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THE POTENTIAL FOR SUPPLYING SOLAR THERMAL ENERGY TO INDUSTRIAL UNIT OPERATIONS

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NOTICE

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ABSTRACT

Previous studies have identified major industries deemed most appropriate for the near-term adoption of solar thermal technology to provide process heat; these studies have been based on surveys that followed standard industrial classifications. This paper presents an alternate, perhaps simpler analysis of this potential, considered in terms of the end-use of energy delivered to industrial unit operations. For example, materials, such as animal feed, can be air dried at much lower temperatures than are currently used. This situation is likely to continue while economic supplies of natural gas are readily available. However, restriction of these supplies could lead to the use of low-temperature processes, which are more easily integrated with solar thermal technology. The adoption of solar technology is also favored by other changes, such as the relative rates of increase of the costs of electricity and natural gas, and by energy conservation measures. Thus, the use of low-pressure steam to provide process heat could be replaced economically with high-temperature hot water systems, which are more compatible with solar technology. On the other hand, for certain operations such as high-temperature catalytic and distillation processes employed in petroleum refining, there is no ready alternative to presently employed fluid fuels.

INTRODUCTION

Major reports published by Battelle (1977) and InterTechnology Corporation (ITC) (1977) contain surveys of industrial energy usage based on standard industrial classifications. An analysis of typical processes employed in each industry determined the quantity of fuels used for industrial process heat (IPH) and the temperature requirements of these processes. Of the 21 quads* of energy consumed by industry in 1976 (American Petroleum Institute 1977), 68% is estimated to have been used for process heating, distributed in the temperature ranges illustrated in Fig. 1 (ITC 1977).**

Just over 50% of industrial process heat is used at temperatures above 593°C (1100°F). The industries operating in this temperature range are few, chiefly primary metals; stone; clay and glass products; and chemicals. The number of facilities operating such high-temperature, energy-intensive processes is also small. For instance, in 1973 there were only 43 integrated iron and steel plants in the United States.

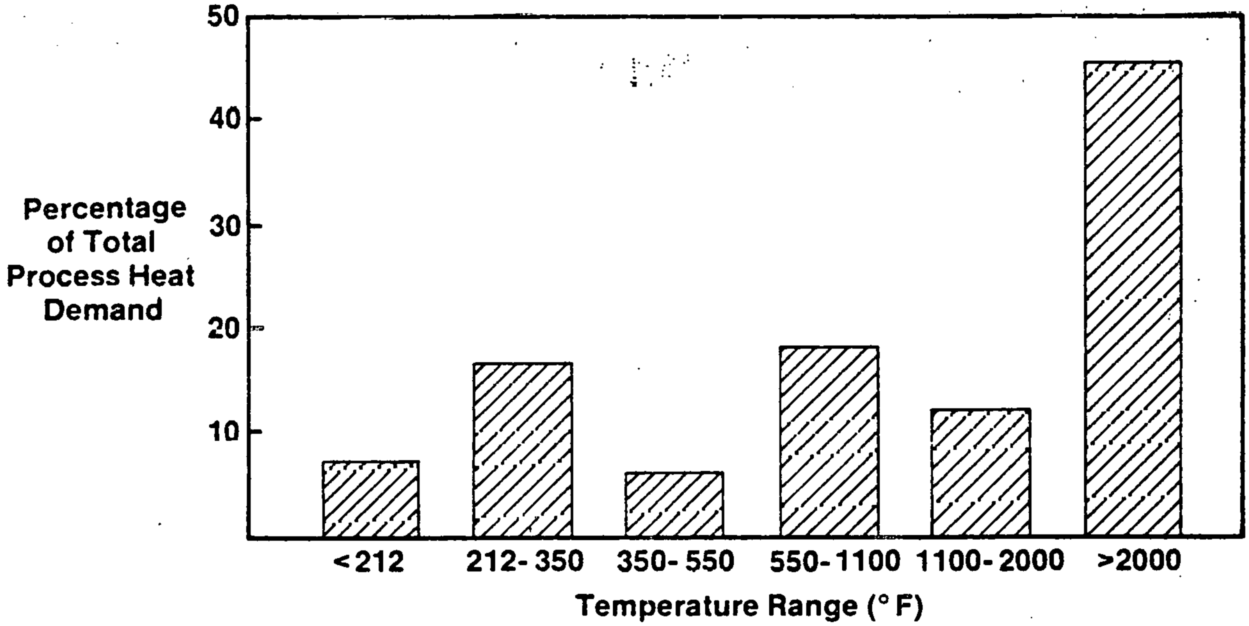

Figure 1. Distribution of Industrial Process Heat Demand by Temperature Range (1974)

*A quad is 10^{15} Btu (1.055×10^{18}J).

**Recent ongoing studies at the Solar Energy Research Institute (SERI) suggest that the Battelle and ITC reports overestimate the quantities of IPH consumed at high temperatures. Actual consumption seems to be distributed more toward the low-temperture ranges. The ITC data suffice, however, to illustrate the points made in this paper.

Over 95% of process heat in the range of 288° to 593°C (550° to 1100°F) is consumed by the petroleum refining industry (Ketels and Reeve 1979). Currently, 297 domestic oil refineries are operating (Cantrell 1980). This range also encompasses the temperatures at which steam is generally produced for electrical generation.

Process heat used below 288°C (550°F) comprises about 28% of the total used by industry. The number of plants operating low-temperature industrial processes is extremely large. For instance, there are approximately 2900 textile and 2500 dairy establishments. Such plants are widely scattered and are much less energy-intensive than plants operating high-temperature processes. It is postulated in this paper that these plants operating low-temperature processes offer the most favorable market for the near-term application of solar thermal technology to provide industrial process heat. By matching process temperature requirements as closely as possible with solar collector operating temperatures, industrial unit operations are broadly ranked according to the ease with which solar radiation can be economically utilized as a source of heat.

SOLAR TECHNOLOGIES

High-Temperature Applications

From both a technical and economic viewpoint, there are great obstacles to applying solar thermal technology to industrial processes requiring temperatures of 593°C (1100°F) or higher. Solar furnaces can generate extremely high temperatures, but the adaption of such technology to industrial processes in the iron and steel industry, for instance, would require the transfer and transport of energy at temperatures outside the operating range of normally available materials. Significant problems involving creep, thermal fatigue, and their interaction need to be overcome (Murr 1980). Major breakthroughs in materials technology will be required before the application of solar energy at temperatures greater than 593°C is technically feasible.

Coal presents serious competition to any possible use of solar energy for high-temperature processes. It is a very economical form of energy and most high-temperature processes can readily use coal as a source of fuel. In iron production, there is no easy substitute for the reducing properties of carbon. High-temperature processes are heated by direct contact of the flue gas with the process material—a very efficient heating method. Equipment design can result in a high degree of air and charge preheat. The large size of high-temperature operating facilities greatly enhances the economics of coal distribution, storage, and handling, and can justify the expense of environmental controls when necessary. Sometimes coal can be burnt with minimal environmental effects; for example, in lime production the product efficiently absorbs fly ash and sulfur. In short, for the near term at least, it is improbable that solar technology will find any applications for process heating at temperatures above 593°C.

Intermediate-Temperature Applications

The technical feasibility of using solar technology to generate IPH in the range of 288° to 593°C can be determined by a study of the predominant user: the petroleum refining industry. Total energy consumption of this industry is about 11% of the energy content of the crude processed (Gordian Associates 1976). This amount is equivalent to about 1.5 million barrels/day of crude oil or nearly 4% of total U.S. energy consumption.

The technical characteristics of refinery process heat use are apparent from a study of the schematic of the naphtha reforming unit illustrated in Fig. 2. To minimize power inputs to the compressor and for process reasons, pressure drop through the recycle system is kept as low as possible. This requires specialized design of heaters, reactors, and exchangers. Refinery units are crowded into the processing area to reduce piping runs and to allow fluids to be transported between units with minimal temperature and pressure drops. Fired heaters operating on fluid fuels allow extremely high rates of heat transfer. Such fuels have very consistent properties, thus permitting the accurate temperature control so important to catalytic processes.

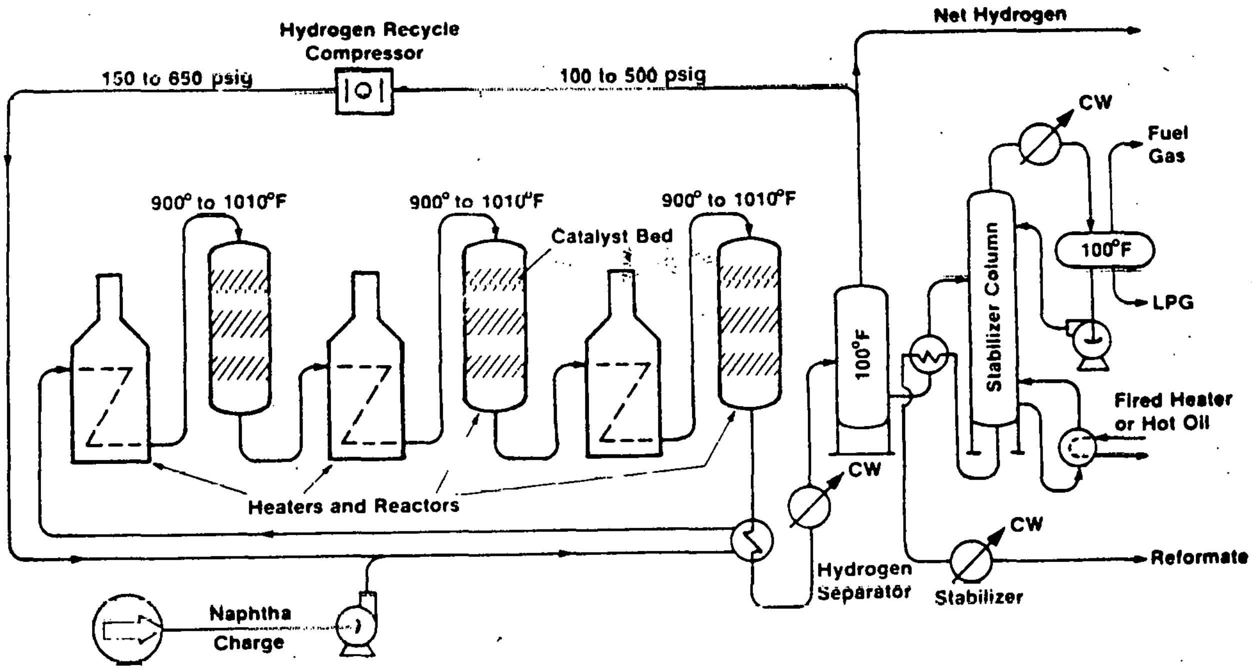

Figure 2. Catalytic Reforming

It is difficult to conceive of a solar system operating with the performance of fired heaters and fitting into the refinery processing environment. A fired heater is compact and allows very high rates of heat transfer with minimal holdup, low pressure drop, and accurate temperature control. A solar hot-air system would have to operate well in excess of 593°C (1100°F) to duplicate the flame temperature of a fired heater. Space limitations could hinder the integration of such a solar system into the refinery processing area. A heat exchanger is an alternative, but it could scarcely meet all the above-mentioned criteria. Again, there is the problem of heat transfer medium. Operations above about 371°C (700°F) are outside the range of commercially available heat transfer liquids and would probably involve the use of molten salts or metals. The mechanical specifications of a hydrocarbon/molten-salt exchanger would be extremely rigorous and molten salts or metals, particularly for safety reasons, are not desirable media to be pumped around an oil refinery. In summary, the application of solar thermal technology to petroleum refinery processes operating above 371°C presents numerous technical difficulties. In fact, serious problems attend the application of solar technology to practically every industrial process operating above 371°C. Feasible, economically attractive applications of solar energy above this temperature seem to be confined to the large-scale generation of electrical energy to replace natural gas and fuel oil.

Low-Temperature Applications

The above discussion highlights the technical difficulties in applying solar-derived process heat to industrial operations conducted at temperatures in excess of 371°C (700°F). Few such difficulties exist in using solar technology to provide heat to processes operating below 371°C. Flat-plate collectors or solar ponds can deliver temperatures up to about 82°C (180°F). Evacuated-tube collectors operate up to about 149°C (300°F), and line-focusing collectors—for example, parabolic troughs—operate with reasonable efficiency up to about 288°C (550°F). Central-receiver technologies utilizing the "power-tower" concept allow high solar concentration ratios to be achieved. Consequently, a temperature of 371°C is easily within their operating range, and such a temperature allows the use of commercially available heat transfer fluids as energy transport media.

Most of the countless number of plants operating industrial processes below 371°C use relatively little energy. Such facilities typically burn premium fuels such as natural gas or distillate, and, consequently, they are particularly vulnerable to large increases in fuel costs or curtailments. Coal is rarely considered an option due to its inherent environmental problems. Apart from the largest heating requirements, low-temperature IPH needs could probably be met using the less sophisticated, fairly well developed solar technologies, such as parabolic troughs, flat-plate collectors, or solar ponds. Some industries do have very large demands for low-quality process heat. The corn processing industry uses considerable quantities of hot water and low pressure steam. Several mining operations—for example, the processing of uranium ore—use fuel primarily to heat water. About 20% of the total energy supplied to a refinery is used to provide process heat at temperatures below 371°C (May 1980). The energy intensity of refineries is such that even this fraction represents nearly 0.8 quad or about 1% of the total U.S. energy consumption. This energy is primarily used for the reboiling of distillation columns, where considerations of pressure drop and temperature control are much less critical than for catalytic processes and where conventional heat exchangers and heat transfer fluids can be used. The cogeneration of electrical power and process heat is always an option for large users of low-temperature heat if the dual uses are suitably matched. The size of the solar collector field for large-scale applications could favor central-receiver technology. For large fields, compared to distributed-receiver technology, the increased thermal efficiency and reduced piping costs and electrical inputs of a central-receiver system could prove economically advantageous.

The large number of plants operating low-temperature industrial processes is an advantage in that the characteristics of some will be favorable to the early application of solar technology; e.g., high fuel costs, location in a rural area with high levels of solar radiation, and progressive management. On the other hand, this diversity can be a disadvantage because small plants may not have skilled technical and engineering work forces, intense competition can discourage risks not associated with the development of new products, investment capital may be lacking, and personnel may not have access to the required information. Some of these issues are addressed by the approach described in the following section.

LOW-TEMPERATURE UNIT OPERATIONS

End-Use Matching

One aspect of the work carried out at the Solar Energy Research Institute (SERI) has been an industrial case studies program aimed at determining the near-term economic and technical feasibility of applying solar thermal technology to industrial processes. Most studies have been performed in response to inquiries from industry. We have found that some of the best prospects for the application of solar systems were overlooked by the large-scale surveys of industrial energy use. There is a need to disseminate information to firms regarding conservation measures and alternative energy sources. Future industrial decision making concerning energy use is likely to involve much more than a selection of the appropriate size of steam generator. A simplified means of evaluating the potential of solar technology could be extremely helpful in this decision process. One means of simplifying this evaluation is to focus on the end use of energy delivered to industrial unit operations.

A major requirement in considering the application of any solar technology is to closely match the solar collector outlet temperature with the required industrial process temperature. This gives rise to the concept of "end-use matching." The performance of all solar thermal systems is affected by thermal losses to an extent much greater than conventional heat generating equipment. As a result, their efficiencies depend quite strongly on the collector operating temperature. It is also generally true that less sophisticated collectors, such as flat-plate collectors operating in their efficient temperature range, can deliver energy more cheaply than more complicated collectors, such as parabolic troughs. The end-use matching approach is analogous to maximizing Second Law (the Second Law of Thermodynamics) efficiency, and it allows some important conclusions to be made regarding the potential of solar thermal technology for providing industrial process heat.

The unit operations of drying, evaporation, crystallization, distillation, baking, and extraction, as well as general heating for applications such as pasteurization, reactor heating, cleaning, dissolving, and sterilization, are universal throughout industry and are often carried out at temperatures below 371°C. For process temperatures below about 204°C (400°F), steam is the preferred heat-transport medium, even though about 7.5% of total process heat usage occurs at temperatures below 100°C, mainly to heat water. To provide heat to processes operating in the 204° to 371°C range, direct-fired heaters are generally employed. Alternatively, heat can be transferred to the process through the use of a circulating heat transfer fluid. Such fluids are generally used when it is not possible to pump the process fluid through the coils of a heater, when it is desired to distribute heat to various locations from a centrally located heater, or for safety reasons.

Industrial processes for which direct solar heating of the process medium is possible afford the opportunity to match closely collector and process operating temperatures. If freezing is not a problem, applications such as distillation, cleaning, sterilization, and dissolving are particularly favorable. Obviously, because the performance and cost of solar collectors depend strongly on operating temperature, the lowest-temperature applications are most favorable. In fact, before the installation of any solar system is contemplated, a thorough analysis of the industrial process is required to determine the operating temperature actually required by the process. This temperature is not necessarily the historical operating temperature.

If possible freezing of the collector fluid presents problems, the above processes and the operations of evaporation, crystallization, and pasteurization are best carried out by the transfer of heat from a heat transfer fluid circulating through the solar collectors. Such operations entail increased equipment costs and lower collector performance resulting from the higher operating temperatures.

Drying, baking, and curing involve heating air. While drying is theoretically possible at almost any temperature, baking and curing are generally carried out at fairly high temperatures, typically about 204° C. Present industrial practice generally is to use direct gas-fired heating. Technological limitations preclude a favorable matching of these processes with solar collector operating temperatures because the efficiency of solar air collectors is poor at temperatures much greater than those required for space heating. Also, moving compressible fluids through great lengths of collector piping consumes considerable quantities of electrical energy. The technical solution for solar hot-air applications at temperatures too high to allow direct heating is to use a liquid heat transport medium and a liquid/air exchanger. This necessity renders unit operations requiring hot air at temperatures greater than about 82° C (180° F) the least favorable solar applications. However, pursuing the end-use matching approach leads to some important insights regarding the drying process and the use of steam as a heat transport medium.

Applications of Solar Energy to the Drying Process

The drying process offers a unique opportunity for the application of solar technology. Drying is a major consumer of industrial process heat and many drying processes operate at temperatures below 288° C. All manner of materials, such as food, lumber, painted and printed materials, and metal ores, are dried. The energy content of biomass and wet coal is enhanced considerably by drying. Much drying is carried out at quite low temperatures to avoid degradation of the material. For instance, plastic films must be dried at temperatures below 93° C (200° F), and lumber-drying kilns typically operate at 38° to 82° C (100° to 180° F). A considerable amount of drying is also carried out at temperatures up to about 649° C (1200° F), although, from a thermodynamic point of view, drying is possible at almost any temperature.

Drying at high temperatures reduces the residence time of the process material, and this reduces the size and capital cost of the drying equipment. Most drying takes place near the wet-bulb temperature and this tends to prevent thermal degradation of the dried product. Often, some loss of quality—for example, in drying animal feed—can be tolerated. High-temperature drying is more efficient thermally and requires less electrical power than drying at low temperatures because of the reduced quantities of air involved. For instance, drying an agricultural product using air at 121° C (250° F), as opposed to air at 316° C (600° F) (assuming the same relative humidity at the dryer outlet), requires 1.6 times the thermal input and 4.8 times the air flow rate. It is unlikely that low-temperature solar energy could be supplied so cheaply as to compensate for such inefficiencies. However, several factors enhance the potential of the solar drying process. First, the drying of materials, particularly at high temperatures, entails high gas velocities, and carry-over of solid material can cause particulate pollution problems. Drying at low temperatures requires longer contact times and hence reduced gas velocities, and the pollution potential is lowered. Second, the drying of many materials at high temperatures—for example, food products such as milk—depends on the direct use of clean-burning natural gas. The supply of natural gas is uncertain. The alternatives to natural gas are probably fuel oil or coal (if available and environmentally acceptable) for generating steam to run an indirect, air-heating process for drying. Such a change brings the drying process into a temperature range that is readily attainable through the use of solar collectors. Finally, and most importantly, if solar technology is a viable alternative, problems of low thermal efficiency and high power inputs, which are inherent to low-temperature drying processes, can be overcome by the direct exposure of the process material to solar radiation. One can envision a transparent glazing over a slowly moving conveyor. Besides providing highly efficient use of solar radiation, which could replace several times the equivalent number of Btu's obtained from conventional sources of fuel, such a system could be constructed very cheaply. The rate of air flow need be sufficient only to control the humidity level of the outlet gas. Gas velocities would be so low as to present little possibility of entrainment. Materials for which the possibility of contamination is not a problem, such as coal, animal feed, biomass prior to combustion, and corn, are prime candidates for such drying. Coal is particularly appropriate because it is a good absorber of solar radiation.

High-Temperature Water as an Alternative to Steam for Heat Transport

Steam has become the universal, low-temperature, heat transport medium even though it is often generated at temperatures far in excess of the required process temperature, and even though few processes other than steam-stripping or humidification necessitate its use. Package steam boilers are available "off the shelf" to meet a wide variety of process heat requirements. They are compact, rapid in response, and extremely reliable. Pumping power requirements are low, and the feed water pump runs at a low temperature, though at high head. The condensation process allows large quantities of heat to be transferred at a constant temperature and low mass flow rate—a particular advantage for direct process heating. However, a body of trade literature (Teller 1976) advocates that the package steam boiler is a relic of the era of low fuel costs. Process heating using high-temperature water (HTW) is feasible up to about 204°C for replacing saturated steam as a heat transport medium. Above this temperature, heat transfer fluids with lower vapor pressure can be used. Liquid systems, compared to steam systems, allow more accurate process temperature control. Energy and money are saved as a result of reductions in water makeup, treatment, and blowdown. The large thermal mass of liquid systems reduces fluctuations in heater output, thus improving heater efficiency and reducing wear. Water is a convenient medium for thermal energy storage. Fewer fittings and less corrosion potential also reduce maintenance costs. The use of HTW to transport heat over large distances appears to offer significant economic benefits compared to any other medium (Hausz 1979).

A switch from steam to more energy-efficient, liquid-based systems involves a trade-off between the present cost of capital and future energy savings. The liquid system requires greater heat transfer area on the process side, larger return lines, and a large additional circulating pump. If fluid fuels are being replaced as energy costs rise much faster than inflation, the balance should continue to shift in favor of capital investments. Another trade-off common to energy conservation measures and to the use of solar systems concerns the relative cost of energy used as heat versus the cost of increased use of electrical power. Energy-saving measures such as HTW systems, forced-draft furnaces, or vapor recompression cycles greatly complicate a process and require additional electrical inputs. However, because the price of electricity in most parts of the United States is based largely on coal, nuclear, and hydroelectric sources, the cost of electricity is likely to increase at a lower rate than the costs of either oil or natural gas. From 1972 to August 1979, for example, the cost of industrial electricity rose

150%, compared to 499% for the wellhead price of natural gas and 364% for the price of refinery fuel oil (Farrar 1980). The relative stability of electricity price and supply has also increased the use of electricity for industrial heating purposes.

The Advantages of Liquid-Based Solar Systems

Although the relative merits of HTW and steam systems for the provision of IPH can be argued, there is no doubt that conditions favoring the industrial installation of liquid heating systems would drastically improve the economics of solar-derived energy. It is relatively easy to retrofit liquid-based heating systems. Figure 3 illustrates one commonly used solar steam system. To prevent boiling in the receiver tubes (the effects of which are unknown), high-pressure water is pumped through the collectors. Steam is generated by flashing across a pressure-reducing valve and discharging into a vapor/liquid separator. Pressure drop through the system is high and, as a result, electrical parasitic power consumption is high. The solar collectors must operate at temperatures much higher than the steam temperature, at considerable detriment to their efficiency. Figure 4 illustrates how a solar system could be integrated into a HTW pasteurization process operated by a dairy. An expansion tank is already a feature of the existing liquid heating system. Solar collectors are simply added as an additional loop.

Liquid-based solar systems allow a close match between technology and process temperature, which is consistent with the end-use matching approach . Thus, flat-plate collectors or solar ponds, in particular instances, could be used to provide heat at temperatures below about 82°C. Using such technologies to produce hot water is a much more favorable solar option than adapting completely to the existing, conventional energy delivery system, which would probably entail the generation of steam at a much higher temperature.

SUMMARY

The major near-term impact of solar energy in the field of industrial process heat is most likely to occur in industries operating processes at temperatures below 371°C (700°F). The potential users in this market constitute the vast majority of all industrial establishments.

Through a procedure of matching the operating temperature of a solar collector as closely as possible with the industrial process temperature, unit operations have been broadly ranked with respect to their suitability for solar energy applications. Processes such as distillation and the heating of water for cleaning purposes, which allow the direct solar heating of the process medium, are highly favorable solar applications. Processes such as evaporation and crystallization, which require indirect heating, rank next. The least suitable process applications involve the heating of air to high temperatures. However, the drying process is a unique opportunity to provide solar IPH economically and on a large scale. Solar drying, as envisioned here, would involve a revolution in currently employed industrial drying practices. It would require a return to age-old concepts of direct solar drying and the application of low-technology solar components.

Another processing consideration emphasized in this paper is the advantage of HTW systems for replacing steam as a heat transport medium. The increased use of HTW systems in industry considerably enhances prospects for the retrofit of solar IPH systems.

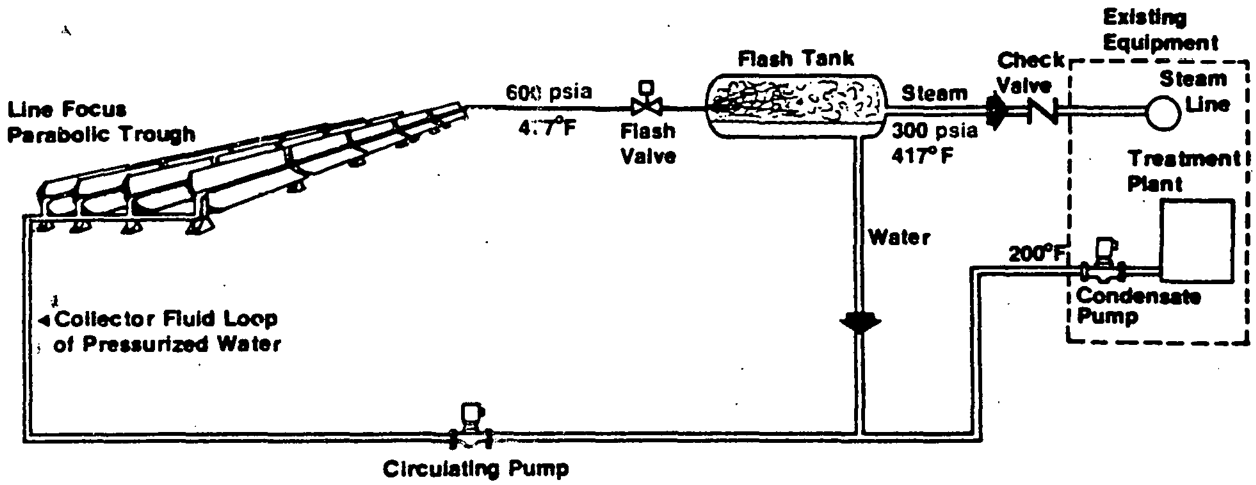

Figure 3. Flash Steam Generating System

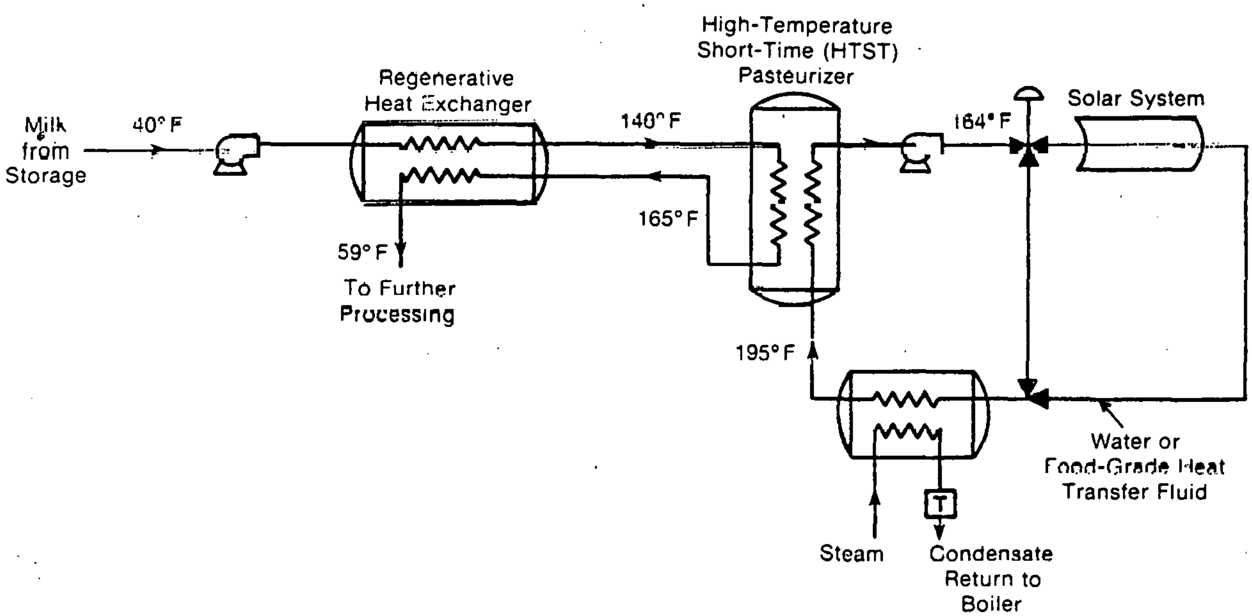

Figure 4. Solar-Heated Milk Pasteurization Process

Other factors, such as government policy and the cost of alternative fuels, will greatly influence the growth of the solar industry. While no one doubts the long-term potential of renewable energy resources, it is a fact that solar technology can have an immediate impact on the energy supplies. The lead time for installing solar systems is very short compared to other energy-producing technologies and the environmental problems are much fewer. This potential will be realized, however, only through the active participation of engineers in industry who have gained a working knowledge of solar technology. Perhaps what is needed more than anything else is a sense of commitment and a willingness to take some risks. The potential for solar technology to provide industrial process heat, and the benefits that this could bring, will only be realized if this commitment is forthcoming from government and from industries currently involved in the design, construction, and use of conventional energy facilities.

ACKNOWLEDGEMENTS

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