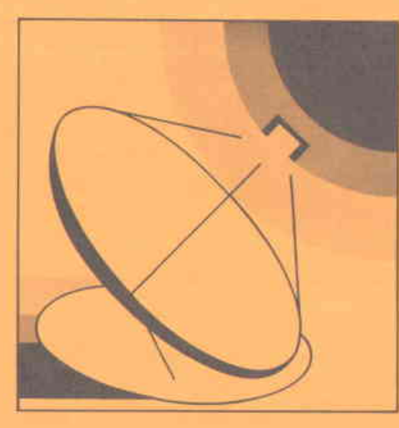
5105-105

Solar Thermal Power Systems Project
Parabolic Dish Systems Development

DESIGN, COST, AND PERFORMANCE COMPARISON OF SEVERAL SOLAR THERMAL SYSTEMS FOR PROCESS HEAT: A CRITIQUE



April 1, 1982

Prepared for
U.S. Department of Energy
Through an agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

5105-105

DESIGN, COST, AND PERFORMANCE COMPARISON OF SEVERAL SOLAR THERMAL SYSTEMS FOR PROCESS HEAT: A CRITIQUE

J. R. BIDDLE

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

SUMMARY

A critique has been made of a study prepared by Sandia National Laboratory, Livermore (SNLL) titled "Design, Cost and Performance Comparisons of Several Solar Thermal Systems for Process Heat." SNLL performance and cost estimates for thermal transport piping networks employed by parabolic dish systems for the production of process heat are shown to yield significantly lower performance and higher costs than published results from recent Jet Propulsion Laboratory (JPL) analyses. These significant differences in the JPL and SNLL results for the energy transport costs are thought to be due, in part, to less than optimal field layouts used by SNLL, differences in the piping optimization methodologies, and the installed, insulated piping cost models. An independently run study by Ford Aerospace and Communications Corp. (FACC) has indicated good agreement with the JPL results.

Differences in methodologies were apparent when, using identical SNLL cost input for field piping, insulation, and fluid, the JPL piping optimization code predicted lower costs and better performance than the SNLL published results. The cost model differences are primarily attributed to SNLL's assumption of conventional labor-intensive techniques for field installation of the piping network. The values used by JPL are predicated on use of labor-saving methods, encompassing automated factory fabrication of piping network components and semi-automated field installation, which are projected to achieve thermal transport cost reductions of as much as 40% compared to conventional methods. These major differences between SNLL and JPL in the approach to fabrication of piping networks obviously alters SNLL's comparison of central receivers, parabolic troughs and parabolic dishes, where the central receiver was favored since it did not require collector field piping. Since the DOE parabolic dish development program, being managed by JPL, is based on technology development such as low-cost piping to enhance penetration into thermal markets, the SNLL comparison based on high-cost piping is not applicable to the systems being developed.

TABLE OF CONTENTS

FIGURES

SECTION I

INTRODUCTION

A recent report [1]* by Sandia National Laboratories, Livermore (SNLL) compared the central receiver, parabolic trough and parabolic dish systems for process heat applications. Volume IV of the report was titled "Energy Centralization" and included items such as field piping, riser/downcomer piping and pipe insulation as well as thermal transport costs and losses. Results from this SNLL study are compared with JPL studies [2 thru 5] in terms of both methodology and cost assumptions.

In an attempt to verify the SNLL optimization methodology for parabolic dish fields an independent comparison was made using the JPL cost optimization methodology. All inputs to the JPL code were modeled as closely as possible to the SNLL values. This includes the cost of piping and insulation used by SNLL which is based on conventional, labor-intensive field construction techniques. For the selected test case, the working fluid is Therminol T-66 with a hot side temperature of 600°F and a cold side temperature of 375°F (operating pressure of 150 psia). The pipe and insulation materials are carbon steel and calcium silicate. The dish area is 95 m^2 and the packing factor is 35%. Since the SNLL baseline configuration has 4 dishes in series, this arrangement was chosen for comparison. The configuration of a parallel arrangement of single dishes (one dish in series) was also treated since it has been more extensively analyzed in the published literature.

To determine the impact of differences in cost assumptions, the JPL advanced cost model [4,5] is used to determine costs for the field piping network and riser/downcomer assembly. This model assumes use of automated welding, factory

---

*Numbers in brackets refer to references found at the end of the report.

assembly of piping and insulation, and minimal field assembly of the components through use of semi-automated installation techniques. Also, risers and downcomers are assumed to be fabricated in the factory as an integral part of the dish concentrator assembly.

The remaining sections of this report present a detailed comparison of the analysis methodologies of both labs and the cost assumptions for field piping and insulation as well as risers and downcomers. The direct costs and transport losses for test cases presented in the SNLL report are compared to calculations for these cases using the JPL approach [4,5].

II. ANALYSIS METHODOLOGIES

A. JPL Computer Code

The pipe optimization methodology of JPL is used to determine the optimum pipe sizes and insulation thicknesses of a given solar thermal field layout. This computerized technique has been previously described [2, 3, 5], but important modifications have been incorporated. Optimum pipe ID's are still determined by the method of Lagrange multipliers, but insulation thicknesses are now calculated using a more direct calculus approach. The optimization procedure utilizes the adjusted transport cost which includes the estimated system cost as well as the economic penalty for thermal loss and pumping power.

The computer program now has the option to choose available pipe sizes for a variety of pipe schedules and pipe materials or to use the theoretically determined pipe sizes. The installed field pipe cost model is based on a parabolic curve fit. Average flow velocities are calculated for all pipes in the field and are kept below the maximum allowable values of 15 ft/sec for fluids and 100 ft/sec for vapors. This improved version of the optimization code yields results not substantially different from the previously used version of the code.

B. SNLL Analytical Approximation

This approximation is described in the SNLL report as a "rough analytical technique". It is based on the use of Lagrange multipliers and the technique and the graphical results remain unchanged from the draft report. Thus the substantial inaccuracies associated with the use of this method identified in an earlier review of draft documents by JPL remain unchanged. However, the graphical results are now clearly marked "analytical approximation only", but even the trends shown by these graphs appear to be based on scaling equations where the caveat of "rough analytical technique" appears to be particularly warranted.

C. SNLL Computer Code

This computerized technique, while purported by SNLL to be "a more exact computational approach which is capable of total systems optimizations and more global tradeoffs" than their approximate analytical technique, is not described in any detail in the final report and no further references are given. However, the results from using this new code are given in tabular form in the final report. It is said to simultaneously optimize both the pipe diameter and insulation thickness for each pipe in the field. The optimization minimizes the levelized energy costs ($/MBTU) for each system size and temperature application. There is no attempt mentioned in the report to check the agreement or to ascertain the extent of the variance between the SNLL "rough analytical technique" and their "more exact computational approach". Therefore, it is impossible from the report or the references to objectively evaluate this computer technique. However, it is emphasized in the report that "This more exact method is used to create all of the tabular data in this volume and for use in other volumes".

In the SNLL computer code the baseline dish size was chosen as 100 m^2 ($\sim$11m diameter) and the packing factor as 0.35. The draft report and the SNLL analytical approximation in the final report are for a baseline dish of 50 m^2 ($\sim$8m diameter) and a packing factor of 0.25 so one should be cautious and not attempt to correlate the graphical results with the tabular results which both appear in the SNLL report.

III. COST ASSUMPTIONS

A. Field Piping

The JPL field piping cost model is based on currently available technology involving low-cost assembly techniques such as the use of automated welding in a factory mass production environment, pre-fabricated pipe supports and special weld fittings [4, 5, 6]. A parabolic model is then used to fit this cost data as a function of pipe diameter (Fig. 1). Similar curves are available for a variety of pipe materials and schedules. The installed insulation cost model also assumes that the pipe insulation is installed in a factory wherever possible. The insulation cost model used was $20/ft^3 installed. This piping cost model has been independently verified by another source [7].

The SNLL field piping cost model is based on Black and Veatch cost data from 1974 escalated to 1979 dollars using a factor of 1.55 (roughly 9% per year). These cost estimates are for conventional labor intensive low productivity field welding and assembly techniques. Pipe cost data was also fit to a parabolic model and it is shown in comparison to JPL's cost model on Figure 1. The SNLL installed insulation cost of $45/ft^3 is also based on labor intensive field insulation techniques.

B. Risers and Downcomers

The cost model used for the small diameter (less than 1" nominal diameter) uninsulated riser and downcomer pipes from the dish receiver to the field piping is $8/ft installed for SNLL and $3/ft for JPL. However, the JPL approach is to design the risers and downcomers to be an integral part of the dish assembly. As such, fabrication and installation of the piping on the dish structure will be done in the factory wherever possible. Labor intensive field installation methods and associated costs are therefore circumvented. The riser and downcomer cost model includes both rigid and flexible pipe. Finally, it should be noted that there is a basic difference between the labs in cost accounting for the riser/downcomer assembly. SNLL chooses to include the cost of this installed piping with the field piping and call the total the thermal transport piping cost. This is probably because using conventional assembly techniques the riser/downcomer piping would be brought to the field site where it would be installed using labor intensive methods. However, the JPL approach, as mentioned above, is to factory install the riser and downcomer piping on the dish components. Being an integral part of the dish components, this cost item is then included in the dish costs.

IV. RESULTS

In order to determine if the JPL and SNLL transport optimization methodologies would yield compatable results, a series of test cases were run. The test cases used the JPL optimization methodology with the input parameters matching the SNLL values as closely as possible (including installed pipe cost model, riser/downcomer cost model, insulation cost model and fluid costs). The initial field layout chosen for comparison was based on use of a parallel arrangement of single dishes (one dish in series) and the plant size ranged from 1 MW_t to 1800 MW_t. The results are shown in Figure 2 along with the SNLL report results. The JPL and SNLL results both include the riser/downcomer costs. The JPL results are shown as bars to indicate the range of values for different system costs (comparable to the levelized energy cost as used in the SNLL report) from \$200 to \$750/kW_t. Also shown on the figure is the JPL results for a system cost of \$350/kW_t since this appears to be the value used by SNLL for their study.

This comparison shows that the JPL optimization methodology consistently predicts lower transport costs than the SNLL optimization methodology over all the ranges of plant sizes studied even though both use the same input parameters. These results yield SNLL costs as much as 26% higher than JPL costs. This indicates that there is still some unresolved differences in the optimization methodologies used since JPL is optimizing to lower transport costs than SNLL while using the same elemental cost models as used by SNLL. Another independent study by FACC has indicated cost and thermal loss results to be in good agreement with the JPL optimization code results [7].

Another interesting result shown on Figure 2 is that the shape of the curve from the JPL work is different from that of the SNLL work. The SNLL work shows a fairly constant direct cost until about 100 MW_t and then a rapidly increasing cost. The JPL work shows an increasing direct cost with increasing plant thermal rating until about 100 MW_t and then the cost appears to level off. Analysis of the JPL results indicates several reasons for this behavior. First, the shape of the curve is very dependent on the dish field layout as individual points on the curve can be shifted up or down by several percent. Field layouts used by SNLL and JPL are not identical for reasons previously given and neither have been completely optimized, but are considered to be typical of practical field layouts. Secondly, the direct costs which are plotted are determined from the minimum adjusted cost of the field (which includes penalties for thermal and pumping loss). It has been generally found that the adjusted cost curve has a broad minimum. Therefore, the actual plotted points for direct costs may be close to but not precisely the minimum cost (this comment is only applicable to the JPL methodology). The use of a precise cost curve minimum is a correct theoretical approach but JPL results are normally based on actual pipe sizes which give costs slightly off the theoretical minimum. The third comment, somewhat related to the second one, is that the individual points are affected by the trade-off between pumping power required and the corresponding thermal loss. For instance, if the required pumping power becomes too large, then a possible solution is to increase the field pipe sizes. The pumping power is decreased, the thermal loss will slightly increase and the net result will be a lower adjusted cost but a higher direct cost due to the larger diameter pipe used. The shape of the JPL direct cost curve in Figure 2 has not been previously identified in JPL work and it is felt that this is the result of a specific combination of factors such as those mentioned above.

As a further extension to this work it was decided to again run the JPL optimization code but this time to use the JPL advanced cost models for installed, insulated field piping and riser/downcomer piping. The result shown in Figure 2 (for $350/$kW_t$) indicates a substantial decrease in the thermal transport direct costs. Compared with the conventional SNLL cost model results, SNLL direct costs are as much as 100% higher than the JPL costs. Using the JPL approach of including the cost of the riser/downcomer assembly in the dish cost gives direct costs for assembled, insulated field piping from $22/$m^2$ to $35/$m^2$ for plant sizes from 1 to 1800 MW_t.

Since SNLL chose four dishes in series as their baseline case it was decided to run the JPL code for fields having four dishes in series with plant sizes ranging from 3 to 150 MW_t. Typical field layouts chosen for these cases are shown in Figures 3 and 4 for plant sizes of 3 and 30 MW_t, respectively. It is important to stress here that no specific plant layouts were given in the SNLL report and that the layouts chosen by JPL have not been optimized. The direct costs as a function of plant size are presented in Figure 5 for the JPL code using SNLL cost parameters (for $350/$kW_t$). Results from the SNLL report are also shown and are as much as 22% higher than the JPL results. Also shown on this figure are the results of using the JPL advanced cost model and results for including installed field piping but not riser/downcomer costs (for $350/$kW_t$). For the latter case direct costs as low as $19/$m^2$ are indicated for plant sizes less than about 10 MW_t. Notice that the shape of the cost curves are similar to the JPL curves shown in Figure 2.

A comparison of transport thermal losses for plant sizes from 3 to 150 MW_t is shown in Figure 6. There, thermal losses are again for the SNLL baseline case of four dishes in series. The SNLL results are as much as 50% higher than those indicated by SNLL for the same input parameters. The differences in the shapes of the curves appear to be due to a field scaling effect. Not knowing precisely the SNLL field layout, the JPL results are for fields like those given in Figures 3 and 4. If the JPL advanced cost parameters are used the thermal losses are further reduced as shown in Figure 6 to less than 6% for plant sizes less than

100 MW_t. Considerable disagreement between the SNLL and JPL optimized results are indicated. Furthermore, the SNLL findings differ with the FACC study which has indicated cost and thermal loss results to be in good agreement with the JPL optimization code results [7]. Without considerably more detail of the "global optimization methodology" and field layouts used by SNLL it is impossible to determine why SNLL consistently predicts higher costs and thermal losses than does other studies, including this one. The results of the JPL runs for four dishes in series indicates that thermal transport costs can be significantly reduced over the case of a single dish layout. Thermal losses for the two cases are comparable. Further studies on dishes in series could yield optimum field layouts and the optimium number of dishes in series (SNLL results indicate four dishes in series to be optimum). The advantages and disadvantages from a control point-of-view should be studied.

V. SUMMARY OF FINDINGS

1. A comparison of the thermal transport optimization methodologies used by JPL and SNLL indicate that the JPL methodology predicts considerably lower transport costs than those predicted by SNLL for the same elemental cost models. This conclusion was found to be true for the SNLL baseline case of 4 dishes in series as well as for the case of a single dish layout. Another independent study by FACC provides good agreement with the JPL results.

2. A comparison of thermal losses for optimized thermal transport with 4 dishes in series indicates that the SNLL results predict significantly larger values ($\sim$50%) especially for plant sizes less than 500 MW_t.

3. The SNLL thermal transport costs using their conventional pipe assembly methods yields costs about 100% greater than those predicted by JPL for non-conventional pipe assembly methods (advanced costs).

4. If the riser/downcomer costs are included in the dish costs, the cost of thermal transport for a single dish layout is reduced to a range of \$22 to \$35/m^2 over a range of plant sizes from 1 to 1800 MW_t. For 4 dishes in series the comparable costs are \$19 to \$22/m^2 for plant sizes from 3 to 150 MW_t.

VI. CONCLUSIONS

1. SNLL performance and cost estimates for thermal transport piping networks used in parabolic dish systems for the production of process heat yield significantly lower performance and higher costs than indicated by JPL and other independent studies.

2. These significant differences in the SNLL and JPL results are thought to be due to

   (a) Differences in piping optimization methodologies,

   (b) Differences in installed, insulated piping cost models, and

   (c) Less than optimal field layouts used by SNLL

3. The lower thermal transport costs and better performance indicated by the JPL work indicates the significant effect that an R&D effort can make in just one subsystem area. Further effort would be expected to yield even lower costs and increased thermal transport efficiency.

REFERENCES

1. Eicker, P. J., et al., "Design, Cost and Performance Comparisons of Several Solar Thermal Systems for Process Heat", SAND79-8282, Sandia National Laboratory, Livermore, March 1981.

2. Caputo, R., "An Initial Study of Solar Power Plants Using a Distributed Network of Point Focusing Collectors", JPL 900-724, (7/75).

3. Turner, R. H., "Economic Optimization of the Energy Transport Component of a Large Distributed Collector Solar Power Plant", Intersociety Energy Conversion Engineering Conference, 1976.

4. Biddle, J., Revere, W. and Fujita, T., "Low-Cost Thermal Transport Piping Networks for Solar Industrial Process Heat Applications", JPL paper presented at the 5th Annual Solar IPH in Houston, TX, December 16-19, 1980.

5. Fujita, T., et al., "Design Options for Low-Cost Thermal Transport Piping Networks for Point Focusing Parabolic Dish Solar Thermal Systems", JPL paper presented at the International Solar Energy Society American Section Annual Meeting, Philadelphia, PA, May 28, 1981.

6. Daksla, C. S., "Thermal Transport Piping Networks - Some Cost Reduction Potential", JPL Internal Report, to be published.

7. Polzien, R. and Rodriquez, D., "Final Report for Task 12 of the Small Community Solar Thermal Power Experiment, Parabolic Dish Technology for Industrial Process Heat Application", SCSE Report 010, Ford Aerospace and Communications Corp., Newport Beach, CA, April 9, 1981.

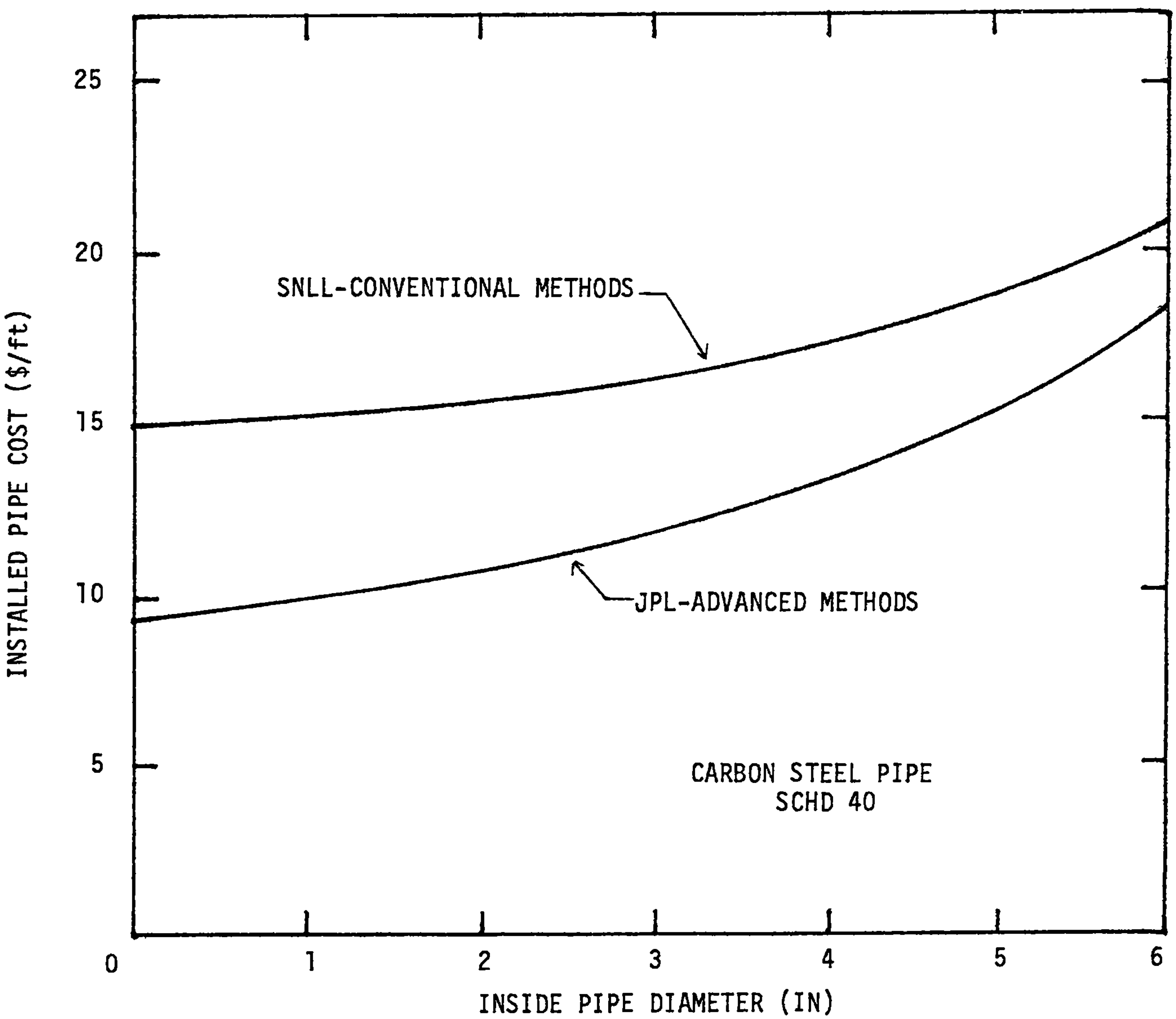


FIGURE 1

INSTALLED PIPE COST MODEL

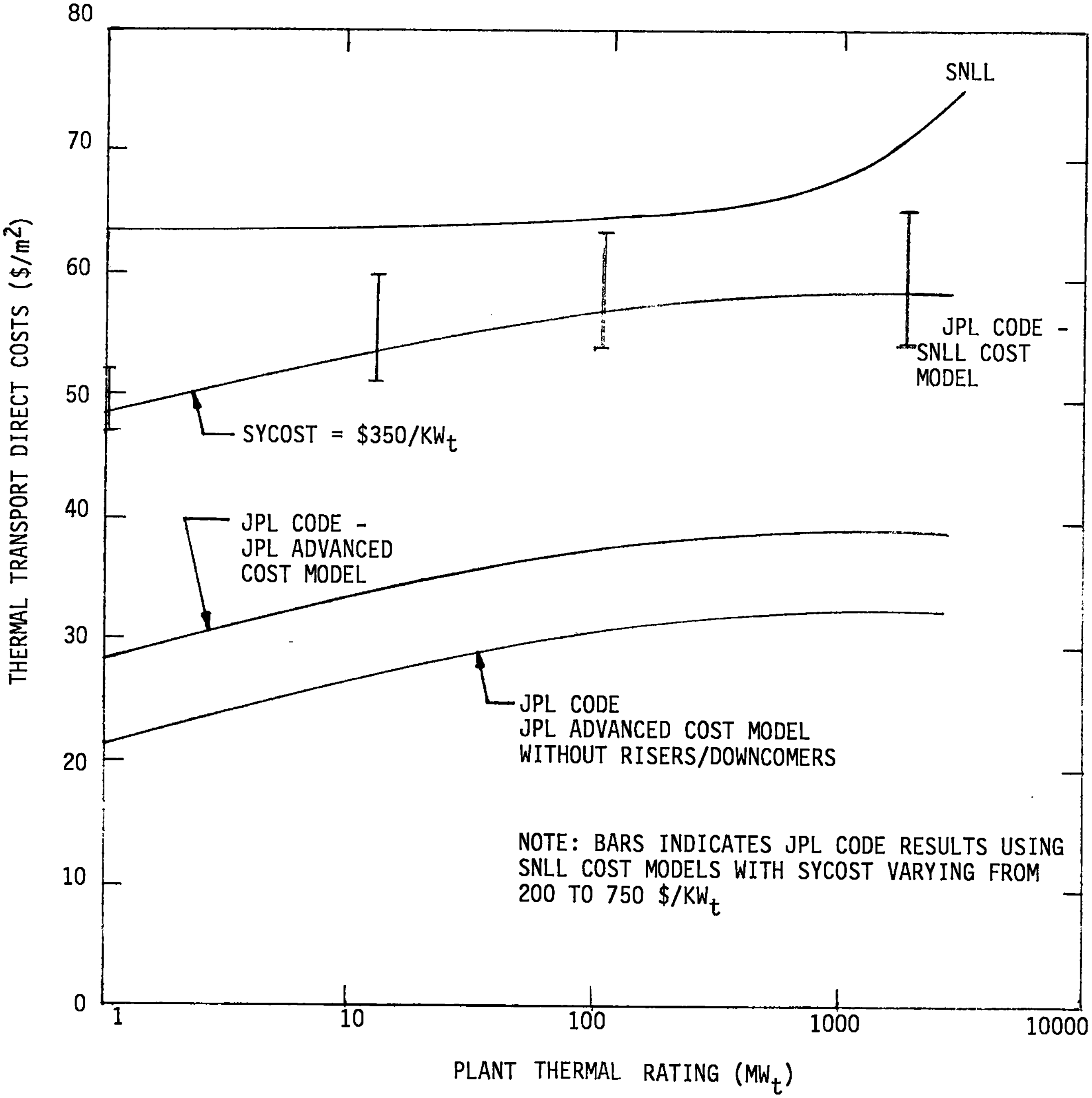


FIGURE 2

THERMAL TRANSPORT DIRECT COSTS

SINGLE DISH LAYOUT

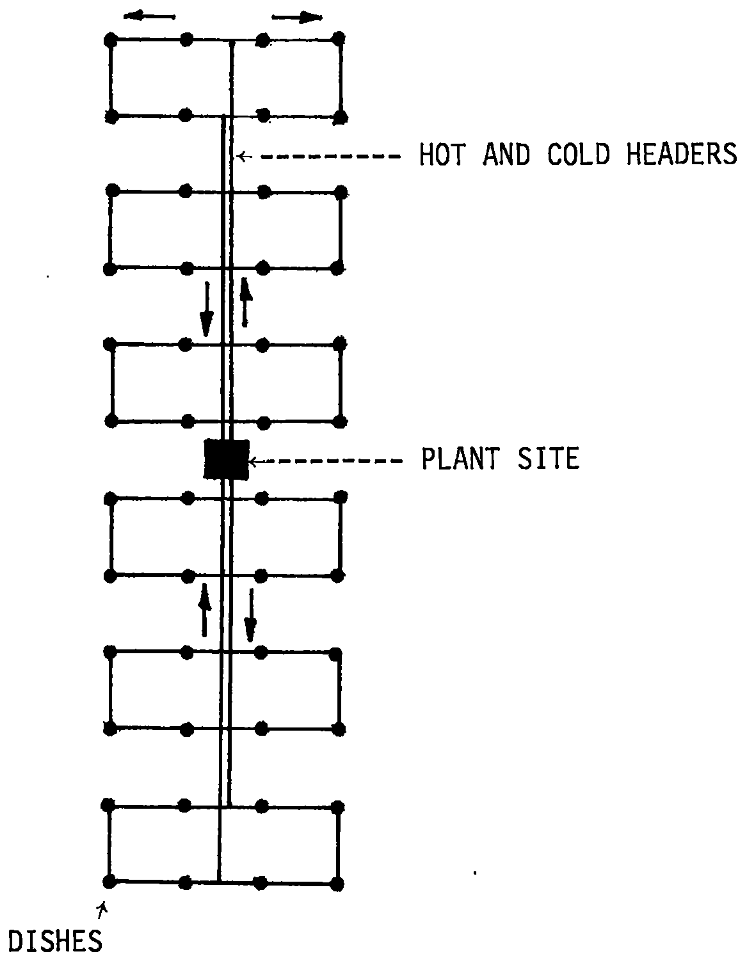
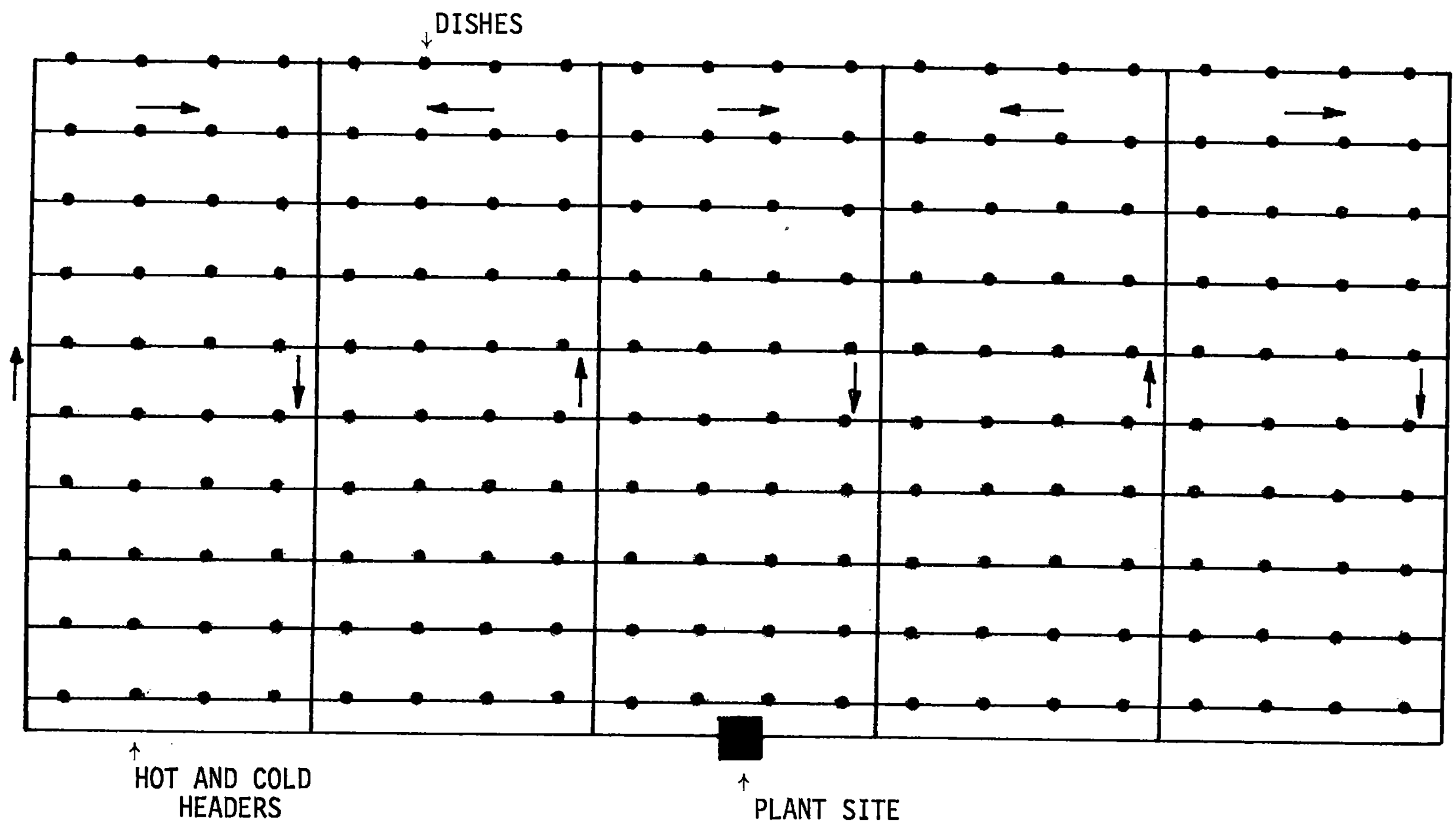


FIGURE 3

$3MW_t$ DISH FIELD LAYOUT

4 DISHES IN SERIES



NOTE: ONLY THE TOP HALF OF THE SYMMETRICAL FIELD IS SHOWN

FIGURE 4

30 MW_t DISH FIELD LAYOUT

4 DISHES IN SERIES

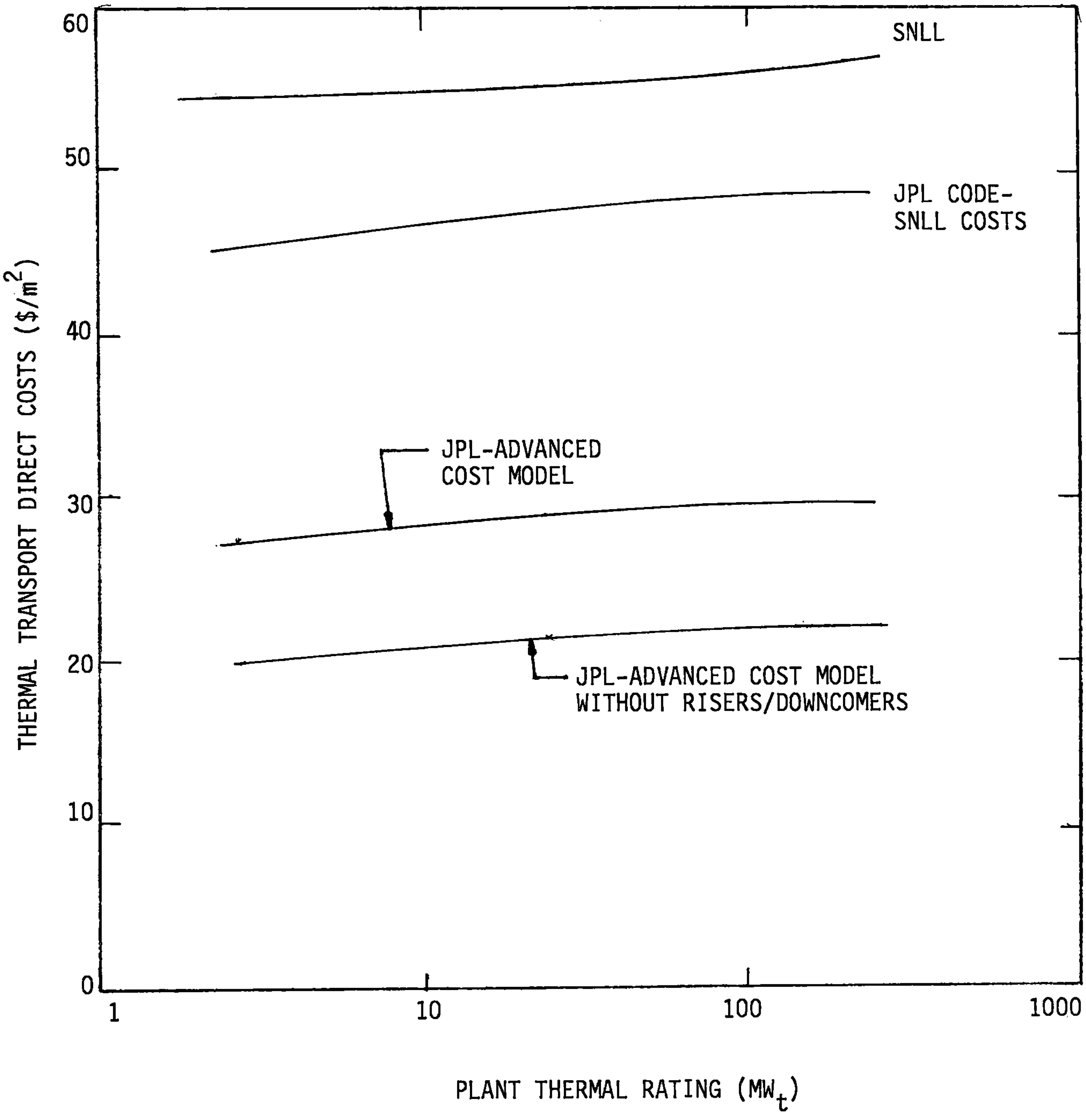
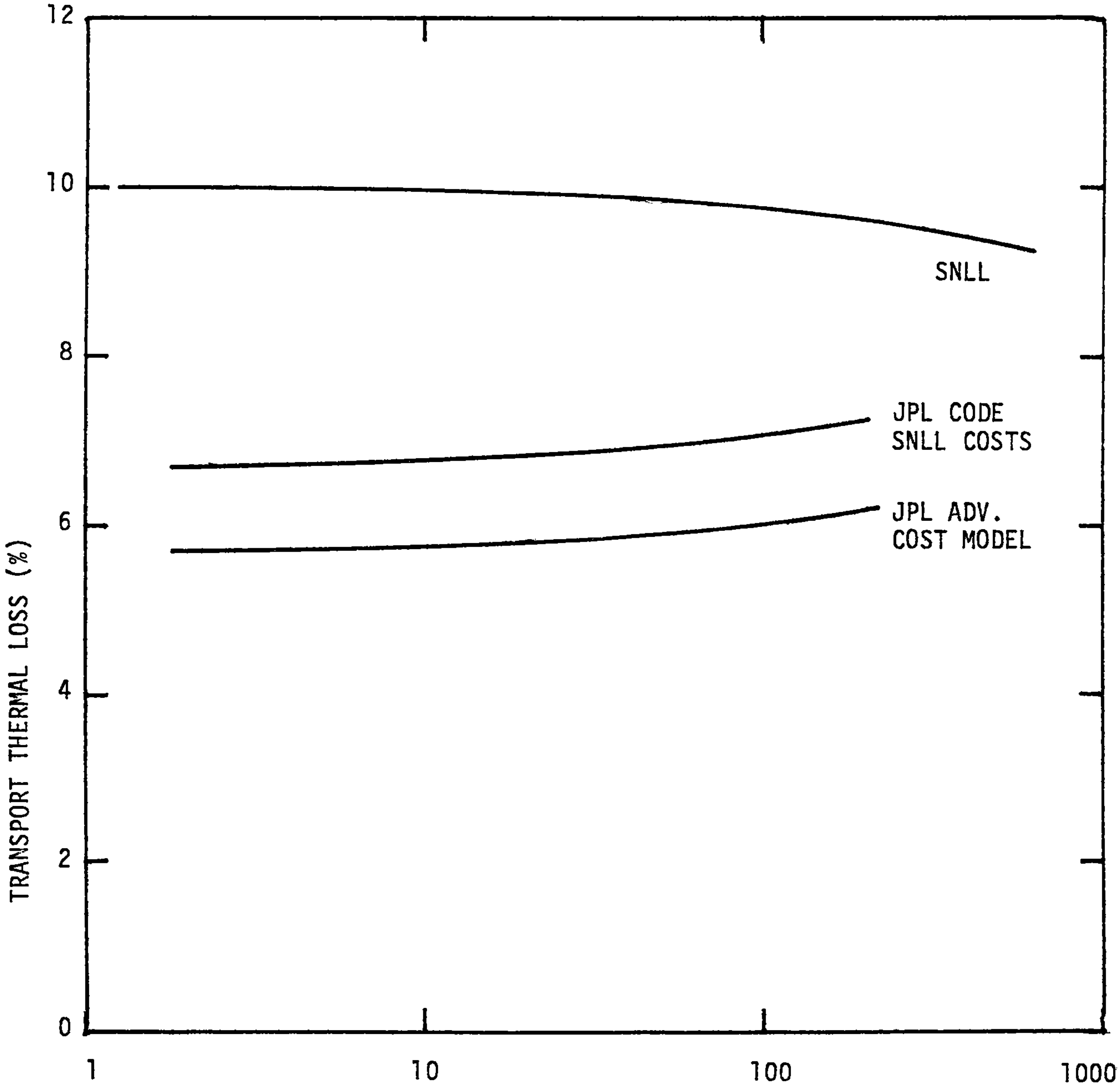


FIGURE 5

THERMAL TRANSPORT DIRECT COSTS

4 DISHES IN SERIES



PLANT THERMAL RATING (MW_t)

FIGURE 6
TRANSPORT THERMAL LOSS
4 DISHES IN SERIES