NREL/TP-432-5027 • UC Category: 234 • DE93000048

Current Performance and Potential Improvements in Solar Thermal Industrial Heat

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*Prepared for the 1993 ASME/ASES Joint Solar Energy Conference,
Washington, D.C., April 4-8, 1993.*

National Renewable Energy Laboratory
(formerly the Solar Energy Research Institute)
1617 Cole Boulevard
Golden, Colorado 80401-3393
A Division of Midwest Research Institute
Operated for the U.S. Department of Energy
under Contract No. DE-AC02-83CH10093

December 1992

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Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A01

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For presentation at the Solar Industrial Process Heating and Cooling session
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ABSTRACT

A representative current state-of-the-art system using parabolic trough technology was developed using data from a system recently installed in Tehachapi, California. A simulation model was used to estimate the annual energy output from the system at three different insolation locations. Based on discussions with industry personnel and within NREL, we identified a number of technology improvements that offer the potential for increasing the energy performance and reducing the energy·cost of the baseline system. The technology improvements modeled included an evacuated-tube receiver, an antireflective coating on the receiver tube, an improved absorber material, a cleaner reflecting surface, a reflecting surface that can withstand contact cleaning, and two silver reflectors. The properties associated with the improvements were incorporated into the model simulation at the three insolation locations to determine if there were any performance gains. The results showed that there was a potential for a more than 50% improvement in the annual energy delivered by a 2677 m^2 system incorporating a combination of the enumerated technology improvements. We discuss the commercial and technological status of each design improvement and present performance predictions for the trough-design improvements. We report on the economic impacts of these design improvements in Williams and Hale [1993].

INTRODUCTION

Solar thermal technologies are capable of providing heat across a wide range of temperatures, making them potentially attractive for meeting end-use energy requirements in industrial process heat (IPH) applications, commercial heating, and commercial cooling. Parabolic trough systems look very promising for delivering industrial process heat for applications in the 95°C to 350°C (200°F to 660°F) delivery-temperature range.

We developed the results in this paper as part of a study to investigate options to improve the economic competitiveness of IPH trough systems relative to fossil fuel sources. In this paper we focus on the effects of technological improvements on the annual energy output of trough systems. The economic impacts of these technological improvements are reported in Williams and Hale [1993].

We began this study by identifying research and development opportunities for solar trough technology that could substantially increase system performance or reliability. We developed and validated a computer model of a representative, state-of-the-art IPH parabolic trough system. Then, we used the model of the representative system to evaluate the relative effects of specific technology improvements on the energy performance of parabolic troughs. The technology improvements modeled included an evacuated-tube receiver, an antireflective (AR) coating on the receiver tube, an improved absorber material, a cleaner reflecting surface, a reflecting surface that can withstand contact cleaning, and two silver reflectors. We performed a simulation for each separate technology improvement and for a combination of improvements. In addition to the technology improvements, different parameters of the model were adjusted to evaluate the component improvements at different locations.

All the objectives of this study were aimed at developing a performance analysis tool to be used in conjunction with an economic analysis to identify technology improvements that could substantially reduce the energy cost of the parabolic trough technology. This report discusses the performance benefits of the technology improvements. Although system performance is not the criteria that determines whether trough systems can compete with fossil systems, it is an important parameter in the life-cycle cost calculation, and it can be improved through research and development.

STUDY APPROACH

A system performance code was needed to project the annual energy production of solar heat systems that are improved through research and development. After evaluating several computer solar system codes for this study, we selected A Transient System Simulation Program (TRNSYS, 1990) to use for the daily and annual performance evaluations. TRNSYS is a general purpose program with a modular structure that makes it readily adaptable to new system configurations. It has been used widely to model solar-thermal system performance. We used weather data from the Typical Meteorological Year (TMY, Hall, et al., 1978) as input to the TRNSYS model.

The system we selected to represent the current state of the art for trough heat was based on the recent trough installation at the California Correctional Institution in Tehachapi, California. We selected the Tehachapi system for several reasons. First, it is the most recent large-scale parabolic trough system installed in the United States, and it is one of the few major IPH trough systems installed in this country within the last several years.

The Tehachapi solar system collector rows are mounted on the ground and oriented along a rotational axis that is 35° off true north-south, or within 10° of northwest/southeast. (This orientation was chosen by the system designers to accommodate access to an electric line that runs above the center of the solar field.) The system has a 2677 m^2 (28,800 ft^2) aperture area, which corresponds to 16 12-module rows. The system fluid, which is 30% ethylene glycol and 70% water, averages 147°C (300°F) when it leaves the bank of collectors. The system transfers its thermal energy to the load through two serially connected heat exchangers which supply the load side with two different application temperatures, 104°C (220°F) and 54°C (130°F). The system does not include thermal storage. The back-up/auxiliary subsystems are a natural gas boiler and natural gas water heaters. A simplified diagram of the system is shown in Figure 1.

The efficiency and energy output of the Tehachapi system are readily available, so we used them as a baseline for calibrating the TRNSYS model. After calibration, the TRNSYS model was used to simulate a similar parabolic trough system at several sites in the western United States.

To determine potential technical improvements for the trough system, we relied heavily on support from industry. Industry contacts made suggestions for research and development that could improve the trough technology. This input was critical to ensure that the technical issues that we selected for evaluation in this study represented the most significant barriers to the full commercial development of the technology. Based on discussions with industry and within NREL, we identified a number of system improvements that could increase system performance while ultimately decreasing the system energy cost. Most of these improvements will require some level of research and development before commercial implementation, although the magnitude of the effort required varies considerably among the options.

We compared all system models incorporating technological improvements against a base-case system model. The base-case system incorporates component features that are being used commercially today for IPH applications in the 93°C to 350°C (200°F to 660°F) range. The base case is very similar to the Tehachapi system, but it has a true north-south orientation. The technology improvements we considered are summarized in Table 1 and discussed in the following paragraphs.

Evacuated-tube receivers can significantly reduce convective losses from the receiver, but they require additional equipment and production steps such as the addition of bellows and a getter for the vacuum and the labor to evacuate the receiver. Evacuated receiver technology for parabolic troughs has been commercially developed on a large scale only by LUZ and is not currently available to industry as a whole for commercial use. In our evacuated receiver model, we accounted for thermal losses from uninsulated bellows, flanges, and supports for every 10-foot receiver section.

The glass tube that envelopes the collector absorber can be made more transparent to light by applying an antireflective (AR) coating to the inner and outer surfaces. To date, LUZ is the only company that has used an AR coating. An AR coating that is currently being investigated for commercial development is sol-gel. Tests show that the sol-gel coating can raise the transmittance of the glass envelope from 0.91 to approximately 0.96 (Ashley, 1984).

Industry requires a durable absorber selective surface that is reasonably priced and readily available for purchase. We modeled a black chrome absorber in our base case; it has excellent absorber qualities (absorptance of 0.95 and emittance of 0.25), but its availability is poor and its price is high. In addition, difficulties in maintaining quality control during production can result in poor durability. A potential alternative for high-temperature (up to approximately 590°C) trough applications is a ceramic palladium material, cermet, that was used by LUZ. Cermet has excellent absorptance and emittance values (0.96 and 0.10, respectively), proven durability, and the potential for being less expensive than the black chrome (Lanxner and Elgat).

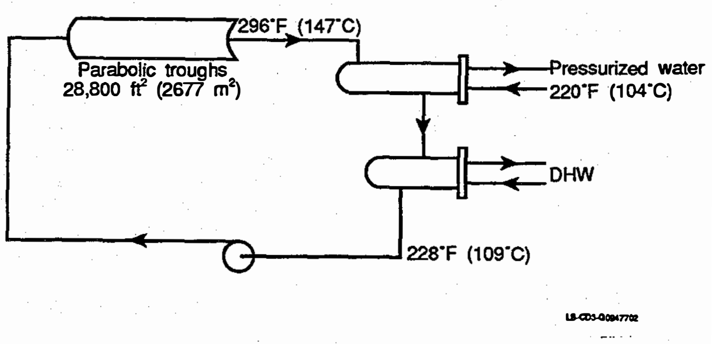

Figure 1: Solar System Diagram

Improved optical materials were identified as the key performance issue by many of the industry representatives that we contacted. The design we selected as the baseline system uses an aluminized polymeric reflective film, and hence the alternative reflectors we investigated were all improved polymeric films. An alternative that was not investigated was to use glass as a reflective surface. Glass would have some advantages over polymer reflectors (notably in durability), but also has significant drawbacks (cost and weight), and more importantly could not be simply substituted as a reflective material for the baseline collector design.

A clean trough reflector performs better than a dirty reflector. Reflectors can be kept cleaner by cleaning them more frequently or by using a nonsoiling reflector surface. Two options for such a surface include silvered Teflon and a renewable surface treatment. NREL has recently funded an industry research and development project to develop silvered Teflon, which shows promise to produce such a material at costs comparable to the baseline system's SA85 material. In our base case we modeled the average reflectivity as 90% of clean. For our soil-resistant case we modeled the average reflectivity as 95% of clean.

Another industry concern was how well reflective films can be cleaned. The polymers currently used in reflective films cannot be contact cleaned (e.g. with brushes) without risk of scratching. This means that once soiled, the polymer cannot be cleaned well enough to bring its reflectivity back to its new value. A scratch-resistant top coat over the reflective film would make contact cleaning possible and improve the reflection of the newly cleaned surface. We modeled clean reflectivity as 91% of new for the base case and 99% of new for the enhanced cleaning case.

An obvious approach to increasing the delivered energy from the collector is to substitute a higher-reflectance silvered polymer for the aluminized polymer in the baseline design. We modeled two different silver reflector cases, the commercially available polymer, ECP-305, and a goal-based polymer. We modeled the ECP-305 by increasing the average reflectivity from the baseline value of 0.83 to 0.92. The goal-based silvered polymer has the same reflectivity as ECP-305 and the enhanced cleaning capabilities of the scratch-resistant top coat.

The final case we modeled combined all the performance improvements described previously. The reflector was the case labeled "silver goal" (Table 1) that had an average reflectivity of 95% of clean, and the receiver had a cermet absorber surrounded by an evacuated-tube with an AR coating.

We modeled the system at three sites, Phoenix, Bakersfield, and Denver, in order to investigate if different climates affected the performance benefits associated with each technological improvement. These three cities supplied a range of insolation levels and ambient temperatures for comparisons.

VALIDATION

We compared the TRNSYS model predictions of collected energy with measured values to ensure that the model was accurate. For validation purposes, an annual energy-delivered comparison would have been preferred. However, the Tehachapi system was still in its start-up phase, annual energy values were not available, therefore, we compared simulated and measured energy on 2 days: December 24, 1991 and December 25, 1991. We chose these two days because of the availability of good data and the variation of insolation conditions. It should be noted that these 2 days represent perhaps the worst case of system performance due to soiled reflectors, low beam irradiance, and the solar position and short days associated with this time of year.

Plots of the energy comparisons for the two days are shown in Figures 2 and 3. Both of the plots show good agreement between the predicted and measured collected energy. On December 24 the modeled and measured collected energy differed by 13.3%; the modeled was 2.12 GJ (2.01 MMBtu) and the measured was 1.87 GJ (1.78 MMBtu). On December 25 the collected energy values differed by 10.3%; 7.15 x 10^{-1} GJ (6.78 x 10^{-1} MMBtu) were predicted by the model and 7.88 x 10^{-1} GJ (7.47 x 10^{-1} MMBtu) were measured. The shape of the two curves for December 25 are well matched except at the end of the operational period where the measured collected energy goes negative for approximately 40 minutes. During this time, the TRNSYS simulation assumes the system has stopped operating.

Table 1: Evaluated Technology Improvements

Name	Design Variation	Performance Benefit
Evacuated	Replace current receiver with evacuated receiver.	Reduced convective heat losses from receiver tube, based upon calculations in TRNSYS.
AR Coating	Add antireflective coating to the glass receiver cover tube.	Increase the cover glass transmittance from 0.91 to 0.96.
Cermet	Replace black chrome receiver coating with cermet surface.	Improve the selective surface absorber properties from the black chrome values (absorptance=0.95 and emittance=0.25) to the cermet values (absorptance=0.96 and emittance=0.10).
Increased Cleaning	Increase cleaning frequency to maintain reflectivity at 95% of clean values rather than 90%.	Set the average reflectivity to 95% of clean value rather than 90%.
Abrasion Resistant	Use reflective film with abrasion- resistant properties such that the film can be contact cleaned to restore its reflectivity to its new value.	Set the clean reflectivity to 99% of new value rather than 91%.
Current Silver	Replace SA85 reflective film with current commercially available ECP-305 silver film.	Increase the new reflectivity from 0.83 to 0.92.
Silver Goal	Replace SA85 reflective film with film having significantly improved cost and lifetime properties compared to current commercially available ECP-305 silver film.	Increase the new reflectivity from 0.83 to 0.92 and set the clean reflectivity to 99% of new value rather that 91%.
Combined	Use evacuated receiver with cermet surface and antireflective coating on cover tube, and the increased cleaning with the silver goal reflective surface.	Incorporate the first four performance benefits and the silver goal into the TRNSYS model.

There is also a small time shift between the two December 25th curves. The cause for the discrepancies between the December 25th model and measurements is a controller time-delay condition for start-up and shutdown that was not incorporated into the model. The features of this time delay are such that its effects would only be noticed on partly cloudy days.

Both of the days simulated show a period of negative energy collection at the beginning of the day. This occurred during the collector warm-up phase; during this period the collector fluid was warmer when it entered the collector than it was when it left the collector. This phenomenon is common for start-up of IPH solar systems and is more severe during the cooler winter months.

Both comparisons between the model-predicted and measured collected energies showed good agreement. Although the short duration of the comparison (two days) precludes it from being a full-scale model

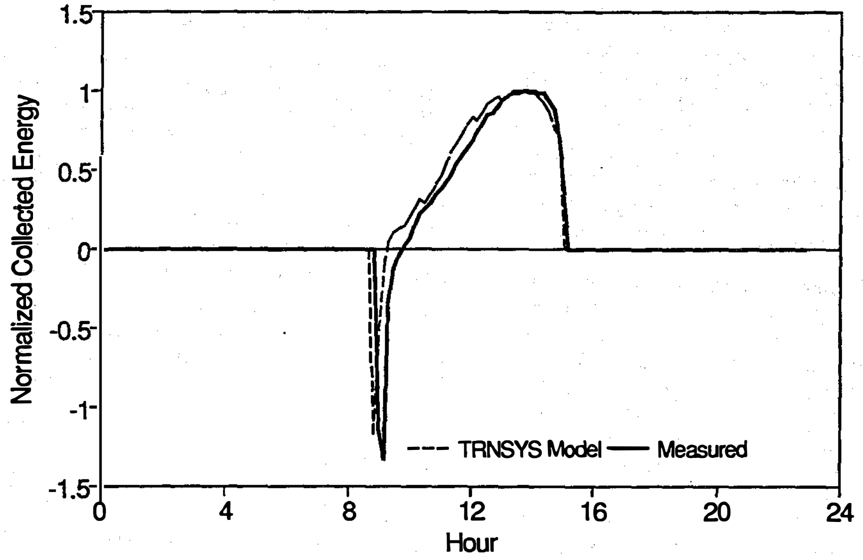

Figure 2: Comparison of TRNSYS Model to Measured Energy on December 24, 1991

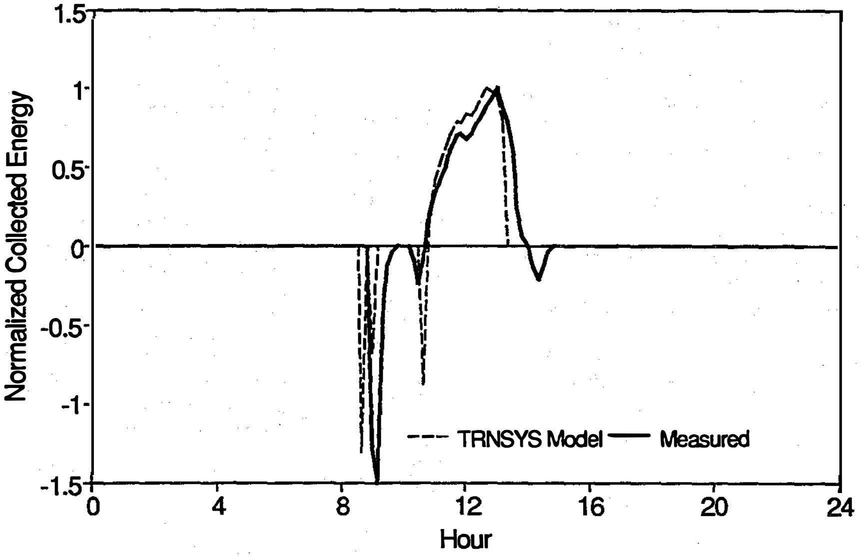

Figure 3: Comparison of TRNSYS Model to Measured Energy on December 25, 1991

validation, the comparison does support the accuracy of the TRNSYS model.

In addition to the comparison described above, we compared our model's energy output projections with Solar Industrial Process Heat (SOLIPH, Kutscher, 1983) model runs performed by Industrial Solar Technology (IST). SOLIPH has been used extensively for trough collector system modeling, and IST uses it extensively for their system design and performance predictions. SOLIPH estimated the annual energy output for the Tehachapi plant with only one load-side heat exchanger at 7696 GJ (7295 MMBtu). The annual energy output for the same system configuration predicted by the TRNSYS model was 7783 GJ (7377 MMBtu), within 2% of the SOLIPH estimates. This comparison also supports the validity of our TRNSYS model.

EVALUATION OF TECHNOLOGY IMPROVEMENTS

The performance gains resulting from each of the improvement options are illustrated in Figures 4 through 6; each figure shows performance results for a different site. The first bar in each plot, the base case, is the energy delivered by the baseline system. The predicted annual energy delivered is 7722 GJ (7319 MMBtu) by the base-case Phoenix site (Figure 4), 7283 GJ (6903 MMBtu) by the Bakersfield site (Figure 5), and 6171 GJ (5849 MMBtu) by the Denver site (Figure 6).

Of the receiver variations modeled, an evacuated receiver showed the greatest performance increase, improving the energy delivery of the baseline system by slightly more than 10% in Bakersfield and Phoenix and 13% in Denver. It is reasonable for the performance enhancement

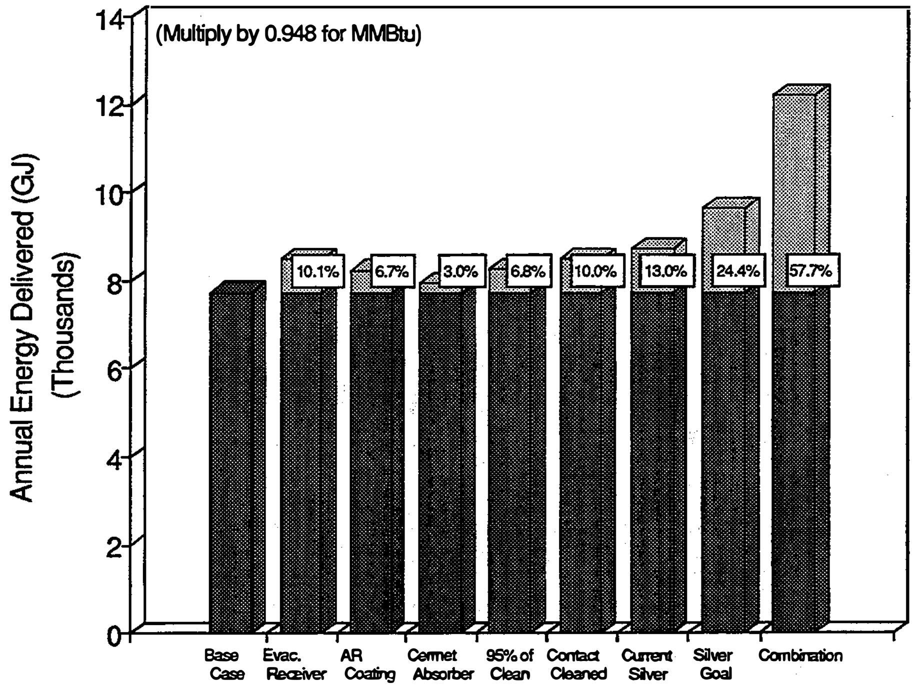

Figure 4: Projected Performance Gains from Technical Improvements for Phoenix Site

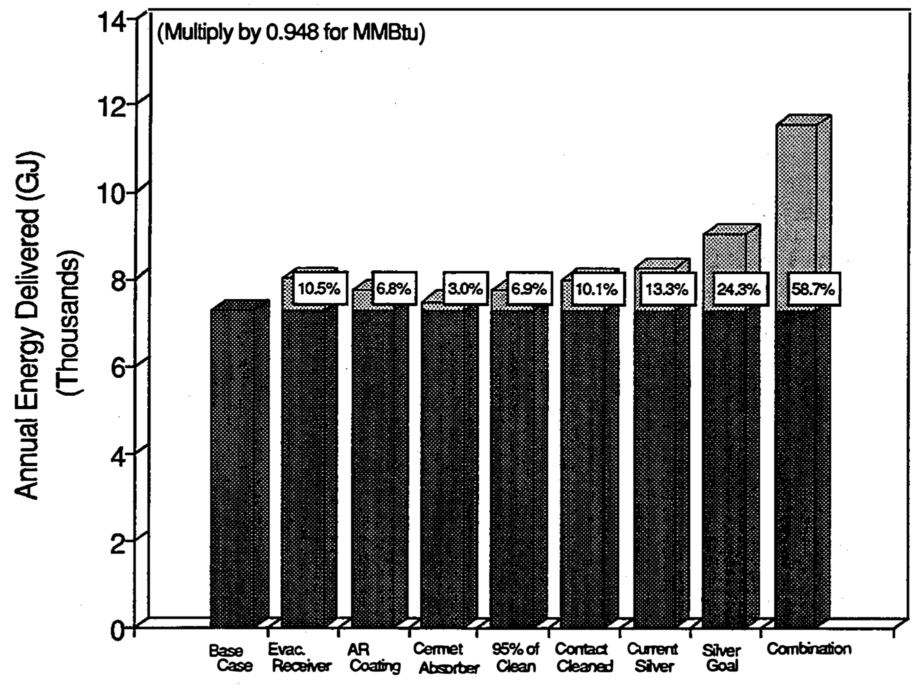

Figure 5: Projected Performance Gains from Technology Improvements for Bakersfield Site

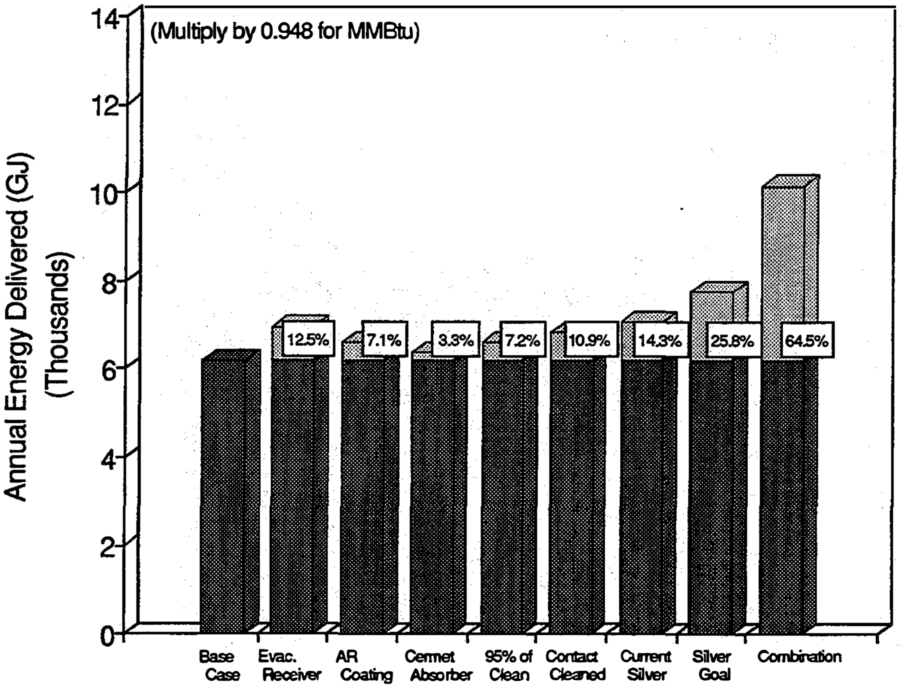

Figure 6: Projected Performance Gains from Technology Improvements at Denver Location

of an evacuated receiver to be more significant in Denver where the colder climate causes more significant heat losses. It should be noted that the baseline system is not a particularly high-temperature system and the performance advantages of the evacuated receiver are expected to be more significant at higher temperatures.

The antireflective coating on the receivers produced the second-largest performance increase of the receiver modifications. Projections based on these data showed that an antireflective coating would increase the annual energy delivered by approximately 7% in all three locations. Finally, the cermet selective-surface absorber projected approximately 3% increase in annual energy delivered. It is likely that the performance benefits of a cermet absorber would also be more significant at higher temperatures.

A cleaner reflector significantly enhanced performance in both cases studied. The results show that a reflector kept at 95% of clean, as opposed to 90% of clean, would increase system performance by roughly 7%. As pointed out previously, one approach to this case is to increase the frequency of washing. An economic evaluation is necessary to decide if this is the best approach. The projections show that a reflector surface that could withstand contact cleaning could increase system performance by 10% to 11%.

Of the individual options evaluated, changing the reflective surface to a silver film resulted in the largest performance gains. The plots in Figure 4 through 6 show that replacing the baseline aluminum reflector (SA85) with a currently available silver film would raise the annual energy delivered by roughly 13% in Phoenix and Bakersfield and 14% in Denver. The silver goal reflector, which included a higher reflectivity as well as the ability to withstand contact cleaning, improves performance even more significantly. Improvements for these cases range from 24% to 26%.

For all locations a combination of all the technology improvements resulted in an increase in system performance of more than 50%. The improvements in the projected annual energy delivered ranged from 58% at the Phoenix site to 65% at the Denver site.

It is interesting to note that for all of the improvement cases evaluated, the Denver site showed the largest performance increase. There are 2 reasons for this. First, the percent increase is higher because the Denver baseline performance is lower to begin with. Therefore, any gain (optical or thermal) causes a larger percent increase in performance. Second, the evacuated receiver and cermet absorber cases both increase performance by limiting thermal losses, and Denver's climate is considerably colder than that of Phoenix or Bakersfield.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results in the previous section the following conclusions can be drawn.

- Based on the comparisons with measured values, our computer model of a representative IPH trough system appears to be supplying valid system energy predictions.

- Of the research and development activities evaluated in this study (evacuated receiver, antireflective receiver coating, cermet absorber, 95% of clean reflector, contact-cleaned reflector, and current and goal silver reflectors) the development of silver reflectors projected the largest performance enhancement potential is for the development of a silver reflector.

- The results of this study show that an IPH trough system incorporating a combination of all of the improvements evaluated would increase the annual energy delivered by more than 50%.

- Trough systems at locations with less desirable solar climates may benefit most from the technical improvements considered in this study. It is possible that this phenomenon could make it possible to reconsider some climates traditionally considered not viable for trough applications.

Possible future issues to investigate include:

- Evaluate performance benefits from relevant technology improvements as a function of delivery temperature for trough systems.
- Perform annual TRNSYS Tehachapi model validation against actual annual energy figures as additional data is collected.
- Evaluate the status and prospects of other types of solar heat technologies including flat-plate systems, transpired collectors, and parabolic dishes.

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