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3X CPC SOLAR COLLECTOR

Technical Progress Report, May 7—November 7, 1978

By
Robert W. Ballheim

December 22, 1978
Date Submitted

Work Performed Under Contract No. ET-78-C-04-4239

Research and Development Division
Chamberlain Manufacturing Corporation
Waterloo, Iowa

U.S. Department of Energy

Solar Energy

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3X CPC SOLAR COLLECTOR

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FOREWORD

This document is the Six-Month Technical Report for DoE Contract ET-78-C-04-4239. The time period covered by this report is 7 May 1978 through 15 November 1978.

The Government Technical Representative for this project is Jerry E. Zimmerman, Special Programs Division, Albuquerque Operations Office.

This work has been supported by the Solar Heating and Cooling Research and Development Branch, Office of Conservation and Solar Applications, U. S. Department of Energy.

SUMMARY

This report documents the technical progress through the first six months of this one-year program under DoE Contract ET-78-C-04-4239 which was effective 1 May 1978.

A 2.6X concentrating high temperature, non-tracking solar energy collector has been designed and prototypes are being built. The key design criteria for optimization of the design was to obtain a maximum collector energy gain to cost ratio at an operating temperature of 400°F. The selected collector is about 4 feet by 8 feet by 9 inches deep and is a completely housed unit with a glass cover to protect the reflectors and receivers from the environment. There are six each 45-inch long CPC cusp-shaped reflector assemblies design-matched to the General Electric evacuated receiver. The reflector design is a truncated 4.1X CPC which requires the collector tilt angle to be adjusted four times each year.

A ray tracing program was used in conjunction with a math model to calculate predicted annual heat gain for many collector configurations. These heat gains were then compared with the specific costs associated with each of the collector components to select the most cost effective collector design with an additional consideration being mass producibility of the collector. A serpentine design compatible with the selected collector and its operating conditions has been designed and tested. A survey of available heat transfer fluids has been completed and a fluid with properties acceptable for use in a collector system has been recommended.

Prototype collectors will be built using mass production techniques to enable accurate collector production cost estimates. These collectors will then be tested for thermal performance to verify theoretical calculations in this report.

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1. INTRODUCTION

The design and development of a cost effective 3X concentrating collector with an evacuated receiver is the main objective of this program. The end use application will be at the Iowa State Capitol Complex at Des Moines, Iowa. This application requires 400°F collector outlet fluid temperature to augment the output of a central steam plant which is used to heat and cool a complex of eight large office buildings. It is anticipated that DoE will continue the present program through two additional phases: (1) pilot plant installation of the collectors being developed in this project, and (2) final system installation utilizing an array of 200,000 to 400,000 square feet of collector.

The major tasks in this project include collector design and development, serpentine development, collector production using mass production techniques, fluid evaluation and selection, Phase II preliminary system design, performance analysis, and a producibility and cost study.

The first priority of this program was to optimize a reflector/receiver configuration to obtain a maximum energy gain/cost ratio for the collector. The cusp type CPC reflector system with a cylindrical receiver was chosen as the baseline design because it does not require diurnal tracking and because the cusp design offers more efficient use of reflector material and uses fewer receivers than other CPC designs utilizing flat receivers. The General Electric evacuated receiver was selected as the best cylindrical design available and the reflector design was based on the General Electric receiver specifications. A heat gain math model was written to compare the effect of collector parameters on the annual heat gain of the collector. These parameters included CPC acceptance angle, truncation height, reflector error, receiver placement error, glazing transmissivity, receiver outer glass tube transmissivity, reflector material, reflectivity, and insolation diffuse/beam ratios. These heat gains were then compared with the specific costs

associated with each of the collector components to select the most cost effective configuration with an additional consideration being mass producibility of the collector.

The reflectors will be roll formed because that process will enable consistently accurate production with very low labor cost involved. There has been a delay in the manufacturing schedule due to problems with the roll form tooling. Although prototype parts have not been available as scheduled, the completion date for the program is not expected to change. The lost time can be made up by intensifying the collector assembly effort during the production phase.

The serpentine development task is on schedule. The serpentine consists of a fluid carrying pipe with an attached fin for transferring energy from the glass shroud to the fluid. It was redesigned because the copper assembly which was used in the standard General Electric collector was not acceptable for this application since the higher operating temperatures would cause oxidation problems. A new serpentine using a stainless steel tube clamped to an aluminum fin has been designed and successfully tested.

The fluid evaluation and selection task is complete and a heat transfer fluid for the end use application has been recommended.

Computer models have been used to calculate predicted annual heat gain under real hourly weather data conditions and to estimate instantaneous performance curves under specific design conditions.

The Design Review meeting has been rescheduled for the month of January. At this time the prototype collector should be available for examination and design approval. Upon approval of the design the production phase of the project will be started. Detailed cost data and production time data will be assembled in order to predict mass production costs accurately. The collectors will be tested for thermal performance at General Electric Company and three collectors will be made available to the Government for their testing if desired.

2. COLLECTOR ASSEMBLY DESCRIPTION

The collector assembly is shown in Figure 1. Overall dimensions are 44.2 x 105.8 x 9.9 inches. It is a completely housed unit with a center manifold and a glass cover. It contains six each 45-inch long CPC cusp-shaped reflector assemblies design-matched to the General Electric evacuated receiver with a 1.75-inch diameter absorber. The reflector is a 4.1X design truncated to a height of 8.0 inches with a resulting actual concentration ratio of 2.6 to 1. The manifold is a sealed insulated area housing the fluid lines which connect the six receivers in series with inlet and outlet tubes extending from one side of the collector at the center.

In the following sections design rationale is discussed in detail for all major components including the reflectors, reflector support assembly, and the housing and cover assembly. In brief, the collector assembly operation is as follows: The reflectors and supports are assembled individually in two modules. The evacuated shrouds are then placed in these subassemblies and are aligned with respect to the reflectors. The serpentine is then inserted and are connected in series by brazing connecting tubes between each serpentine with the free end of the tube on one serpentine being attached to the fixed end on the next (the serpentine is a U-tube with the fin attached to only one leg of the U). Two of these assemblies are then positioned in the preassembled housing and are attached to the housing by spot welding the receiver support brackets to the box sides. The fluid lines are joined with a flexible connector and the preattached inlet/outlet bulkhead connectors are attached to the box. All housing joints in the manifold area are then caulked and the insulation is added. The manifold cover is then installed using four self-drilling and tapping screws. EPDM (ethylene propylene diene monomer) foam tape with adhesive

Figure 1. Collector Assembly

on one side is applied to the top surface of the box and the cover glass is positioned. A bead of silicone rubber is laid at the outside glass/box interface and the cover angle is attached using screws through it and into the vertical outer edge of the box as shown in Figure 2.

Figure 2. Cover Assembly

3. REFLECTOR DESIGN

3.1 Reflector Material Selection

The selection of the optimum reflector material required consideration in several areas. These included the material cost and availability, reflectivity, adaptability to mass production techniques, durability under all expected collector environments, and the influence of the design and material on the collector cost effectiveness. Prior experience in the design and production of reflector systems under Argonne National Laboratories Contract 31-109-38-3496 and our experience in assembling a 1.5X CPC prototype under a Company-funded program indicated that a formed metal reflector attached to two or more bulkhead type support structures offered the best combination of reflector surface accuracy and low production costs. There are two methods of manufacture which could utilize this concept.

- Form the reflector out of an inexpensive material such as galvanized steel and attach a thin film reflector material to it.
- Form the reflector out of the reflective material itself such as polished aluminum.

Investigation of the former indicated that metalized plastic films such as 3M Scotchcal 5400, FEK 163, and FEK 244, would not stand up to the temperatures likely to occur in the collector. Data from 3M Company indicated that their films are rated at 175°F maximum temperature. The temperature of the reflector near the receiver will be about 75°F above ambient under normal operating conditions and will exceed 250°F under stagnation conditions. That this is the case is evident when one considers that under stagnation the collector heat losses are equal to the insolation input. Most of

these losses originate as radiation from the receiver to the glass tube. The losses from the glass tube go to the cover glass, the reflectors, and the air inside the collector. In turn, the losses from the reflectors and glass tubes will be much like those from the absorber plate in a single glazed collector which under a 300 BTU/hr-ft² insolation rate input will have a plate temperature about 200°F over ambient. Temperatures over 175°F cause the film to shrink which would cause it to peel from the metal backing form. The reflectivity of 3M FEK-244 is .85 to .87 and the cost was quoted to be \$.85 to \$1.00 per square foot. The additional labor cost involved in applying the film to the shaped form was estimated to be at least \$10 per collector which would allow four man-minutes per trough for each of six troughs. This is equivalent to about 30 cents/ft² in material cost. There is also concern about the difficulty involved in applying the material to the form which has a fairly small radius at the bottom of the cusp. It is likely that wrinkles and stretching would occur in this area.

The alternative is to use a reflective material and form it to the proper shape. Several types of materials were examined including polished aluminum, plated steel and polished stainless steel. Reflectivity of chrome or nickel plated steel and polished stainless steel is quite low, approximately .60 for the Air Mass 2 spectrum. Other plating processes such as silver with protective coating were considered to be too expensive and were rejected. There are several polished aluminum products on the market which have their origin in the lighting industries. Those looked at under this effort included the following:

Kinglux, Type C-4, Kingston Industries, New York, New York

Coilzak, Aluminum Company of America, Pittsburgh, Pennsylvania

Alcoa Type 1, Aluminum Company of America, Pittsburgh, Pennsylvania

Manufacturers' data for each is given below:

KING-LUX:

"KING-LUX Pre-Anodized Coil is a super high-purity based aluminum, electro-chemically processed to obtain extraordinarily high quality surfaces. A multitude of finishes are available ranging from lustrous metallics to varying degrees of satin matte in a full spectrum of colors. With precise control of the transparent anodic oxide film, a range of predetermined physical and performance characteristics can be obtained for specific uses. This film acts as a protective barrier to all atmospheric attacks and is highly abrasion resistant. The metal surface has a ductile tough non-flaking layer that can be postformed with negligible surface disturbance.

The surface of Type No. C4 (specular) has an extra high total reflectance factor of 87.4% in the visible region of the spectrum. The low diffuse component is only 2.84%. Therefore, the KING-LUX Type No. C4 reflector sheet has the ability to reflect without image distortion and with full directional control of the energy source. This property is found in both sheet and coil.

The KING-LUX Reflector Sheet or Coil has a standard anodic thickness of 2 microns. This acts as a formidable protective barrier to weathering. The diamond hard coating resists abrasive cleaning in maintenance assuring long-life surface effective reflectivity.

Kingston Industries Corporation can deliver all material with a polyethylene peel-off for a mar-free fabricated finish. Coil and sheet can be stored for a long period with no difficulty in removing the strippable layer."

Coilzak and Alcoa Type 1:

"Alcoa Coilzak Lighting Sheet is an Alzak processed reflector material produced from specially developed alloys and processed in coil form. Coilzak lighting sheet approaches the quality of Type 1 lighting sheet yet the cost is lower due to the economies of coil processing. The three standard types of Coilzak sheet are Specular, Semi-Specular and Diffuse and they are available either as coiled or cut-to-length sheet.

Coilzak Lighting Sheet Specular is made from bright-rolled reflector quality coiled sheet developed specifically to give good finishing response when processed in coil form. This type of Coilzak Lighting Sheet has a guaranteed minimum total reflectivity of 80 percent (compared to 83 percent for Type 1 - Specular) and a specularity level suitable for many applications.

Alcoa Type 1 Lighting Sheet is the highest quality lighting sheet produced by Alcoa. It is made from high-purity clad Alcoa reflector sheet and offers the most uniform appearance and highest reflectivity of the two types of Alcoa lighting sheet. It is supplied in both Specular and Diffuse grades.

Alcoa Type 1 - Lighting Sheet Specular is a flat sheet product made from bright-rolled Alcoa reflector sheet having a high-purity cladding. After it is Alzak finished, this sheet provides 83 percent reflectivity and a very high degree of specularity."

As can be seen from the above data the reflectivity of the three types of material varies from .874 for KING-LUX to .83 for Alcoa Type 1 and .80 for Coilzak. Prices quoted in mid-1978 for large quantities (greater than 100,000 ft²) were \$1.45, \$2.20, and \$.74 respectively, with the KING-LUX and Coilzak prices being for material in coil form and the Alcoa Type 1 in precut standard sizes all in .020 inch thick material. The KING-LUX

material is rated for exterior marine service while the quoted reflectance properties above are for mild interior service in the case of the Alcoa products. Reflectivity for the Type 1 sheet for exterior marine service is given as .78. Coilzak reflectivity for exterior marine service is not given but it is probably about .75.

The durability of these three products under the collector environment is not known. However, Chamberlain Manufacturing Corporation has investigated the effects of ultraviolet and humidity weathering on KING-LUX. Table 1 summarizes these results.

TABLE 1. REFLECTANCE PROPERTIES OF KING-LUX^a TYPE C-4
(INCLUDING WEATHERING TESTS)

<u>Exposure Time</u> <u>(hours)</u>	<u>Solar</u> <u>Reflectance</u>
0	86.7%
175	86.7%
343	85.8%
536	87.0%
704	87.3%
871	87.3%
4,151	87.4%

^a Manufactured by Kingston Industries, New York, New York.

The reflectivity of the material in Table 1 was measured using a Lion Precision Corporation Model R25C reflectometer with a weighting factor applied to correspond to the Air Mass 2 (AM2) solar spectrum. The samples were cycled between six hours of ultraviolet light at 130°F followed by six hours of 100% humidity at 100°F in a Q-Panel ultraviolet weathering tester.

Conclusions

Since the thin films do not offer an advantage in reflectivity, do not have a significant cost advantage when assembly costs are considered, and do have durability problems under likely collector environments, they were ruled out as an acceptable material.

The Alcoa Type 1 material was eliminated because of its higher cost and lower reflectivity as compared directly to the Kinglux material. The tradeoff then becomes one of cost effectiveness; i.e., does the higher reflectivity of Kinglux result in a sufficient increase in collector performance to justify the higher price as compared to the Coilzak. The results of the cost effectiveness study, Section 12.1, indicate that the advantage lies with the Kinglux in a cost versus performance comparison. It should also be pointed out that the Kinglux appears to be a better choice from a durability standpoint than the other products.

Kinglux was selected as the optimum reflector material for use in the collector on the basis of the above data and the cost effectiveness study in Section 12.1. This subtask is complete.

3.2 Reflector Design Analysis

The reflector design process was based on several parameters that were considered fixed for this program. Those items included the following:

- The receiver would be tubular with an absorber diameter of 1.75 inches.
- The reflector would be a cusp type non-imaging CPC designed for use with a tubular receiver as defined in Reference 1.
- The concentration ratio would be between 2:1 and 4:1.
- Six or less collector slope adjustments per year would be acceptable.
- Standard size reflector material would be used to insure availability and lowest material cost.

The collector math model described in Section 12.1 was used to predict heat gains for many reflector designs. The reflector parameters used in that analysis included the following:

- Concentration ratios of 3.5X, 4.1X, 4.7X, and 5.2X with four slope adjustments per year; and 4.7X, 5.2X, and 6.2X with six slope adjustments per year.
- Truncation heights used were 4, 6, 8 and 10 inches.
- Reflectivity was considered to be all specular and included values of .75, .81 and .87.
- Reflector error was introduced to determine the effect of not having a perfectly shaped reflector. This error was induced by adding either 1° or 2° to the incident angle of each ray entering the collector.
- Receiver placement error was set at 0 and .06 inch. The purpose of this was to check the effect of assembly error on the performance of each reflector configuration. This error consisted of moving the receiver laterally out of the center of the reflector trough resulting in some rays missing the receiver that would normally strike it. It was expected that this error would have a greater effect on the collectors with larger truncation heights and/or smaller acceptance angles.

Conclusion

The reflector design selected as the optimum from a collector cost effectiveness standpoint was a 4.1X concentration ratio cusp type non-imaging CPC truncated to a height of 8 inches with a resulting concentration ratio of 2.6X. The collector will require four slope adjustments of 22° each annually. It was found that the reflector error caused significant reduction in heat gain for the higher concentration ratio reflector systems.

Additional discussion of this is presented in the cost effectiveness study in Section 12.1.

Figure 3 shows the reflector design selected. With this design, the costs and complexity of the roll-form tooling were minimized. Had the design called for the full trough of the reflector to be roll-formed in one operation, the necessary tooling would have cost much more and would not have as good a chance to roll the proper shape without extensive tooling modifications. The material blank width for the reflector is 12 inches which can be obtained with no waste from the standard coil or sheet width of 24 inches available from Kingston Industries. This task has been completed.

Figure 3. Selected Reflector Configuration

4. REFLECTOR TOOLING AND PROTOTYPE

The reflector tooling is being done by the Monroe Division of Chamberlain. The completion of this task has been delayed because of a manpower scheduling problem in the toolroom at that facility. This problem has created a three-month delay in the delivery of prototype reflectors for the preproduction prototype assembly. This task which was originally scheduled for completion in August has now been rescheduled for the end of December.

The roll-form tooling has been designed and the machining of the rolls is about 70% complete. There will be nine stations in the roll-form machine and 2-1/2 are now complete. All rolls have been I.D. bored and faced. Prototype reflectors will be rolled and shipped to R&D as soon as tooling is complete. If the tooling does not have to be modified, this delay should not affect the program completion date. Tooling modification will be required only if we are unable to obtain an accurate reflector shape in assembly with the reflector support. This is considered to be very unlikely.

5. HOUSING ASSEMBLY DESIGN

The housing was designed to provide a low-cost durable assembly which gives protection from the environment as well as rigidity to the collector assembly. Galvanized steel was selected over aluminum as the better material for the major housing components because of an advantage in cost and strength. Table 2 shows the weights calculated for various height aluminum and galvanized steel housings. The aluminum housing weighs about 2 pounds per square foot less than the steel but would cost \$.50 to \$1.00 per square foot more to produce.

TABLE 2. COLLECTOR TOTAL WEIGHT¹

Material ²	Box Height				
	<u>4 In.</u>	<u>6 In.</u>	<u>8 In.</u>	<u>10 In.</u>	<u>12 In.</u>
Aluminum	101.64	122.78	153.61	170.74	186.96
Galvanized Steel	128.13	157.35	195.31	219.41	242.55

¹ All collectors use 3/16 inch thick glass cover.

² All metal parts except reflector.

All exterior surfaces will be painted to insure a minimum lifetime of 20 years. The box sides and ends are designed to be roll-formed under high production rates but are adaptable to brake forming on a press for low production quantities which do not justify the high initial cost for roll-form tooling.

As shown in Figure 4, the sides, ends and bottom pieces all interlock or overlap when assembled. They are fastened together by spotwelding after the box has been squared up on an assembly fixture. The box will be assembled upside down on a flat table to insure proper alignment of the top surfaces at the corners. This will aid in the assembly of the glass

Figure 4. Exploded View of Housing Assembly

cover to the box and will provide an even base for the foam seal under the glass cover. All corner joints will be caulked on the inside to prevent water infiltration. The box sides and ends will be 20 gauge steel with paintable quality zinc coating (galvanized). The box bottom will be 25 gauge galvanized steel. External corner supports are added at each corner as a reinforcement for added box strength and to cover the sharp edges where the end and sides meet. Holes will be punched in this area for mounting access.

Also included as part of the housing design task was the manifold housing. The height of the manifold has been reduced to a minimum in order to lower the shading losses while at the same time providing effective insulation for the fluid lines. By using a peaked manifold cover the effective thickness of insulation is maintained at about 2-1/2 to 3 inches, but the shading effect of a flat cover has been eliminated. Further discussion of this design is included in Section 8 of this report.

6. GLAZING SELECTION

The materials considered for glazing material for the collector included the following:

- Low iron content tempered glass.
- Low iron content tempered glass with anti-reflection treatment.
- Waterwhite glass.
- Polycarbonate sheet.
- Acrylic sheet.
- Teflon film .001 thick.

Evaluation of these materials was done in a sequential elimination process using the following criteria in the order shown:

1. Lifetime must be expected to be 20 years without significant deterioration in either physical or optical properties.
2. Cost effectiveness considerations included the effects on collector producibility, the base material cost and the transmissivity of the material for Air Mass 2 spectrum.
3. It was considered highly desirable from a production and performance viewpoint to use a one-piece cover for the collector. The size required, 106 inches long by approximately 42 inches wide, dictated that the thickness of the glass cover be at least 3/16 inch. The one-piece cover allows the use of a lower center manifold which reduces shading effects and also reduces cover assembly time and weather sealing problems.

Conclusions

Teflon film was eliminated because it does not have the necessary mechanical properties. A much thicker film would be required for which the cost/transmissivity ratio would not be competitive with glass.

Polycarbonate and acrylic optical properties are known to deteriorate when exposed to outside environments. The better of these two would be the acrylic material but its transmissivity is known to drop approximately 10% over a 20-year period (Reference 2). The cost effectiveness study indicated that this 10% decrease would represent about a 15% decrease in collector performance. The advantage of these materials, especially the polycarbonates, lies in the resistance to breakage. However, this advantage does not outweigh the weathering problems nor the cost and the plastics were eliminated in favor of glass.

The waterwhite glass which is manufactured by ASG Industries, Inc., Kingsport, Tennessee and is referred to as Sunadex[®], has a very low iron oxide content (less than .01%). It consequently has a higher transmissivity than other types of glass, 91.3% for 3/16 inch thick. However, the cost of this glass is quite high as shown in Table 3. The glass is only available with a stippled surface on one side which tends to diffuse the transmitted light. The effect of this diffusion on the performance of a CPC collector is not known by Chamberlain. If the light rays are deflected less than three or four degrees, the effect on performance would probably be insignificant.

TABLE 3. GLASS COVER MATERIAL COST AND TRANSMISSIVITY
FOR 3/16 INCH THICK GLASS AND
AIR MASS 2 SOLAR SPECTRUM

<u>Glass Product</u>	<u>Cost/Ft² 40,000 Lbs. Min.^a</u>	<u>Transmissivity (Advertised)</u>
Sunadex [®]	\$1.11	.913
Lo-Iron [®]	.70	.878
Lo-Iron With Anti-Reflection Treatment	1.10	.93 to .95 ^b

^a 15% surcharge for glass longer than 84 inches.

^b Data from Nor-El1, Inc. by telephone conversation.

Because of the change in light ray angles striking the reflector some rays that normally would be outside the acceptance angles would be brought back inside and some which would normally be just inside would be deflected outside and lost. This product was eliminated as a result of the cost effectiveness study because the cost was equal to the anti-reflection treated low iron content glass which has higher transmissivity.

The low iron content glass is also manufactured by ASG and is referred to as Lo-Iron[®]. It has an iron oxide content of less than .05% and has a transmissivity of 87.8% for 3/16 inch thick material. It is a smooth faced product (as opposed to the Sunadex[®]) which is adaptable to an etching treatment which can be used to greatly reduce reflection losses off both glass surfaces. This anti-reflective treatment was developed at Honeywell and is commercially available from Nor-Ell, Inc., St. Paul, Minnesota. The projected near term cost for treating large quantities of glass is \$.40/ft² (Reference 3). This treatment should increase the transmissivity of the glass by 5 to 7 percent. The results of the cost effectiveness study indicated that each 1% increase in cover transmissivity is worth about \$.20/ft². This option is obviously cost effective and it was decided that the cover material would be ASG Lo-Iron[®] glass with the Nor-Ell anti-reflective treatment. This task is complete.

7. REFLECTOR SUPPORT ASSEMBLY DESIGN

The reflector supports serve both as a method of positioning the reflector trough with respect to the absorber and as a device to "fine tune" the shape of the roll-formed reflector material. Reflector accuracy has a significant effect on the usefulness of the reflector system and in order to obtain the most accurate reflector shape, it was decided to stamp the supports to insure that this surface could be used to help shape the reflector. Figure 5 shows the configuration of the support that will be used.

The reflectors will be attached to the support directly under the receiver with a rivet. The rivets will be inserted through prepunched holes in the reflectors and through a hole drilled in the tab on the support as shown in Figure 6. Additional rivets will be used each 10 to 12 inches under the receiver to aid in holding the reflectors in position. The reflector will be pulled down onto the support by hooking a spring through and over the reflector at the peak and hooking the other end to the support with a tension of 10 to 25 pounds. This method of attachment was tried on a Company-funded project in late 1977 and worked quite well on a cusp type reflector with a height of 5 inches. Modification of this design may be necessary after trial assembly of prototype hardware is accomplished.

Figure 5. Reflector Support Configuration

Figure 6. Reflector Support Assembly

8. INTERNAL MANIFOLD DESIGN

There were two major considerations in the manifold design process: (1) designing the plumbing connections to provide for mass production assembly, and (2) designing the manifold to provide effective insulation to prevent heat loss from the manifold tube while not causing excessive shading problems for the receiver.

The plumbing connections for the internal manifold will be as shown in Figure 7. Design rationale was as follows. For informational purposes, the serpentine (the fluid carrying heat removal devices that are fitted into the glass shrouds) are constructed with a U-tube and a thin aluminum cylindrical fin. One side of the U-tube is clamped securely to the fin and the other side is left free. In order to allow the individual receivers to be positioned properly with respect to their own reflector troughs it was necessary to connect a fixed tube on one serpentine to the free tube on the serpentine next to it. This allows lateral movement of one serpentine relative to the others beside it. Secondly, since it was considered highly desirable to have bulkhead type fluid connections for collector hookup it was mandatory that there should be a flexible connection between the serpentine and the two inlet/outlet bulkhead connectors which are secured to the side of the collector housing. The easiest and most inexpensive method was to attach the free end of each serpentine U-tube that was nearest the side of the housing to the bulkhead connector. Examination of Figure 7 shows that both these ideas could be used if there was a method of connecting the fixed ends of the two serpentes opposite the bulkhead side of the collector. This was accomplished by using a piece of tubing between the two which had a 360° bend (loop). This allows a positive method of eliminating any misalignment of the two fixed tubes relative to each other. This connection is made after both reflector/receiver assembly modules have been secured in the housing. All other plumbing connections will be made in a jig prior to

Figure 7. Manifold Plumbing Connection Schematic

assembly of the serpentines into the glass shrouds. The bulkhead connectors also will be pre-assembled and will only require attachment to the insulating plate with three screws each after the module has been installed in the housing.

The serpentine will be installed in the collector with the fixed side of the U-tube at the lowest point of the receiver. Ray tracing results show that a major portion of the incoming light rays are reflected to the lower side of the receiver under most operating conditions. By locating the fixed side of the tube in this area the length of the conductive path from the fin to the tubes is minimized.

To provide an optimum design for reducing to a minimum the thermal losses from the manifolding several considerations were made. First, an estimate of the thermal losses from the manifold was made by assuming the following:

- The average manifold pipe temperature was 400°F and the average temperature outside of the manifold was 100°F (approximately 3/4 of the manifold area is inside the collector housing which will be about 75°F above ambient under normal operating conditions).
- Since the major portion of the pipes outside of the glass shrouds are the transition pieces from one receiver to the next, it was assumed that the major portion of the losses that could be controlled would be from this portion. These tubes are run within 1/2 inch of each other for most of their length and thus were assumed to be losing heat as a single pipe. The length was assumed to be 36 inches. The losses occurring from the transition tubes as they exit from the evacuated glass shrouds and proceed to the center of the manifold were not calculated because they can not be controlled and would be very difficult to calculate accurately. These losses could be reduced by bending the end of the fixed tube on the serpentine up away from the glass shroud. This modification to the serpentine will be made if General Electric Company determines that it can be done cost effectively.

Insulation would be low binder content fiberglass as is used in the Chamberlain flat plate collectors. It is type AWX-HT-26 made by Owens-Corning. By compressing the insulation to about 0.6 of its unrestrained volume, Owens-Corning states that a k-factor of $.345 \text{ BTU/hr-ft}^2\text{-}^\circ\text{F/in.}$ is obtained when the mean temperature is 250°F .

The manifold design that resulted from this effort is shown in Figure 8. The manifold cover is a peaked design which provides a minimum of 2-1/2 inches of insulation around the tubes while not causing any additional shading of the receivers as would have resulted if the entire width of the manifold had been increased in height. The original design was a rectangular manifold extending to the height of the box. The height was reduced to the minimum required for the receiver support in order to eliminate excessive shading of the receivers at hours other than solar noon. The width of the manifold area is 6 inches and the height at the edges is 4 inches with a height at the peak of 5.5 inches. In the assembly operation a 4-inch thick layer of fiberglass insulation will be placed under the manifold piping and another 4 inch-thick layer will be added on top before the manifold cover is put in place. Additional insulation will be packed around the ends of the glass shrouds which extend into the manifold area about 0.4 inch.

Total thermal losses from the manifold pipes have been calculated to average about 60 BTU/hr under normal operating conditions for the configuration discussed above.

The fluid connections to the collector array piping are made via two bulk-head connectors mounted on an insulator plate. The connectors will be machined by Chamberlain for this program because a source for a standard part has not been located. The unit will be made of brass with a 1/4-inch NPT female connection to the outside. The connectors will be spaced 1-1/2 inches apart on a vertical line and will be mounted on a 4 inches by 5 inches

Figure 8. Side View of Manifold Area

by 1/8 inch thick piece of laminated high temperature plastic. The final material selection has not yet been made. A rectangular hole 3 inches wide by 4 inches high is cut out of the side of the box and the plastic plate is mounted to the box with screws and caulked to seal the area against water leaks.

9.. PROTOTYPE ASSEMBLY

This task has been rescheduled for completion in January 1979. There has been a delay in the completion of the roll-form tooling which will be used to shape the reflectors. It is expected that prototype reflectors will be available in mid-December and that the prototype collector will be completed in early January. This delay was caused by a manpower scheduling problem at our Monroe Division which was to have full responsibility for all prototype tooling and component manufacture. The Research and Development Division has taken over all prototype tooling and manufacturing of components except for the roll-form tooling. Work is progressing and no problems other than the schedule delay are anticipated.

10. SERPENTINE MANUFACTURING DEVELOPMENT

The predicted temperature environment of the 3X collector presents oxidation problems in the copper serpentine assembly currently in use in the General Electric TC-100 collector. Therefore, it was necessary to design a new serpentine that would be compatible with the collector.

The objective of this task is to develop an efficient heat transfer mechanism to transfer the absorbed energy from the inner glass tube of the evacuated shroud to the working fluid. The heat must flow from the absorber coating, through the glass wall, across an air gap, along a fin, through a fin-tube joint (either welded or clamped), and from the fluid-carrying tube to the fluid itself. Associated with the heat flow is a temperature drop between absorber and fluid. The temperature drop and heat flow are related by the thermal resistance of the total assembly. The higher this resistance, the higher is the absorber temperature for a given working fluid temperature. Since thermal losses increase with absorber temperature the absorber-fluid resistance degrades performance. It is necessary to quantitatively assess this performance penalty in order to design a cost effective fin-tube joint for the collector. It is always possible to reduce the thermal resistance by adding dollars to the collector cost. However, it is eventually cheaper to install more collectors in a given application than to continue to increase the efficiency of each collector. The theoretical effect of this resistance to heat flow on the efficiency of the receiver and thus the collector is characterized in Figure 9. The value Z given as the ordinate in this figure is equal to the theoretical efficiency of a receiver with thermal resistance as shown on the abscissa divided by the efficiency the receiver would have in the ideal case where the thermal resistance was zero. The thermal resistance of the copper serpentine used in the General Electric TC-100 collector is about $0.4^{\circ}\text{F-hr/BTU/ft}$ which was the design goal for the new serpentine. This results in a K value of about .95 at 400°F which means that the thermal resistance costs 5% in performance.

Figure 9. Theoretical Effect on Collector Efficiency of Thermal Resistance of the Receiver

For the improved serpentine a material selection which avoids oxidation and yet has low thermal resistance is an aluminum fin mated to a stainless steel tube. However, the different expansion coefficients of the materials make it impossible to chemically bond the two without thermal cycling eventually leading to buckling and cracking. An alternate means of attaching the stainless steel and aluminum is to join them with a metal clamp. Figure 10 shows the design that was tested and accepted as the new serpentine fin/tube assembly. It utilizes an aluminum fin which is in two 22-inch long segments with six each fin springs and tube clamps spaced at 3-1/2 inch intervals. The tube clamp material is Inconel which was selected for its excellent physical properties at elevated temperatures. The clamps are 1-inch long as are the fin springs which are thin Inconel springs used to apply light force on the aluminum fin to press it against the glass shroud for better heat conduction. It was found that without this support the aluminum fin deformed under stagnation temperatures causing an unacceptable air gap at the fin/glass interface.

Laboratory test data has verified that the thermal resistance of this design is about the same as the copper serpentine. Results indicate that the thermal resistance of the absorber will be between .35 and .40°F-hr/BTU/ft. The foot in that dimension refers to receiver length. Under normal operating conditions this will result in a temperature difference of about 40 to 60°F between the absorber coating and the fluid.

Figure 10. Serpentine Fin/Tube Assembly

11. FLUIDS ANALYSIS

11.1 Introduction

This section details the results of a survey made to identify potential collector fluids and the selection of one for use in a 3X concentrating solar collector. A search was conducted among manufacturers of fluids identified for collector application and other fluids which indicated potential application, applying the following considerations for each fluid identified:

- Viscosity - The allowable viscosity limit for a fluid used in a 3X solar collector was identified in an earlier General Electric study. The report concluded that any fluid with a viscosity less than $0.055 \text{ ft}^2/\text{hr}$ at operating temperature was acceptable on the basis of thermal performance. This limit was used as a screening element in comparing the various candidate fluids (see Table 4).
- Thermal Conductivity - Prior study by General Electric concluded that the thermal conductivity at operating temperature should be greater than $0.05 \text{ BTU-ft/hr-ft}^2\text{°F}$ for thermal performance. This limit was incorporated into the screening process.
- Operating Temperatures - Peak operating temperature was estimated at 400°F . Maximum stagnation temperature was given as 870°F for the 3X collector configuration. Based on Des Moines, Iowa weather data and extremes of $\pm 30\text{°F}$, the lowest temperature would be about -8°F . A temperature of -10°F was arbitrarily established as the minimum for a pour or freeze point of the fluid to be evaluated further, and was factored into the screening process.

TABLE 4.
IDENTIFICATION OF POTENTIAL FLUIDS EVALUATED

FLUID	TYPE	MANUFACTURER/SUPPLIER
1. Therminol 44	Modified Ester Based	Monsanto Industrial Chem. Co.
2. Therminol 55	Syn. Hydrocarbon Mixture	Monsanto Industrial Chem. Co.
3. Therminol 60	Polyaromatic Compounds	Monsanto Industrial Chem. Co.
4. Therminol 66	Modified TER Phenyl	Monsanto Industrial Chem. Co.
5. Dowtherm G	Mixt. of Di & Tri aryl Ethers	Dow Chemical
6. Dowtherm HP	Aromatic Oil	Dow Chemical
7. Dowtherm J	Alkylated Aromatic	Dow Chemical
8. Caloria HT43	Refined Petroleum Oil	Exxon Co.
9. Mobiltherm 600	Petroleum (Mineral) Oil	Mobil Oil Corp.
10. Mobiltherm 603	Petroleum (Mineral) Oil	Mobil Oil Corp.
11. Sun 21	Paraffinic Oil	Sun Oil Co.
12. R Temp	High Molecular Weight Paraffinic Oil	RTE Corp.
13. MCS 1958	Developmental Chlorinated, Organic Fluid	Monsanto Industrial Chem. Co.
14. Drewsol	Water Miscible, Organic Heat Transfer Fluid/ Corrosion Inhibitor	Drew Chemical Co.
15. Sun-Temp	Nonaqueous Heat Transfer Fluid	Resource Technology Corp.
16. H-30c	Synthetic Hydrocarbon	Mark Enterprises, Inc.
17. Uniroyal PAO	Synthetic Polyalphaolefin	Uniroyal Chemical
18. Synfluids	Synthetic Polyalphaolefin	Gulf Oil Chemicals Co.
19. Ethyl ESH Series	Synthetic Polyalphaolefin	Ethyl Corp.
20. Syltherm 800	Stripped Silicone Oil + Additive	Dow Corning Corp.
21. UCON HTF 500	Partially Water Soluble UCON-Fluid	Union Carbide

- Flammability Properties - Since the average operating temperature was estimated as 400°F, it was considered appropriate to require that a fluid show flash and fire points significantly above 400°F. Properties of all the candidate fluids are included in Table 5.
- Boiling or Distillation Temperature - From the standpoint of preventing any high pressure buildup during operation, fluids showing a boiling or distilling temperature as high as possible above 400°F were emphasized.
- Other Considerations - Data and information in addition to the above also were collected for comparative purposes on the following elements:
 - (1) Thermal Properties:
 - Recommended use temperature range
 - Autoignition temperature
 - Specific heat
 - Coefficient of expansion
 - (2) Physical Properties:
 - Density
 - Vapor pressure
 - (3) Operational Characteristics:
 - Materials compatibility
 - Temperature stability
 - Toxicity
 - Pollution potential
 - Disposability
 - Maintenance/monitoring
 - Cost

As a result of the survey, 25 nonaqueous organic fluids were selected for comparative evaluation with each other and with water.

TABLE 5
THERMAL PROPERTIES

FLUID	USE TEMP., °F	FLASH POINT °F	FIRE POINT, °F	AUTO IGNITION POINT, °F	Cp BTU/lb.°F @400°F	K @400°F	COEF. OF EXPANSION, ML/ML/°C
1. Therminol 44	- 50 to 425	405	438	705	0.574	0.0651	8.0×10^{-4}
2. Therminol 55	0 to 600	355	410	675	0.611	0.0627	8.7×10^{-4}
3. Therminol 60	- 60 to 600	310	320	835	0.543	0.0681	8.2×10^{-4}
4. Therminol 66	0 to 650	355	382	705	0.534	0.0612	7.0×10^{-4}
5. Dowtherm G	12 to 650	305	315	>1,030	0.478	0.0720	-
6. Dowtherm HP	15 to 550	420	460	880	0.640	0.0705	-
7. Dowtherm J	-100 to 575	145	155	806	0.595	0.0680	-
8. Caloria HT43	15 to 600	400	~450	-	0.599	0.0555	-
9. Mobiltherm 600	- 5 to 600	350	390	-	0.560	0.0620	-
10. Mobiltherm 603	20 to 600	380	430	-	0.650	0.0695	-
11. Sun 21/25	0 to 600	440	490	715	0.650	0.0683	-
12. R Temp	- 20 to -	545	594	1,004	0.46 (77°F)	0.0750	8.5×10^{-4}
13. MCS 1958	- 40 to 500	360	None	1,080	0.384	0.0550	4.4×10^{-4}
14. Drewsol	- 29 to 230	None	-	-	0.7 (77°F)	-	(to 500°F)
15. Sun-Temp	- 40 to 671	380	-	824	0.56 (77°F)	0.0700	-
16. H - 30C	- 40 to 620	360	-	-	0.60 (250°F)	0.07-.075 (212°F)	-
17. UCON HTF 500	- 35 to 500	500	600	750	0.560	0.081	-
18. Uniroyal PAO-LV	- 80 to 600	395	425	-	0.50 (68°F)	0.0726 (68°F)	7.5×10^{-4}
19. Uniroyal PAO-10	- 40 to 600	400	500	-	0.50 (68°F)	0.0726 (68°F)	7.5×10^{-4}
20. Uniroyal PAO-20E	- 35 to 600	530	585	-	0.50 (68°F)	0.0726 (68°F)	7.5×10^{-4}
21. Synfluid PAO 4cs	-100 to 600	445	495	710	0.669	0.0737 (300°F)	4.5×10^{-4}
22. Synfluid PAO 6cs	- 90 to 600	465	520	710	0.590	0.0729	4.2×10^{-4}
23. Ethyl PAO ESH-4	<- 90 to 600	435	475	740	0.69 (392°F)	0.065 (392°F)	4.5×10^{-4}
24. Ethyl PAO ESH-6	<- 90 to 600	460	510	760	0.59 (392°F)	0.067 (392°F)	4.2×10^{-4}
25. Syltherm 800	- 40 to 795	310	380	820	0.460	0.072	-
26. Water	32 to -	None	None	None	1.080	0.382	-

The types and manufacturers or suppliers of the potential fluids are listed in Table 4. Available data on the thermal properties of these fluids are given in Table 5. The properties covered include recommended use temperature, flash and fire points, autoignition point, specific heat and thermal conductivity at 400°F, and coefficient of expansion. Table 6 lists the physical properties which include the available data on boiling point, pour or freeze point, and density, viscosity, and vapor pressure at 400°F. In Table 7, the screening process applied to all the fluids is delineated. The five fluids evolved in Table 7 are then compared in Table 8 for operational considerations, such as materials compatibility, temperature stability, toxicity, pollution potential, disposability, maintenance and monitoring requirement, and cost per gallon.

11.2 Fluids Selection Process

Data and characteristics shown in the various tables included in this report were obtained from brochures and letter/or telephone conversations with the manufacturers of the candidate fluids. The only experimental work performed was the fluid-asphalt shingle compatibility test on several available fluid samples, which is reported in Table 8. A discussion of major areas of the selection process follows.

• Flammability

Of the candidate fluids, water is the only fluid without a flammability characteristic. Drewsol is indicated as nonflashing, but shows a high temperature limitation of only 230°F. MCS 1958 shows a flash point less than 400°F, but no fire point. Using requirements of greater than 400°F for the flash and fire points, pour or freeze points less than -10°F, and viscosity less than .055 ft²/hr at 400°F in the screening process leaves only the Synfluids, Ethyl's ESH-4, and Therminol 44. MCS 1958 also was included based on its fire resistance which is considered to be of greater significance by the Solar Energy Industries Association (Reference 4) than the flash point. This approach is in contrast with the National Bureau of Standards' interim requirement (Reference 5) which states that "liquids

TABLE 6
PHYSICAL PROPERTIES

FLUID	B. P., °F	POUR/ FREEZING POINT, °F	DENSITY, lb/FT ³ , @ 400°F	VISCOSITY, FT ² /HR., 400°F	VAPOR PRESSURE, mm Hg., 400°F
1. Therminol 44	638 (10%)	- 80 (P)	48.7	0.0329	5.5
2. Therminol 55	635 (10%)	- 40 (P)	47.3	0.0399	18.2
3. Therminol 60	550 (10%)	- 90 (P)	54.6	0.0240	65.0
4. Therminol 66	643 (10%)	- 18 (P)	55.0	0.0376	20.0
5. Dowtherm G	575	- 18 (P)	59.6	0.0277	1.3 PSIA
6. Dowtherm HP	695	15 (P)	46.8	0.045	0.3 PSIA
7. Dowtherm J	358	<-100	44.4	0.0077	25.3 PSIA
8. Caloria HT43	700 (1%)	15 (P)	52.7	0.0568	28.5
9. Mobiltherm 600	645 (10%)	0 (P)	53.7	0.0454	200.0
10. Mobiltherm 603	705 (10%)	20 (P)	46.8	0.0473	75.0
11. Sun 21/25	720 (1%)	0/5 (P)	47.4	0.030	-
12. R Temp	-	- 22 (P)	54.6 (77°F)	0.0853	-
13. MCS 1958	620	- 40.5 (P)	70.5	0.0223	25.0
14. Drewsol	230	- 28.5	70.9 (77°F)	-	-
15. Sun-Temp	671	- 40.0	-	-	21.0
16. H-30C	620	- 40.0	46.2 (300°F)	0.0775 (300°F)	-
17. UCON HTF 500	-	- 35.0 (P)	56.7	0.1300	-
18. Uniroyal PAO-LV	-	- 80.0 (P)	51.9 (68°F)	0.0202	-
19. Uniroyal PAO-10	-	- 40.0 (P)	52.0 (68°F)	0.0581	-
20. Uniroyal PAO-20E	-	- 35.0 (P)	52.4 (68°F)	0.0853	-
21. Synfluid PAO-4cs	743 (10%)(1)	-100.0 (P)	45.0	0.0430	4.1
22. Synfluid PAO-6cs	802 (10%)(1)	- 90.0 (P)	45.1	0.0543	3.8
23. Ethyl ESH-4	779 (10%)(2)	- 90.0 (P)	43.7	0.0465	1.0
24. Ethyl ESH-6	819 (10%)(2)	- 90.0 (P)	44.1	0.062	0.7
25. Syltherm 800	> 670	- 40.0	48.4	0.050	<760 (670°F)
26. Water	212	32.0	52.7	0.0061	247 PSIA

Notes:

(1) Vacuum Distillation @ 1mm Hg adjusted to 760 mm.

(2) Vacuum Distillation @ 1mm Hg.

(P) Pour Point.

TABLE 7

SCREENING PROCESS

FLUIDS WITH KIN. OS. C.P. 1.0/HR. FT. 2°F	FLUIDS WITH VISCOSITY C.P. 0.055 FT. 2/HR.	FLUIDS WITH POUR/FREEZE POINTS, °F -10°F	FLUIDS WITH FLASH/FIRE POINTS, >400°F	10% DISTILLATION RANKING, °F	RANKING OF RECOMMENDED USE BULK TEMP., °F	VAPOR PRESSURE RANKING, mm Hg @ 400°F	RANKING OF C.P. 400°F
Therminol 44 Therminol 55 Therminol 60 Therminol 66 Dowtherm G Dowtherm HP Dowtherm J Caloria HT43 Mobiltherm 600 Mobiltherm 603 Sun 21 P-1-mp MCS 1958 Sun-1-mp M-100 UCC-HTF 500 PAO-LV PAO-10 PAO-20E Synfluid - 4cs Synfluid - 6cs Ethyl ESH-4 Ethyl ESH-6 Syltherm 800 Water	Water - 0.0061 Dowtherm J - 0.0077 PAO-LV - 0.0202 MCS 1958 - 0.0273 Therminol 60 - 0.0240 Dowtherm G - 0.0277 Sun 21 - 0.0300 Therminol 44 - 0.0329 Therminol 66 - 0.0376 Therminol 55 - 0.0399 Synfluid 4cs - 0.0430 Dowtherm HP - 0.0450 Mobiltherm 600 - 0.0454 Ethyl ESH-4 - 0.0465 Mobiltherm 603 - 0.0473 Syltherm 800 - 0.0500 Synfluid 6cs - 0.0540	Synfluid 4cs - 100 Dowtherm J - 100 Synfluid 6cs - 90 Ethyl ESH-4 - 90 Therminol 60 - 90 Therminol 44 - 80 PAO-LV - 80 MCS 1958 - 40.5 Therminol 55 - 40 Syltherm 800 - 40 Therminol 66 - 18 Dowtherm G - 18	MCS 1958: 360, None Synfluid 6cs, 465, 520 Synfluid 4cs, 445, 495 Ethyl ESH-4, 435, 475 Therminol 44, 405, 438	Synfluid 6cs - 802 Ethyl ESH-4 - 779 Synfluid 4cs - 743 Therminol 44 - 638 MCS 1958 - 620	Ethyl ESH-4 - 600 Synfluid 4cs - 600 Synfluid 6cs - 600 MCS 1958 - 500 Therminol 44 - 425	Ethyl ESH-4 - 1.0 Synfluid 6cs - 3.0 Synfluid 4cs - 4.1 Therminol 44 - 5.5 MCS 1958 - 25	Ethyl ESH-4 - 0.69 Synfluid 4cs - 0.67 Synfluid 6cs - 0.59 Therminol 44 - 0.57 MCS 1958 - 0.38

TABLE 8
COMPARATIVE OPERATIONAL CHARACTERISTICS

	ETHYL ESH-4	SYNFLUID 4cs	SYNFLUID 6cs	THERMINOL 44	MCS 1958
MATERIALS COMPATIBILITY					
Effect on Metals (M ₆ /CM ² , 100 Hrs. @ 200°F):					
Al	<-0.1			S to 400°F	NO
Cu	<-0.1	{-0.04 -0.22(3)	{-0.03 -0.09(3)	S to 400°F	NO
Steel	<-0.1	-0.05(3)	-0.66(3)	S	NO
Effect on Elastomers @ 200°F:					
Butyl Rubber (1)	+225	+225.49	-180.43	NO	NO
Neoprene (2)	-13	-13.32	-11.09	Fell Apart (4)	NO
Buna N (2)	-3.0	-3.05	-3.41	+28 (4)	NO
Silicone (1)	+17	+17.03	+10.59	+37 (4)	NO
Building Materials Asphalt Roofing	Light Yellow- ish Colora- tion (5)	Light Yellow- ish Colora- tion (5)	Very Light Yellowish Coloration (5)	NO	Immediate Attack At RT
Reaction with Air	NO	See Temp. Stability	See Temp. Stability	When Hot May Oxidize in Air. N ₂ Blanketing Recommended.	NO
Reaction with Water	NO	Resistant to Hydrolysis. 96 Hrs. @ 200°F shows -0.1% Change in Viscosity.		Moisture Removal Recommended.	NO
TEMPERATURE STABILITY	NO	No Decomposition up to 611°F. Cincinnati Millicron Hydraul- ic Fluid Test, 168 Hrs. @ 300°F in air, shows 6-7% in- crease in Viscosity and 1-5MGs/100 ML Sludge.		Max. Bulk Temp. 425°F; Max Film Temp. 475°F	Successful Loop Tests >1,900Hrs @ 500°F
TOXICITY	Higher Vis- cosity Simi- lar Hydro- carbon showed Oral LD50 (Mouse) is 57400MG/Kg. WT. Considered Nontoxic or- ally & derm- ally. Avoid contact with eyes.	Acute Oral LD50 (Rats) is >33600MG/KG Wt.; TLV of 5MG/M ³ for Oil Mist. Ordinary skin Contact Nontoxic; Avoid eye Contact & Prolonged Fume In- halation. Considered rela- tively harmless.		Oral LD50 (Rats) is 13000MG/KG Wt. Dermal LD50 (Rabbits) is >7900MG/Kg Wt. Practically Non- toxic by inges- tion in single doses & single Dermal Applica- tions. Hot Vapors may be mildly irritating on prolonged expo- sure.	Acute Oral LD50 (Rats) is 8000 Mg/Kg Wt. Prac- tically Non- toxic by Single Dose Ingestion.
POLLUTION POTENTIAL	No Serious Problem	No Serious Problem	No Serious Problem	No Serious Prob- lem	NO
DISPOSABILITY	NO Should be Similar to Synfluids	Absorb & Scrape Up; Inciner- ate under Controlled Condi- tions, Observe Federal Spill & Water Quality Regulations; Biodegradable.		Observe Local Regulations	Biodegradable
FLUID MONITORING	NO Should be Similar to Synfluids	Fluid Analysis Every 3 Mos. in 1st Year, then Every 6 Mos.			NO
COST, \$/GAL., 55 Gal. Drums	5.50	5.50	5.50	8.20	10 - 16

Notes:

- (1) % Swell
- (2) % Shrinkage
- (3) 168 Hrs. @ 300°F in Air
- (4) 166 Hrs. @ 302°F
- (5) No Immediate Attack. Observations Made After One Hour Immersion @ RT.
- NO - No Data
- S - Satisfactory

used in solar powered equipment shall not be heated to temperatures greater than 100°F below their flash points under either operating or nonflow conditions."

The following is given in Reference 6:

"It is anticipated that the flash point requirement may be changed by the Department of Housing and Urban Development (HUD) to the less stringent provision given below recognizing the differing levels of hazard presented by different types of installations. However, before such changes can be made, HUD procedures require public review and comment.

Proposed Revision

"The Flash Point of a liquid heat transfer fluid shall equal or exceed each of the following temperatures:

- A. 100°F;
- B. 50°F above the maximum design operating temperature of the solar system;
- C. 1) 200°F below the maximum stagnation temperature attained during the test required by Section S-515-2.1.2, provided that the collector manifold assembly is located outside the building and exposed to the weather;
- 2) The maximum stagnation temperature, as defined above, in all other manifold configurations."

The rationale for the different values in item C is that a system leak under no-flow conditions is most likely to occur in the collector or in the collector manifold assembly. A lower flash point liquid will be acceptable when the manifold assembly is external to the building, since there is a significant lower hazard of

ignition under such conditions. Where a leak could occur in an enclosed area which might have an ignition source (attic-located heater, fan, or other electrical device for instance), there is a higher hazard justifying a higher safety standard."

Even the proposed revision would be severely restrictive and difficult to apply in selecting a potentially usable nonaqueous type fluid. However, if the fire points of fluids which are above 400°F are compared, it is apparent that MCS 1958 and the polyalphaolefin type offer a good margin (greater than 50°F) of safety above the 400°F operating temperature:

<u>Fluid</u>	<u>Fire Point, °F</u>
MCS 1958	None
Synfluid 6cs	520
Synfluid 4cs	495
Ethyl ESH-4	475
Therminol 44	438

The only one of the above fluids that would provide fire resistance at the no-flow temperature of 850°F appears to be MCS 1958. However, this fluid with a flash point of 360°F could not pass even the proposed revised requirement of 570°F. Therminol 44 is not classified as a fire-resistant fluid. In this regard, the Monsanto literature (Reference 7) specifically advises that the use of protective devices may be required to minimize fire risk. In addition, consultation with an insurance company is advised for guidance on the selection and sizing of fire protection equipment to safeguard the installation.

Leakage at high temperature is an especially important consideration, particularly if the fluid passes into open cell insulation material. Therminol fluids exhibit a slow auto-oxidation reaction with air trapped inside the voids of the insulation at about 500°F. A possible catalysis occurs with insulating material ingredients, such as magnesium oxide,

silicate bonded asbestos or calcium silicate, that can result in ignition of the fluid. A possible fire can be prevented by removing and replacing the fluid soaked insulation as soon as possible. It is claimed that this effect seems to occur less with closed cell insulation.

• Materials Compatibility

Table 8 shows the only available data on compatibility of the five fluids, resulting from the screening in Table 7, with aluminum, copper, and steel. The data for 200°F and 300°F exposures for Ethyl ESH-4, Synfluid 4cs and 6cs indicate no gross attack, a satisfactory condition for Therminol 44 at 400°F, but no data are available for the developmental fluid MCS 1958. At 200°F the Synfluid 6cs appears to show less effect on butyl rubber, neoprene, Buna N and silicone elastomers than the 4cs polyalphaolefins. Therminol 44 caused severe attack at 300°F on neoprene and significant swelling of Buna N and silicone.

A 1-inch by 1-inch section of typical asphalt shingle material was immersed at room temperature in each of five fluids available. The polyalphaolefins showed no immediate effect, while MCS 1958 attacked the asphalt sample, immediately turning black. After one hour, the Synfluid 6cs developed only a very light yellowish coloration in the original clear, waterwhite fluid, while the 4cs Synfluid and ESH-4 showed a light yellowish coloration. Therminol 44 was not tested, but if its reactivity is similar to Therminol 66, the effect on asphalt roofing material would be similar to MCS 1958. Only water and silicone fluids appear to be compatible with asphaltic roofing materials.

For open systems involving exposure to air and moisture, the nonaqueous fluids in general appear to be limited to 300°F. For higher temperature exposures, nitrogen blanketing and moisture removal from the system are ordinarily recommended.

- Temperature Use Range

While water shows many advantages as a heat transfer fluid, it does have disadvantages in the low temperature limit of 32°F, in developing high vapor pressures at elevated temperatures, and, thereby requiring a different system design approach. The nonaqueous fluids overcome these disadvantages, but are susceptible to oxidation at high temperatures in air. A closed system preferably with nitrogen blanketing, can significantly prevent organic fluid oxidative effects and, thereby, extend their stability life. For example, even some silicone fluids exposed to air will increase in viscosity as the temperature rises above 300°F until a gel is formed within a few hundred hours at 250°C (482°F). If air is excluded or nitrogen blanketing is used, the silicone fluid will operate up to 250°C for extended periods of time with very little change in the original properties.

- Temperature Stability

There is very little data available on the long term stability of any of these fluids. Most of the statements made are qualitative, indicating that exposure of the fluid below the maximum temperature in closed systems will give excellent stability. Gulf reports that no decomposition was observed at temperatures up to 611°F for the polyalphaolefins. Performance of the Cincinnati Millicron Hydraulic Fluid test for 168 hours at 300°F in air, showed a 6-7% increase in viscosity and 1-5 mgs of sludge per 100 ml fluid (100 mgs is considered the maximum for this test).

For Therminol 44, the recommended maximum bulk temperature is 425°F, while the maximum film temperature is 475°F.

- Toxicity

Based on the data included in Table 8 and using the widely accepted Sterner & Hodge acute toxicity classification system (Table 9), Therminol 44 and MCS 1958 may be considered practically nontoxic, while the three polyalphaolefins are relatively harmless. It is interesting to note that the latter

TABLE 9
STERNER & HODGE ACUTE TOXICITY
TERMINOLOGY & CORRELATION

ACTIVE TOXICITY CLASS	LD50 RAT ORAL AMOUNT/KG. WT. (1)	PROBABLE LETHAL ORAL DOSE FOR MAN
Extremely Toxic	1 mg.	A Taste
Highly Toxic	1-50 mg.	1 Teaspoon
Moderately Toxic	50-500 mg.	1 Ounce
Slightly Toxic	0.5-5 g.	1 Pint
Practically Non-Toxic	5-15 g.	1 Quart
Relatively Harmless	>15 g.	>1 Quart

Notes:

(1) LD50 is the lethal dose for 50% of the animals in a test group.

Ref: Solvents and Safety, J. M. Nielsen, Material Information Services,
 GE CR&D Center, Schenectady, N. Y., 1977.

are sometimes referred to as synthetic mineral oils. The levels of toxicity shown in Table 9 refer to ingestion in a single dose. Single dermal applications are also considered relatively harmless for the polyalphaolefins. However, precautions are given to avoid prolonged vapor inhalation and eye contact. Hot vapors may be mildly irritating on prolonged exposure for the polyalphaolefins, Therminol 44, and MCS 1958.

- Pollution Potential and Disposability

Each of the fluids listed in Table 8 has been described as not presenting a serious pollution hazard. A precaution is given in Reference 9 that Therminol fluids should be vented outside a building. No information is available on the new developmental fluid MCS 1958. While water definitely does not present a pollution hazard, any corrosion inhibitors selected should be restricted to the nonpolluting type.

No detailed information was obtained on the disposal of Therminol 44 or MCS 1958. The Material Safety Data Sheets (Form OSHA-20) prepared for the Synfluid polyalphaolefin fluids describe a procedure for spillage or leakage involving absorbing and scraping up, incinerating under controlled condition, and observing Federal spill and water quality standards. This procedure is a general one and undoubtedly applicable to many organic fluids. The economics of reclamation of any fluid would depend on the extent of contamination, the initial cost of fluid, and cost of reprocessing including packaging and delivery.

- Fluid Monitoring

Suggested monitoring frequency of fluids is given in Table 8. In the absence of data on the long term stability life of any of these fluids, quarterly sampling and testing during the first year is a wise precaution for maintaining close surveillance of the fluid in the early stages of a new application. The tests recommended are intended to detect the presence of contamination and degradation products and to develop some indication of the

decomposition rate. After the first year testing, the results should give a better indication for the necessary follow-on sampling frequency.

- Fluid Costs

The per gallon cost of the fluids shown in Table 8 is given for 55 gallon quantities. To bring the total cost for fluid used in a collector system into perspective, it is necessary to approximate the total fluid inventory. If 100 serpentine coils would be involved in an installation, and about 1/3 of a gallon for each collector, the following represents the comparative minimum fluid costs for an estimated total requirement of about 40 gallons:

<u>Fluid</u>	<u>Estimated Total Cost, \$</u>
ESH-4	220
Synfluid 4cs	220
Synfluid 6cs	220
Therminol 44	328
MCS 1958	520

As shown above, the polyalphaolefin fluids offer a significant cost savings.

11.3 Screening of Fluids

To identify the optimum fluids for the application described in Section 11.1 from among the 26 selected for consideration, the screening process detailed in Table 7 was followed. Specific requirements were identified for thermal conductivity and viscosity, and were used as the first two screening steps. Pour/freezing point and flash/fire point limits were arbitrarily selected and used as the second and third screening steps. This resulted in the selection of five fluids: Three saturated polyalphaolefin types, ESH-4, Synfluids 4cs and 6cs, Therminol 44, and MCS 1958. These fluids were then ranked in the order of decreasing specific heat at 400°F, of increasing vapor pressure at 400°F, decreasing temperature for the 10%

distillation point, and decreasing recommended use bulk temperature to identify the fluids showing superior properties. The five fluids were further compared for operational characteristics in Table 8, and rated in a preferential order in Table 10, for each property and other considerations. Numbers were assigned for each consideration in a preferential order, with number 1 being the most preferable and 5 the least preferable. The ratings for each fluid were then added for a total value, showing the fluid with the lowest total as the most preferable. On the basis of the properties, materials compatibilities, toxicity, and cost, the polyalpha-olefin type fluids ESH-4, Synfluids 4cs and 6cs emerge as preferable for the 3X collector operating conditions. While this type of fluid should show excellent stability up to 550°-600°F, exposure to the estimated stagnation temperature of 870°F should be avoided. Based on available data, the base stock Synfluids apparently begin to decompose at 611°F. It is quite possible that the addition of a small amount (approximately 0.1%) of oxidation inhibitor can increase the temperature resistance, but this approach would require experimental investigation.

Principal applications of the PAO fluids have been in crankcase oils (Mobil 1 and Delvac 1), gear oils, hydraulic fluids, and compressor and gas turbine lubricants. The Ethyl Corporation is making plans to expand their production of the PAO fluids. The Gulf Oil Chemicals Company is now manufacturing Synfluid 4cs and 6cs at a rate of about 500,000 gallons per year in their semi-works at Harmarville, Pennsylvania. A new 5,000,000 gallons per year Synfluid plant is due on stream near Houston in early 1980.

11.4 . Conclusions and Recommendations

11.4.1 While water shows the advantages of the best heat transfer properties, low cost, and no flammability or toxicity problems, the low temperature limit of 32°F without a drain-down system design and high vapor pressure at 400°F resulted in its elimination during the screening process.

TABLE 10
RATING OF SCREENED FLUIDS FOR SPECIFIC CONSIDERATIONS

	ESH- 4	SYNFLUID 4cs	SYNFLUID 6cs	THERMINOL 44	MCS 1958
Viscosity	4	3	5	2	1
Pour/Freeze Point	2	1	2	3	4
Flammability Props.	4	3	2	5	1
Distillation Props.	2	3	1	4	5
Max. Use Temp.	1	1	1	3	2
Vapor Pressure	1	3	2	4	5
Cp	1	2	3	4	5
K	2	1	1	3	4
Materials Compat.	2	2	1	3	3
Toxicity	1	1	1	2	3
Cost	1	1	1	2	3
Total Rating	<u>21</u>	<u>21</u>	<u>20</u>	<u>35</u>	<u>36</u>

Notes:
 Numbers correspond to relative preferential rating for each consideration.
 1 = Most Preferable
 5 = Least Preferable
 Based on Data in Tables, 2, 3, 4, 5, and 6.

Based on the overall requirements applied to the 25 nonaqueous fluids selected for evaluation, only five fluids emerge as potential candidates:

Ethyl ESH-4

Gulf Synfluids 4cs and 6cs

Monsanto's Therminol 44, MCS 1958

11.4.2 A comparison of overall properties and other considerations for the five fluids as detailed in Table 10, shows the superiority of the poly-alphaolefin type fluids ESH-4, Synfluids 4cs and 6cs over Therminol 44 and MCS 1958. The ratings applied to the polyalphaolefin fluids indicate that there are small differences among them with Synfluid 6cs being slightly superior overall. If the viscosity requirement is the prime consideration, Ethyl ESH-4 or Synfluid 4cs could be used.

11.4.3 While the viscosity of Synfluid 6cs is rather marginal compared to the stipulated requirement, it provides the highest flash and fire points, boiling point, and thermal conductivity, and the best overall materials compatibility. Its specific heat is slightly lower than the Ethyl and Synfluid 4cs fluids, but it is comparable on toxicity levels and cost, which is very significantly lower than the cost of Therminol 44 or MCS 1958. The chemical stability of Synfluid 6cs, being a higher molecular weight blend, undoubtedly would be for a longer period of time, particularly if exposed to an operating temperature of 400°F under a blanket of nitrogen. However, since the decomposition temperature of the Synfluids has been found to be 611°F, exposure to the predicted stagnation temperature of 870°F must be avoided for long life stability.

11.4.4 If Synfluid 6cs, Synfluid 4cs or Ethyl ESH-4 is used in a test loop, a regular sampling and monitoring program is recommended. An initial sample should be taken after charging and circulating in the system, and then monthly sampling. These samples should then be analyzed for the following:

Viscosity

Acid Number

Appearance

Composition - Carbon Number Distribution

Based on the test results obtained over a six month period, some prediction could be made for a longer interval monitoring period, e.g., every six or 12 months.

12. PERFORMANCE ANALYSIS

The performance analysis task has included the following tasks to date:

- Performance/Cost Analysis for Design Optimization
- Performance Predictions on an Annual Basis
- Instantaneous Performance Predictions

The analytical procedures and rationale used for these analyses are delineated in detail on the following pages. The cost analysis subsection includes a complete description of the basic computer model used for all three subtasks listed above. It also includes a discussion of collector parameters and their effect on performance and the cost effectiveness index of the various collector configurations studied. Decision making processes are described which led to the selection of the recommended collector design. Also included is a discussion of the effect of material selection on cost and performance.

The annual thermal performance under real hourly weather conditions is calculated for the end use application in Des Moines, Iowa. The model is discussed and the calculation procedures are shown.

Instantaneous efficiency versus collector inlet temperature is shown for three different insolation levels and the analytical procedure is defined.

After prototype collectors are built later in the program, the collectors will be tested to verify the performance calculations. A test plan will be prepared and thermal performance will be analyzed under a variety of test conditions.

12.1 Performance/Cost Analysis for Design Optimization

The objective of this task was to utilize a basic math model to evaluate collector annual performance to optimize the collector design to obtain the maximum BTU gain/collector cost ratio under the specified end use conditions. Parameters studied included reflector design (concentration ratio and height), reflector reflectivity, and cover transmissivity. The planned application requires 400°F output temperature and the location is Des Moines, Iowa. For the purposes of this study average monthly ambient temperatures for Des Moines and clear day 40° latitude hourly insolation data for the 21st of each month was used with the collector output temperature assumed to be a constant 400°F. All cost effectiveness analysis was based only on collector costs. The system installation costs associated with installing and operating additional square footage of collector was not considered in the selection of optimum collector design.

Collector Cost

Labor and material costs were estimated for five different collector sizes corresponding to reflector truncation heights of 4, 6, 8 and 10 inches. The costs were estimated as our minimum selling price under reasonable production volume, i.e., more than 250 collectors per month. These costs were a near linear function of the housing height which is a direct function of the reflector truncation height. The costs shown in Figure 11 are for a collector with a galvanized steel housing, anti-reflection treated tempered glass cover, .020 inch thick polished aluminum reflectors, six General Electric receivers and a 4.1X cusp type CPC reflector system. Preliminary examination of the collector performance data indicated that this configuration would most likely be selected, so that design was used as a baseline for the cost effectiveness evaluation for all designs.

Collector Performance

Collector performance was evaluated using a heat gain math model which utilized the following equation for the energy gain calculation. Heat

Figure 11. Estimated Collector Selling Price Versus Reflector Truncation Height

gains were calculated for each hour for the 21st day of each month and summed up to obtain annual heat gain.

$$HG = \tau_1 \tau_2 \alpha \rho^n \gamma \% I WF - RL \quad (1)$$

where:

HG = heat gain in BTU's per ft² aperture

τ_1 = transmissivity of cover glazing

τ_2 = transmissivity of outer receiver tube

α = absorptivity of coating on receiver tube

ρ = reflectivity of reflector material

n = average number of reflections

γ = diffuse insolation usability factor which is assumed to be equal to beam ratio + diffuse ratio times sin (acceptance half angle)

$\%$ = proportion of all entering rays that strike the absorber

I = insolation rate

W = factor used to account for reflection losses off the receiver

F = receiver shading factor

RL = heat losses, which are considered to be only by radiation

A discussion of each parameter listed above in Equation (1) follows:

- τ_1 - The transmissivity of the cover glazing was assigned values of .88, .91 and .95. These values correspond to the transmissivity of 3/16-inch thick low iron glass, 3/16-inch thick waterwhite (no iron content) glass and anti-reflective surface treated 3/16-inch thick low iron content glass.
- τ_2 - The transmissivity of the outer receiver tube was assigned values of .89 and .92. Chamberlain later tested the transmissivity of a piece of the outer tube and found it to be .90 to .91.

- α - The absorptivity of the coating on the receiver was given by General Electric Company to be .89.
- ρ - The reflectivity of the reflector material was assigned values of .75, .81 and .87 and each was assumed to be all specular. It was felt that this range covered both the lowest acceptable value and also the highest economically feasible value for available materials.
- n - The average number of reflections before a ray of light reaches the receiver was calculated for each hourly condition. This value is calculated in a separate computer program which traces 100 rays entering across the aperture at the prescribed angle for that hourly calculation and outputs the average number of reflections to collection.
- % - This is also an output of the ray tracing program. It is the percentage of the rays entering the aperture that are reflected and hit the absorber for the prescribed angle. It is close to 1.00 for all angles of incidence less than the acceptance half angle. Rays within the acceptance angle miss the absorber either because they pass under it where part of the reflector has been removed to make room for the outer glass of the receiver or because of prescribed reflector or receiver placement errors which are inputs to the ray tracing program.
- γ - This factor is used to compensate for the fact that all the diffuse portion of the insolation is not utilized by the CPC. It is assumed that the CPC will use all of the beam radiation and a portion of the diffuse equal to the diffuse component multiplied by the sine of the acceptance half angle for the reflector design being studied.

- I - The insolation rate in BTU's/hr-ft² that is assumed to be incident on the collector front surface. Insolation data was taken from ASHRAE 93-77 tables for 40° latitude. Insolation rates are given for 30°, 40°, 50° and 60° collector slopes and those data were used for incident radiation on the collector by using the data nearest to the actual slope of the collectors for any given time of the year. For example for the 4.1X collector which requires four slope adjustments per year, the slope is varied from latitude +22° to latitude +0° to latitude -22° to latitude +0° on specific days of the year to obtain the maximum time of useful solar input. In January, then, the collector slope would be latitude +22°, for the case of Des Moines this is 62°. Insolation data for 40° latitude and 60° slope was used for the incident radiation. The ratio of beam radiation to total was assumed to be constant for all hours and months and calculations were made for three different beam ratios: .70, .78 and .85. While this method is not exact, it is considered valid because all cost-effectiveness decisions were made on a model to model comparison basis that reduces the need for accuracy on an absolute basis.
- W - This factor is used to account for reflection losses from the receiver outer glass tube and the absorber coating resulting from high angles of incidence when the sun is not directly south of the collector. It is an approximation only and does not directly include effects of the approach angle of the rays coming from the reflector in the north-south plane which strike the outer glass and absorber surface at varying angles of incidence. The approximation used in this study was $W = (\cos \omega)^{.25}$, ω = hour angle.
- F - The receiver and the reflector are shaded by both the ends of the housing and the center manifold when the sun is not directly

south of the collector. This effect is more extreme as the hour angle increases. The inclusion of this factor pointed out the need for a significant change in the design in the center manifold area. The proposed collector was made up of two 4 ft by 4 ft modules with separate glass covers. This design caused significant shading losses in the morning and afternoon hours because the box is so deep and the manifold end of the receiver has an effective absorbing area to within 1/2 inch of the end of the receiver. The shading problem was greatly reduced by using a center manifold that was much lower than the box sides and ends and by eliminating the two piece glazing. As a result of the redesign the shading problem is significant only before 9 a.m. and after 3 p.m.

- RL - Because the receiver is evacuated it was assumed that all heat losses from the absorber would be by radiation only. These losses would be from the absorber to the outer glass tube of the receiver. The losses from the outer glass tube are of concern only to determine the temperature of the glass to which the absorber surface is emitting. Laboratory tests at Chamberlain indicated that under operating conditions (absorber temperature about 375°F greater than ambient) the outer glass temperature was about 75°F higher than ambient. The emissivity of the absorber surface at a temperature of 430°F was determined to be .07 by General Electric Company. The radiation losses for this study were calculated using the above data, the average monthly temperatures for Des Moines, Iowa, and an assumed average absorber surface temperature of 430°F with the formula shown below. The losses per square foot of absorber surface are calculated and divided by the concentration ratio to convert to losses per aperture area.

$$RL = \frac{1}{ACON} \sigma \frac{(T_p^4 - T_g^4)}{J}$$

RL = Radiation losses in BTU's per square foot of aperture per hour
 $ACON$ = Actual Concentration Ratio after truncation
 σ = Stefan-Boltzmann constant = $.1714 \times 10^{-8}$ BTU/hr-ft²-°R⁴
 T_p = Average absorber surface temperature, assumed to be 430°F for this cost effectiveness study
 T_g = Average temperature of the outer glass tube on the receiver to which the absorber emits. The temperature was assumed to be 75°F higher than the average monthly ambient temperature.

$$J = \frac{1}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \frac{(1 - \epsilon_2)}{\epsilon_2}}, \text{ where}$$

ϵ_1 and ϵ_2 are the emissivity of the absorber surface and the outer glass tube respectively and A_1 and A_2 are the areas of the respective surfaces (Reference 8).

Reflector/Receiver Configurations Studied

The following paragraphs delineate the various collector physical considerations included in this study.

- It was assumed that the collector would be a non-tracking design which would not require more than six adjustments per year and would have an overall concentration ratio of about 3 to 1. With this in mind the following designs were studied.
 - Four slope adjustments per year with design concentration ratios of 3.5, 4.1, 4.7 and 5.2X, each of these was truncated at four different heights: 4, 6, 8 and 10 inches.
 - Six slope adjustments per year with design concentration ratios of 4.7, 5.2, and 6.2X, each of these was truncated at four different heights: 4, 6, 8 and 10 inches.
- Reflector contour inaccuracies were induced into the ray tracing program by reducing the acceptance angle of each design by both 1° and 2°. Chamberlain staff think that 1° is probably quite

optimistic and we prefer to use $1\text{-}1/2^\circ$ or 2° as a more realistic estimate for a mass production tolerance. It should be noted that any error in setting the slope of the collector is also included here.

- Manufacturing errors in the placement of the receiver relative to the reflector assembly were also considered. These errors were induced into the ray tracing program by positioning the receiver off the true center position. Errors of .03 and .06 inch were used. We think that .06 is a more realistic estimate of this error.

Performance Results

The collector performance calculations discussed above were compared to ascertain the effect of the various design parameters on the annual performance of the collector. Tables 11, 12 and 13 are copies of three of the many pages of computer printout from the cost effectiveness study. Again, it must be emphasized that these performance figures are for 100% clear day sun and are considered to be valid on a comparative basis but are not indicative of expected output under real weather conditions. The model was later expanded and adapted to utilize NOAA weather tapes to more accurately predict annual gain under realistic operating conditions. A discussion of that model and the initial results are presented in Section 12.2. Tables 11, 12, and 13 respectively show data generated for: (1) the 4.1X truncated at 8 inches with a reflector error of 1° and tube placement error of .06 inch, (2) the 4.1X truncated at 8 inches with a reflector error of 2° and tube placement error of .06 inch, and (3) the 4.1X truncated at 6 inches with a reflector error of 2° and tube placement error of .06 inch. The data columns reading across the page from left to right are identified as follows:

Annual H.G. Coll - Annual heat gain in BTU's for the collector.

It is the heat gain per square foot multiplied by the active length

CPC HEAT GAIN PERFORMANCE

ANNUAL H.G. COLL	INPUT CON	CALC. CON	TRUN HT.	WIDTH	COM. ERROR	TUBE ERROR	COV. TAU	TUBE TAU	ALPHA	RHO	DIR. RATIO	EMISS	ANNUAL H.G. FT.
5307111.	4.10	2.60	8.28	14.27	1.00	-0.06	0.88	0.89	0.89	0.75	0.70	0.07	200585.
5657583.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	221390.
6341605.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	239684.
5874037.	4.10	2.60	8.28	14.27	1.00	-0.06				0.81	0.70	0.07	222012.
6472444.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	244629.
6998273.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	264503.
6444858.	4.10	2.60	8.28	14.27	1.00	-0.06				0.87	0.70	0.07	243587.
7090900.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	268004.
7656522.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	289382.
5544289.	4.10	2.60	8.28	14.27	1.00	-0.06		0.92		0.75	0.70	0.07	209549.
6114199.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	231089.
6615659.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	250042.
6131304.	4.10	2.60	8.28	14.27	1.00	-0.06				0.81	0.70	0.07	231736.
6751391.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	255172.
7295460.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	275736.
6722995.	4.10	2.60	8.28	14.27	1.00	-0.06				0.87	0.70	0.07	254099.
7391209.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	279355.
7975896.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	301453.
5546984.	4.10	2.60	8.28	14.27	1.00	-0.06	0.91	0.89		0.75	0.70	0.07	209651.
6117117.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	231200.
6618774.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	250160.
6134236.	4.10	2.60	8.28	14.27	1.00	-0.06				0.81	0.70	0.07	231847.
6754567.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	255292.
7298837.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	275863.
6726161.	4.10	2.60	8.28	14.27	1.00	-0.06				0.87	0.70	0.07	254219.
7394623.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	279484.
7979527.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	301590.
5792246.	4.10	2.60	8.28	14.27	1.00	-0.06		0.92		0.75	0.70	0.07	218921.
6383350.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	241222.
6902947.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	260900.
6401301.	4.10	2.60	8.28	14.27	1.00	-0.06				0.81	0.70	0.07	241940.
7043540.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	266214.
7606155.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	287479.
7014175.	4.10	2.60	8.28	14.27	1.00	-0.06				0.87	0.70	0.07	265104.
7705169.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	291221.
8309788.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	314073.
5866814.	4.10	2.60	8.28	14.27	1.00	-0.06	0.95	0.89		0.75	0.70	0.07	221739.
6464367.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	244324.
6989410.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	264168.
6482497.	4.10	2.60	8.28	14.27	1.00	-0.06				0.81	0.70	0.07	245009.
7131397.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	269335.
7699590.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	291010.
7101741.	4.10	2.60	8.28	14.27	1.00	-0.06				0.87	0.70	0.07	268414.
7799585.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	294789.
8410200.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	317868.
6123778.	4.10	2.60	8.28	14.27	1.00	-0.06		0.92		0.75	0.70	0.07	231451.
6742778.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	254847.
7286299.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	275389.
6761820.	4.10	2.60	8.28	14.27	1.00	-0.06				0.81	0.70	0.07	255566.
7433071.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	280937.
8020416.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	303136.
7402418.	4.10	2.60	8.28	14.27	1.00	-0.06				0.87	0.70	0.07	279778.
8123784.	4.10	2.60	8.28	14.27	1.00	-0.06					0.78	0.07	307043.
8754980.	4.10	2.60	8.28	14.27	1.00	-0.06					0.85	0.07	330899.

Table 11. Sample of Performance Parametric Study Output
for 4.1X Truncated to 8-Inch Height with 1° Reflector
Error

ANNUAL H.G. COLL	INPUT CON	CALL. CON	TRUN HT.	WIDTH	COM. ERROR	TUBE ERROR	COV. TAU	TUBL TAU	ALPHA	KHO	DIR. RATIO	EMISS	ANNUAL H.G. FT.
5281670.	4.10	2.60	8.28	14.27	2.00	-0.06	0.88	0.89	0.89	0.75	0.70	0.07	199623.
5830151.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	220354.
6311649.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	238552.
5842880.	4.10	2.60	8.28	14.27	2.00	-0.06				0.81	0.70	0.07	220835.
6437850.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	243322.
6961635.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	263119.
6406533.	4.10	2.60	8.28	14.27	2.00	-0.06				0.87	0.70	0.07	242138.
7049381.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	266435.
7612366.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	287713.
5517990.	4.10	2.60	8.28	14.27	2.00	-0.06		0.92		0.75	0.70	0.07	208555.
6085117.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	229990.
6584973.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	248882.
6098313.	4.10	2.60	8.28	14.27	2.00	-0.06				0.81	0.70	0.07	230489.
6715781.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	253826.
7257588.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	274304.
6683190.	4.10	2.60	8.28	14.27	2.00	-0.06				0.87	0.70	0.07	252595.
7348290.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	277732.
7930252.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	299728.
5520675.	4.10	2.60	8.28	14.27	2.00	-0.06	0.91	0.89		0.75	0.70	0.07	208657.
6088025.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	230100.
6588087.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	249000.
6101224.	4.10	2.60	8.28	14.27	2.00	-0.06				0.81	0.70	0.07	230599.
6718944.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	253946.
7260950.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	274431.
6686341.	4.10	2.60	8.28	14.27	2.00	-0.06				0.87	0.70	0.07	252714.
7351686.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	277861.
7933865.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	299865.
5765051.	4.10	2.60	8.28	14.27	2.00	-0.06		0.92		0.75	0.70	0.07	217893.
6353239.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	240124.
6871447.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	259710.
6367004.	4.10	2.60	8.28	14.27	2.00	-0.06				0.81	0.70	0.07	240644.
7006715.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	264822.
7566992.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	285998.
6973013.	4.10	2.60	8.28	14.27	2.00	-0.06				0.87	0.70	0.07	263549.
7660786.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	289543.
8262589.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	312289.
5839349.	4.10	2.60	8.28	14.27	2.00	-0.06	0.95	0.89		0.75	0.70	0.07	220701.
6433958.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	243175.
6957598.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	262966.
6447861.	4.10	2.60	8.28	14.27	2.00	-0.06				0.81	0.70	0.07	243700.
7094207.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	268129.
7660039.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	289511.
7060170.	4.10	2.60	8.28	14.27	2.00	-0.06				0.87	0.70	0.07	266843.
7754763.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	293095.
8362530.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	316066.
6094662.	4.10	2.60	8.28	14.27	2.00	-0.06		0.92		0.75	0.70	0.07	230351.
6711857.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	253678.
7253414.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	274147.
6726165.	4.10	2.60	8.28	14.27	2.00	-0.06				0.81	0.70	0.07	254219.
7394627.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	279484.
7979532.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	301591.
7359445.	4.10	2.60	8.28	14.27	2.00	-0.06				0.87	0.70	0.07	278154.
8077448.	4.10	2.60	8.28	14.27	2.00	-0.06					0.78	0.07	305291.
8705705.	4.10	2.60	8.28	14.27	2.00	-0.06					0.85	0.07	329037.

Table 12. Sample of Performance Parametric Study Output
for 4.1X Truncated to 8-Inch Height with 2° Reflector
Error

CPC HEAT GAIN PERFORMANCE													ANNUAL H.G. FT.
ANNUAL H.G. COLL	INPUT CON	CALC. CON	TRUN HT.	WIDTH	CON. ERRCH	TUBE ERROR	COV. TAU	TUBE TAU	ALPHA	RHO	DIR. RATIO	EMISS	
4641261.	4.10	2.29	6.01	12.57	2.00	-0.06	0.88	0.89	0.89	0.75	0.70	0.07	199118.
5143178.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	220651.
5585025.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	239607.
5118699.	4.10	2.29	6.01	12.57	2.00	-0.06				0.81	0.70	0.07	219600.
5661882.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	242904.
6140262.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	263427.
5597018.	4.10	2.29	6.01	12.57	2.00	-0.06				0.87	0.70	0.07	240121.
6181435.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	265194.
6692799.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	287132.
4857518.	4.10	2.29	6.01	12.57	2.00	-0.06		0.92		0.75	0.70	0.07	208395.
5377101.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	230686.
5836386.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	250390.
5351669.	4.10	2.29	6.01	12.57	2.00	-0.06				0.81	0.70	0.07	229595.
5915872.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	253800.
6410377.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	275016.
5848821.	4.10	2.29	6.01	12.57	2.00	-0.06				0.87	0.70	0.07	250924.
6452937.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	276841.
6981530.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	299519.
4859977.	4.10	2.29	6.01	12.57	2.00	-0.06	0.91	0.89		0.75	0.70	0.07	208501.
5379776.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	230801.
5839242.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	250513.
5354334.	4.10	2.29	6.01	12.57	2.00	-0.06				0.81	0.70	0.07	229710.
5918758.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	253924.
6413446.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	275147.
5851683.	4.10	2.29	6.01	12.57	2.00	-0.06				0.87	0.70	0.07	251047.
6456022.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	276974.
6984821.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	299660.
5083606.	4.10	2.29	6.01	12.57	2.00	-0.06		0.92		0.75	0.70	0.07	218095.
5623281.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	241248.
6099210.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	261666.
5596993.	4.10	2.29	6.01	12.57	2.00	-0.06				0.81	0.70	0.07	240120.
6181407.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	265192.
6692769.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	287131.
6112070.	4.10	2.29	6.01	12.57	2.00	-0.06				0.87	0.70	0.07	262218.
6736781.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	289019.
7283402.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	312470.
5151597.	4.10	2.29	6.01	12.57	2.00	-0.06	0.95	0.89		0.75	0.70	0.07	221012.
5697602.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	244436.
6178249.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	265057.
5671051.	4.10	2.29	6.01	12.57	2.00	-0.06				0.81	0.70	0.07	243297.
6261261.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	268618.
6777691.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	290774.
6191236.	4.10	2.29	6.01	12.57	2.00	-0.06				0.87	0.70	0.07	265614.
6822139.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	292681.
7374182.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	316364.
5385883.	4.10	2.29	6.01	12.57	2.00	-0.06		0.92		0.75	0.70	0.07	231063.
5952794.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	235385.
6449644.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	276700.
5925350.	4.10	2.29	6.01	12.57	2.00	-0.06				0.81	0.70	0.07	254207.
6535454.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	280382.
7069293.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	303284.
6463068.	4.10	2.29	6.01	12.57	2.00	-0.06				0.87	0.70	0.07	277276.
7115239.	4.10	2.29	6.01	12.57	2.00	-0.06					0.78	0.07	30525..
7685887.	4.10	2.29	6.01	12.57	2.00	-0.06					0.85	0.07	329737.

Table 13. Sample of Performance Parametric Study Output
for 4.1X Truncated to 6-Inch Height

of the receiver (3.71 ft) times the width of one reflector trough times the number of receivers per collector (6).

Input Con - This is the design concentration ratio which is equal to $1/\sin(\theta_a)$.

Calc. Con - The calculated concentration after truncation to the specified height. It is equal to the trough width divided by the circumference of the absorber.

Trun Ht. - The truncation height in inches of the reflector as it is carried in the ray tracing program. Because of the way the reflector surface is generated by the ray tracing program, the truncation height is always slightly greater than the specified truncation height.

Width - This is the width in inches of a reflector trough at the given truncation height.

Con. Error - The reflector error in degrees due to contour inaccuracies.

Tube Error - The tube placement error in inches off the true center of the reflector.

Cov. Tau - The transmissivity of the cover glazing.

Tube Tau - The transmissivity of the outer glass tube on the receiver.

Alpha - The absorptivity of the absorber surface on the receiver.

Rho - The total reflectivity of the reflector material which was assumed to be all specular.

Dir. Ratio - The ratio of the insolation beam component to the total insolation.

Emiss - The hemispherical emissivity of the absorber surface.

Annual H.G. Ft. - The annual heat gain in BTU's per square foot of aperture.

Examination of the data indicated the following performance trends developed in this parametric study.

- Errors due to inaccurate reflector contours significantly affected performance, and as expected the effect of the errors was much more evident for the collectors with the smaller acceptance angle. In fact, this effect steered us toward the 4.1X rather than the 4.7X design because of concern over possible manufacturing problems in holding tolerances in the assembly operation. The acceptance half angle for the 4.1X and the 4.7X are 14.1° and 12.3° respectively. Results show that very little effect was caused on the 3.5X and 4.1X by increasing the ray error from 1° to 2° but for the 4.7X and 5.2X the effect was much more pronounced. At the 8-inch truncation height this effect of increasing the reflector error from Figures 12 and 13 is shown to be 0.6% for the 4.1X and 5.0% for the 4.7X. It is evident that a substantial amount of energy is being gained when the rays are near the maximum acceptance angle. The error effects did not appear to be directly related to truncation height.
- Errors in receiver tube placement relative to the reflectors did not affect the performance to the degree that the reflector error did. The difference in performance between errors of .03 and .06 was less than 1/2% in most cases. We think that there should be no problems at all in maintaining a tolerance of $\pm .06$ inch in tube placement under mass production assembly operations.

- Changes in the cover glazing transmissivity had a very significant effect on collector performance as would be expected. Table 11 is a typical example of all the performance results relative to varying cover transmissivities. Results of the computer modeling indicated that the performance of the collector under ideal insolation conditions increased about 1.4% for each 1% increase in cover transmissivity. As the insolation rate decreases the effect would be even greater and would eventually make the difference between losing or gaining energy under marginal operating conditions.
- The same reasoning as above applies to the outer receiver tube transmissivity. Although that design is considered fixed, it does appear that a significant increase in performance could be obtained by treating the glass to reduce reflection losses. Chamberlain experience in treating the same type glass tubes has been that a high rate of glass breakage occurs when using the etching technique developed by Honeywell Corporation.
- The reflectivity of the reflector material has an even more significant effect on performance than does the cover glazing transmissivity. An increase of 1% in reflectivity will result in about a 1.65% increase in thermal performance. This effect is essentially independent of the other parameters. The model does not consider the difference between specular and diffuse reflectivity. The calculations are based on the assumption that the reflectivity is all specular. Although this will not be the case it is considered to be a good measure of the effect of varying the reflectivity. This is a consideration that was included in the final reflector material selection.
- The ratio of beam to total insolation affected the overall collector performance but did not influence the effect of the

other parameters in this study. The smaller the acceptance angle, the greater will be the effect of varying this ratio. For example for a 4.1X truncated to 2.6X (8 inches high) changing the beam ratio from .85 to .78 caused a reduction in performance of about 8.0%. A similar change for a 5.2X truncated to 2.7X (8 inches high) resulted in a decrease in performance of about 9.0%. This is simply a result of the method used in the computer model to determine the portion of the diffuse insolation that can be utilized by a CPC.

Performance/Cost Analysis Results

The method used to determine the optimum collector configuration was a two part analysis: (1) determine the most cost effective reflector system design based on the specified end use condition (location: Des Moines, Iowa, collector outlet temperature 400°F, all year usage), and (2) determine on a cost effectiveness basis the optimum glazing and reflector materials. These analyses are discussed in the following paragraphs.

The reflector system design was selected based on the curves presented in Figures 12, 13, and 14. These curves were generated by combining the collector thermal performance data discussed in the previous paragraphs with the collector cost data shown in Figure 11. These data are based on collector cost only; no provision is made to include system costs in this study. Examination of Figures 12, 13, and 14 indicates the following trends.

- There is a definite "peaking out" in cost effectiveness in the 8 to 9-inch truncation height range. This is probably the result of the increased end shading effects as the housing gets deeper and the fact that the slope of the reflector at this height is steep enough that a given increase in reflector height costs more in dollars than the additional width provides in performance.

1° REFLECTOR ERROR
 .06 INCH RECEIVER PLACEMENT ERROR
 .95 COVER TRANSMISSIVITY
 .89 TUBE TRANSMISSIVITY
 .87 REFLECTIVITY
 .78 BEAM INSOLATION RATIO
 4 SLOPE ADJUSTMENTS PER YEAR

Figure 12 . Collector Cost Effectiveness Versus Reflector Truncation Height for Given Design Concentration Ratio

Figure 13. Collector Cost Effectiveness Versus Reflector Truncation Height for Given Design Concentration Ratio

1° REFLECTOR ERROR
 .06 INCH RECEIVER PLACEMENT ERROR
 .95 COVER TRANSMISSIVITY
 .89 TUBE TRANSMISSIVITY

.87 REFLECTIVITY
 .78 BEAM INSULATION RATIO
 6 SLOPE ADJUSTMENTS PER YEAR

Figure 14. Collector Cost Effectiveness Versus Reflector Truncation Height for Given Design Concentration Ratio

- Comparison of Figures 12 and 13 shows that an increase in reflector error from 1° to 2° causes a much greater decrease in performance for the higher concentration ratio collectors. Note the comparatively drastic decrease in performance for both the 4.7X and 5.2X designs. This indicates that there is a significant amount of the collector annual gain occurring when the projected angle of the sun is in the 10 - 12° range. The 4.1X, 4.7X and 5.2X designs have acceptance half angles of 14.1 , 12.3 and 11.1 degrees respectively. Manufacturing costs associated with maintaining a high degree of accuracy in the reflector shape may be found to be excessively high. This cannot be determined until hardware is actually built under mass production methods but the error effect evident in these figures strongly influenced our decision toward using the 4.1X rather than the 4.7X which had a slightly higher cost effectiveness index with the 1° reflector error.
- Figure 14 shows cost effectiveness data assuming six adjustments of collector slope each year. The 5.2X in this case is 2.7% better than the 4.1X with four adjustments per year. The performance data for a 2° reflector error for six adjustments per year would probably result in the effect being the same as it was for the four adjustments per year as discussed above.

The decision was made to go with the 4.1X with four slope adjustments per year rather than the other "best" design, a 5.2X with six slope adjustments. The increase of only 2.7% did not seem to justify the requirement for the additional two slope adjustments each year. The cost effectiveness data indicated that in either case a truncation height of 8-9 inches was optimal and the actual calculated concentration of the 5.2X and the 4.1X at a height of 8 inches were nearly the same, 2.7X and 2.6X respectively. This indicated that the thermal performance would depend nearly entirely on the optical efficiency of the two concentrators. The average daily collection time for

the 4.1X and 5.2X over the year was nearly equal, 8.76 and 8.60 hours (Reference 9) respectively, so there was no advantage for either in this case. The fact that the 4.1X could tolerate a greater error in reflector accuracy before showing significant performance degradation implied that it would be a better performer under real manufacturing and field use conditions.

The determination of the optimum glazing material was straightforward once the reflector system and thus the collector physical size and cost were fairly well prescribed. As discussed in the section on glazing selection, it was decided that glass should be used for the cover material. The question then became one of selecting between three options:

- 1) Low iron content glass at \$.70/ft²
- 2) Waterwhite glass which has no iron content at \$1.11/ft²
- 3) Low iron glass with an anti-reflective treatment at \$.70 + \$.40 = \$1.10/ft².

The transmissivity of each was assumed to be .88, .91 and .93 to .95 respectively. Obviously the waterwhite glass was not competitive with the low iron with anti-reflective treatment in terms of transmissivity per cost. As pointed out previously, the performance of the collector increased by about 1.4% for each 1% increase in transmissivity of the glazing. Then, given a total collector cost of \$470 for the 4.1X truncated at 8 inches, we can calculate that the anti-reflective treatment which will increase the transmissivity by 5% to 7% (Reference 3) is worth at least $5 \times 1.4\% \times \$470 = \32.90 per collector in increased performance. The collector requires 32.2 ft² of glass so if the cost of the anti-reflective treatment is less than \$1.02/ft² then it would be cost effective. The process cost is in fact \$.40 to \$.50/ft² (Reference 3) at the treating facility plus shipping charges. This is obviously a very cost effective option and the decision was made to use 3/16-inch thick Lo-IronTM tempered glass from ASG Industries, Kingsport, Tennessee, and to have it surface treated by NorEl1, Inc., St. Paul, Minnesota to reduce reflection losses.

The same type of reasoning was used on the selection of the reflector material. The performance of the collector was increased by about 1.65% for each 1% increase in reflectivity. At the projected cost of \$470 per collector each increase of 1% in reflectivity is worth \$7.75 in collector cost. There are 48 ft² of reflector material used for production of the collector. Then, each increase of 1% in reflectivity is worth \$.16 per square foot of reflector material. As discussed in Section 3.1, Reflector Material Selection, the two competitive products, Kinglux and Coilzak, have reflectivities of .874 and .80 and cost \$1.45 and \$.74 respectively. The 7.4% difference in reflectivity is worth 1.18 ft² of material and Kinglux was chosen as the most cost effective material.

This analysis was considered to have adequately defined the optimum collector configuration and is considered complete. It is realized that a more accurate analysis (on an absolute scale) could have been done by using real weather data entering actual insolation diffuse and beam components which are available on the NOAA weather tapes and hourly ambient temperatures. However, the time and cost required for that type analysis would have been prohibitive. The model was modified to use NOAA tapes to obtain actual predicted performance data. That task is discussed in Section 12.2.

12.2 Performance Predictions on an Annual Basis

The purpose of this task was to predict on an annual basis the thermal performance in terms of total heat gain of the selected collector design under real time weather conditions. The model discussed in the previous section was modified to use hourly weather data (direct insolation, diffuse insolation, ambient temperature) available from the National Oceanic and Atmosphere Administration, NOAA. The performance predictions were based on the end use defined for the collector in this project, which is supplying 400°F fluid for heating and air conditioning the State Capitol Complex at Des Moines, Iowa with a year-round energy requirement. The annual heat gain predicted for the collector under these conditions is 181,436 BTU/yr-ft², or in terms of total energy gained per collector 4,767,600 BTU/yr-collector. Figure 15 is a copy of the computer model output which shows the heat gain per square foot of aperture by the month for an entire year.

CHAMBERLAIN MFG. CORP./ENERGY SYSTEMS GROUP
MONTHLY CPC HEAT GAIN (KBTU'S/SQ. FT.)

HEAT GAIN IN BTU'S PER SQUARE FOOT OF APERTURE TOTAL HEAT GAIN FOR THIS CPC IS 181436.

Figure 15. Predicted Annual Heat Gain for Average Hourly Weather Conditions, Des Moines, Iowa

The annual calculations assume that the collector slope angle is varied four times a year as shown below.

23 Feb - 19 Apr: Slope = $41\frac{1}{2}^{\circ}$ Off Horizontal
20 Apr - 22 Aug: Slope = $19\frac{1}{2}^{\circ}$ Off Horizontal
23 Aug - 18 Oct: Slope = $41\frac{1}{2}^{\circ}$ Off Horizontal
19 Oct - 22 Feb: Slope = $63\frac{1}{2}^{\circ}$ Off Horizontal

The heat gain model used in this study was the same as that discussed in Section 12.1 with some modifications as discussed below. The following values were used for these calculations of annual gain under real weather conditions.

τ_1 - cover transmissivity = .94
 τ_2 - receiver tube transmissivity = .91
 α - absorptivity of receiver = .89
 ρ - reflectivity of reflector = .87

Manufacturing assembly errors were imposed on the model. An error of 0.06 inch in lateral displacement of the receiver and a 1° error in reflector surface accuracy was used in the heat gain calculations.

The hourly weather data tape for a typical meteorological year for Omaha, Nebraska, was used for the calculations because no data of this type are available for Des Moines. The Omaha data are considered to be a very good match for Des Moines weather. Omaha is located 120 miles west and 20 miles south of Des Moines. All other cities for which hourly data are available are substantially further from Des Moines and are located in a different weather pattern area. Examination of NOAA Meteorological Data for the two cities indicated that their insolation and temperature conditions are very comparable. Figures 16 and 17 are copies of the average weather data over the past years for the two cities as furnished by NOAA. The average monthly and annual temperatures are quite close, with Omaha having very slightly higher ambient temperature (2 to 3°F). The only comparison available for

Meteorological Data For The Current Year

Station:	DES MOINES, IOWA # 14933							MUNICIPAL AIRPORT				Standard time used: CENTRAL				Latitude 41° 32' N		Longitude 93° 39' W		Elevation (ground) 938 feet		Year: 1976																					
Month	Temperature °F						Degree days Base 65 °F		Precipitation in inches						Relative humidity, pct.				Wind				Average sky cover, tenths, sunrise to sunset		Number of days						Average station pressure mb 963 feet m.s.l.												
	Averages			Extremes					Water equivalent			Snow, ice pellets			Resultant		Fastest mile		Sunrise to sunset		Precipitation .01 inch or more				Snow, ice pellets 1.0 inch or more		Thunderstorms		Heavy fog, visibility 1/2 mile or less				Temperature °F										
	Daily maximum	Daily minimum	Monthly	Highest	Date	Lowest	Date	Heating	Cooling	Total	Greatest in 24 hrs.	Date	Total	Greatest in 24 hrs.					Date	Hour	Hour	Hour	Hour	Direction	Speed m.p.h.	Average speed m.p.h.	Speed m.p.h.	Direction	Date	Percent of possible sunshine	Clear	Partly cloudy	Cloudy	Precipitation 0.01 inch or more	Snow, ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility 1/2 mile or less	(b) 90° and above	37° and below	32° and below	0° and below	Elev.	
	(Local time)																Direction		Speed m.p.h.		Average speed m.p.h.		Speed m.p.h.		Direction		Date																
JAN	34.2	11.5	22.9	56	23	-10	8	1297	0	0.23	0.20	25	2.4	2.0	25	66	70	52	58	29	5.5	13.6	35	NW	15	62	3.5	9	11	11	2	1	0	1	0	9	31	7	984.4				
FEB	44.3	23.9	34.1	62	27	0	4	890	0	2.43	1.60	20-21	11.8	10.5	20-21	67	70	55	57	31	2.4	12.4	38	NE	20	64	6.3	7	8	14	8	2	3	1	0	5	22	0	980.0				
MAR	49.2	30.3	39.7	78	19	14	6	780	0	3.04	1.26	4	0.9	0.9	4	67	70	55	54	28	2.4	13.3	40	NW	12	58	7.1	8	4	19	7	0	1	2	0	2	19	0	978.0				
APR	66.7	44.6	55.4	82	14	31	12	302	19	7.76	3.08	17-18	0.0	0.0	0	68	73	53	48	13	2.8	11.4	34	S	16	64	5.8	8	12	10	8	0	0	0	0	0	2	0	0	981.7			
MAY	71.6	49.8	60.7	88	20	33	3	160	36	2.84	1.27	16	T	T	2	61	70	45	44	33	0.2	10.4	38	SW	5	65	6.2	8	9	14	8	0	0	0	0	0	0	0	0	980.4			
JUN	82.1	60.6	71.4	91	13	52	19	4	203	7.25	3.00	27-28	0.0	0.0	0	65	70	48	44	17	4.4	10.7	46	S	14	78	3.9	13	13	4	8	0	0	0	0	0	0	0	980.4				
JUL	87.1	67.3	77.2	97	9	55	17	0	385	1.87	0.98	21-22	0.0	0.0	0	68	73	50	51	19	2.2	8.7	31	NW	14	75	5.4	10	10	11	7	0	0	0	0	0	0	0	981.4				
AUG	84.8	62.7	73.8	93	26	51	7	1	283	2.26	1.42	11	0.0	0.0	0	68	73	50	51	19	4.5	8.4	34	NW	13	72	4.6	10	10	11	6	0	0	0	0	0	0	0	984.1				
SEP	77.4	54.0	65.7	91	7	44	30	76	104	1.00	0.44	19	0.0	0.0	0	65	73	46	45	13	1.1	8.6	34	SW	6	70	5.2	11	8	11	6	0	0	0	0	1	0	11	0	983.1			
OCT	59.7	37.3	48.5	92	1	21	22	527	20	1.11	0.34	4-5	T	T	19	64	73	47	50	31	1.2	8.9	34	SW	14	59	5.7	12	5	14	8	0	0	0	0	0	0	0	0	984.1			
NOV	43.5	21.7	32.6	71	18	-1	30	964	0	0.10	0.08	26-27	1.1	0.8	26-27	60	65	43	47	29	5.6	10.8	29	NW	9	51	5.1	8	16	6	3	0	0	0	0	7	26	3	984.4				
DEC	33.1	10.3	21.8	64	18	-12	31	1333	0	0.12	0.03	28	2.8	0.8	5	64	67	52	58	28	4.0	10.9	31	N	19	63	5.9	7	13	11	5	0	0	0	0	17	31	7	982.7				
YEAR	61.1	39.5	50.3	97	9	-12	31	6334	1050	30.01	3.08	APR	19.0	10.5	20-21	66	71	50	51	25	1.3	10.7	46	S	14	67	5.6	114	117	135	75	3	38	5	23	40	142	17	982.1				

* DATA CORRECTED AFTER PUBLICATION OF THE MONTHLY ISSUE.

Normals, Means, And Extremes

Month	Temperatures °F							Normal Degree days Base 65 °F		Precipitation in inches										Relative humidity pct.			Wind				Pct. of possible sunshine	Mean day cover, tenths, sunrise to sunset	Mean number of days										Average station pressure mb. 963 feet m.s.l.				
	Normal			Extremes						Water equivalent					Snow, ice pellets					Hour	Hour	Hour	Fastest mile			Clear			Partly cloudy	Cloudy	Precipitation 0.01 inch or more	Snow, ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility 1/2 mile or less	Temperatures °F								
	Daily maximum	Daily minimum	Monthly	Record highest	Year	Record lowest	Year	Heating	Cooling	Normal	Maximum monthly	Year	Minimum monthly	Year	Maximum in 24 hrs.	Year	Maximum monthly	Year	Maximum in 24 hrs.	Year	00	Hour	Hour	Hour	Mean speed m.p.h.		Prevailing direction	Speed m.p.h.							Direction	Year	(b)	37° and below	37° and below	37° and below	0° and below	Elev.	
	00	Hour	Hour	Hour	Mean speed m.p.h.	Prevailing direction	Speed m.p.h.	Direction	Year	37°	Year	37°	Year	37°	Year	37°	Year	37°	Year	37°	Year	15	15	15	15		27	19							26	26	26	27	27	27	27	37	37
	(a)				37		37					37		37		37		37		37		15	15	15	15	27	19	26	26	26	27	27	27	27	37	37	37	27	15	15	15	15	4
J	27.5	11.3	19.4	62	1967	-24	1970	1414	0	1.14	4.38	1960	0.07	1954	2.97	1960	19.8	1942	19.8	1942	76	77	70	71	11.7	NW	66	NW	1953	51	6.6	8	7	16	7	2	0	2	0	18	30	9	985.7
F	32.5	15.6	24.2	73	1972	-20	1958	1142	0	1.05	2.99	1931	0.11	1968	1.77	1961	21.3	1962	12.1	1950	78	80	68	68	11.8	NW	56	N	1952	54	6.4	8	5	15	7	2	0	0	14	27	4	982.2	
M	42.5	25.2	33.9	83	1968	-22	1962	964	0	2.31	5.37	1961	0.41	1971	2.42	1945	18.8	1948	8.3	1957	74	79	63	61	13.1	NW	66	SSE	1953	54	6.9	8	8	17	10	2	2	0	0	6	22	0	978.9
A	59.7	39.2	49.3	90	1970	9	1975	465	0	2.94	7.76	1976	1.05	1942	3.80	1974	15.1	1973	10.4	1973	71	79	57	54	13.3	NW	70	N	1965	55	6.7	7	7	16	10	0	0	0	0	0	0	979.5	
M	70.9	50.9	60.9	98	1967	30	1967	186	59	4.21	7.53	1960	1.23	1949	2.79	1947	0.2	1944	0.2	1944	71	79	50	53	11.6	SE	70	N	1959	60	6.5	7	9	15	11	0	0	0	0	0	0	977.9	
J	79.8	61.1	70.5	100	1956	38	1945	26	191	4.90	14.19	1947	1.13	1963	5.50	1947	0.0	0.0	0.0	0.0	74	81	57	55	10.5	S	76	NW	1953	67	9.9	8	11	11	11	0	10	1	4	0	0	0	978.5
J	84.9	65.3	75.1	105	1955	47	1971	0	317	3.28	10.51	1958	0.04	1975	5.14	1958	0.0	0.0	0.0	0.0	75	81	56	56	9.0	S	73	N	1968	71	5.3	10	12	9	9	0	8	1	9	0	0	0	981.0
A	83.2	63.4	73.3	102	1954	40	1950	13	270	3.30	10.47	1954	0.71	1953	6.18	1975	0.0	0.0	0.0	0.0	78	84	57	57	8.8	S	60	SSE	1960	70	5.2	11	10	10	9	0	7	1	6	0	0	0	982.3
S	74.6	54.0	64.3	101	1939	26	1942	94	73	3.07	10.19	1961	0.41	1950	4.47	1961	T	1942	T	1942	79	85	60	61	9.0	S	55	NW	1953	64	5.3	12	6	12	9	0	5	1	0	0	0	0	983.5
D	64.9	43.6	54.3	95	1963	14	1972	350	18	2.14	7.29	1941	0.03	1952	2.81	1947	2.4	1967	2.4	1967	71	78	54	56	10.5	S	72	N	1952	64	5.1	12	7	12	7	0	3	0	0	0	0	0	983.6
N	46.4	29.2	37.8	76	1965	-3	1964	816	0	1.42	4.60	1932	0.03	1969	3.33	1952	13.3	1968	11.8	1968	75	79	64	66	11.7	NW	76	N	1952	50	6.5	7	8	15	6	1	1	0	0	0	0	982.4	
O	32.8	17.2	25.0	69	1946	-16	1963	1240	0	1.09	2.90	1941	0.12	1967	1.46	1973	23.9	1961	11.0	1961	78	80	71	72	11.5	NW	61	SW	1951	45	6.9	7	6	18	7	2	0	0	15	29	3	982.8	
VR	58.3	39.7	49.0	103	1955	-24	1970	6710	928	30.85	14.19	1947	0.03	1969	6.18	1975	23.9	1961	19.8	1942	75	80	61	61	11.1	NW	76	N	1965	60	6.1	103	96	166	106	10	50	17	21	56	137	16	981.5

Means and extremes above are from existing and comparable exposures. Annual extremes have been exceeded at other sites in the locality as follows: Highest temperature 110 in July 1936 and earlier; lowest temperature -30 in January 1884; maximum monthly precipitation 15.79 in June 1881; maximum monthly snowfall 37.0 in January 1886.

- (a) Length of record, years, through the current year unless otherwise noted, based on January data.
(b) 70° and above at Alaskan stations.
* Less than one half.
T Trace.

NORMALS - Based on record for the 1941-1970 period.
DATE OF AN EXTREME - The most recent in cases of multiple occurrence.
PREVAILING WIND DIRECTION - Record through 1963.
WIND DIRECTION - Numerals indicate tens of degrees clockwise from true north. 00 indicates calm.
FASTEST MILE WIND - Speed is fastest observed 1-minute value when the direction is in tens of degrees.

Figure 16. NOAA Weather Data for Des Moines, Iowa

Meteorological Data For The Current Year

Station: OMAHA, NEBRASKA EPPLEY AIRFIELD Standard time used: CENTRAL Latitude: 41° 19' N Longitude: 95° 54' W Elevation (ground): 977 feet Year: 1976

8 1992																																							
Month	Temperature °F							Degree days Base 65 °F		Precipitation in inches						Relative humidity, pct.				Wind				Percent of possible sunshine		Average sky cover, tenths, sunrise to sunset		Number of days					Average station pressure mb						
	Averages			Extremes						Water equivalent			Snow, ice pellets			Resultant		Fastest mile		Surprise to sunset			Temperature °F																
	Daily maximum	Daily minimum	Monthly	Highest	Date	Lowest	Date	Heating	Cooling	Total	Greatest in 24 hrs.	Date	Total	Greatest in 24 hrs.	Date	Hour 00	Hour 06	Hour 12	Hour 18	Direction	Speed m.p.h.	Average speed m.p.h.	Speed m.p.h.	Direction	Date	Clear	Partly cloudy	Cloudy	Precipitation .01 inch or more	Snow, ice pellets 1.0 inch or more	Thunderstorms	Heavy fog, visibility 1/4 mile or less	90° and above	37° and below	37° and above	0° and below	Elev. feet m.s.l.		
	(Local time)																																988						
JAN	38.0	12.9	25.5	60	23	-11	7	1219	0	0.11	0.05	30	1.8	1.0	30	70	74	56	58	31	4.1	11.2	34	NW	19	71	5.5	11	9	11	4	1	0	0	10	31	4	984.1	
FEB	49.8	25.1	37.5	75	27	7	6	791	0	1.39	0.43	16	7.1	4.1	1-2	75	74	53	97	35	2.3	10.5	41	N	21	62	6.0	9	8	12	6	2	3	1	0	4	22	0	979.3
MAR	52.1	26.6	40.4	85	19	10	5	757	0	2.13	1.10	29-30	4.2	3.9	4	70	75	57	34	33	2.1	11.5	41	S	23	56	6.6	8	5	18	7	1	3	1	0	3	21	0	977.3
APR	69.1	44.3	56.8	87	14	26	1	261	21	2.98	0.79	23-24	0.0	0.0	0	69	77	52	68	15	2.8	11.2	58	S	16	58	6.1	10	5	15	9	0	6	0	0	2	0	980.4	
MAY	74.0	46.3	60.2	89	20	27	3	177	34	3.55	1.69	22-23	0.0	0.0	0	73	80	50	48	07	1.2	9.9	33	NW	2	68	5.7	10	8	13	7	0	4	1	8	0	2	0	979.3
JUN	86.4	58.9	72.7	100	11	47	19	4	240	2.84	1.08	26-27	0.0	0.0	0	73	78	49	48	17	5.1	11.2	34	NW	26	75	4.2	11	16	3	8	0	8	1	16	0	0	978.3	
JUL	90.9	67.0	79.0	103	9	52	5	440	0	1.52	0.92	26-27	0.0	0.0	0	75	81	53	52	16	4.0	9.2	34	N	15	59	5.7	8	10	13	6	0	6	0	17	0	0	980.0	
AUG	90.1	62.5	76.3	101	26	48	28	0	358	0.62	0.45	14	0.0	0.0	0	76	83	51	49	15	5.5	9.4	33	NW	14	70	4.8	12	11	8	5	0	7	0	18	0	0	982.1	
SEP	80.6	54.2	67.4	97	3	39	29	61	139	1.64	0.73	24-25	0.0	0.0	0	71	79	52	50	13	2.4	10.0	26	NW	26	71	5.1	13	6	11	8	0	4	1	10	0	0	982.1	
OCT	61.7	35.3	48.3	94	1	18	17	522	17	1.35	0.63	3-4	1.4	1.4	18	80	85	52	34	35	1.8	9.4	30	NW	15	60	5.6	10	8	13	7	1	3	0	7	0	11	0	983.7
NOV	46.6	19.9	33.3	72	18	-4	28	947	0	0.03	0.02	30	0.5	0.4	30	71	77	47	50	32	3.7	9.8	32	NW	26	66	4.2	12	11	7	2	0	0	0	5	26	3	985.1	
DEC	37.7	10.4	24.1	69	18	-15	30	1265	0	0.21	0.12	5-6	2.8	1.3	7	75	81	59	63	31	2.3	8.9	34	NW	19	60	5.3	11	8	12	4	2	0	0	14	31	8	982.7	
YEAR	64.8	38.8	51.8	103	JUL	DEC	30	6004	1249	18.37	1.69	22-23	17.8	4.1	1-2	73	79	53	53	18	0.4	10.2	58	5	65	5.4	125	105	136	73	7	44	5	57	36	146	15	981.2	

† DATA CORRECTED AFTER PUBLICATION OF THE MONTHLY ISSUE.

Normals, Means, And Extremes

Month	Temperatures °F							Normal Degree days Base 65 °F		Precipitation in inches										Relative humidity pct.				Wind				Pct. of possible sunshine	Mean sky cover, tenths, sunrise to sunset	Mean number of days								Average station pressure mb.					
	Normal			Extremes						Water equivalent					Snow, ice pellets					Fastest mile				Sunrise to sunset						Temperatures °F				Elev. feet m.s.l.									
	Daily maximum	Daily minimum	Monthly	Record highest	Year	Record lowest	Year	Heating	Cooling	Normal	Maximum monthly	Year	Minimum monthly	Year	Maximum in 24 hrs.	Year	Maximum monthly	Year	Minimum in 24 hrs.	Year	Mean speed m.p.h.	Prevailing direction	Speed m.p.h.	Direction	Year	Clear	Partly cloudy			Cloudy	Precipitation in 0.01 inch or more	Snow, ice pellets 1.0 inch or more	Thunderstorms		Heavy fog, visibility 1/4 mile or less	(b) 90° and above	37° and below	37° and below	0° and below				
																																								Max.	Min.		
(a)				41		41					41		41		41		41		41		13	13	13	41	15	41	41	41	41	41	41	41	41	41	13	13	13	13	4				
J	32.7	12.4	22.6	69	1944	-22	1974	1314	0	0.76	3.70	1949	0.05	1943	1.52	1967	25.7	1936	13.1	1946	74	76	65	67	11.1	NNW	57	NW	1938	55	6.1	9	8	14	7	2	0	14	33	8	982.7		
F	38.5	17.4	28.0	78	1972	-19	1975	1036	0	0.98	2.97	1965	0.10	1968	2.24	1954	25.4	1969	18.3	1965	74	76	61	62	11.5	NNW	57	NW	1947	55	6.3	7	8	13	7	2	0	9	26	2	981.6		
M	47.7	26.4	37.1	89	1968	-16	1948	865	0	1.39	5.96	1973	0.12	1956	1.45	1959	27.2	1968	13.0	1948	71	76	57	54	12.7	NNW	73	NW	1950	55	6.6	7	8	16	9	2	1	1	0	4	21	0	977.7
A	64.4	40.1	52.3	93	1965	9	1975	391	10	2.97	6.45	1951	0.23	1936	2.56	1988	9.6	1945	9.6	1945	68	76	54	48	13.2	NNW	65	NW	1937	53	6.3	7	9	14	9	6	4	1	0	0	978.2		
M	74.4	51.5	63.0	99	1939	27	1976	148	86	4.11	10.33	1959	0.56	1948	3.58	1984	2.0	1945	2.0	1945	71	79	54	50	11.4	SSE	73	NW	1936	62	6.2	7	10	14	12	6	8	1	2	0	0	977.0	
J	83.1	61.3	72.2	105	1953	39	1945	20	236	4.94	10.81	1947	1.03	1972	3.48	1942	0.0		0.0		75	81	53	52	10.6	SSE	72	N	1942	68	5.6	8	12	10	11	0	10	0	0	0	977.1		
J	88.6	65.8	77.2	114	1936	44	1972	0	378	3.71	9.60	1958	0.46	1975	3.37	1958	0.0		0.0		77	82	56	54	9.1	SSE	109	N	1936	75	4.8	12	12	7	9	0	8	1	14	0	0	979.8	
A	87.2	64.0	75.6	110	1936	43	1967	6	334	3.97	9.12	1959	0.62	1976	3.40	1959	0.0		0.0		79	86	58	57	9.2	SSE	66	N	1944	72	4.7	13	10	8	9	0	8	1	10	0	0	980.5	
S	78.6	54.0	66.3	104	1939	30	1942	71	110	3.27	13.75	1965	0.41	1953	6.47	1965	T	1961	T	1961	82	87	61	60	9.7	SSE	47	E	1948	67	4.8	13	7	10	8	0	5	1	3	0	0	982.2	
O	69.1	42.6	53.9	96	1938	13	1972	301	19	1.93	4.99	1961	T	1952	3.13	1968	7.2	1941	7.2	1941	76	82	54	56	10.1	SSE	62	NW	1966	67	4.7	13	8	10	6	0	3	1	0	0	6	982.4	
N	50.9	29.1	40.0	80	1964	-6	1964	750	0	1.11	4.05	1948	0.03	1976	2.53	1948	12.0	1957	8.7	1957	77	81	62	65	11.2	SSE	56	NW	1951	52	6.0	9	7	14	5	1	2	0	2	20	0	982.0	
D	37.8	18.1	28.0	72	1939	-15	1976	1147	0	0.84	3.30	1941	T	1943	1.79	1941	19.9	1969	10.2	1969	78	80	67	71	10.8	SSE	52	NW	1938	49	6.4	8	8	15	6	2	0	11	29	2	982.1		
YR	62.8	40.2	51.5	114	1936	-22	1974	6049	1173	30.18	13.75	1965	T	1952	6.47	1965	27.2	1948	18.3	1965	75	80	59	58	10.9	SSE	109	N	1936	62	5.7	113	107	145	99	9	48	15	36	40	138	13	980.3

Means and extremes above are from existing and comparable exposures. Annual extremes have been exceeded at other sites in the locality as follows: Lowest temperature -32 in January 1884; maximum precipitation in 24 hours 7.03 in August 1903; maximum monthly snowfall 29.2 in March 1912.

- (a) Length of record, years, through the current year unless otherwise noted, based on January data.
(b) 70° and above at Alaskan stations.
* Less than one half.
† Trace.

NORMALS - Based on record for the 1941-1970 period.
DATE OF AN EXTREME - The most recent in cases of multiple occurrence.
PREVAILING WIND DIRECTION - Record through 1963.
WIND DIRECTION - Numerals indicate tens of degrees clockwise from true north. 00 indicates calm.
FASTEST MILE WIND - Speed is fastest observed 1-minute value when the direction is in tens of degrees.

Figure 17. NOAA Weather Data for Omaha, Nebraska

relative insolation conditions can be found under the columns labeled "Percent of possible sunshine" and "Mean sky cover, tenths, sunrise to sunset." Examination of these data indicate that the Omaha region consistently has about 1 to 4% more insolation than the Des Moines area. Because of the close physical proximity and the common weather characteristics of the two cities it is considered that the use of Omaha data for predicting performance on an annual basis will result in accurate data for the Des Moines area.

A discussion of the modifications made on the heat gain model which was defined in Section 12.1 follows. The changes are delineated below. A discussion of each item is found in the following paragraphs.

- Adapt the program to use weather data tapes from NOAA to input hourly insolation rates and ambient temperatures.
- Using heat transfer data for the receiver calculate the average receiver temperature for each hourly condition to more accurately determine the radiation losses off the receiver.
- Include internal manifold heat losses for the collector in addition to the radiation losses off the receiver for collector heat gain calculations.

The hourly insolation data given in the NOAA weather tapes are used in the following manner.

- Direct beam insolation and total radiation on a horizontal surface (standard year corrected radiation) is read off the data tape.
- Because diffuse data were not available on the tape it is calculated by converting by standard methods (Reference 10) the direct beam radiation to find the beam component on a horizontal surface. This value is then subtracted from the "standard year corrected radiation" on a horizontal surface to find the diffuse

component on a horizontal surface. This diffuse component is then multiplied by $(1 + \cos(\text{tilt}))/2$ to estimate the amount of diffuse insolation on the south facing collector at the proper tilt angle off horizontal (Reference 10). Ground reflectance is ignored because in the end use application the collector array will be located on a south facing hillside which is about 40° off horizontal, thus the collectors are approximately parallel to the ground even in the winter months when the collector slope is 62° .

- The calculated diffuse component is then multiplied by the sin of the acceptance half angle for the collector to estimate the amount of the diffuse component that strikes the receiver.
- The direct beam radiation is converted to find the beam component incident on the south facing collector for the tilt angle at which the collector is adjusted for that time of the year.

The average receiver temperature is calculated in this model by using the results of the serpentine development task reported in Section 10. The thermal resistance to the transfer of energy from the absorber to the fluid is assumed to be $.35^\circ\text{F-hr/BTU/ft}$ (the foot dimension refers to the length of the receiver). The temperature of the receiver emitting surface is then a function of the amount of energy per unit time being transferred to the fluid. The $\text{BTU/ft}^2\text{-hr}$ gain for the collector is first calculated assuming a receiver temperature of 420°F . The gain determined from the approximation is then used to determine a better estimate of the average receiver temperature using the above resistance for the receiver. The collector outlet temperature is assumed to be 400°F at all times with an average fluid temperature of 390°F . The average receiver temperature is then calculated by multiplying the approximated gain per ft^2 times the aperture area covered by a 1-foot long segment of receiver times $.35^\circ\text{F-hr/BTU}$ and adding 390°F . This calculated receiver temperature is then used to determine the radiation losses from the receiver for that hourly condition and the heat gain is then recalculated.

The heat losses, from the center internal manifold area have been included in this model. As discussed in Section 8 these losses will be less than 3 BTU/hr-ft².

12.3 Instantaneous Performance Predictions

Theoretical instantaneous performance for the collector is shown in Figure 18. Thermal efficiency based on aperture area is shown as a function of collector inlet fluid temperature for three insolation levels (100, 200, and 300 BTU/hr-ft²) with an ambient temperature of 50°F. The insolation is further assumed to be 15% diffuse and 85% beam with an incidence angle of 0° to the collector. The curves were generated by application of the computer model discussed in Sections 12.1 and 12.2. Because the inlet temperature was varied over a large range of values, it was necessary to define the hemispherical emissivity of the absorber coating as a function of the operating temperature of the collector. Measured values for the optical coating are shown in Figure 19 as a function of the absorber temperature. The only other modification to the computer model was to vary the temperature difference between ambient and the outer tube of the receiver as a function of the collector operating temperature and the insolation rate. Preliminary calculations indicate that the temperature inside the collector housing and thus the temperature of the outer receiver tube can be estimated as a function of the insolation rate. Tube temperature was assumed to be 25, 50 and 75°F greater than ambient for insolation rates of 100, 200 and 300 BTU/hr-ft², respectively. These estimates will be adjusted later in the program when prototype hardware becomes available for test.

$$T_{amb} = 50^{\circ}\text{F}$$

$$I = \text{BTU/hr-ft}^2 \text{ (85\% Beam)}$$

Figure 18. Predicted Collector Instantaneous Efficiency Based on Aperture Area as a Function of Inlet Temperature

Figure 19. Hemispherical Emissivity of the Absorber Coating on the General Electric Evacuated Shroud

NOMENCLATURE

- A - Aperture area
- A_1 - Area of absorber surface
- A_2 - Area of outer glass receiver tube
- ACON - Concentration ratio after truncation
- F - Receiver shading factor
- HG - Collector heat gain
- I - Insolation rate
- k - Thermal conductivity
- n - Average number of reflections
- RL - Radiation heat loss per ft^2 per hour
- T_g - Temperature of outer glass
- T_p - Temperature of absorber surface
- W - Factor used to account for reflection losses off the outer glass of the receiver and the absorber
- Z - Fluid-absorber thermal resistance correction factor
- α - Absorptivity
- γ - Diffuse insolation usability factor
- ϵ_1 - Emissivity of absorber surface
- ϵ_2 - Emissivity of outer glass receiver tube
- ρ - Reflectivity
- σ - Stefan-Boltzmann constant
- τ_1 - Transmissivity of collector glazing
- τ_2 - Transmissivity of outer glass receiver tube
- ω - Hour angle

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