values of the separate cost distributions for capital expenditure and recurrent operating, maintenance, and fuel costs. (Fuel costs for a solar

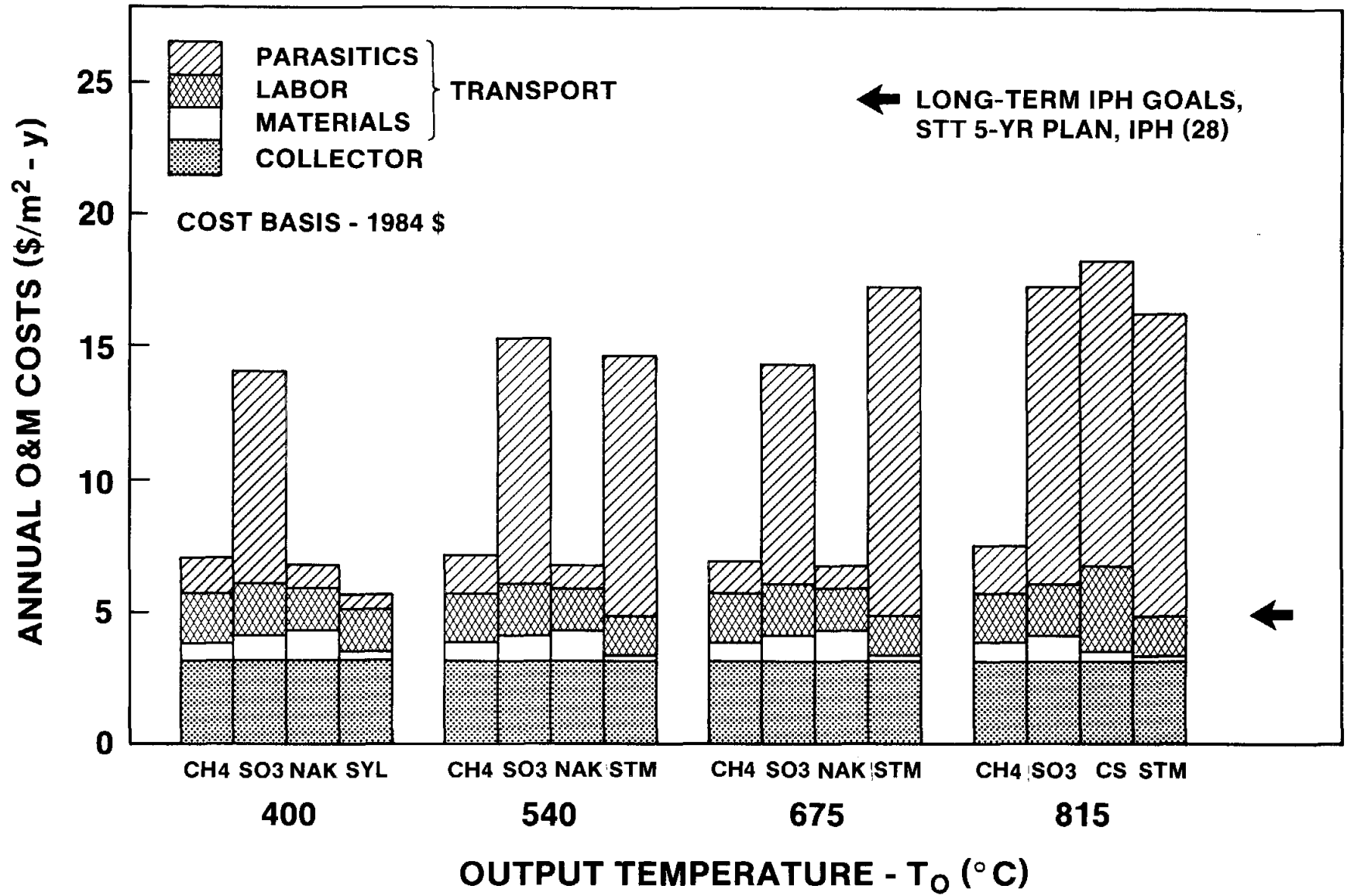


Figure 9 - Collector and transport system annual O&M costs.

system are assumed to be zero). The resulting expression for levelized energy cost is

$$LEC = \frac{(1 + g)^{-d} [\overline{FCR} * CI_{pv} + CRF_{r,N} (OP_{pv} + MNT_{pv} + FL_{pv})]}{MWH_A} \quad (6)$$

where:

- LEC = levelized energy cost (\$/MWh_{th})
- g = general inflation rate
- d = y_{co} - y_b
- y_{co} = first year of commercial operation
- y_b = base year for costs
- \overline{FCR} = annualized fixed charge rate
- CI_{pv} = present value of capital investment in current dollars, as of year y_{co}
- CRF_{r,N} = capital recovery factor (rate r, period N years)
- OP_{pv}, MNT_{pv}, FL_{pv} = present value of operating, maintenance and fuel costs, respectively, in current dollars, as of year y_{co}
- MWH_A = expected annual energy output (MWh_{th})

Levelized energy costs for the various SEN and TC collector/transport systems were computed using a simplified economic analysis program, ECANAL, which employs the methodology of Doane et al. [27]. The total installed capital costs, total annual O&M costs and annual energy output are input for each system. The total installed capital cost is assumed to occur in three equal disbursements over the three year construction period (N_{con}). The system operating lifetime, or plant life (N), is used as the analysis period for all financial computations. Thus, the present value computations for capital investment expenditures (CI) and recurrent costs (OP, MNT, and FL) normalize these outlays to their respective "present" values (CI_{pv}, OP_{pv}, MNT_{pv}, and FL_{pv}) as of January 1 of the first year of commercial operation (y_{co}). These present values are annualized from unique lump sums to a single series of uniform annual payments over the life of the project, expressed in constant y_b dollars. This annualized system-resultant cost is obtained by multiplying the present value of the sum of all system-resultant costs by the capital recovery factor (CRF_{r,N})

and adjusting back to y_b dollars. For electrical power systems, MWH_A is the annual electrical energy output and LEC is equivalent to the levelized busbar energy cost. In the present analysis, however, the output of the collector/transport systems is thermal energy and MWH_A is taken to be the annual output energy, Q_o (MWh_{th}). Details of the development, including descriptions of the various terms, are given in Reference 27.

Values for the economic parameters used in the computations are given in Table 6. The first eight parameters are the same as the levelized cost assumptions used in the STT 5-Year Plan [28] for determining the long-term component goals for IPH systems.

Table 6 - Economic Parameters

Assumed:

Plant Construction Time (N_{con})	3 y
Plant Life (N)	20 y
Accounting Lifetime (Depreciation) (n)	5 y
Depreciation Schedule	ACRS
Investment Tax Credit (α)	0.1
Discount Rate (r)	0.1
Base Year for Costs (y_b)	1984
Percentage of Capital Cost for Indirects and Contingencies (C_{ind})	20%
Effective Annual Income Tax Rate (τ)	0.5
Effective Annual Rate for Other Taxes and Insurance ($\beta_1 + \beta_2$)	0.01
General Inflation Rate (g)	0.0
Escalation Rate for Capital Costs (g_c)	0.0
Escalation Rate for O&M Costs (g_{om})	0.0

Computed:

Capital Recovery Factor ($CRF_{r,N}$)	0.1175
Fixed Charge Rate (FCR)	0.1334

The resulting LECs are compared in Figure 10 where the contributions attributed to capital costs, O&M costs, and indirects and contingencies are indicated by the shading on the bars. The relative magnitudes of the LECs for the different systems at the four output temperatures are not surprising in view of the performance and cost estimates presented in Figures 7, 8, and 9. Once again they demonstrate 1) the impracticality of

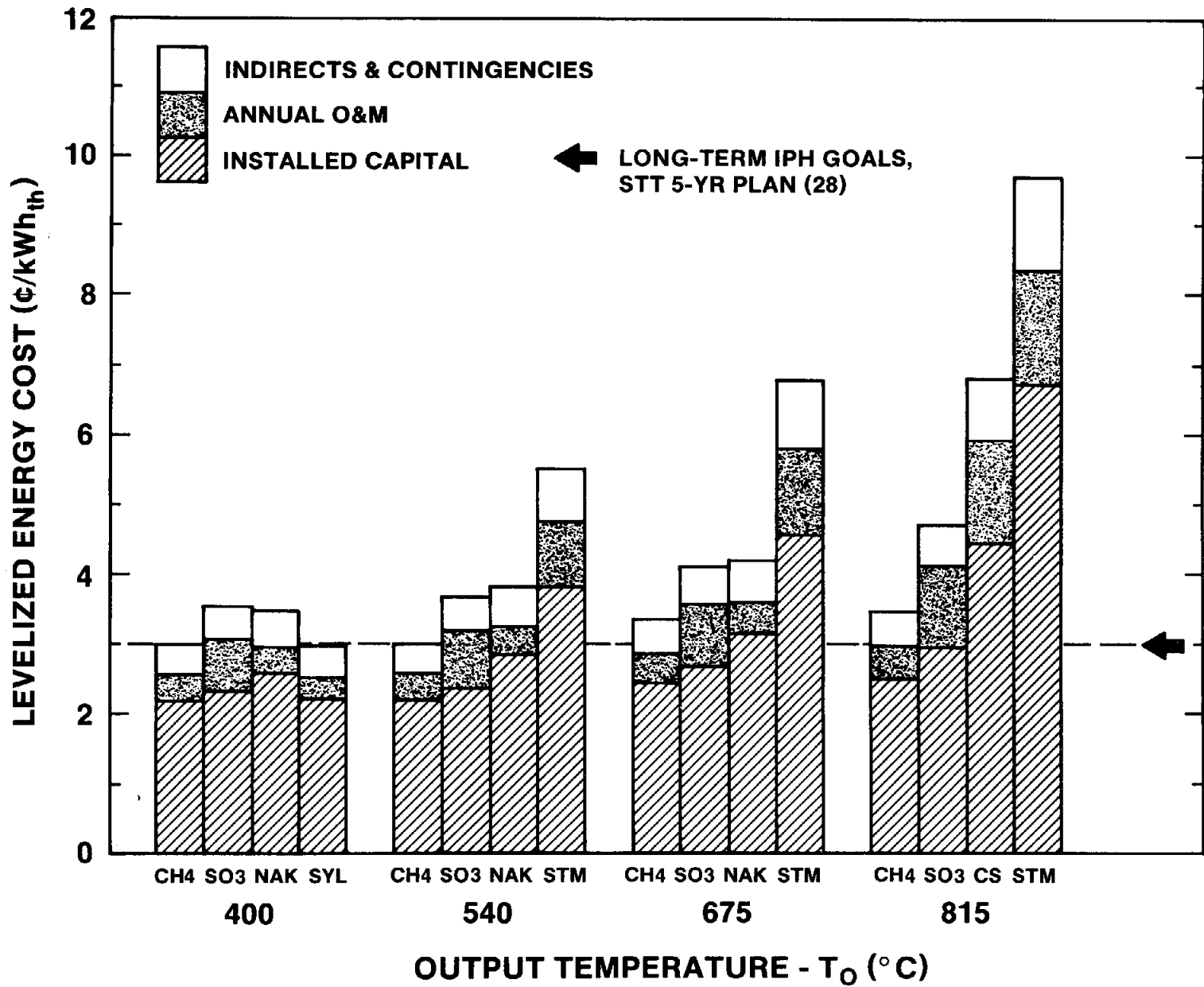


Figure 10 - Collector/transport system levelized energy costs.

SEN transport at high temperatures using a gaseous working fluid; 2) the economic penalties associated with heat tracing (CS) and high pumping power (SO3 versus CH4 and STM); 3) the comparable economics of the SEN and TC systems at 400°C; and 4) the increasing economic advantage of TC transport, in particular the CH4 system, over SEN transport at higher output temperatures. It is interesting to note that the much higher parasitic costs of SO3, relative to NAK, are completely offset by its somewhat lower capital costs and higher energy output so that on a LEC basis the two systems are quite comparable. Finally, on an absolute level, the CH4 TC transport system appears closest to meeting the long term STT Program goal (IPH) of 3 ¢/kWh_{th} (9 \$/MBtu_{th}), particularly at the higher output temperatures.

OBSERVATIONS

Performance and cost estimates have been generated for sensible and thermochemical energy transport systems for a large field of paraboloidal dish collectors producing $\sim 40 \text{ MW}_{\text{th}}$ of high temperature thermal energy. Two SEN and two TC transport systems are evaluated at each of four output temperatures ranging from 400 to 815°C. Reasonable care has been taken to provide realistic performance and cost estimates. However, as a consequence of the assumptions and methodology employed, the values are more meaningful in a relative than in an absolute sense.

Some perspective on the absolute values of the present estimates can be obtained by comparing them with the results of other transport system performance/cost analyses presented in Tables 1 & 2. Although the value of such comparisons is limited due to significant differences in the performance and cost assumptions employed, the following general observations can be made: 1) collector costs are comparable to, but somewhat higher than, the values appearing in the tables, and 2) transport system component and overall costs generally fall within the cost ranges given in the tables for similar output temperatures. The latter are closest to the values given by Caputo [14], somewhat below the values of Schredder [18], and much lower than the estimates of Nix [15].

Certain aspects of the SEN and TC transport systems that bear on the comparisons, but are not explicitly included in the analysis, are: 1) the effect of the corrosive nature of the carbonate salt and SO_3 fluids on the performance and costs of these systems; 2) the likelihood that the SO_3 system will have to be heat traced (to $\sim 65^\circ\text{C}$) to prevent SO_3 condensation; 3) the effects of side reactions in the CO_2/CH_4 system that have the potential for water and carbon generation; 4) the likelihood that off-design (low insolation) operation will cause a much greater reduction in the performance of SEN transport systems than in that of TC systems because increased thermal losses in the former, as a result of lower flow rates, consume an even greater fraction of the absorbed energy than in design

operation; and 5) the potential of TC transport systems for more rapid start-up each morning since nighttime thermal losses that need to be made up are much smaller than SEN system losses.

CONCLUSIONS

Within the context of the assumptions and methodology employed in the analysis, the major conclusions are:

1. At 400°C, despite some performance and cost differences, the levelized energy costs of the two SEN and two TC transport systems are about the same.
2. At higher output temperatures, TC transport is more cost-effective and is the only viable option at temperatures above 700°C.
3. The CO₂/CH₄ system has better performance and lower costs than the SO₃ system at all output temperatures.
4. The CO₂/CH₄ TC system is the most cost-effective transport system at all temperatures and appears closest to meeting the STT Program long-term IPH goal of 3 ¢/kWh_{th} (9 \$/MBtu_{th}) levelized energy cost.
5. The steam system exhibits the poorest performance and highest costs of all transport systems at the three highest temperatures. The use of an all gaseous system for high temperature sensible energy transport, therefore, is not cost-effective.
6. The high capital and parasitic costs required to heat trace the carbonate salt system illustrate the severe economic penalty that will be associated with any transport system that needs to be heat traced.

REFERENCES

1. "The National Energy Policy, A Report to the Congress Required by Title VIII of the Department of Energy Organization Act (Public Law 9591)," United States Department of Energy, 1985.
2. Mechanical Technology Incorporated, "Central Heat Engine Cost and Availability Study," SAND87-7020, Sandia National Laboratories, Albuquerque, NM, November 1987.
3. J. J. Iannucci, "Survey of U.S. Industrial Process Heat Usage Distributions," SAND80-8234, Sandia National Laboratories, Livermore, CA, January 1981.
4. J. D. Fish, "Solar Industrial Process Heat Markets for Central Receiver Technology," SAND80-8214, Sandia National Laboratories, Livermore, CA, April 1980.
5. D. R. Brown, L. L. Fassbender, and A. D. Chockie, "The Value of Solar Thermal Industrial Process Heat," PNL-5629, Pacific Northwest Laboratory, Richland, WA, March 1986.
6. "National Solar Thermal Technology Program: Five Year Research and Development Plan, 1986-1990," available from the Division of Solar Thermal Technology, U.S. Department of Energy, September 1986.
7. J. D. Fish, "Overture to CLEA: The Closed Loop Efficiency Analysis Project," SAND84-0502, Sandia National Laboratories, Albuquerque, NM, April 1985.
8. B. Hohlein, R. Menzer and J. Range, "High Temperature Methanation in the Long-Distance Nuclear Energy Transport System," Applied Catalysis, 1, pp. 125-139, 1981.
9. R. L. Graves, "Screening Study on High Temperature Energy Transport Systems," ORNL/TM-7390, Oak Ridge National Laboratory, Oak Ridge, TN, October 1980.
10. Rocket Research Company, "Reversible Chemical Reactions for Electrical Utility Energy Applications," Final Report, EPRI Contract TPS 76-658, April 1977.
11. S. H. Kalfayan and H. E. Marsh, "Chemical Energy Storage Systems Screening and Preliminary Selection," Report No. 5105-40, Jet Propulsion Laboratory, Pasadena, CA, August 1980.
12. C. H. Li and E. W. Schmidt, "Heat and Mass Transfer Analysis of a Chemical Converter/Heat Exchanger for the SO₂/SO₃ Distributed Solar Energy Collection System," presented at the 1979 International Congress of ISES, Atlanta, GA, May 28-June 1, 1979.

13. J. H. McCrary, et al., "An Experimental Study of the CO₂/CH₄ Reforming-Methanation Cycle as a Mechanism for Converting and Transporting Solar Energy," Solar Energy, Vol. 29, No. 2, pp. 141-151, 1982.
14. R. S. Caputo, "An Initial Study of Solar Power Plants Using a Distributed Network of Point Focusing Collectors," Report No. 900-724, Jet Propulsion Laboratory, Pasadena, CA, July 1975.
15. R. G. Nix, "Thermochemical Energy Transport in One 1-MW Industrial Process Heat Solar System," SERI/TP-234-1785, Solar Energy Research Institute, Golden, CO, January 1983.
16. O. M. Williams, "Thermochemical Energy Transport Costs for a Distributed Solar Power Plant," Solar Energy, Vol. 20, pp. 333-342, 1978.
17. R. D. Smith, "Chemical Energy Transport for Distributed Solar Thermal Electric Conversion," Rocket Research Company, SAND81-8190, Sandia National Laboratories, Livermore, CA, February 1982.
18. J. M. Schredder, "Performance and Cost of Energy Transport and Storage Systems for Dish Applications Using Reversible Chemical Reactions," Report No. 5105-142, Jet Propulsion Laboratory, Pasadena, CA, October 15, 1984.
19. J. V. Fox, "Thermochemical Energy Transport Systems Study," J. V. Fox Consulting Service Company, SAND83-7464, Sandia National Laboratories, Albuquerque, NM, March 1984.
20. "Solar Total Energy Project, Shenandoah; System Description, Final Design Report," Document No. 78SDS4234, Revision 1, General Electric Company, Space Division, Philadelphia, PA, January 10, 1980.
21. J. S. Barnhart, "ETRANS: An Energy Transport System Optimization Code for Distributed Networks of Solar Collectors," PNL-3327, Pacific Northwest Laboratory, Richland, WA, September 1980.
22. L. D. Hostetler and J. J. Iannucci, "Optimized Design of Distributed Solar Thermal Transport Systems for Process Heat," Proceedings of the 1981 Annual Meeting, Philadelphia, Pennsylvania, American Section of the International Solar Energy Society, Inc., Vol. 4.1, pp. 592-596, 1981.
23. M. E. Larsen and R. L. Akau, "Piping Heat Loss Study for Dish Collector Fields (Interim Report)," Memo to J. M. Diggs, 6227, Sandia National Laboratories, Albuquerque, NM, May 30, 1984.
24. J. M. Diggs, "Pipe Design Optimization Study," Proceedings of the Distributed Receiver Solar Thermal Technology Conference, Albuquerque, New Mexico, April 24-25, 1985," SAND84-2454, Sandia National Laboratories, Albuquerque, NM, pp. 185-189, April 1985.

25. "Solar Radiation Energy Resource Atlas of the United States," SERI/SP-642-1037, Solar Energy Research Institute, Golden, CO, p. 103, October 1981.
26. T. Baumeister and L. S. Marks, eds., "Standard Handbook for Mechanical Engineers," 7th Edition, McGraw-Hill Book Company, New York, NY, pp. 3-59 - 3-60, 1969.
27. J. W. Doane et al., "The Cost of Energy from Utility-Owned Solar Electric Systems," JPL 5040-29, ERDA/JPL-1012-76/3, Jet Propulsion Laboratory, Pasadena, CA, June 1976.
28. "National Solar Thermal Technology Program: Five-Year Research and Development Plan, 1985-1989," available from the Division of Solar Thermal Technology, U.S. Department of Energy, 1985.
29. "Means Mechanical Cost Data, 1984," 7th Edition, R. S. Means Company, Inc., Kingston, MA, 1984.

APPENDIX A

DETAILS OF PERFORMANCE AND ECONOMICS ANALYSES

APPENDIX A

DETAILS OF PERFORMANCE AND ECONOMICS ANALYSES

Details supporting the SEN and TC performance and economics analyses, including assumptions, methodology, input data, and computed parameters, are presented in this appendix.

PERFORMANCE

GENERAL ASSUMPTIONS

$$\begin{array}{ll}
 N_{\text{CON}} = 690 & \bar{I}_{\text{dn}} = 867 \text{ W/m}^2 \\
 D_{\text{CON}} = 12 \text{ m} & Q_{\text{I}} = 67.7 \text{ MW} \\
 A_{\text{CON}} = 113.10 \text{ m}^2 & Q_{\text{I}} = 210.4 \text{ GWh/y} \\
 \eta_{\text{CON}} = 85 \% & \text{CR} = 1500 \\
 \eta_{\text{REC}} = f(Q_{\text{I}}, \eta_{\text{CON}}, T_{\text{REC}}, A_{\text{REC}})
 \end{array}$$

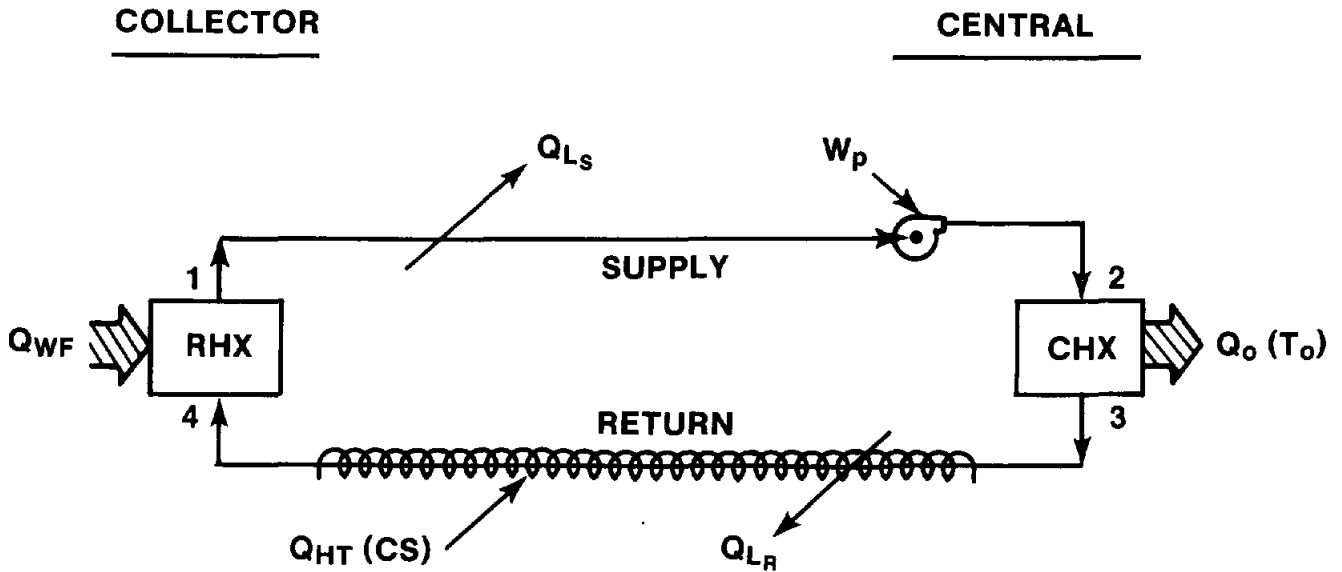
$$\text{Operating Time: } t_{\text{OP}} = 10 \text{ (h/d)} * 311 \text{ (d/y)} = 3110 \text{ (h/y)}$$

$$\text{Shutdown Time: } t_{\text{SD}} = \sum_{i=1}^4 (t_{\text{SD}})_i N_i \text{ (h/y)}$$

Event	Shutdown Time per Event ($t_{\text{SD}})_i$ (h/event)	Events per Year N_i (event/y)	$(t_{\text{SD}})_i N_i$ (h/y)
Overnight (ON)	14	276	3864
ON + 1 d	38	20	760
ON + 2 d	62	11	682
ON + 3 d	86	4	344

$$\therefore t_{\text{SD}} = 5650 \text{ (h/y)}$$

SENSIBLE SYSTEMS



Schematic of SEN System

Operating Conditions

$$T_2 = T_o \quad (^\circ\text{C})$$

$$T_A = 25 \quad (^\circ\text{C})$$

$$Q_{WF} = \eta_{CON} \eta_{REC} Q_I \quad (\text{GWh/y})$$

$$\Delta T_{CHX} = T_3 - T_2 = -139 \quad (^\circ\text{C})$$

Steady-State Operating Losses

$$Q_{L_{CON}} = Q_I (1 - \eta_{CON}) = 31.56 \quad (\text{GWh/y})$$

$$Q_{L_{REC}} = Q_I \eta_{CON} (1 - \eta_{REC}) \quad (\text{GWh/y})$$

$$(\Delta T_f)_{L/A} = \sum_{j=1}^m \frac{Q_{L_j}}{\dot{m}_f c_p} \quad (^\circ\text{C})$$

Fluid temperature drop in supply and return lines from pipe network optimization calculations of Larson and Akau [23]

where: $Q_{L_j} = (UA)_j (\bar{T}_f - T_A) \quad (\text{kW})$ Heat loss from pipe segment j

\bar{T}_f = Average fluid temperature in piping network (including both supply and return lines) $(^\circ\text{C})$

T_A = Ambient air temperature $(^\circ\text{C})$

$$(UA)_j = \frac{2\pi k_{ins} L_j}{(\ln(r_o/r_i)_{ins})_j} \quad (\text{kW/K}) \quad \text{Thermal conductance of pipe segment } j$$

$$\dot{m}_{f_j} = \text{Fluid flow rate in pipe segment } j \quad (\text{kg/s})$$

$$\bar{c}_{p_f} = \text{Average specific heat of fluid at } \bar{T}_f \quad (\text{kJ/kg-K})$$

m = Number of pipe segments in the supply or return line from the central conversion point to the most distant receiver.

$$\Delta T_S \approx 2(\Delta T_f)_{L/A} \qquad \Delta T_R \approx 1 \ 1/2(\Delta T_f)_{L/A} \quad (^\circ\text{C})$$

$$T_3 = T_2 + \Delta T_{CHX} \qquad T_4 = T_3 - \Delta T_R \quad (^\circ\text{C})$$

$$T_1 = T_2 + \Delta T_S \qquad T_{REC} = T_1 + 5 \text{ to } 14 \quad (^\circ\text{C})$$

$$\dot{m}_f = \frac{10^3 Q_{WF} N_{CON}}{\bar{c}_{p_f} (T_1 - T_4)} \quad (\text{kg/s})$$

$$Q_{L_S} = 10^{-6} \dot{m}_f \bar{c}_{p_f} \Delta T_S t_{OP} \qquad Q_{L_R} = 10^{-6} \dot{m}_f \bar{c}_{p_f} \Delta T_R t_{OP} \quad (\text{GWh/y})$$

Transient Shutdown Losses

$$Q_{L_N} = 10^{-6} \sum_{i=1}^4 \left[N_i \sum_{j=1}^n Q_{tr_j} \left[(t_{SD})_i \right] \right] \quad (\text{GWh/y})$$

- where: $(t_{SD})_i$ = Shutdown time per event i
 N_i = Number of shutdown events, i , per year
 $Q_{tr_j} \left[(t_{SD})_i \right]$ = Heat loss from pipe segment j during event i
 n = Total number of pipe segments, j , in entire pipe network (both supply and return lines).

SYL, NAK, and STM:

$$Q_{tr_j} \left[(t_{SD})_i \right] = (\bar{m}c_p)_j (\bar{T}_f - T_A) \left[1 - e^{-\left[\frac{(t_{SD})_i}{\tau_j} \right]} \right] \quad (\text{kWh/event})$$

$$\text{where: } (\bar{m}c_p)_j = [(\rho c_p V)_{fluid} + (\rho c_p V)_{pipe} + F*(\rho c_p V)_{ins}]_j \quad (\text{kJ/K})$$

Lumped thermal capacitance of fluid, pipe, and that portion of the insulation, F:

$$F = 1 - \frac{1}{1 - (r_i/r_o)_{ins}^2} + \frac{1}{2 \ln(r_o/r_i)_{ins}},$$

which would contain the energy stored therein at the average fluid temperature, \bar{T}_f , for pipe segment j [23]

\bar{T}_f = Average temperature of fluid throughout piping network, supply and return lines, at time of shutdown

$$\tau_j = \frac{(\overline{mc}_p)_j}{3600 * 2 (UA)_j} \quad (h) \quad \text{Time constant of the lumped fluid-pipe-insulation mass for pipe segment j (thermal conductances are doubled to account for actual losses in real operating systems)}$$

$$(UA)_j = \frac{2\pi k_{ins} L_j}{(\ln(r_o/r_i)_{ins})_j} \quad (kW/K) \quad \text{Thermal conductance of pipe segment j.}$$

CS: Heat traced to insure line temperatures never decreased below $T_{HT} = 400^\circ C$.

Time for fluid temperature to decrease to T_{HT} :

$$t_{HT_j} = -\tau_j \ln \left[\frac{T_{HT} - T_A}{\bar{T}_f - T_A} \right] \quad (h)$$

$$\text{For: } (t_{SD})_i < t_{HT_j} : Q_{tr_j} \left[(t_{SD})_i \right] = (\overline{mc}_p)_j (\bar{T}_f - T_A) \left[1 - e^{-\left\{ \frac{(t_{SD})_i}{\tau_j} \right\}} \right] \quad (kWh/event)$$

$$(t_{SD})_i \geq t_{HT_j} : Q_{tr_j} \left[(t_{SD})_i \right] = (\overline{mc}_p)_j (\bar{T}_f - T_{HT}) \quad (kWh/event)$$

Heat Trace Energy

$$Q_{HT} = 2 * 10^{-6} (T_{HT} - T_A) t_{SD} \sum_{j=1}^n (UA)_j \quad (GWh/y)$$

where, as above, the thermal conductances are doubled to account for actual losses in real systems.

CS: $Q_{HT} = 14.8 \text{ (GWh/y)}$

System Pressure Drop:

The pressure drop through the system, which defines the pressure rise through the pump (or compressor), $\Delta p_P = (p_o - p_i)_P$, is estimated by summing the pressure losses in the central conversion device, the pipe segments and fittings in the supply and return lines from the central conversion point to the most distant receiver, and the receiver heat exchanger, as follows:

$$\Delta p_P = 10^{-6} \left[\bar{\rho}_f \sum_{j=1}^m f_j \left(\frac{L_j}{d_j} \right) \left(\frac{V_{fj}^2}{2g_c} \right) + \sum_{k=1}^{\tilde{m}} k_k \left(\frac{V_{fk}^2}{2g_c} \right) + \sum_{l=1}^2 \Delta p_l \right] \quad \text{(MPa)}$$

where: $\bar{\rho}_f$ = Average fluid density at \bar{T}_f (kg/m³)
 f_j = $f(\text{Re and } \epsilon/d_j)$ Friction factor from the Colebrook relation (using $\epsilon = 45.72 \mu\text{m}$) for pipe segment j

L_j = Length of pipe segment j (m)

d_j = I.D. of pipe segment j (m)

V_{fj} = Bulk fluid velocity in pipe segment j (m/s)

m = Number of pipe segments, j , in the supply and return lines from the central conversion point to the most distant receiver

k_k = Loss coefficient for pipe fitting k

\tilde{m} = Number of pipe fittings, k , in the supply and return lines from the central conversion point to the most distant receiver

Δp_l = Pressure loss for component l (MPa). Values assumed for these estimates:

$\Delta p(\text{RHX}) = 0.069 \text{ MPa}$

$\Delta p(\text{CHX}) = 0.24 \text{ MPa}$

Pump Work:

SYL, NAK, and CS:

For steady, adiabatic, incompressible flow:

$$W_P = 10^{-3} t_{OP} \left(\frac{\dot{m}_f \Delta p}{\rho_f \eta_P} \right) \quad (\text{GWh/y})$$

where: \dot{m}_f = Total mass flow of fluid in the system (kg/s)

η_P = Pump efficiency = 60%

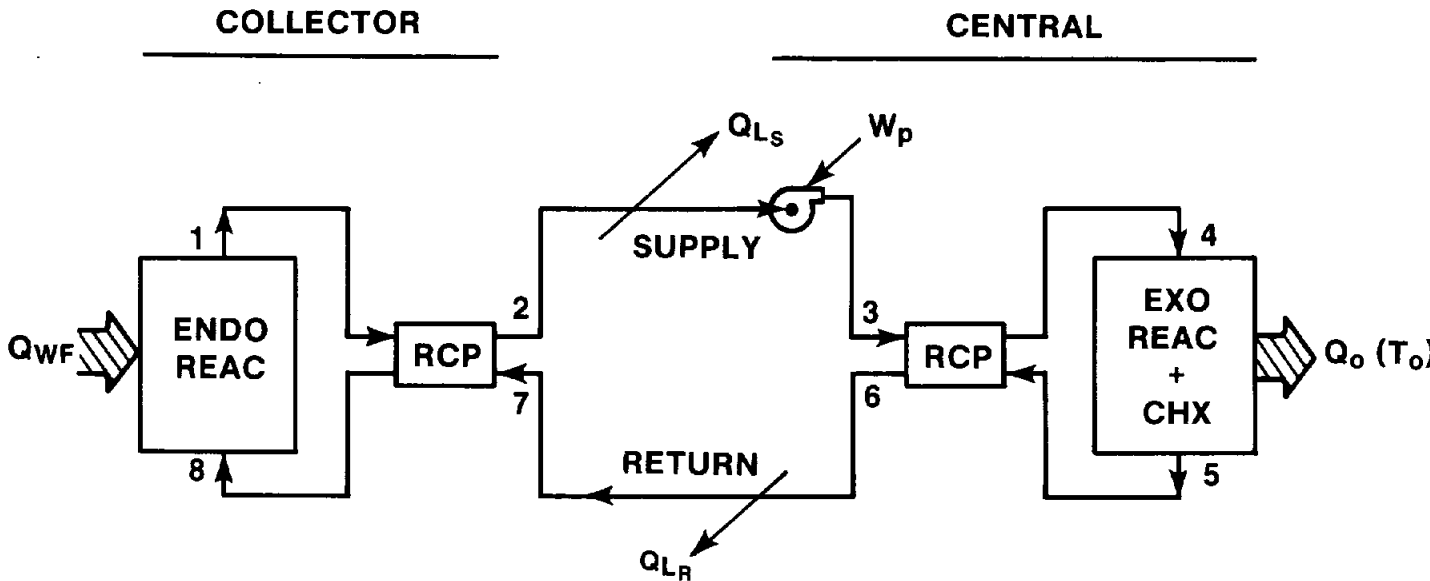
STM:

For steady, adiabatic flow:

$$W_P = 10^{-6} t_{OP} \left(\frac{\dot{m}_f \Delta h_P}{\eta_P} \right) \quad (\text{GWh/y})$$

where: $\Delta h_P = (h_f(T_o, P_o) - h_f(T_i, P_i))_P$ (kJ/kg)

THERMOCHEMICAL SYSTEMS



Schematic of TC System

Operating Conditions

$$Q_{WF} = \eta_{CON} \eta_{REC} Q_I \quad (\text{GWh/y})$$

$$T_A = 25 \quad (^\circ\text{C})$$

$$T_1 = \text{Endothermic reaction temperature (927 \& 1127 } ^\circ\text{C)}$$

$$\begin{array}{ll}
T_{\text{REC}} = T_1 & T_5 = T_o \quad (^\circ\text{C}) \\
\text{CH4: } T_3 = T_A & T_7 = T_A \quad (^\circ\text{C}) \\
T_1 - T_8 = 25 & T_6 - T_3 = 25 \quad (^\circ\text{C}) \\
\text{SO3: } T_3 = 121 & T_7 = 121 \quad (^\circ\text{C}) \\
T_7 - T_2 = 25 & T_5 - T_4 = 25 \quad (^\circ\text{C})
\end{array}$$

Remaining temperatures obtained from CLEA code calculations.

Steady-State Operating Losses

$$Q_{L\text{CON}} = Q_I(1 - \eta_{\text{CON}}) = 31.56 \quad (\text{GWh/y})$$

$$Q_{L\text{REC}} = Q_I \eta_{\text{CON}}(1 - \eta_{\text{REC}}) \quad (\text{GWh/y})$$

$$\dot{m}_f = \frac{10^3 Q_{\text{WF}}}{\Delta h_{\text{ENDO REAC}}} \quad (\text{kg/s})$$

where: $\Delta h_{\text{ENDO REAC}} = h_{\text{prod}}(T_1, P_1) - h_{\text{reac}}(T_8, P_8) \quad (\text{kJ/kg})$

$$Q_{L\text{S}} = 10^{-6} \dot{m}_f t_{\text{OP}} (\Delta h_{\text{prod}})_{2-3} \quad Q_{L\text{R}} = 10^{-6} \dot{m}_f t_{\text{OP}} (\Delta h_{\text{reac}})_{6-7} \quad (\text{GWh/y})$$

where: $(\Delta h_{\text{prod}})_{2-3} = (h(T_2, P_2) - h(T_3, P_3))_{\text{prod}} \quad (\text{kJ/kg})$
 $(\Delta h_{\text{reac}})_{6-7} = (h(T_6, P_6) - h(T_7, P_7))_{\text{reac}} \quad (\text{kJ/kg})$

Transient Shutdown Losses

CH4: Since the pipelines are uninsulated, the sensible energy in the gases leaving the recuperators is assumed to be lost fairly quickly so that the gas temperature in the lines is close to ambient throughout much of the network. Thus:

$$Q_{L\text{N}} = \text{Negligible}$$

for all shutdown periods.

SO3: To avoid SO₃ condensation in the lines during shutdowns, the system is run for a time prior to shutdown with the

synthesizer bypassed to eliminate all SO₃ from the lines. This would leave the lines filled with SO₂ and O₂. The average temperature in the lines is assumed to be 121°C. The transient shutdown losses are estimated using the calculation procedure described above for SYL, NAK, and STM.

System Pressure Drop

System pressure drops were estimated using the same methodology as for the SEN systems, described above, with the following exceptions:

1. The supply and return lines were treated separately as the composition of the gases (reactants and products) and their temperatures (and hence also their average densities and bulk velocities) differed between the two lines.
2. The receiver and central conversion component pressure drops were different:

$$\begin{aligned}\Delta p(\text{ENDO REAC} + \text{RCP}) &= 0.10 \text{ MPa} \\ \Delta p(\text{EXO REAC} + \text{CHX} + \text{RCP}) &= 0.069 \text{ MPa}\end{aligned}$$

Pump Work

For steady, adiabatic, ideal gas flow:

$$W_P = 10^{-6} t_{OP} \left(\frac{\dot{m}_f}{\eta_P} \right) \left(\frac{R T_i}{M_i} \right) \left(\frac{\gamma}{1 - \gamma} \right) \left[r^{\left(\frac{\gamma - 1}{\gamma} \right)} - 1 \right] \quad (\text{GWh/y})$$

where: $R = 8.3141 \text{ (kJ/(mol-K))}$

$T_i = \text{Gas temperature at pump inlet (K)}$

$M_i = \text{Gas molecular weight at pump inlet (kg/mol)}$

$\gamma = \text{Isentropic exponent}$

$r = p_o/p_i$ Pressure ratio at pump inlet, where:

$$p_o = p_i + \Delta p_P$$

PERFORMANCE PARAMETERS

Values of the principal performance parameters for the sixteen systems analyzed are presented in Table A-1.

Table A-1 Performance Parameters

System	T _o (°C)	Receiver		Transport System							Overall System		
		η _{REC} (%)	Q _{LREC} (GWh/y)	Q _{WF} (GWh/y)	M _I (kg/s)	Q _{LS} (GWh/y)	Q _{LR} (GWh/y)	Q _{LN} (GWh/y)	Δp (kPa)	W _p (GWh/y)	η _{TRN} (%)	Q _o (GWh/y)	η _{C/T} (%)
CH4	400 ↓	86	25	154	15	9	2	0	321	1.7	90	143	^a 66
SO3		86	25	154	52	3	5	1	460	10.5	74	145	54
NAK		97	6	173	381	15	12	5	476	1.2	80	141	65
SYL		97	6	173	165	15	12	4	545	0.7	81	142	66
CH4	540 ↓	86	25	154	16	9	2	0	335	1.9	89	143	65
SO3		86	25	154	56	3	6	2	499	12.1	69	143	51
NAK		95	8	171	368	20	11	8	465	1.2	76	132	61
STM		95	8	171	136	20	11	17	360	12.8	50	123	40
CH4	675 ↓	76	42	137	13	7	2	0	305	1.6	90	128	59
SO3		76	42	137	52	3	7	2	441	10.9	68	125	44
NAK		93	13	166	344	21	16	9	462	1.1	70	120	55
STM		93	13	166	130	21	16	21	361	16.3	35	108	28
CH4	815 ↓	76	42	137	21	8	3	0	275	2.3	87	126	57
SO3		76	42	137	94	5	11	2	314	14.7	54	119	35
CS		88	21	158	127	32	21	8	827	0.3	33	97 ^b	25 ^b
STM		88	21	158	103	32	21	28	354	14.9	21	77	15

^a Includes η_{CON} = 85%.

^b Includes Q_{HT} = 14.8 (GWh/y).

ECONOMICS

INPUTS

Inputs required for computing levelized energy costs (LECs) using the required revenue methodology of Doane et al. [27] include estimates of the installed capital costs and annual O&M costs, which are presented in Tables A-2 and A-3, respectively, and the estimated annual energy output, Q_o , which is given in Table A-1.

ASSUMPTIONS

Values assumed for many of the economic parameters used in the calculations are given in Table 6. Values for the remaining parameters are given below.

First Year of Commercial Operation (y_{co})	1984
Price Year of an Expenditure (y_p)	1984
Year of a Particular Cash Flow (y_t)	
Construction: ($y_1 - y_3$)	1981 - 1983
Depreciation: ($y_1 - y_5$)	1984 - 1988

METHODOLOGY

Cursory definitions of the terms in the LEC expression (Equation (6)) are given below. A complete and detailed development of the required revenue methodology is given in Reference 27.

General Inflation Factor: $(1 + g)^{-d}$

where: $d = y_{co} - y_b$

Capital Recovery Factor:

$$CRF_{r,N} = \frac{r}{1 - (1 + r)^{-N}}$$

$$CRF_{r,N} = 0.11746 \quad \text{for } r = 10\% \text{ and } N = 20 \text{ years}$$

Table A-2 Installed Capital Costs (1984\$)^a

System	T _o (°C)	Transport System										Overall System	
		Piping	Insulation	Pump/ Blower	Endo. React. & Recup.	Exo. React. & HX	User HX	Bellows Seals - 3 Valves /coll.	Flex Hoses, Base Cont. Valves	Misc. Elec. Controls	Working Fluid Charge	Total Trans. System Costs	Total Costs
CH4	400	0.672	—	0.100	1.380	0.220	—	—	1.380	0.150	0.001	3.903	21.073
SO3	↓	1.056	1.054	0.150	1.380	0.220	—	—	—	0.150	0.010	5.400	22.570
NAK	↓	1.287	1.449	0.300	—	—	0.080	1.050	—	0.500	1.500	7.546	24.716
SYL	↓	0.753	1.142	0.045	—	—	0.080	—	—	0.080	0.550	4.030	21.200
CH4	540	0.679	—	0.100	1.380	0.220	—	—	—	0.150	0.001	3.910	21.080
SO3	↓	1.112	1.074	0.150	1.380	0.220	—	—	—	0.150	0.010	5.476	22.646
NAK	↓	1.302	2.138	0.300	—	—	0.080	1.050	—	0.500	1.500	8.250	25.420
STM	↓	7.192	4.412	0.750	—	—	0.300	—	—	0.600	0.0001	14.634	31.804
CH4	675	0.783	—	0.125	1.380	0.220	—	—	—	0.150	0.001	4.039	21.209
SO3	↓	1.121	1.080	0.200	1.380	0.220	—	—	—	0.150	0.010	5.541	22.711
NAK	↓	1.293	2.360	0.300	—	—	0.080	1.050	—	0.500	1.400	8.363	25.533
STM	↓	7.421	5.516	0.750	—	—	0.300	—	—	0.600	0.0001	15.967	33.137
CH4	815	0.924	—	0.125	1.380	0.220	—	—	—	0.150	0.001	4.180	21.350
SO3	↓	1.953	1.301	0.200	1.380	0.220	—	—	—	0.150	0.010	6.594	23.764
CS	↓	1.762	6.994 ^b	0.100	—	—	0.200	1.050	—	0.150	0.590	12.226	29.396
STM	↓	7.531	7.455	0.750	—	—	0.300	—	—	0.600	0.0001	18.016	35.186

^a All costs in M\$ unless otherwise specified.

^b Includes insulation (2.238 M\$) and heat trace system (4.756 M\$).

^c Based on 2 k\$ per collector.

^d Includes cost of catalyst, estimated to be \$20 per kg.

^e Based on \$500 per seal x 2100 valves.

^f Assume 2 k\$ per collector.

^g Includes 140\$/m² for concentrators, 30\$/m² for receivers, and 50\$/m² for B.O.P.

Table A-3 Annual O&M Costs (1984\$)^a

System	T _o (°C)	Transport System			Total Transport System Costs	Collector Costs	Overall System Total Costs
		Materials	Labor	Parasitics			
CH4	400	50	150	b 101	301	250	551
SO3	↓	75	150	627	852		1,102
NAK	↓	90	120	71	281		531
SYL	↓	30	120	42	192		442
CH4	540	50	150	111	311		561
SO3	↓	75	150	728	953		1,203
NAK	↓	90	120	70	280		530
STM	↓	10	120	768	898		1,148
CH4	675	50	150	94	294		544
SO3	↓	75	150	652	877		1,127
NAK	↓	90	120	68	278		528
STM	↓	10	120	976	1,106		1,356
CH4	815	50	150	137	337		587
SO3	↓	75	150	884	1,109	1,359	
CS	↓	30	250	905 ^c	1,185	1,435	
STM	↓	10	120	892	1,022	1,272	

^a All costs in k\$/y unless otherwise specified.

^b Based on 6¢/kWh, primarily for pump work.

^c Includes cost of both pumping (17 k\$/y) and heat tracing (888 k\$/y).

Total installed capital costs (investment expenditures):

$$CI_{Tot} = (1 + C_{ind}) \sum_e CI_e$$

where: CI_e = individual or classes of capital expenditures, e.g., collectors, piping, pumps, reactors, heat exchangers, controls, working fluid, etc.

These expenditures are assumed to occur in three equal disbursements over the three year construction period. Thus, the capital expenditure in year y_t , expressed in y_p dollars, is:

$$CI_t = \frac{CI_{Tot}}{N_{con}}$$

Present Value of Installed Capital Costs:

$$CI_{pv} = (1 + g_c)^p \sum_{t=1}^{N_{con}} \left[CI_t \left(\frac{1 + g_c}{1 + r} \right)^j \right]$$

where: $p = y_{co} - y_p$

$j = y_t - y_{co} + 1$

Present Value of Recurrent Costs (OP, MNT, & FL):

For cost streams that grow at a uniform rate (escalation):

$$X_{pv} = \begin{cases} (1 + g_x)^p X_o \left(\frac{1 + g_x}{r + g_x} \right) \left[1 - \left(\frac{1 + g_x}{1 + r} \right)^N \right] & \text{if } r \neq g_x \\ (1 + g_x)^p X_o N & \text{if } r = g_x \end{cases}$$

where: X = OP, MNT, or FL

X_o = Cash flow in year y_{co} expressed in y_p dollars

g_x = The appropriate uniform escalation rate

Depreciation:

Annual Depreciation: $DEP_t = P_t CI_{pv}$

where: DEP_t = Depreciation in year y_t expressed in y_t dollars

P_t = Depreciation percentage for year y_t from the appropriate ACRS table for n years

Present Value of Annual Depreciation:

$$(\text{DEP}_t)_{\text{pv}} = \frac{\text{DEP}_t}{(1+r)^j} = \text{CI}_{\text{pv}} \left(\frac{P_t}{(1+r)^j} \right)$$

where: $j = y_t - y_{\text{co}} + 1$

$$\text{also: } \text{PV}\{\text{DEP}_t\} = \sum_t (\text{DEP}_t)_{\text{pv}} = \text{CI}_{\text{pv}} \sum_t \left(\frac{P_t}{(1+r)^j} \right)$$

Depreciation Factor:

$$\text{DPF}_{m,r,n} = \frac{\text{PV}\{\text{DEP}_t\}}{\text{CI}_{\text{pv}}} = \sum_t \frac{P_t}{(1+r)^j}$$

where: m = method of depreciation
 r = discount rate
 n = accounting lifetime

$\text{DPF}_{m,r,n} = 0.74978$ for $m = \text{ACRS}$, $r = 10\%$, and $n = 5$ years.

Annualized Fixed Charge Rate:

$$\overline{\text{FCR}} = \text{CRF}_{r,N} \left[\frac{1 - \tau \text{DPF}_{m,r,n} - \alpha}{(1 - \tau)} \right] + (\beta_1 + \beta_2)$$

$\overline{\text{FCR}} = 0.13336$ for the present assumptions.

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