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APPLICATION OF SOLAR ENERGY TO INDUSTRIAL DRYING OR
DEHYDRATION PROCESSES

Final Report

MASTER

March 17, 1977

Work Performed Under Contract No. EY-76-C-05-5121

Midwest Research Institute
Kansas City, Missouri

U.S. Department of Energy

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Solar Energy

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FINAL REPORT
March 17, 1977

ERDA Contract No. E-(40-1)-5121
MRI Project No. 4247-E

For

Division of Solar Energy
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PREFACE

This report documents the analysis of applying solar energy to rotary drying and dehydrating processes. The information contained in this report is the result of Phase I of a three-phase program to demonstrate the technical and economic feasibility of solar drying and dehydration. Phase II and III, respectively, incorporate the construction and evaluation of the demonstration system. This study was funded in the amount of \$64,200 by the Agricultural and Process Heat Branch of the Division of Solar Energy, U.S. Energy Research and Development Administration.

The project leader was Mr. Jerry O. Bradley, Senior Engineer. Members of the project team include Dr. R. E. Athey, Mr. Carl Dingham, Mr. David Posner and Mr. Dennis Costello, all of MRI; Mr. Ralph Proton, P.E., and Ms. Lucy Ronning of Burns and McDonnell Consulting Engineers; and Dr. Dan Ward of Consulting Solar Energy Engineers.

Approved for:

MIDWEST RESEARCH INSTITUTE

L. J. Shannon, Director
Environmental and Materials Sciences Division

March 17, 1977

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SUMMARY

Application Highlights

The application of a solar energy system to the Lawrence, Kansas alfalfa dehydration plant, owned by the Western Alfalfa Corporation, is an attractive opportunity to demonstrate the feasibility of using solar energy to supply industrial process heat.

- Rotary drying and dehydration processes currently consume 1.5×10^{15} Btus annually. This is a significant portion of the total consumption in the U.S. Alfalfa dehydration facilities, by themselves, consume 2×10^{13} Btus annually.

- Many alfalfa dehydration plants depend on natural gas and are thus vulnerable to curtailments in the event of future shortages.

- The American Dehydrators Association, with 232 industrial members, is enthusiastic about the potential of this demonstration project. The association can serve as a vehicle to educate the industry concerning the potential of solar energy.

A demonstration at the Lawrence, Kansas plant is particularly attractive because:

- The Lawrence, Kansas plant, located less than a mile from an exit on U.S. Interstate 70, 40 miles west of Kansas City, is easily accessible for view by members of industries utilizing rotary drying equipment and by the general public.

- The plant is located just over a mile from the University of Kansas. The solar energy system can thus be used as an educational tool by both students and faculty.

System Design Highlights

The objective of the solar system design process was to obtain the most cost-effective system for producing energy. Highlights of the system design process include:

- Solar collectors were compared on the basis of a Cost-Effectiveness Index to arrive at the optimal combination of collectors in the array. (The Cost-Effectiveness Index is defined as the efficiency of the collector divided by its installed cost per square foot.)

- TRNSYS computer simulations of the performance of the collector array were used to verify that the specified array design is the optimal design. The simulations showed that a collector array with a combination of flat plate and focusing collectors supplies energy at a lower cost than an array made up of all flat plate or all focusing collectors.

- TRNSYS simulations of the solar system performance show that the system will supply approximately 13% of the annual energy needs of the dehydrator. Should the plant convert to energy conserving field wilting techniques, the system would supply over 20% of the annual energy requirements.

- All detailed engineering drawings and specifications necessary for the construction of the system were developed.

System Costs

After the design of the solar system and the production of the detailed engineering drawings and specifications were completed, bids were solicited from area contractors for the construction of the system. The solicitation of actual construction bids produced the most realistic estimate possible of the cost of the solar system to be used in the economic analysis. The low bid was \$372,200. The economic analysis was done in the Lawrence Livermore Laboratory format. This analysis showed that:

- The conventional energy system (Plan A) costs approximately \$3.89/million Btu.

- The combined solar and conventional system (Plan B) costs approximately \$7.00/million Btu in Albuquerque and \$7.14/million Btu in Omaha.

- The solar portion of the system alone costs \$22.38/million Btu in Albuquerque and \$30.17/million Btu in Omaha.

- The payback period of the combined system (Plan B) was 24 years in Albuquerque and 26 years in Omaha.

System Interface

The installation of the solar energy system will not significantly disrupt the plant operation.

- The interface of the solar array with the dehydration can be installed before the season begins. Once the construction of the system has been completed, the connection between the dehydrator and the array can be made with minimal interruption of plant operation.

● The interface between the solar system and the dehydrator has been designed so that the plant can operate at any time without the assistance of the solar system.

● All controls for the solar system operate automatically. No additional labor, other than routine maintenance, is required for the daily operation of the plant.

I. INTRODUCTION

This report documents the detailed engineering design of a solar array applied to the preheating of both combustion and excess air for a rotary alfalfa dehydrator. The intent of this demonstration installation of a solar array is to prove the technical feasibility and assess the economic feasibility of preheating air for rotary dryers applied to drying a number of products. Rotary drying and dehydration processes were selected because:

- Rotary drying is applied to the processing of several types of products and accounts for the consumption of substantial amounts of energy in the United States. It is estimated that the total energy requirements of rotary drying and dehydration equipment exceed 1.5×10^{15} Btus per year.

- Many rotary drying and dehydration processes currently utilize natural gas. Considerable concern has recently risen in industry regarding the future availability of this primary energy source.

- Many industrial facilities which employ rotary drying and dehydration equipment are located in relatively uncongested areas, thereby enhancing the availability of land area for solar collectors.

- Many of the applications of rotary drying and dehydration involve the processing of organic materials. Such materials generally begin oxidizing at temperatures near 500°F. Therefore, many drying and dehydration operations are carried out at lower temperatures which are closely matched to the capabilities of solar energy systems.

Rotary drying equipment is applied to the processing of a wide range of industrial and agricultural products including alfalfa, brewer's grains, wood products, sugar beets, dehydrated fruit products, tobacco, industrial waste, sewage sludge, and many other products. The dehydration of alfalfa was selected from these processes for analysis, based upon the following reasons:

- Dehydrated alfalfa is a key ingredient in formula animal feeds and is therefore important to much of the U.S. food industry.

- Dehydration increases crop yield by 20 to 40% through elimination of shattering and dusting losses which occur with field curing of alfalfa hay.

- Dehydration helps retain valuable nutrients such as carotene and xanthophyll, most of which would be lost in field curing.

- The dehydration of alfalfa requires significant quantities of energy. Over 10 million Btus are required to produce 1 ton of dehydrated alfalfa and U.S. production is currently in the range of 1.7 million tons per year. Thus, the industry consumes approximately 2×10^{13} Btus of energy in the dehydration process per year.

- The alfalfa dehydration industry is highly dependent on natural gas as an energy source. Approximately 80 to 90% of the total energy required for dehydration is currently provided by natural gas.

- As natural gas supplies become less available, the alfalfa dehydration industry must find new sources of energy.

- The temporal energy demands for alfalfa dehydration match the daily and seasonal availability of solar radiation. During rainy periods when radiation is minimal, the alfalfa is not harvested and dehydrated. During sunny, dry periods the alfalfa is harvested and energy is required to dehydrate the alfalfa.

- The alfalfa dehydration season is much longer than other crop-drying seasons. For most of the industry the season begins in late April and continues through October with the season lasting year-round in some southern locations in the United States.

Although alfalfa dehydration has been selected for this analysis, the results of construction and operation of the proposed solar energy system will have direct application to many of the other rotary drying and dehydration processes used throughout American industry.

Section I-A of this chapter describes the alfalfa dehydration process, while Section I-B provides an overview of the final system design. Finally, Section I-C explains the organization of the remainder of the report.

A. The Alfalfa Dehydration Process

The alfalfa dehydration process begins with the cutting, chopping, and hauling the fresh alfalfa to the dehydrating plant. Figure 1 illustrates the alfalfa in the field while Figure 2 shows the harvesting and chopping operation. The green, chopped alfalfa is next fed into a rotary dehydrator supplied with heat from a gas-fired furnace. Figure 3 illustrates a typical furnace and rotary drum. The dried alfalfa is finally ground in a hammermill, pelletized, cooled, weighed and shipped. Figure 4 is a photograph of a typical alfalfa dehydrating plant while Figure 5 illustrates a schematic of such a dehydrating plant. Figure 6 depicts the energy flow in the alfalfa dehydration process and illustrates that the majority of purchased fuel (93%) is consumed directly in dehydrating the alfalfa.

6 1. Alfalfa

Figure 1

2. Alfalfa Harvester-Chopper

Figure 2

3. Furnace & Rotary Drum Dryer

Figure 3

4. Alfalfa Dehydrating Plant

Figure 4

Source: Industrial Energy Study of Selected Food Industries,
Federal Energy Office, prepared by Development
Planning and Research Associates, Inc., Manhattan,
Kansas, July 1974

Figure 6 - Material and Energy Flow for a Typical Dehydrated
Alfalfa Plant. (Energy Units in Btu's per Ton
of Dehydrated Alfalfa.)

From approximately 30 alfalfa dehydration facilities owned by the Western Alfalfa Corporation, the Lawrence, Kansas facility was selected for the solar demonstration design. The Lawrence facility consists of two identical Heil model 824 rotary dehydrators. Having two identical dehydrators operating side by side under identical conditions, will provide direct evidence of the energy savings provided by solar augmentation of one of the dehydrators. In addition to having two identical dehydrators, over 1 acre of flat, unused land is adjacent to one of the dehydrators and is available for construction of the solar array. Figure 7 illustrates a schematic diagram of the Lawrence, Kansas alfalfa dehydration facility. Each of the Heil 824 rotary dehydrators is capable of producing between 1 and 1.25 tons of dehydrated alfalfa per hour. Each rotary dehydrator will consume approximately 8 to 15 million Btus/hr, depending upon the moisture content of the alfalfa. After drying, the alfalfa flows from the drums to the cyclone separator, through a rotary lock and into a hammer mill where it is chopped to a fine powder or meal. This meal is transferred by means of an air conveyor to the meal bin and is fed into the pelletizing mill which compresses the alfalfa into pellets approximately 1/4 in. in diameter and 1/2 in. long. These pellets are then conveyed by air to the cooler where they are allowed to air cool to prevent oxidization. The pellets are then weighed and conveyed into boxcars for hauling to storage or to feed processing plants. The system is a negative pressure system in which the alfalfa, the alfalfa meal and the pelletized alfalfa are conveyed by air driven by 200 hp electric motor.

B. Overview of Final System Design

The final design of the solar energy system is the result of a comprehensive design process. The design approach resulted in the selection of the most cost-effective combination of solar collectors. The final collector array consists of 304 flat plate collectors manufactured by Sunworks and 38 focusing collectors manufactured by the Hexcel Corporation. This is equivalent to an aperture area of 5,679 ft² of Sunworks collectors and 5,804 ft² of Hexcel collectors.

Highlights of the system design approach include:

- Commercially available collectors and field-erected collectors designed by the project team were compared using a Cost-Effectiveness Index (CEI). The CEI is the collector efficiency divided by the installed cost of the collector per square foot.

- Superimposition of plots of the CEI versus the average temperature of the collector fluid for candidate collectors allowed the combination of collectors offering the highest energy output per dollar invested to be identified.

Figure 7 - Schematic of Lawrence Kansas Alfalfa Dehydration Plant

- The preliminary design of the collector array was based upon seasonal averages for the hourly solar radiation. A calculation was made of the area of Sunworks collectors required to heat the airflow of the dehydrator from ambient temperature up to the temperature at which the Hexcel collector becomes the most cost-effective collector. The area of Hexcel collectors was determined by space availability and the need for a sufficient number of Hexcel collectors connected in parallel to minimize pressure drop through the array.

- The TRNSYS solar energy system simulation program was modified to simulate the performance of the Hexcel parabolic trough.

- The hourly performance of the preliminary array design was simulated over the entire dehydration season using the TRNSYS computer program. A sensitivity analysis of the performance of other combinations of areas of Sunworks and Hexcel collectors using TRNSYS simulations was conducted to verify that the preliminary array design was in fact the optimal design.

Once the design of the collector array was completed, detailed engineering drawings and specifications of the array construction, duct work, air handling equipment, system controls, and data acquisition and monitoring equipment were prepared. Bids for the construction of the system were solicited from area contractors. Kansas Construction Company, with a low bid of \$372,200, was chosen as the company to construct the project.

An economic analysis of the solar energy system in the format supplied by the Lawrence Livermore Laboratory was performed.^{1/} The results of this analysis showed that:

- The combined solar and conventional system (Plan B) costs approximately \$7.00/10⁶ Btu in Albuquerque and \$7.14/10⁶ Btu in Omaha.

- The solar portion of the system alone costs \$22.38/10⁶ Btu in Albuquerque and \$30.17/10⁶ Btu in Omaha.

- The payback period of the combined system (Plan B) was 24 years in Albuquerque and 26 years in Omaha.

1/ Method of Economic Analysis for Comparison of Solar Process Heat Systems, W. C. Dickenson, J. N. Schearer, Lawrence Livermore Laboratory, Livermore, California, August 1, 1976.

The solar energy system is expected to provide approximately 13% of the annual energy needs of the alfalfa dehydrator. Should the Lawrence plant implement energy conservations techniques and change over to field wilting, the system could provide 20 to 30% of the dehydrator's annual energy needs. The maximum output temperature of the solar system is expected to be approximately 300 to 400°F.

The installation of the solar energy system will have little adverse impact on the operation of the plant. The duct work and equipment interfacing with the dehydrator can be installed before the season has started. Once installation of the array has been completed, it can be connected to the dehydrator with minimal interruption in operation. After the construction of the solar system has been completed, the solar system will have no impact on the plant's day-to-day operation. The system is designed to allow the plant to operate without the assistance of the solar array at any time.

Automated system controls have been designed so that no new procedures need to be adopted to operate the dehydrator. The only additional operating procedures would be occasional, minimal maintenance of the collector array.

C. Organization of Report

The following six chapters review the work undertaken for this project. Chapter III discusses the design parameters of the dehydrator, including the energy consumed by the plant (Section III A), the airflow requirements of the dehydrator (Section III B) and the interface between the dehydrator and the solar array (Section III C). Chapter IV discusses the design of the collector array. The selection of solar collectors (Section IV A), the calculation of collector areas for the array (Section IV B) and the simulations of the system performance (Section IV C) are addressed in this chapter. Discussions of the detailed engineering drawings and specifications of the array construction (Section V A), duct work (Section V B), air handling equipment (Section V C), system controls (Section V D) and data monitoring and acquisition systems (Section V E) are presented in Chapter V. The results of the contractors' bids based on these drawings and specifications are contained in Chapter VI. Chapter VII presents an economic analysis of the solar system using the Lawrence Livermore Laboratory format. Finally, the impact of the solar system on the process energy requirements (Section VII A) and on the operation of the plant (Section VII B) are discussed in Chapter VIII.

Additional information and supporting calculations for material covered in the text of the report are contained in the appendices. Each appendix is referred to at the appropriate point in the text. Also, this

report refers to the Bid Specification Book and Engineering Drawings which were prepared by Burns and McDonnell, Consulting Engineers. Because of their size, these two documents are not bound into this report.

The cost estimates for Phases II and III are contained in a separate letter addressed to Mr. William Cherry dated January 12, 1977.

II. DESIGN PARAMETERS OF ROTARY ALFALFA DEHYDRATOR

A. Background on Energy Consumed by the Alfalfa Dehydration Process

This chapter briefly reviews the design parameters of the rotary alfalfa dehydrator. Section II A discusses energy consumption of the air-flow requirements of the Heil Model 8-24 dehydrator, while Section II C concludes the chapter with a discussion of the interface between the solar array and the rotary dehydrator.

Alfalfa dehydration is a seasonal industry whose peak production ranges from 250,000 to 350,000 tons of product per month during the summer months (June, July and August) to less than 25,000 tons of dry product per month during the winter months (November, December, January, February, March, April). The total annual production of dehydrated alfalfa in the United States is in the range of 1.7 million tons per year.

The Lawrence, Kansas alfalfa dehydration plant has a total capacity of approximately 60 tons of dehydrated product per day. Normal production for the Lawrence plant is approximately 5,000 to 6,000 tons of dehydrated alfalfa per year. In Lawrence, Kansas, the alfalfa production season ranges from late April or early May through October, with peak production occurring in the month of June.

The energy required to dehydrate alfalfa is highly dependent upon the moisture content of the alfalfa when it is introduced to the dehydration process. Production records for the Lawrence, Kansas plant indicates that gas consumption has been in the range of 11 to 12 million Btus/ton of product produced. Additional information regarding the energy requirements of the alfalfa dehydration process is contained in Appendix A "Energy Requirements of Alfalfa Dehydration Process."

B. Airflow Requirement of the Heil Model 8-24 Rotary Dehydrator

The Heil model SD-8-24 Ardrier dehydrator used in the Lawrence plant, has a rated evaporation capacity of 6,000 lb of water per hour. This rating is based upon an exhaust temperature from the rotary dehydrator of 300°F at a mass flow of 12,000 acfm, and a fuel consumption of 10,000 cu ft of natural gas per hour. It is a common practice within the alfalfa dehydration industry to operate dehydrating equipment beyond its rated capacity. The reason for operating the dehydration equipment beyond rated capacity is to increase the production and thus profitability of a given dehydration facility. In order to properly size the solar array for this particular installation, it was necessary to estimate the quantity of combustion air and excess air consumed by the rotary dehydrator.

The details of this analysis are contained in Appendix B "Airflow Requirements for the Heil 8-24 Model Dehydrator." The results of this analysis indicated that the quantity of air consumed by the dehydrator decreased with increasing moisture content of the alfalfa. Under design conditions, the rotary dehydrator would consume a total of 6,100 scfm of combustion and excess air.

This airflow rate was selected as the design airflow rate for the solar array. However, to assure that the air handling system had sufficient capacity to supply the air requirements of the dehydrator, a fan capacity of 7,500 scfm was specified for the array air handler.

C. Interface Between Solar Array and Dehydrator Furnace

Currently, the energy input to the Heil 8-24 rotary dehydrator is supplied by a burner array consisting of six cast-iron venturi-type burners. These burners utilize a venturi action produced by the flow of natural gas to mix the gas with primary and secondary combustion air. Excess air required to reduce the hot gas temperature to the 1,000 to 1,800°F level, enters the dehydrator furnace in an annulus between the burner array and the mouth of the furnace. After reviewing a number of alternatives such as replacing the venturi burners with a new forced-draft burner, it was decided by the project team that the best way to introduce the energy from the solar array into the dehydrator was by means of a plenum surrounding the burner array and the furnace inlet. This approach allowed retention of the existing burner and control system and resulted in the least impact upon the existing process.

The proposed plenum is equipped with a set of dampers which can be opened to admit ambient air to the burners and furnace. This damper will allow operation of the rotary dehydrator independent of the solar array and its air handler. Thus, production capability can be maintained in the event of malfunctioning of the solar portion of the system. Details of the burner plenum are contained in the Specifications Document 76-038-1 prepared by Burns and McDonnell Engineers-Architects-Consultants and dated December 15, 1976.

III. SOLAR ARRAY DESIGN

The final design of the collector array is the result of a comprehensive design process. Commercially available collectors and field-erected collectors designed by the project team were compared using an MRI developed "Cost-Effectiveness Index" (CEI). (CEI is defined as the collector efficiency divided by the installed cost of the collector per square foot.) Plots of the CEI versus $\Delta T/H$ (the average temperature rise through the collector divided by the solar flux) were prepared for candidate collectors. These plots enabled the selection of the combination of collectors which promised the most cost-effective array for providing energy. Preliminary calculations of optimal aperture areas for the selected collectors were then made using annual averages for climatic conditions. The hourly performance of the array over the entire dehydration season was simulated using a modified version of the TRNSYS computer program. TRNSYS simulations were also used to verify that the preliminary calculations of the array design resulted in the most cost-effective solar energy system.

The final collector array design consists of 304 flat plate collectors manufactured by Sunworks and 38 focusing collectors manufactured by Hexcel. The Sunworks collectors are mounted at a 9.6 degree angle above the horizontal facing the south. The Hexcel collectors are horizontally mounted on a north-south axis and track the sun from east to west.

This chapter describes the design process used to optimize the collector array. Section III A discusses the selection of the collectors for use in the array. Section III B describes the calculations used to make preliminary determinations of the appropriate areas for the selected collectors. The rationale for the specified orientations of the collectors is also discussed in Section III B. In Section III C, the results of TRNSYS simulations of the specified array design and other combinations of Sunworks and Hexcel collectors, in conjunction with cost estimates, are used to verify that the array configuration specified is, in fact, the most cost-effective configuration.

A. Selection of Solar Collectors

Candidate solar collectors were compared on the basis of their cost effectiveness. A graphical method of comparison was used. Plots of the CEI versus $\Delta T/H$ were prepared for candidate collectors. To develop the CEI versus $\Delta T/H$ plots, the efficiency of the collector as a function of $\Delta T/H$ was divided by the installed cost per square foot of collector. The cost used to calculate the CEI was the estimated installed cost per square foot of collector, including purchase cost, delivery cost, and all installation costs specific to the array.

Because the alfalfa dehydration process uses heated air as the drying medium, only solar collectors which utilize air as the heat transfer fluid were considered. This approach eliminated the need for freeze protection procedures and liquid-to-air heat exchangers which would be required for collectors that utilize liquids as the heat transfer fluid.

Over 30 collector manufacturers were contacted to provide performance data and cost information on their solar collectors. After a preliminary screening, five flat plate collectors were selected for detailed cost estimates. These collectors were manufactured by R-M Products Company, Solar Energy Products Company, Contemporary Systems, Inc., Sunworks and Solaron Corporation. Only one company, the Hexcel Corporation, was found that manufactured a focusing collector that could use air as the heat transfer medium. Detailed cost estimates were prepared for the Hexcel collector. By using the performance data supplied by the manufacturers, and the estimates of the installed cost per nominal square foot of collector area prepared by the project team, CEI versus $\Delta T/H$ plots were developed for the manufactured collectors. These plots, as well as summary cost estimates for the manufactured collectors, are contained in Appendix C, "Manufactured Solar Collectors."

The Sunworks collector was found to be the most desirable flat plate collector. A high CEI, independent test data on the collector performance, high quality of materials and fabrication, and a sizable number of successful installations warranted the selection of the Sunworks collector over the other candidate flat plate collectors.

The Hexcel collector was the only focusing collector available that can use air as the heat transfer medium. Figure 8 shows that the CEI of the Hexcel collector is higher than the CEI of the Sunworks collector at values of $\Delta T/H$ above 0.41. This figure indicates that the most cost-effective solar array made up of manufactured collectors, and operating at values of $\Delta T/H$ above 0.41 would be a two-collector array of Sunworks and Hexcel collectors. Values of $\Delta T/H$ above 0.41 are necessary if the array is to make a significant contribution to the energy requirements of the dehydrator. (For detailed cost estimates for the Sunworks and Hexcel collectors, refer to Appendix C.)

The cost effectiveness of field-erecting collectors, from state-of-the-art materials was also evaluated for use in the low temperature range. Eleven field-erected collectors using a black-painted rock bed absorber were designed and costed by the project team. These 11 collector designs were designated type A-K. Eight of the 11 collector types were selected on the basis of cost for further study. The expected performances of these eight collectors were calculated using the equations developed by Whillier.^{1/}

^{1/} Whillier, Austin, "Design Factors Influencing Solar Collector Performance," Low Temperature Engineering Application of Solar Energy, ASHRAE, 1967.

Figure 8 - Cost Effectiveness Index Versus $\Delta T/H$ Plots for Sunworks and Hexcel Collectors

Plots of the CEI versus $\Delta T/H$ were prepared for the field-erected collectors using the calculated values for performance and estimated installed costs per square foot. The field-erected collector Type J, which is double glazed with Kalwall, appeared to be the collector with the greatest potential. Although the Type C collector, which is single glazed with tedlar film, also showed potential as a highly cost-effective collector, the uncertain durability of the tedlar cover made it less attractive than Type J. Descriptions, predicted performances, cost estimates and the CEIs of the field-erected collectors are contained in Appendix D, "Field-Erected Solar Collectors."

A comparison of the cost effectiveness of the Type J collector to the Sunworks collector showed that a two-collector array made up of the Type J collector and Hexcel collector had the potential of being significantly more cost-effective than a Sunworks and Hexcel array. The uncertainty surrounding the predicted performance of collector Type J, however, presented a significant problem. A concerted effort was made to substantiate the predicted performance of the Type J collector. A thorough literature search was conducted (see Appendix E, "Review of Literature on Solar Air Collectors"), which indicated that the predicted performance of the Type J collector may have been overly optimistic. Conclusive performance data on collectors with characteristics similar to Type J do not appear to be available. Thus, construction and testing of this collector type would be required.

An analysis of the trade-offs of designing an array made up of the Type J and Hexcel collectors as opposed to a Sunworks and Hexcel array was undertaken (see Appendix F, "Preliminary Determination of Array Configuration"). The analysis showed that while the Type J collector has significant potential as a highly cost-effective collector, lack of clear documentation of its performance prohibits its use without experimental verification of performance. Experimental verification of the performance was beyond the scope of this project. A two-collector array using the proven Sunworks and Hexcel collectors was, therefore, specified for use in the solar dehydration system.

B. Calculation of Collector Areas for Array

Having selected the Sunworks and Hexcel collectors for use in the solar array, the orientations of these two collectors were specified. Subsequently, the optimal combination of areas of the Hexcel and Sunworks collectors in the array was determined. This section discusses the rationale for the specified orientations and the calculation of the aperture area of each of the collectors.

The Sunworks collectors are to be mounted at an angle of 9.6 degrees to the horizontal, tilted toward the south. A nearly horizontal mount was thought desirable for two major reasons. First, the zenith angle of the sun over the dehydration season approaches 90 degrees, and a tilted surface,

therefore, does not intercept a significantly greater amount of radiation. Second, a nearly horizontal array of flat plate collectors is less expensive to construct than a tilted array. A slight tilt angle was ultimately chosen because this angle enabled a convenient connection between the flat plate and focusing collectors and permitted drainage of the flat plate array.

The Hexcel collectors are to be mounted horizontally along a north-south rotational axis. The collectors will track the sun from the east to the west. As in the case of the flat plate collector, a horizontal mount offered lower installation costs than a tilted mount, at no significant reduction in flux. A north-south axis of orientation was chosen because during the dehydration season, the flux on the north-south oriented, hourly tracking collector, is greater than an east-west oriented, elevation tracking collector.

The optimal area of the Sunworks collector was determined by calculating, under average operating conditions of the dehydrator, the area required to heat the incoming airflow from ambient temperature to the temperature at which the Hexcel collector becomes more cost effective. In order to find this crossover temperature, plots of CEI versus the average temperature of the collector fluid were prepared for the two collectors.

To construct plots of CEI versus temperature, the average hourly values of the solar radiation over the dehydration season on the flat plate and focusing collectors were calculated. Figure 9 presents the results of these calculations. These seasonal, hourly values were again averaged to obtain a single average value of hourly radiation for each collector. The seasonal average radiation on the flat plate collector ($\bar{H}_T$) was calculated to be 180 Btu/ft²/hr. The seasonal average radiation on the focusing collector ($\bar{H}_T$) was calculated to be 148 Btu/ft²/hr. These radiation values were used to transform the x-coordinates of the efficiency versus $\Delta T/H$ plots of the two collectors to a temperature scale. The average daytime ambient temperature during the dehydration season is 75°F. Figure 10 shows the efficiencies of the Sunworks and Hexcel collectors as a function of average temperature of the collector fluid. The efficiency versus temperature plots were converted to CEI versus temperature plots by dividing the y-coordinates of the efficiency plots by the installed costs per square foot of the collectors. The CEIs versus average temperature of the collector fluid are graphed in Figure 11.

Figure 11 shows that a temperature below 157.3°F, the Sunworks collector is more cost effective than the Hexcel collector. The most cost effective array would therefore consist of enough Sunworks collector to heat the airflow to 157.3°F under average operating conditions. Using the average flux level on the flat plate collector of 180 Btu/ft²/hr, the average ambient temperature of 75°F, and the flow rate of 6,100 scfm (the flow rate required by the dehydrator), it was calculated that 5,324 ft² of aperture of Sunworks collector are required to heat the airflow to a temperature of 157°F.

Figure 9 - Average Hourly Insolation During the Alfalfa Dehydration Season for Flat Plate and Focusing Collectors

Figure 10 - Efficiency of Sunworks and Hexcel Collectors Versus Average Temperature of Collector Fluid

Figure 11 - Cost Effectiveness Index Versus Average Temperature of Collector Fluid for Sunworks and Hexcel Collectors

(Refer to Appendix G, "Calculation of Optimal Area for Sunworks Collector," for a detailed illustration of this calculation.)

The optimal area of Hexcel collectors in the array was somewhat flexible, because at all output temperatures above 157.3°F, the Hexcel collector is the most cost-effective collector. The absolute upward limit of the area of the Hexcel collector would be the area required to heat the air from the output temperature of the Sunworks collectors, (157.3°F), to the operating temperature of the dehydrator. Space availability and the availability of funds, however, proved to be more limiting constraints. Another consideration in choosing the area of Hexcel collectors was the pressure drop through the receiver tube of the focusing collector. It was necessary to have enough Hexcel collectors in parallel so that the pressure drop through the receiver tube would not be excessive. Calculations showed that a minimum of 19 collectors in parallel resulted in acceptable pressure drop.

A final consideration in determining the optimal area of Hexcel collectors was that there are economic benefits to having collectors connected in series. The same tracking mechanism can drive a number of collectors series. The cost of the tracking mechanism, therefore, can be distributed over a larger aperture area, resulting in a more cost-effective array. Accounting for all of these factors, 38 Hexcel collector modules or 5,804 ft² of Hexcel collector aperture area were specified in the array design. Nineteen parallel rows of two Hexcel collector modules connected in series were specified as the layout of the Hexcel collectors on the dehydration plant site.

Consideration of the layout of the collector array on the plant site indicated that installation of Sunworks collectors in rows of 38 modules would provide a convenient interface to the 19 parallel rows of Hexcel collectors. The calculated optimal aperture area for the Sunworks collector, 5,324 ft², represents 7-1/2 rows of 38 collectors per row. It was felt that a half row of collectors in the array would not be advisable. Therefore, the optimal area of 5,324 ft² was rounded up to 5,629 ft² or to eight rows of 38 collector modules for a total of 304 Sunworks collector modules. This extra area of Sunworks collectors is only a small increase from the calculated optimal area, and should have an insignificant impact on the overall cost-effectiveness of the operation of the collector array.

In conclusion, calculations of the optimal area of Sunworks collector and consideration of the layout of the collector array on the plant site determined the specified areas of the two collectors in the array. These dimensions are summarized in Table 1. The total aperture area of the preliminary array design is 11,483 ft².

TABLE 1

PRELIMINARY CONFIGURATION OF COLLECTOR ARRAY

	<u>Aperature Area of Collector</u>	<u>Number of Collector Modules</u>
Sunworks	5,679 ft ²	304
Hexcel	5,804 ft ²	38

C. TRNSYS Simulations of System Performance

After the preliminary calculations of the optimal areas of the Sunworks and Hexcel collectors were completed, the TRNSYS program was set up to simulate the hourly performance of the array design over the dehydration season. A sensitivity analysis of other combinations of areas of the Sunworks and Hexcel collectors was performed using TRNSYS simulations to verify that the specified preliminary array design was, in fact, the optimal design.

In order to simulate the hourly performance of the array over the dehydration season, a composite year of hourly insolation and weather data for Columbia, Missouri, was developed. (Solar radiation data are not available for Lawrence, Kansas.) Although the Columbia radiation data may understate the radiation in Lawrence, Kansas, by 10 to 15%, it was felt that the Columbia data are the best available for system design and optimization.

Two modifications of the TRNSYS programs were made in order to simulate the performance of the focusing collector. First, the program was modified to derive hourly values of the beam radiation incident on the focusing collector from the available data, the hourly total radiation on a horizontal surface. Second, changes were made to account for the end losses of the focusing collector as a function of the incidence angle of the beam radiation. These modifications are explained in detail in Appendix H, "TRNSYS Program Modifications for Focusing Collector."

The TRNSYS simulations were set up so that the entire airflow requirements of the dehydrator, 6,100 scfm passed first through the flat plate collectors and then into the focusing collectors. All parameters affecting the efficiency of the flat plate and focusing collectors were entered into the program. Losses in the duct work of the array were accounted for by slightly overstating the loss coefficients of the concentrating collectors.

The TRNSYS simulations were used to produce integrated values of the energy output of the array over one dehydration season. In addition to

simulating the energy output of the preliminary array design, four other simulations were performed for arrays with different combinations of flat plate and focusing collectors. The total seasonal energy output for each array was then divided by the total cost of the array to yield a seasonal value for the energy output of each array per dollar invested. The results of this sensitivity analysis are summarized in Table 2. A graph of the energy output per season per dollar of capital cost as a function of the ratio of the area of focusing collector in the array to the total area of the array is shown in Figure 12.

The optimal combination of flat plate and focusing collectors is that combination which yields the maximum energy output per season per dollar of capital cost. It can be seen from Table 2 and Figure 12 that the preliminary array design (area focusing/area total = 0.505) is significantly more cost effective than an array made up of either all flat plate or all focusing collectors. Examination of Figure 12 shows that the optimal combination of flat plate and focusing collectors is between a ratio of area of focusing collector to total area of 0.25 (aperture area Sunworks = 8,612 ft², aperture area Hexcel = 2,871 ft²) and the area ratio at the preliminary design point, 0.505.

The curve of kilojoules collected per season, per dollar capital cost as a function of the focusing area to total area ratio appears to be relatively flat between 0.25 and 0.505, the design ratio. Although Figure 12 indicates that the maximum energy output per dollar would occur with an array made up of more flat plate collectors than in the preliminary array design, the difference in cost effectiveness would appear to be minimal.

No modification of the preliminary array design was made as a result of this sensitivity analysis. While an array with more Sunworks collectors appears to be marginally more cost effective than the preliminary design, it was believed that the savings realized by a revised design did not warrant modification. The Columbia, Missouri, weather data used in the simulation understates the direct radiation on the focusing collector to be located in Lawrence Kansas. The simulation therefore underestimated the energy output of the concentration array and appears to reduce the desirability of using less focusing collector area.

The results of this design process indicate that a two-collector array made up of 304 Sunworks flat plate collectors and 38 Hexcel focusing collectors is potentially the most cost-effective solar array. These collector areas were used in the preparation of all detailed engineering drawings and specifications of the solar energy system.

TABLE 2

SENSITIVITY ANALYSIS OF ENERGY OUTPUT PER SEASON PER DOLLAR OF
CAPITAL COST FOR DIFFERENT AREAS OF SUNWORKS AND
HEXCEL COLLECTORS

Area Total = 11,483 sq ft

<u>Area Focusing</u> Area Total	<u>0.0</u>	<u>0.25</u>	<u>0.505</u> <u>(Design)</u>	<u>0.75</u>	<u>1.00</u>
Area Flat Plate at \$22.18/sq ft*	11,483 sq ft	8,612	5,679	2,871	0
Cost of Flat Plate	\$254,693	\$191,014	\$125,960	\$ 63,679	0
Area of Focusing at \$28.82/sq ft*	0	2,871	5,804	8,612	11,483
Cost of Focusing	0	\$ 82,742	\$167,271	\$248,198	\$330,940
Total Variable Cost	\$254,643	\$273,756	\$293,231	\$311,877	\$330,940
8,000 CFM Fan System and Duct Work	\$ 14,400	\$ 14,400	\$ 14,400	\$ 14,400	\$ 14,400
Electrical Controls and Monitoring	\$ 3,000	\$ 3,000	\$ 3,000	\$ 3,000	\$ 3,000
Total Cost	\$272,093	\$291,156	\$310,631	\$329,277	\$348,340
109KJ/Season	1.9	2.09	2.23	2.27	2.2
KJ/Season - \$ Cost	6,983	7,178	7,179	6,894	6,316

* Estimated installed cost of solar collector array.

Figure 12 - Sensitivity Analysis of Energy Output Per Season Per Dollar of Capital Cost for Different Areas of Sunworks and Hexcel Collectors

IV. DETAILED ENGINEERING DRAWINGS, SPECIFICATIONS, AND CONTRACTOR BIDS

The approach taken by the project team was to prepare a set of detailed engineering drawings and specifications defining the design of the solar array and associated equipment. These detailed drawings and specifications were prepared by Burns and McDonnell, Engineers-Architects-Consultants, subcontractors to MRI, and submitted to several general contractors for bids. Because of the size of the specifications and the loss of detail that would result in further reduction of drawings, the specifications and drawings are separate from this report. The specifications are titled, "Application of Solar Energy to Alfalfa Dehydration," dated December 15, 1976 and carry the identification number 76-038-1. The drawings consist of nine drawings as identified in Table 3.

A. Array Construction

The final array design as shown in Figure 13, consists of 304 Sunworks flat plate air collectors mounted in a planar array having a tilt of approximately 9.6 degrees above horizontal. The aperture area of the flat plate portion of the array is 5,679 sq ft. The remainder of the array consists of 38 parabolic trough concentrating collectors rotating about a north-south horizontal axis. These concentrating collectors, manufactured by the Hexcel Corporation, are arranged in a series-parallel configuration of 19 parallel modules consisting of two Hexcel collectors in series. Each Hexcel collector has an aperture area of approximately 153 sq ft per module (8-1/2 ft wide by 19-1/2 ft long less receiver tube projected area). The total aperture area of the concentrating collector is 5,804 sq ft. The total array aperture area is 11,483 sq ft.

The array was designed for an airflow of 6,100 scfm. Thus, the airflow through the array is approximately 1.88 scfm/sq ft of aperture.

The array is to be operated under a slight negative pressure. Air will be drawn at ambient conditions through filters at the inlet side of the flat plate planar array. As the air flows through the flat plate array the temperature of the air will increase until it is more cost effective to continue heating the air with the higher efficiency Hexcel concentrating collector. At this point the air is collected in an insulated manifold which supplies 19, 4-in. diameter ducts located at the focal point of the 25:1 concentration ratio Hexcel parabolic trough collectors.

The specifications covering the solar collectors are located in Section 15E of the Specifications Book. The details of the flat plate solar array construction are shown in Mechanical Drawing M-2 while the details of the construction of the concentrating parabolic trough array are shown in Mechanical Drawing M-3.

APPLICATION OF SOLAR ENERGY
TO ROTARY DRYING & DEHYDRATION

WESTERN ALFALFA - LAWRENCE, KANSAS PLANT

Figure 13 - Artists Concept of Solar-Augmented Alfalfa Dehydration

TABLE 3

APPLICATION OF SOLAR ENERGY TO ALFALFA DEHYDRATION
(List of Drawings)

Civil

Drawing No.: T-1
Title: Plot Plan

Structural

Drawing No.: S-1
Title: Foundation Plan and Details

Drawing No.: S-2
Title: Framing Plan and Details

Drawing No.: S-3
Title: Rock Storage Vault and Instrument House Details

Mechanical

Drawing No.: M-1
Title: Solar Collector Array Sight Plan

Drawing No.: M-2
Title: Partial Solar Array Plan--Flat Plate Collectors

Drawing No.: M-3
Title: Partial Solar Array Plan--Tracking Concentrators

Drawing No.: M-4
Title: Rock Storage Vault--Alternate No. 1

Instrument House--Alternate No. 2
Burner Plenum and Fan Details

Electrical

Drawing No.: E-1
Title: Electrical Plan and Details

B. Duct Work

The Sunworks flat plate collectors are constructed such that ducting between collectors is not necessary. At the exit point of the flat plate array, duct work is necessary to provide the transition between the flat plate array and the concentrating array. Details of this duct are shown in drawing M-2. At the outlet of the array of concentrating collectors, a manifold of varying cross-sectional area collects the heated air from the array and transports it to a 30-in. diameter below grade duct. Details of the manifold are illustrated in Mechanical Drawing M-3, while the details of the 30-in. diameter round duct are illustrated in Drawing M-4. The specifications of the insulation and sheet metal work are discussed in Section 15C and 15D of the Specifications Book.

C. Air Handling Equipment

Only one air supply fan will be required to power the entire array. The air supply fan is located near the existing rotary dehydrator to minimize wiring costs and to place the array under negative pressure. By operating the solar array at negative pressure, minor air leaks will not result in a loss of energy from the array. If the array were operated at positive pressure, air leaks would cause heated air to escape to the atmosphere and result in lost energy. This design approach thus makes the control of air leaks less critical.

The air supply fan and associated mounting and duct work are illustrated in Mechanical Drawing M-4. The specifications for the fan are discussed in Section 15E of the Specifications Book.

D. Burner Plenum

The preheated air from the solar array is supplied to a burner plenum house by the fan unit. The burner plenum house consists of a building 8 ft by 8 ft by 8 ft with additional insulation and modifications to handle high temperatures. The burner plenum house is provided with an access door for burner service and a damper for admitting ambient air to the burner plenum house if bypassing of the solar array becomes necessary. Details of the burner plenum house are shown in Mechanical Drawing M-4 and the construction requirements are discussed in Section 13A of the Specifications Book.

E. System Controls

The controls for operating the solar array are relatively simple because no storage is incorporated. (Minimal storage to smooth temperature fluctuations was considered as an alternative, but was dropped because of cost.) Storage is not necessary because the energy output of the solar array is small in comparison to the total energy required by the rotary dehydrator. Activation of the solar energy system will be performed automatically with a manual override by operators at the dehydration plant. With the burners operating, the air supply fan of the solar array is turned on. The dampers on the side of the burner plenum are closed and all air consumed by the dehydrator has to pass through the solar array. The parabolic concentrators are controlled by a self-contained sun tracking system. This system utilizes solid-state components on replacable circuit boards. Therefore, in the event of a malfunction of one of the tracking mechanisms, in-plant maintenance personnel can make this system operational by replacing a plug-in circuit board and returning the defective circuit board to the manufacturer for repair. The air supply fan is a variable volume device having control louvers on the inlet side. The output of the fan will be controlled such that the pressure within the plenum house is slightly above ambient pressure. This will prevent an additional load on the existing dehydration plant's air supply fan and will automatically compensate for variations in the amount of air demanded by the rotary dehydrator. In the event of loss of power to the solar array's air supply fan or negative pressure conditions within the plenum house, the damper on the plenum house, will go to full open admitting ambient air and allowing the dehydrator to operate in its normal mode. Batteries provide sufficient energy to store the concentrating collector in the inverted position in the event of a power failure.

The parabolic concentrating collectors are provided with additional controls which allow setting the threshold radiation level at which the tracking system is activated. Thus, the concentrator will not function unless sufficient radiation is available for collection. In addition, a wind speed sensor is integrated into the control system such that, when wind speeds exceed a pre-set velocity, the concentrator returns to its inverted position, thus protecting the reflecting surface of the concentrator from possible hail damage and reducing the profile of the concentrator to minimize wind loading.

F. Data Acquisition and Monitoring System

An instrumentation building has been provided in the design to house the data acquisition subsystem and to house on-site monitors and recording devices that will be required during the evaluation phase of the system performance. The description of the instrument house is provided in Drawing M-4 and Section 13D of the Specifications Book. A detailed discussion of the instrumentation system is contained in Appendix I.

G. Results of Contractors' Bids

Four contractors submitted bids for the construction of the solar energy system. The results of the contractors' bids are presented in Table 4. The base bid amount includes all labor and materials required to construct the collector array, and install the duct work, air handling equipment and controls necessary for the operation of the solar system, as outlined in the detailed engineering drawings and specifications. Alternative No. 1, Rock Storage Vault, is a separate bid for the optional storage subsystem as detailed in the construction specification. Alternate No. 2, Instrument House, is a separate bid for the construction of a building to house the data acquisition and monitoring equipment.

Kansas Construction Company offered the lowest base bid, of \$372,200, and has therefore been selected from the bid offers as the company that will construct the project if Phase II funding is granted by ERDA.

Alternate No. 1 will not be included in the construction of the solar energy system. It was felt by the project team that the benefits of the rock storage system did not justify the cost of the system. Should fluctuations in the output temperature of the array present a problem to the operation of the existing controls of the burner, these controls could be modified at a cost substantially less than \$5,000 (the cost of the storage option) to alleviate any problem. It is not expected that the fluctuations of temperature output of the array will cause any problem. In the event that a problem does occur, it would be more economical to modify the controls of the burner than to install the storage alternate.

The bid by Kansas Construction Company of \$372,200 is used as the cost of adding a solar energy system to the Lawrence plant in the economic analysis presented in Chapter VII. Because this figure is an actual bid, it represents the most accurate estimate possible of the cost of the system. The costs of Alternate No. 2, and of data acquisition and monitoring equipment, are not included in the cost of adding the solar system used in the economic analysis. The data acquisition and monitoring system is not required for the operation of the system, and is an additional cost resulting from the system's function as a demonstration project.

TABLE 4

BID TABULATION

<u>Bidder</u>	<u>Bid Record</u>	<u>Base Bid Amount</u>	<u>Alternate No. 1 Rock Storage Vault</u>	<u>Alternate No. 2 Instrument House</u>	<u>Bid Form Complete</u>	<u>Bid Bond Complete</u>	<u>Certification of Nonsegreg Facilities</u>	<u>Experience Statements Complete</u>	<u>Engineers Estimate Base Bid</u>
B. A. Green Construction Company	Yes	\$379,293.00	\$4,890.00	\$6,386.00	Yes	Yes	Yes	Yes	\$371,000.00
B. B. Andersen Construction Company	Yes	397,333.00	4,330.00	6,140.00	Yes	Yes	No	Yes	371,000.00
Casson Construction Company	Yes	439,987.00	5,346.00	3,731.00	Yes	Yes	Yes	Yes	371,000.00
Harris Construction Company	No	--	--	--	--	--	--	--	
Kansas Construction Company	Yes	372,200.00	4,875.00	7,500.00	Yes	Yes	Yes	No	371,000.00
Markowitz Builders	No	--	--	--	--	--	--	--	

V. ECONOMIC ANALYSIS OF SYSTEM

The cost analysis presented in this chapter is based almost entirely on a method provided by Lawrence Livermore Laboratory, entitled "Method of Economic Analysis for Comparison of Solar Process Heat Systems." Separate cost calculations are made for the Albuquerque and Omaha locations.

Table 5 presents the Plan A cost calculation. Plan A represents the use of a conventional oil-fired energy system in the dehydration process. The major assumptions of the calculation, excluding the energy process requirements, were taken from the Lawrence Livermore Laboratory (LLL) Method. Because the same cost assumptions are used, the answer obtained (\$3.89/million Btu) is the same as the cost obtained by LLL.

The majority of the alfalfa dehydrators currently in use in the United States use natural gas. A direct firing process is used yielding a conversion efficiency of approximately 98%, compared to 70% for an oil-fired boiler. The direct-fired approach also requires less expensive capital equipment than a boiler. Most importantly, natural gas prices are significantly less than the \$15/bbl fuel oil price assumed in Table 5. All of these factors tend to decrease the economic viability of the solar energy design.

Table 6 presents the cost calculation using Plan B. Plan B represents the solar design to be used in Phases II and III of the research program. The major additional assumptions are presented at the beginning of the table. The solar design chosen contains 11,483 ft² of collector aperture area (including both flat plate and focusing collectors). The capital cost of the solar system used in the analysis was the lowest competitive bid from Kansas City area contractors. The capital cost (\$372,200) is therefore very realistic. The system was originally designed for Lawrence, Kansas. The method used to estimate the system output in Albuquerque and Omaha is discussed below.

A comparison of the average daily radiation over the dehydration season (May-October) on the flat plate collector, mounted at a 10 degree tilt above horizontal and the focusing collector, which rotates about a horizontal north-south axis, for Lawrence, Kansas (approximated with Columbia, Missouri data), Albuquerque, New Mexico and Omaha, Nebraska is presented in Table 7. The average daily radiation over the dehydration season for the flat plate and focusing collectors in Lawrence was taken from the modified TRNSYS program outputs. The values for Albuquerque and Omaha were derived by using the appropriate radiation values provided on pages 18 and 19 of the Lawrence Livermore cost methodology, and developing a seasonal weighted average for each collector in the two locations.

TABLE 5

PLAN A - ANNUAL ENERGY COST CALCULATION
(Process Fired by Fuel Oil)

Assumptions:

1. Annual requirement for process heat = 16.45×10^3 million Btu
2. \$15 bbl fuel oil
3. 5.8 million Btu/bbl
4. 0.7 efficiency of fuel oil process

Plan A

$$1. \text{ Cost of fuel oil energy} = \frac{\$15/\text{bbl} \times 16.45 \times 10^3 \text{ million Btu}}{5.8 \text{ million Btu/bbl} \times 0.7} = \$60,776$$

$$2. \text{ Boilers: } \$0.20/\text{million Btu} \times 16.45 \times 10^3 \text{ million Btu} = \$3,290$$

Deductible Expenses:

Fuel Oil	=	\$60,776
Boilers	=	<u>3,290</u>
Total	=	\$64,066

$$3. \text{ Effect of expenditures for Plan A on income taxes} = -\$32,033$$

$$4. \text{ Plan A after-tax energy cost} = \$32,033$$

$$5. \text{ Plan B before-tax energy cost} = \$64,066$$

$$6. \text{ Albuquerque and Omaha} = \frac{\$64,066}{16.45 \times 10^3 \text{ million Btu}} = \$3.89/\text{million Btu}$$

TABLE 6

PLAN B - ANNUAL ENERGY COST CALCULATION
Albuquerque [Omaha]

Assumptions:

1. Annual contribution from solar facility = 2.71×10^3 million Btu
 (16%) [2.01×10^3 million Btu (12%)]
2. Area of solar collectors = 11,483 ft²
3. Installed solar system cost = \$32.41 ft²
 (\$372,200 ÷ 11,483 ft² = \$32.41/ft²)
4. Annual O+M, replacement and insurance = \$565

Plan B

1. Repayment to equity for solar facility = \$43,719
 [\$372,200 x 0.11746]
2. 10% investment tax credit = -\$4,372
3. Cost of fuel oil energy = \$51,052 [\$53,483]
4. Boilers = \$3,290
5. Solar O+M, replacement and insurance (OMRI) = \$565

Deductible Expenses:

Fuel Oil	=	\$51,052	[\$53,483]
Boilers	=	3,290	
OMRI	=	565	
Depreciation	=	18,610	
Total	=	\$73,517	[\$75,948]

6. Effect of expenditures for Plan B on income taxes = -\$36,759 [-\$37,974]
7. Plan B after-tax energy cost = \$57,496 [\$58,711]
8. Plan B before-tax energy cost = \$114,990 [\$117,422]
9. Albuquerque:

$\frac{\$114,990}{16.45 \times 10^3 \text{ million Btu}} = \$6.99/\text{million Btu}$

10. Omaha:

$\frac{\$117,422}{16.45 \times 10^3 \text{ million Btu}} = \$7.14/\text{million Btu}$

TABLE 7

AVERAGE DAILY RADIATION OVER DEHYDRATION SEASON

	<u>Lawrence, Kansas</u>	<u>Albuquerque, New Mexico</u>	<u>Omaha, Nebraska</u>
Seasonal Average			
Daily Total Radiation on Flat Plate Collector Tilted at 10° (Btu/ft ² -day)	1884	2075	1755
Seasonal Average			
Daily Direct Radiation on Focusing Collector which Rotates About Horizontal North-South Axis	1608	2154	1396

The weights assigned to the seasons were intended to represent the proportion of the dehydration season in a given traditional season (i.e., spring, summer or winter), to the entire dehydration season. Specifically:

$$\begin{aligned}
 &0.25 \text{ Spring Average Daily Radiation} \\
 &+0.50 \text{ Summer Average Daily Radiation} \\
 &+0.25 \text{ Fall Average Daily Radiation} \\
 &= \text{Weighted Seasonal Average Daily Radiation.}
 \end{aligned}$$

The ratio of the average daily radiation for the flat plate collector in Albuquerque to the average daily radiation for the flat plate collector in Lawrence was multiplied by the energy output of the flat plate collector in Lawrence (as determined by TRNSYS simulation) to obtain the energy output of that collector in Albuquerque. Similarly, the ratio of the average daily radiation for the focusing collector in Albuquerque to the average daily radiation for the focusing collector in Lawrence was multiplied by the energy output of the focusing collectors in Lawrence (as determined by TRNSYS simulations) to obtain the energy output of those collectors in Albuquerque. The sum of these two values yielded the approximate total energy output of the collector array in Albuquerque. A similar calculation was done with the appropriate values to estimate the annual energy output of the array in Omaha. The energy outputs for all locations were then multiplied by a 0.95 utilization factor. The results of these calculations are presented in Table 8.

TABLE 8

ENERGY OUTPUTS OF SOLAR SYSTEM IN SELECTED LOCATIONS

	<u>Lawrence, Kansas</u>	<u>Albuquerque, New Mexico</u>	<u>Omaha, Nebraska</u>
Annual Energy Output of Solar System (0.95 utilization factor) 10^9 Btus	2.23	2.71	2.01

One other assumption used in Table 6 also warrants a brief discussion. The annual operation, maintenance, replacement and insurance costs for the solar design are assumed to equal \$565. The components included in that estimate are detailed in Table 9. Note that no additional insurance premiums are expected by Western Alfalfa Corporation because they are self-insured.

The cost estimates obtained from the assumptions discussed above are shown at the bottom of Table 6. The solar design in Albuquerque will cost \$57,495 annually (after taxes) or \$6.99/million Btu (using before-tax costs). In Omaha, the after-tax annual cost of the system would be \$58,711 or \$7.14/million Btu (using before-tax costs).

The solar design (Plan B) is more expensive than the conventional system (Plan A) in both locations. This result is expected because 100% backup capacity is required for Plan B and the annual savings in conventional fuel costs do not outweigh the additional annual costs of the solar equipment.

The contribution of the solar portion of Plan B to the total system cost is illustrated in more detail in Table 10. The table presents only those costs attributable to the solar equipment. The energy produced from the solar array costs approximately \$22.38/million Btu in Albuquerque and \$30.17/million Btu in Omaha.

Payback period calculations are often used by industry investors instead of the levelized annual cost approach discussed above. Table 11 presents the payback periods for the solar design (Plan B). In Albuquerque, the system would pay for itself in 24 years. The payback period in Omaha is 26 years.

All the calculations presented above have assumed the value of conventional fuel oil would remain at \$15/bbl over the next 20 years. However, the non-inflated price of this resource will undoubtedly increase.

TABLE 9

ANNUAL OPERATING, MAINTENANCE, REPLACEMENT AND
INSURANCE COSTS FOR SOLAR ENERGY SYSTEM

<u>Item</u>	<u>Annual Cost</u>
1. Wash collectors four times per season; labor, 6 man-hr per wash, or 24 man-hr per season at \$15.00/hr	\$360
2. Replace glazing on two flat plate collectors per season; materials, \$60 per season; labor, 4 man-hr per season at \$15.00/hr	120
3. Repair tracking mechanism; materials, \$25 per season; labor, 4 man-hr at \$15.00/hr	85
4. Insurance premium (Western Alfalfa Corp. is self-insured. Corporate liability insurance is paid but it does not change with the addition of an asset).	0
Total	<u>\$565/yr</u>

TABLE 10

ANNUAL COST CALCULATION FOR SOLAR ENERGY ALONE

1. Repayment to equity for solar facility = \$43,719
2. 10% investment tax credit = -4,372
3. Solar O+M, replacement and insurance = 565

Deductible Expenses:

OMRI	= \$	565
Depreciation	=	<u>18,610</u>
Total	=	\$19,175

4. Effect of expenditures for solar heat on income taxes = -\$9,588
5. After-tax cost of solar energy alone = \$30,324
6. Before-tax cost of solar energy alone = \$60,648
7. Albuquerque =
$$\frac{\$60,648}{2.71 \times 10^3 \text{ million Btu}} = \$22.38/\text{million Btu}$$
8. Omaha =
$$\frac{\$60.648}{2.01 \times 10^3 \text{ million Btu}} = \$30.17/\text{million Btu}$$

TABLE 11

PAYBACK PERIOD FOR PLAN B

1. Assumptions

I = Initial solar investment = \$372,200

K = Fraction of needs supplied by solar in Plan B = 16% (Albuquerque),
12% (Omaha)

N = System lifetime = 20 yr

F_o = Annual Plan A fuel oil bill = \$60,776

2. Payback Period Equation

$$\frac{I - 0.1 I}{0.5 [KF_o - OMRI + \frac{I}{N}]} = \text{payback (yr)}$$

3. Payback (Albuquerque)

$$\frac{372,200 - 0.1 (372,200)}{0.5 [.16 (60,776) - 565 + \frac{372,200}{20}]} = 24.13 \text{ yr}$$

4. Payback (Omaha)

$$\frac{372,200 - 0.1 (372,200)}{0.5 [.12 (60,776) - 565 + \frac{372,200}{20}]} = 26.44 \text{ yr}$$

Additional assumptions provided by Lawrence Livermore Laboratories were used to construct Table 12. It is assumed in the table that fuel oil will escalate at a 5% annual rate over the next 20 years, yielding a \$21.34/bbl equivalent annual fuel cost (at a 10% discount rate). The cost of energy using only a conventional system increases to \$5.46/million Btu. The solar design (Plan B) costs \$8.30/million Btu in Albuquerque and \$8.51/million Btu in Omaha.

All the cost estimates presented in this section use the methodologies forwarded by Lawrence Livermore Laboratories. Actual methods used in the alfalfa dehydration industry vary widely, depending on the size of the company. However, most methods used appear to range between the simple payback criteria and the more complete levelized annual cost method. Many of the firms use an internal rate of return calculation which is algebraically equivalent to the levelized annual cost approach.

Based on these industry practices, the project team has concluded that the cost estimates derived above give a sufficient indication of the economic viability of the solar design. However, one additional investment criterion has been ignored in the discussion. The availability of natural gas and other fossil fuels in the future for the dehydration industry is questionable. The lack of energy alternatives may be the single most important factor in a solar investment decision. The availability of other energy forms has been assumed in all the cost estimates presented in this section.

TABLE 12

PLANS A AND B FOR CASE OF ESCALATION IN FUEL COSTSA. Assume

\$15/bbl oil escalated at 5% over 20 yr with a discount factor of 10% yields an equivalent levelized cost of \$21.34/bbl

B. Plan A

$$1. \text{ Cost of fuel oil energy} = \frac{\$21.34/\text{bbl} \times 16.45 \times 10^3 \text{ million Btu}}{5.8 \text{ million Btu/bbl} \times 0.7} = 86,464$$

$$2. \text{ Boilers} = \$3,290$$

Deductible Expenses:

$$\begin{array}{rcl} \text{Fuel Oil} & = & \$86,464 \\ \text{Boilers} & = & \underline{3,290} \\ \text{Total} & = & \$89,754 \end{array}$$

$$3. \text{ Effect of expenditures for Plan A on income taxes} = -\$44,877$$

$$4. \text{ Plan A after-tax energy cost} = \$44,877$$

$$5. \text{ Plan A before-tax energy cost} = \$89,754$$

$$6. \text{ Albuquerque and [Omaha]} = \frac{89,754}{16.45 \times 10^3 \text{ million Btu}} = \$5.46/\text{million Btu}$$

C. Plan B - Albuquerque [Omaha]

$$1. \text{ Repayment of equity} = \$43,719$$

$$2. \text{ 10\% investment tax credit} = -\$4,372$$

$$3. \text{ Cost of fuel oil} = \$72,630 \text{ } [\$76,088]$$

$$4. \text{ Boilers} = \$3,290$$

$$5. \text{ Solar O\&M, replacement insurance} = \$565$$

Deductible Expenses:

$$\text{Total } \$95,095 \text{ } [\$98,553]$$

$$6. \text{ Effect on income taxes} = -\$47,548 \text{ } [-\$49,276]$$

$$7. \text{ Plan B after-tax energy cost} = \$68,284 \text{ } [\$70,014]$$

TABLE 12 (Concluded)

8. Plan B before-tax energy cost = \$136,568 [\$140,028]

9. Albuquerque =
$$\frac{\$136,568}{16.45 \times 10^3 \text{ million Btu}} = \$8.30/\text{million Btu}$$

10. Omaha =
$$\frac{\$140,028}{16.45 \times 10^3 \text{ million Btu}} = \$8.51/\text{million Btu}$$

VI. IMPACT OF SOLAR SYSTEM ON ALFALFA DEHYDRATION PLANT

The addition of a solar energy system to the Lawrence plant will result in an annual energy contribution by the solar system to the energy requirements of the dehydrator of approximately 13%. Should the Lawrence plant convert to field-wilting of the alfalfa, this contribution would increase to over 20%. Section A below discusses the impact of the solar system on the process energy requirements of the plant. The impact of the solar system on plant operation is discussed below in Section B.

A. Impact on Process Energy Requirements

The results of the TRNSYS simulations of the performance of the solar array indicated that the total energy output of the array during the dehydration season (May-October) is approximately equal to 2.35×10^9 Btu. By assuming that the energy output of the array cannot be utilized approximately 5% of the time, 95% of the energy output of the array can be utilized by the plant. The annual contribution of the solar system is therefore expected to be 2.23×10^9 Btu.

Production records for the Lawrence plant for 1974 and 1975 are presented in Table 13.

TABLE 13

PRODUCTION RECORD FOR THE LAWRENCE, KANSAS ALFALFA DEHYDRATING MILL (TONS)

	<u>1974</u>	<u>1975</u>
May	588	371
June	899	646
July	621	645
August	423	408
September	446	358
October	<u>159</u>	<u>114</u>
Total	3,126	2,542
Gas Usage (10^3 cu ft)	37,803	28,658
Gas Usage (10^3 cu ft/ton product)	12.09	11.27

Averaging the 2 years, the annual gas consumption of the plant was $33,230 \times 10^3$ cu ft. Because the Lawrence plant has two dehydrators which operate approximately the same amount of time, this figure is divided by two to obtain the gas consumption of the dehydrator to which the solar system is to be added, $16,615 \times 10^3$ cu ft/year. With 1,000 Btu/cu ft of gas, and an assumed gas utilization factor of 0.99 (direct fired process), the average annual energy requirement of the dehydrator for 1974 and 1975 was 16.45×10^9 Btu.

The annual percentage contribution of useable energy by the solar sytem is the annual useable solar energy produced by the system, divided by the annual energy requirements of the dehydrator, multiplied by 100, or:

$$\frac{2.23 \times 10^9 \text{ Btu}}{16.45 \times 10^9 \text{ Btu}} \times 100 = 13.6\%$$

This figure shows reasonable agreement with the results of a theoretical analysis of gas consumption as a function of solar air preheat temperature. This discussion is presented in Appendix J, "Effect of Solar Heating on Natural Gas Consumption During Alfalfa Drying."

It is likely, as the price of natural gas goes up, that the Lawrence plant will implement energy-conserving, field wilting techniques. Field wilting will reduce the energy required to dehydrate a ton of alfalfa by approximately 35%.^{1/} Should the Lawrence plant adopt field wilting techniques, the annual energy requirement of the dehydrator would be reduced to 10.69×10^9 Btu. The annual energy contribution of the solar array would then be approximately 20% of the process requirements.

B. Impact on Plant Operation and Processes

Incorporation of the solar array into the Lawrence Kansas alfalfa dehydration plant can be accomplished with minimal interruption of the process. The alfalfa dehydration process is seasonal and usually does not begin until May, depending upon weather. If ERDA approval for Phase II were granted on or before February 28, 1976, it is likely that the underground duct and burner plenum could be installed prior to the start of the dehydration season. This early installation of the interface equipment would allow truck access and normal operation of the dehydrator while the remainder of the solar installation is being completed.

^{1/} Letter from C. A. Vinci, Vice President-Operations, Western Alfalfa Corporation, to Ralph E. Preston, Burns and McDonnell, September 22, 1976.

If the starting date is delayed beyond the last of February, then the interface with the rotary dehydrator must be made while the process is underway. Through careful coordination of construction activities and scheduling of the cutting alfalfa, the rotary dehydrator can be shutdown for periods of up to 48 hr. Two or three 24 to 48 hr shutdowns should allow all interfacing construction to be completed. The remainder of the construction activities can be carried out while the dehydrator is operating.

After completion of the solar array, the rotary dehydrator may be operated in one of two modes. The first mode consists of solar augmentation by preheating the dehydrator inlet air. In this mode, the damper on the plenum house is closed and the air supply fan draws air through the solar array at a rate such that the pressure within the plenum is slightly (less than 1/4 in. of water column) above atmospheric pressure. Thus, all air entering the dehydrator is preheated to a temperature proportional to the incident radiation (300-400°F maximum). Existing controls on the rotary dehydrator will monitor the dehydrator exhaust temperature and vary the gas input to the burners to control the exhaust temperature to the set point.

Operation of the solar array during dehydration operation will be automatic. Start-up and shutdown of the solar supply fan will be controlled by the solar radiation threshold switch on the control system for the focusing solar collector. A manual override will be provided to allow manual start-up and shutdown of the solar array by the plant operating personnel.

The second mode of operation of the dehydrator is without solar augmentation. This mode will be utilized for dehydration during the night and on cloudy days, or in the event of a malfunction of the solar array. In this mode, the solar array air supply fan is off and the plenum damper is open. Combustion air and excess air are drawn into the plenum through the open damper. The dehydration process is controlled by adjusting the gas input to the burner array to maintain a constant exhaust temperature. In this mode, the operation of the solar augmented dehydrator is identical to a conventional rotary dehydrator.

APPENDIX A

ENERGY REQUIREMENTS OF ALFALFA DEHYDRATION PROCESS

The energy requirements of the alfalfa dehydration process as currently practiced will be used as the baseline from which the effect of using solar energy can be measured. Production figures from the Lawrence, Kansas dehydration mill, along with the gas usage per ton of product meal, are presented in the following discussion. A comparison is made between the production of dehydrated alfalfa meal at the Lawrence, Kansas mill and the production in the U.S.

A production record for the Lawrence, Kansas mill during the past 30 months is presented in Table A-I. These production figures were supplied by the Western Alfalfa Corporation. Although the data for 1976 are complete only through July, the remainder of the data for 1976 should be available before the project is completed.

The tons of dehydrated alfalfa presented in the data actually contain about 10% moisture by weight. Therefore, of the 3,126 tons of meal produced during 1974, over 300 tons were water. Both gas and electricity usages are based on the tons of dehydrated alfalfa (including moisture).

Production figures from Table A-I show that the output in 1975 was approximately 20% less than in 1974. While the data for this year are not complete, it appears that 1976 will exceed both 1974 and 1975 as far as production is concerned.

Because the billing periods for gas and electricity do not coincide with monthly production periods, the only statistics which are meaningful are the yearly values. Gas usage declined 7% from 12.09 thousand cubic feet per ton of dehydrated alfalfa in 1974 to 11.27 thousand cubic feet per ton in 1975. Electricity usage remained relatively constant at 120 kw-hr/ton of dehydrated alfalfa produced.

The production of dehydrated alfalfa from the Lawrence, Kansas mill is shown graphically in Figure A-1. The shaded area represents the maximum and minimum value for each month, thus giving the range for individual months. Some pattern is discernable, even though it is erratic. This is partially due to the variance resulting from weather and economic factors, coupled with the limited amount of data available.

In order to place the production of dehydrated alfalfa from the Lawrence, Kansas mill into its proper perspective, the production from all

TABLE A-I

PRODUCTION RECORD FOR THE LAWRENCE, KANSAS
ALFALFA DEHYDRATING MILL (TONS)

	1974	1975	1976
May	578	371	729
June	899	646	894
July	621	645	597
August	423	408	--
September	446	358	--
October	159	114	--
Total	3,126	2,542	2,220
Gas Usage (10^3 cu ft)	37,803	28,658	23,494
Electricity Usage (10^3 kw-hr)	385.215	305.920	294.400
Gas Usage (10^3 cu ft/ton product)	12.09	11.27	--
Electricity Usage (kw-hr/ton product)	123	120	--

mills in the U.S. is shown in Figure A-2. Data for this figure were taken from USDA records. A careful examination of Figure A-1 and A-2 reveals that the two production records are similar in shape. This reflects the fact that the Kansas alfalfa crop is located in a geographically representative area of the country.

The amount of gas required to dehydrate alfalfa depends both on the inlet moisture content of the alfalfa and on the efficiency of the dehydrator. At a theoretical efficiency of 100%, the evaporation rate of water as a function of the tons of dehydrated alfalfa produced per hour is presented in Figure A-3. Inlet moisture contents between 50% and 88% are used in these calculations.

Values for the evaporation rate of water in pounds per hour represent, to a rough approximation, the amount of gas required in cubic feet per hour. As an example, the evaporation rate for 5 tons of product meal per hour with an initial moisture content of 80% is 35,000 lb of water per hour. As a result, 35,000 ft³ of natural gas will be required for the drying process.

It is recognized that the dehydration process is not 100% efficient. The gas required per ton of dehydrated alfalfa is shown in Figure A-4 for various overall process efficiencies and inlet moisture contents. The efficiency referred to in Figure A-4 includes both the burner efficiency and the rotary dryer efficiency.

The shaded areas on Figure A-5 represent probably gas consumption rates for anticipated initial moisture values of alfalfa, both for green chop and field wilt. Statistics presented at the 32nd annual convention of the American Dehydrators Association in 1974^{1/} indicate that it required 11,100 ft³ of gas per ton of dehydrated alfalfa when the feed was green chop. This compares closely with the values of 12,090 and 11,270 presented in Table A-I. Green chop contains between 75 to 85% moisture by weight.^{2/}

Gas usage for dehydrating field-wilted alfalfa was given as 5,000-7,000 ft³ per ton of product.^{1/} Moisture contents for field-wilt material vary with the amount of time allowed and the ambient conditions, but average values range between 60 to 65%.^{1,2/}

^{1/} Private Communication from Mr. C. A. Vinci, Vice President of Western Alfalfa Corporation.

^{2/} "A Theoretical Analysis of Rotary Alfalfa Drying," Air Resources, Inc., Report Prepared for the American Dehydrators Association, October 1, 1975.

Figure A-I - Production of Dehydrated Alfalfa From the Lawrence, Kansas Mill

Figure A-2 - Production of Dehydrated Alfalfa From All Mills in the U.S.

Figure A-3 - Evaporation Rate (Also Gas Usage) Per Ton of Dehydrated Alfalfa

Figure A-4 - Gas Usage Per Ton of Product Meal As a Function of Dehydrator Efficiency

An examination of the areas of concern in Figure A-4 would indicate that while dehydration of field-wilt alfalfa does use less gas than required for green chop, the overall efficiency of the dehydration process is significantly reduced. As the industry turns toward field wilting as the primary method dehydration, changes in dryer design in order to increase the overall efficiency of the process may be expected.

APPENDIX B

AIR FLOW REQUIREMENTS FOR THE HEIL 8-24 MODEL DEHYDRATOR

The alfalfa dehydrator system used at the Lawrence, Kansas, plant is a Heil Model SD-8-24 Ardrier Dehydrator. A description of the system operation provided by Heil is as follows:

"An automatically controlled, rotary flame furnace, with a scientifically designed combustion chamber fired by oil or natural gas, supplies the necessary heat for the drying process. Hot gases pass directly from the combustion chamber through the intake tube and enter the inner drum cylinder at a temperature ranging from 1,000 to 1,800°F, depending upon the moisture content of the material to be dehydrated. An automatic cold-air damper is provided to alleviate any overheated condition.

The material to be dried is chopped or shredded and fed into the suction-sealed feed conveyor which conveys it into the receiving hopper of the intake tube.

The drum unit consists of three concentric drying cylinders into which the hot gases and the material to be dried enter by way of the intake tube. The material is then advanced through the drying drum by "means of a suction fan." The three cylinders are concentrically arranged, mechanically interlocked, and rotate at the same speed. The material is repeatedly carried to the top of each cylinder by the cylinder flights and dropped through the hot gases, giving off moisture as it passes progressively forward through the inner cylinder, then back through the intermediate cylinder, and forward again through the outside cylinder to the suction fan at the discharge end of the machine. With this type of concentric cylinder construction, the material is exposed to the drying medium for about 70 ft, insuring complete utilization of heat through radiation from each cylinder.

After the material passes through the drying drum it is blown into the large drying collector, where the vapor-laden air escapes out of the top at the rate of about 6,000 lb/hr, and the dried material passes into the cooling hopper and gravity separator, where the foreign materials are removed. A second fan propels the material into the cooling collector where it swirls downward into the sacking pipes or into the hammermill, as may be desired."

Design parameters for the Heil 8-24 dryer are:

Evaporation rate - 6,000 lb H₂O/hr
Back end dryer flow - 12,000 acfm at 300°F
Fan speed - 990 rpm
Fan pressure drop - 7.0 in. H₂O for standard air (70°F)
Fuel consumption - 10,000 ft³ gas/hr

Based on these design parameters, it is possible to calculate the air flow through the dryer. Studies of the combustion characteristics of the Heil 8-24 dryer using a typical natural gas have resulted in establishing that 10.65 standard cu ft of combustion products are exhausted for every cu ft of gas consumed. Also, 9.63 standard cu ft of air are required per cu ft of gas consumed.

Using the information presented above, the following representative calculations can be used to determine the air flow requirements. Gas flow volumes at an evaporation rate of 6,000 lb of water per hr and an exhaust temperature of 300°F are:

Water

$$\frac{6,000 \text{ lb H}_2\text{O}}{1 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{30.53 \text{ ft}^3 \text{ H}_2\text{O}}{1 \text{ lb H}_2\text{O}} = 3,053 \text{ acfm at } 300^\circ\text{F}$$

Combustion products (theoretical)

$$\frac{10,000 \text{ ft}^3 \text{ gas}}{1 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{10.65 \text{ ft}^3 \text{ products}}{1 \text{ ft}^3 \text{ gas}} \times \frac{760^\circ\text{R}}{530^\circ\text{R}} =$$

$$2,545 \text{ acfm at } 300^\circ\text{F}$$

Excess air

$$12,000 - 3,053 - 2,545 = 6,402 \text{ acfm at } 300^\circ\text{F or}$$

$$6,402 \text{ acfm} \times 530^\circ\text{R}/760^\circ\text{R} = 4,465 \text{ scfm}$$

Primary air

$$\frac{10,000 \text{ ft}^3 \text{ gas}}{1 \text{ hr}} \times \frac{1 \text{ hr}}{60 \text{ min}} \times \frac{9.63 \text{ ft}^3 \text{ air}}{1 \text{ ft}^3 \text{ gas}} = 1,605 \text{ scfm}$$

Total air

$$4,465 + 1,605 = 6,070 \text{ scfm}$$

Table B-I presents the results of carrying out similar calculations for various evaporation rates, and also for an increase in the volumetric flow rate through the dryer. These results are shown graphically in Figure B-1.

Based on the results presented in Figure B-1, it was decided that the air handling system should be sized to meet the maximum anticipated air flow requirements, i.e., 7,500 scfm. The solar array should be designed to meet the dehydrator design requirements of 6,100 scfm of air. [Note: air requirements met by the solar preheat system capacity are shown to the left on the dashed vertical line in Figure B-1]. This arrangement would mean for example, that a dehydrator pulling 13,000 acfm of gas (at 300°F) with an evaporation rate of 7,000 lb H₂O/hr would not require more air than could be handled by the designed solar preheat system.

TABLE B-I

Evaporation Rate (lb H ₂ O/hr)	Gas Consumption (cu ft/hr)	Primary Air Flow (scfm)	Exhaust Water Vapor (acfm at 300°F)	Exhaust Com- bustion Products (acfm at 300°F)	Excess Air Flow (acfm at 300°F)		Total Air Flow (scfm)	
					12,000 acfm	14,000 acfm	12,000 acfm	14,000 acfm
6,000	10,000	1,605	3,053	2,545	6,402	8,402	6,070	7,464
6,500	10,833	1,739	3,307	2,757	5,936	7,936	5,879	7,273
7,000	11,667	1,873	3,562	2,969	5,469	7,469	5,687	7,082
7,500	12,500	2,006	3,816	3,182	5,002	7,002	5,494	6,889
8,000	13,333	2,140	4,071	3,394	4,535	6,535	5,303	6,697

Figure B-1 - Air Flow Requirements for a Heil 8-24 Dehydration System as a Function of Evaporation Rate

APPENDIX C

MANUFACTURED SOLAR COLLECTORS

A detailed comparison of six manufactured flat plate collectors that use air as the heat transfer medium was undertaken for this project. Cost estimates were prepared by the Estimating Department of Burns and McDonnell for an array having approximately 1,000 ft² of each collector. All costs specific to the array were included in the estimates. The result was a total estimate for approximately 1,000 ft² of nominal collector area for each of the six collectors. Dividing this total estimate by the square footage of the array, an installed cost per square foot of nominal collector area was divided for each of the six collectors.

Table C-I summarizes the estimated installed cost per square foot of nominal collector area for the six collectors evaluated. Detailed estimates for a 1,008 ft² array of Sunworks and a 916.4 ft² array of Hexcel collectors are shown in Tables C-II and C-III, respectively. Similar cost estimates were prepared for the other four collectors and are the basis of the estimates contained in Table C-I.

Figure C-1 shows the efficiency versus $\Delta T/H$ plots for the six manufactured collectors. These plots are based on data supplied by the manufacturers.

The CEI versus $\Delta T/H$ plots for the six collectors are shown in Figure C-2. These plots were produced by dividing the efficiency curves of each collector in Figure C-1 by the appropriate cost estimate from Table C-I.

It should be noted that while the installed cost per nominal square foot of collector area was used to construct the CEI plots in Figure C-2, once the Sunworks and Hexcel collectors were selected as the most desirable manufactured collectors, the installed cost per square foot of collector aperture was used for all future analyses. The Sunworks collector has an installed cost of \$19.57 per nominal square foot of collector area. Although each collector module has 21 ft² of nominal area, only 18.68 ft² of each module is aperture area because of trim moldings. The estimate of the installed cost of 1,008 ft² of nominal area of Sunworks collectors is equivalent to an estimate for 889.5 ft² of aperture area. The installed cost per square foot of Sunworks aperture is derived by dividing the estimate of the installed cost of 1,008 ft² of nominal area by 889.5 or:

$$\frac{\$19,720}{889.5 \text{ ft}^2} = \frac{\$22.18}{\text{ft}^2}$$

The cost per square foot of aperture provides a more exact indication of the cost effectiveness of the collector.

TABLE C-I

COST ESTIMATES FOR MANUFACTURED COLLECTORS

<u>Collector Manufacturer</u>	<u>Installed Cost Per Nominal Square Foot of Collector Area</u>
Solaron Corporation	\$23.93
Hexcel Corporation	28.82
Solar Energy Products Company	21.42
RM Products Company	19.69
Sunworks	19.57
Contemporary Systems, Inc.	18.29

TABLE C-II

DETAILED COST ESTIMATE FOR INSTALLATION OF 1,008 FT² OF SUNWORKS COLLECTORS

<u>Description</u>	<u>Quantity</u>	<u>Unit</u>	<u>Labor</u>		<u>Material</u>	
			<u>Unit</u>	<u>Extension</u>	<u>Unit</u>	<u>Extension</u>
Drill holes for posts	42	EA		--	16	672
Set posts in concrete	42	EA	14	588	7	294
Gravel base	1,200	SF	0.10	120	0.10	120
Erect wood beams	720	BF	0.20	144	0.50	360
Install collector panels	48	EA	25	1,200	5	240
Collector panels		LS		--	9,840	<u>9,840</u>
Subtotal (Collector)				2,052		11,526
Ductwork	800	LB	1.50	1,200	0.50	400
Insulation	500	SF	0.60	300	0.20	100
Weather proofing		JOB	100	100	50	50
Perimeter flashing	132	LF	1.00	<u>132</u>	1.00	<u>132</u>
Subtotal (Ductwork)				1,732		682
Total Bare Costs				3,784		12,208
35% Burden on Labor				<u>1,324</u>		
				5,108		<u>5,108</u>
10% General Profit						<u>17,316</u>
						<u>1,732</u>
						19,048
Deliver panels to site						<u>675</u>
				Total Estimate		\$19,723

TABLE C-III

DETAILED COST ESTIMATE FOR INSTALLATION OF 916.4 FT² OF
HEXCEL CORPORATION FOCUSING COLLECTORS

<u>Description</u>	<u>Quantity</u>	<u>Unit</u>	<u>Labor</u>		<u>Material</u>	
			<u>Unit</u>	<u>Extension</u>	<u>Unit</u>	<u>Extension</u>
Excavation and backfill						
Machine	12	CY	3	36	6	72
Hand		LS		200		--
Forms	240	LF	0.60	144	0.32	72
Reinforcing	0.2	TON	150	30	415	83
Concrete	11	CY	2.75	185	31	341
Anchor bolts	96	EA	3	288	2	192
Collectors delivered		JOB		--		17,076
Install collectors	12	EA	30	<u>360</u>		<u>--</u>
Subtotal (Collectors)				1,143		17,836
Ductwork (round)	1,150	LB	1.25	1,433	0.50	575
Ductwork (flex) 5 in. diameter	60	LF	0.60	36	1.20	72
Insulation	600	SF	0.50	300	1	600
Dampers	6	EA	12	<u>72</u>	20	<u>120</u>
Subtotal (Ductwork)				1,846		1,367
Total Bare Costs				2,989		19,203
35% Burden on Labor				<u>1,046</u>		
				4,035		<u>4,035</u>
10% General Profit						23,238
						<u>2,324</u>
						25,562
Electric Motor Drives						<u>850</u>
				Total Estimate		\$26,412

Figure C-1 - Performance of Manufactured Collectors

Figure C-2 - Plots of Cost Effectiveness Index Versus $\Delta T/H$ for Manufactured Collectors

APPENDIX D

FIELD-ERECTED SOLAR COLLECTORS

Eleven field-erected Solar Collectors were designed by the project team. Eight of these were selected for further evaluation. Cost estimates were prepared by the Estimating Department of Burns and McDonnell using the same method as for the manufactured collector estimates (Refer to Appendix C). The results of these estimates for the eight collectors of interest are summarized in Table D-I.

Figure D-1 shows the performance of the field-erected collectors as calculated using the equations developed by Whillier.^{1/}

The CEI versus $\Delta T/H$ plots are shown in Figure D-2. These plots were produced by dividing the efficiency curves of each collector in Figure D-1 by the appropriate cost estimates from Table D-I.

Drawings of collector Types A, B, C and D are provided in Figures D-3, 4, 5 and 6, respectively. Type G is identical to Type A except that it is glazed with a thermopane patio door. Type H is identical to Type A except that it is double glazed with 0.040 Plexiglas. Type I is identical to Type A except that it is double glazed with 0.40 Kalwall. Type J is similar to Type A, except that it has a convex double glazing of 0.040 Kalwall.

^{1/} Whillier, Austin, "Design Factors Influencing Solar Collector Performance," Low Temperature Engineering Application of Solar Energy, ASHRAE, 1967.

TABLE D-I

COST ESTIMATES FOR FIELD-ERECTED COLLECTORS

<u>Field-Erected Collector Type</u>	<u>Description</u>	<u>Installed Cost Per Nominal Square Foot of Collector Area</u>
A	Single-glazed glass, rock absorber, no insulation	\$13.90
B	Single-glazed glass, rock absorber, 1 in. foam	13.90
C	Single-glazed tedlar film, rock absorber, 1 in. foam	11.68
D	Single-glazed with corrugated FRP sheet, rock absorber, 1 in. foam	13.90
G	Thermopane patio door glazing, rock absorber, no insulation	17.95
H	Double glazed with 0.040 plexiglas, rock absorber, no insulation	16.06
I	Double glazed with 0.040 Kalwall, rock absorber, no insulation	15.38
J	Double glazed with 0.040 Kalwall, convex glazing on 12 ft-mtg centers, rock absorber, no insulation	10.64

Figure D-1 - Performance of MRI Field-Erected Collectors

Figure D-2 - Plots of Cost Effectiveness Index Versus $\Delta T/H$ for Field-Erected Collectors

NOTE: ROCK BED MAY VARY 4" - 6".

Figure D-3

FC-A	TYPE "A" FIELD ERECTED	PROJECT NO.
8-17-76		76-038-1

Figure D-4

FC-B

8-17-76

TYPE 'B'
FIELD ERECTED

MR14247-1

76-038-1

Figure D-5

FC-C	TYPE "C"	CONTRACT NO.
DATE	FIELD ERECTED	MRI 4247-1
8-17-76		PROJECT NO.
		76-038-1

Figure D-6

FC-D

8-17-76

TYPE "D"
FIELD ERECTED

MR 4247-1

76-038-1

APPENDIX E

REVIEW OF LITERATURE ON SOLAR AIR COLLECTORS

In an effort to obtain support for the performance curves that were calculated for the field-erected collectors, a literature search has been conducted. The objective of this search was to find empirical performance data for solar air collectors similar in design to the types specified by Burns & McDonnell. Theoretical determinations of performance characteristics were also thought to be of interest, as they could be compared to our own calculations.

The literature search sought documentation of the performance of collectors which used a rock bed as an absorber and forced air passing between the rock bed and the cover assembly as the heat transfer medium. No usable data on a collector of this exact configuration were found.

Only one study of a rock air collector similar to our design appears to be available. This is the final report to ERDA entitled Design of Collectors and Instrumentation for Application to Solar Drying of Peanuts, Tobacco and Forage^{1/} by Dr. J. H. Schlag at Georgia Institute of Technology. Part III of this study presents empirical data on a "Rock Absorption and Storage Collector System" similar to our own design, with the exception that the rock bed occupies the entire space between the base of the collector and the cover assembly. Our rock collector design specified an air space of 7 in.

In any case, the experiments conducted by Dr. Schlag are not adequate for our purposes. The primary problem is that all measurements were taken without any load on the collector. The measurements were of surface rock and internal rock temperatures while the collector was in a stagnating mode. Without some information on air temperature as a function of flow rate through the collector, it is impossible to estimate the efficiency of this collector.

There appears to be a substantial amount of data in the literature on air collector designs which remove the heat from the absorber on the back side; the area between the cover assembly and the absorber plate serving as a dead air space.^{2/} Data on this type of collector are of little relevance because the coefficient of heat loss, U_L , is likely to be considerably different than in our situation where force air is circulated between the absorbing surface and the cover assembly.

1/ Schlag, J. H., Design of Collectors and Instrumentation for Application to Solar Drying of Peanuts, Tobacco and Forage. Final Report to the Energy Research and Development Administration, Georgia Institute of Technology, June 1976.

2/ Whillier, Austin, "Black-Painted Solar Air Heaters of Conventional Design," Solar Energy, 8, (1), pp. 31-37 (1964).

Although no study that supplied data on a collector of our exact design was found, a small number of articles on air collectors with some correspondence to our own was obtained. Four articles examined collectors of designs somewhat similar to our own. But after further analysis, those articles failed to yield useful information. Shoemaker^{1/} examined a collector with a blackened expanded foil mesh as the absorber. Collectors with a foil mesh completely filling and partially filling the space between the cover and the base of collector are compared to a collector with a flat surfaced absorber. Lack of insulation data, however, make it impossible to determine collector efficiencies. Chiou, Duffie, and El-Wakil^{2/} also examine foil matrix collectors. But again, sufficient data are not provided to produce efficiency vs. $\Delta T/H$ plots. Beville and Brandt^{3/} have conducted an experiment on a collector with a finned, selective absorber. The data on these experiments are only for a small range of temperatures, making it difficult to construct an accurate efficiency vs. $\Delta T/H$ plot. It is also unclear where the air flow in this collector is located. The results are therefore even less useful. Swartman and Ogunlade^{4/} have conducted an experiment with a collector similar to our own design. However, the heat transfer medium used in their work was water. As a result, their performance results are not applicable to our situation.

Close^{5/} has generated efficiency vs. $\Delta T/H$ plots for a large number of collector configurations. Collector Type I in Close's article is very similar to the Type C site-constructed collector. Performance curves are provided in this article for the Type I collector with three different absorber geometries, flat plate, finned plate, and V corrugated plate, all painted with a flat black paint. Apparently Close's data was in part theoretically derived, and in part derived from data accumulated by Tabor.^{6,7/} Despite the fact that no rock bed absorber was examined, the affinity in design of the Close Type I collector to the Type C collector makes a comparison of their performance curves useful. These curves are presented in Figure E-1.

- ^{1/} Shoemaker, M. J., "Notes on a Solar Collector with Unique Air Permeable Media," Solar Energy, 5, (4), pp. 138-141, (1964).
- ^{2/} Chiou, Duffie, and El-Wakil, "A Slit-and-Expanded Aluminum-Foil Matrix Solar Collector," ASME Reprint No. 64-WA/SOL-10, (1964).
- ^{3/} Beville and Brandt, "A Solar Energy Collector for Heating Air," Solar Energy, 12, pp. 19-29, (1968).
- ^{4/} Swartman and Ogunlade, "An Investigation of Packed-Bed Collectors," Solar Energy, 10, (3), (1966).
- ^{5/} Close, D. J., "Solar Air Heaters for Low and Moderate Temperature Applications," Solar Energy, 7, (3), (1963).
- ^{6/} Tabor, H., "Solar Energy Collector Design," Bull. of the Res. Council of Israel, 5C, (1), (1955).
- ^{7/} Tabor, H., "Radiation, Convection and Conduction Coefficients in Solar Collectors," Bull. of the Res. Council of Israel, 6C, (3), (1958).

Figure E-1 - Comparison of Performance Curves from Literature Search and MRI Field-Erected Collectors

Tests on solar air heaters by Gupta and Garg^{1/} are a second source of useful performance data. In their work, Gupta and Garg tested a collector (Type III) with an absorber element of a blackened, galvanized iron wire mesh held diagonally between a single glass cover and a blackened corrugated iron sheet base. Air was thus circulated across the plate and through the wire mesh. The performance curve for the Gupta and Garg Type III collector is also presented in Figure E-1.

These analyses by Close and by Gupta represent the only information from the literature review which was applicable to a reevaluation of the performance of the site-constructed collectors. Our calculated performance curve of the Type J collector (rock absorber, arched double Kalwall absorber) is included in Figure E-1.

Because no usable information in the literature was found that examined the performance of a double-glazed collector similar to Type J, it is impossible to refute or verify the MRI performance curve for this collector. It is, however, possible to discuss the performance of the Type C collector.

It is clearly evident from Figure E-1 that predicted performance of the Type C collector is more optimistic than the performance of the collectors examined by Close and by Gupta and Garg. This discrepancy can be accounted for by the differences in the values of the parameters, $\tau\alpha F'$, and U_L . The values of these parameters for each collector are presented in Table E-I.

It is unlikely that $\tau\alpha$ is a potential source of significant error in the predicted performance of Type C. Both the transmissivity of Tedlar PVF film and the absorptivity of black paint are well-defined quantities. A comparison of Close's performance curves and the Type C curve, therefore, indicates that our calculations have overestimated F' and underestimated U_L . There is a possibility that the higher F' of the Type C collector may be accounted for to some extent by a higher heat transfer coefficient between the air flow and the rock absorber than the heat transfer coefficient of the surfaces examined by Close.

It is somewhat difficult to interpret the implications of the performance curve for the Gupta and Garg collector. The extremely high value of the Y-intercept is especially peculiar. This may result from a high level of scatter in the data used to plot the curve. The high value

^{1/} Gupta and Garg, "Performance Studies on Solar Air Heaters," Solar Energy, 11, (1), pp. 25-31, (1967).

TABLE E-I

<u>Collector</u>	<u>$\tau\alpha$</u>	<u>F'</u>	<u>U_L</u>
Close, Type I (flat plate)	0.855	0.64	3.07
Close Type I (finned and V corrugated plate)	0.855	0.74	2.83
Gupta and Garg Type III	--	0.89	2.17 (1.69)*
MRI Type C	0.87	0.943	1.096

* Table 2, p. 30, in Gupta and Garg's article specifies $U_L = 1.68 \frac{\text{Btu}}{\text{Ft}^2\text{-}^\circ\text{F-Hr}}$

Interpolation from the graph of efficiency vs. $\Delta T/H$ results in a

$$U_L = 2.17 \frac{\text{Btu}}{\text{Ft}^2\text{-}^\circ\text{F-Hr}}$$

of F' may also be accounted for by a high heat transfer coefficient between the air flow and the wire mesh. Perhaps this could be considered the upper limit for F' of the Type C collector.

The higher values of U_L for both the Close and Gupta and Garg collectors suggest that higher U_L would more accurately predict the performance of the Type C collector.

This literature review has provided only very limited success in verifying the accuracy of the predicted performance of the Type C collector. Only a very small amount of useful information was found. Nevertheless, this information could be used to modify the predicted performance of the Type C collector. The limited success of the literature review is evidence by the fact that the previous uncertainty surrounding the performance of this collector can now at best be transformed into a new uncertainty.

If we assume that values of F' and U_L for Close's flat plate collector represent the lower and upper limits respectively for F' and U_L of the Type C collector, and that similarly F' and U_L for the Gupta and Garg collector represent upper and lower limits, the performance curve of the Type C collector will be in between the curves for these two. It seems reasonable to expect an F' higher than that of Close's flat plate because of a higher heat transfer coefficient of the rocks due to increased surface area and roughness. Similarly, the heat transfer coefficient of Gupta and Close is basically the upper limit of F' for Type C, as this represents air flowing through the absorbing medium.

This band of performance for the Type C collector has been used to plot the cost effectiveness vs. $\Delta T/H$ for this new range of expected performance in Figure E-2.

The uncertainty surrounding performance of the Type C collector continues to pose problems for future system design. At what point within this band of uncertainty the real performance curve lies will determine the amount of area of Type C to be used, as well as the amount of manufactured collector area.

Figure E-2 - Band of CEI for MRI Type C Collector Derived from Literature Search Performance Data

COVERAGE OF LITERATURE SEARCH

1. References supplied by consultant, Dr. Dan S. Ward, Colorado State University, Fort Collins, Colorado.
2. Card Catalogue, Linda Hall Library, Kansas City, Missouri.
3. Solar Energy, Volumes I to XVIII, 1956 to 1976, articles and abstracts.
4. Engineering Index, 1958 to present.
5. Applied Science and Technology Index, 1958 to present.
6. Energy Index, entire.
7. Biological and Agricultural Index, 1964 to present.

APPENDIX F

PRELIMINARY DETERMINATION OF ARRAY CONFIGURATION

A preliminary determination of the array configuration for use in future system design tasks has been completed. This working paper documents the rationale for selecting the collectors to be used in the array.* Also included in this paper are the calculated areas for specified design parameters and an estimate of array cost. The determination of the array configuration is the result of a five-step process.

Step One

The first step was to select the most desirable manufactured flat plate collector for use in conjunction with the Hexcel collector in a two collector array. The criteria used to make this selection were: (1) the cost effectiveness of the manufactured flat plate collectors in the low temperature range, (2) the quality of the manufacturer's performance data and (3) the durability of the collector. Figure F-1 shows the Cost Effectiveness Index (CEI) versus $\Delta T/H$ for the Contemporary System Inc., Sunworks and Hexcel collectors. The cost used to calculate the CEI was the estimated installed cost per square foot of collector, including the purchase cost, delivery cost, and all installation costs specific to the array. Contemporary Systems and Sunworks were chosen for further examination because their CEIs were considerably higher than other candidate collectors.

It is evident from Figure F-1 that the CEI of the Contemporary Systems collector is slightly higher than the CEI for Sunworks. However, the better documentation of the performance characteristics and collector construction of the Sunworks collector offset this slight advantage. Sunworks has provided independent test data on their collector. Detailed material and construction specifications were also contained in the Sunworks literature. The high quality of materials and construction, combined with a sizeable number of successful installations suggest that the Sunworks collector is durable. The low uncertainty surrounding the performance and durability of the Sunworks collector warrants its selection over the less proven Contemporary Systems collector as the more desirable flat plate collector.

* This analysis is presented to show the trade-offs between using a two collector array made up of Sunworks and Hexcel collectors and an array made up of field-erected Type J and Hexcel collectors. The cost estimates that were used in this analysis were later revised. The results of this analysis, therefore, should not be interpreted as the preliminary array design.

Figure F-1 - Cost Effectiveness Index versus $\Delta T/H$ Curves for Most Effective Manufactured Collectors

Step Two

The second step in determining the array configuration was to calculate the amount of area of the Sunworks and Hexcel collectors that would be used in the most cost effective array design using these two collectors. These areas were calculated for a design output temperature of 250°F, a design flow rate of 6,100 scfm, a flux level of 175 Btu/hr, and an ambient temperature of 75°F. The results of these calculations are presented in Table F-I. Also presented in Table F-I is the estimated cost of the Sunworks and Hexcel array.

TABLE F-I

COST AND CONFIGURATION OF ARRAY USING
SUNWORKS AND HEXCEL COLLECTORS*

Collector	Area	Array Cost	Total Array Cost
Sunworks	5,894 ft ²	\$116,230	\$285,741
Hexcel	6,375 ft ²	169,511	

- * T_{out} = 250°F
- H = 175 Btu/hr
- T_{ambient} = 75°F
- Flow Rate = 6,100 scfm

Step Three

Step three was directed at obtaining support for the performance curves that were calculated for the field-erected collectors. A thorough literature search was conducted. The literature search sought documentation of the performance of collectors which used a rock bed as an absorber and forced-air as the heat transfer medium passing between the rock bed and the cover assembly. An effort was also made to obtain the results of research projects now in progress that might yield relevant data.

The search produced only two articles containing usable performance data that had some applicability to the MRI field-erected collectors. Neither of these articles specifically addressed a collector with a rock absorber.

D. J. Close^{1/} generated efficiency versus $\Delta T/H$ plots for a single-glazed collector (Type I) similar to the Type C collector. Performance curves are provided in the Close article for the Type I collector with three different absorber geometries, flat plate, finned plate, and V corrugated plate, all painted with a flat black paint. These curves are presented in Figure F-2. Also presented in Figure F-2 are the performance curves for the MRI Type C and Type J collectors. Tests on solar air heaters by Gupta and Garg^{2/} are a second source of useful performance data. In their work, Gupta and Garg tested a collector (Type III) with an absorber element of a blackened, galvanized iron wire mesh held diagonally between a single glass cover and a blackened corrugated iron sheet base. Air was thus circulated across the plate and through the wire mesh. The performance curve for the Gupta and Garg Type III collector is included in Figure F-2.

MRI collector Type J, which is double-glazed with Kalwall, appears to be the field-erected collector with the greatest potential. Although Type C also shows potential as a highly cost effective collector, the uncertain durability of the Tedlar cover makes it less attractive than Type J.

Recognizing the possibility that the calculated performance for the Type J collector was overly optimistic, the data from the literature search was used to modify the predicted performance. Figure F-3 shows four possible performances of collector Type J. Performance A represents the lower limit of performance. It is based on Close's collector with a flat plate absorber. The better heat transfer properties of the rock absorber as compared to a flat plate, and the reduced heat loss coefficient of a double glazed collector as compared to a single glazed, justify the assumption that the performance of the Type J collector is likely to be at least as good as Performance A. Performance B is based on the value of the Y-intercept ($F' \tau \alpha$) from the MRI Type J calculated performance and the slope of the Gupta and Garg collector performance. Performance C represents a 38% increase in the MRI calculated slope for the Type J collector. Performance D is the MRI calculated performance for the Type J collector and may be considered the upper limit of performance.

Step Four

In step four, the four possible collector Type J performances defined in step three were used to analyze the effect of uncertain collector performance on the configuration of the array and on the performance of the array as a whole.

^{1/} Close, D. J., "Solar Air Heaters for Low and Moderate Temperature Applications," Solar Energy, 7, (3), 1963.

^{2/} Gupta and Garg, "Performance Studies on Solar Air Heaters," Solar Energy 11, (1), pp. 25-31 (1967).

Figure F-2 - Comparison of Performance Curves from Literature Search and MRI Field-Erected Collectors

Figure F-3 - Efficiency versus $\Delta T/H$ Curves for Four Possible Performances of Collector Type J and for Sunworks and Hexcel Collectors

Table F-II presents the amount of area of the Type J and Hexcel collectors that would be used in the most cost-effective array design, assuming four performances for Type J. Also presented are the array costs. The same design parameters were used for these calculations as were used in the calculations for the Sunworks and Hexcel array in Table F-I.

A comparison of Table F-II and Table F-I suggests that even assuming the worst performance for collector Type J (Performance A), an array using the Type J and Hexcel collectors produces the same energy output for nearly the same cost. Assuming the most optimistic performance (Performance D), the Type J and Hexcel array produces the same energy output as the Sunworks and Hexcel array at a 20% reduction in array cost.

TABLE F-II
COST AND CONFIGURATION OF ARRAY FOR FOUR POSSIBLE
PERFORMANCES OF COLLECTOR TYPE J*

Collector Type J Design Performance	Collector	Area	Array Cost	Total Array Cost
Performance A	Type J Hexcel	2,303 ft ² 10,191 ft ²	\$ 24,504 270,979	\$295,483
Performance B	Type J Hexcel	3,027 ft ² 9,565 ft ²	32,207 254,333	286,540
Performance C	Type J Hexcel	6,644 ft ² 7,100 ft ²	70,692 188,789	259,481
Performance D	Type J Hexcel	9,731 ft ² 4,875 ft ²	103,534 126,626	230,160

* $T_{out} = 250^{\circ}\text{F}$
 $H = 175 \text{ Btu/hr}$
 $T_{ambient} = 75^{\circ}\text{F}$
Flow Rate = 6,100 gpm

Table F-III illustrates the trade-offs between different design approaches using collector Type J. Figures F-4, 5, 6 and 7 depict these trade-offs graphically. It is clear from Table F-I, and from these figures that given a situation in which uncertainty surrounds collector performance, a conservative design approach is preferred. Figure F-4 shows that if the array was designed for Performance A, and the performance turned out to be B, C, or D, the cost effectiveness of the array is increased. In contrast,

TABLE F-III

TRADE-OFF OF DESIGN APPROACHES FOR FOUR POSSIBLE PERFORMANCES OF COLLECTOR TYPE J*

	Actual Performance A			Actual Performance B			Actual Performance C			Actual Performance D		
	T _{out}	$\frac{T_{out}}{T_{design}}$	Energy Output	T _{out}	$\frac{T_{out}}{T_{design}}$	Energy Output	T _{out}	$\frac{T_{out}}{T_{design}}$	Energy Output	T _{out}	$\frac{T_{out}}{T_{design}}$	Energy Output
Design Performance A	250°F	1	1.176 million Btus/hr	253	1.014	1.199	256	1.025	1.218	257	1.028	1.223
Design Performance B	246	0.984	1.149	250	1	1.176	255	1.02	1.209	257	1.027	1.221
Design Performance C	228	0.912	1.028	235	0.941	1.077	250	1	1.176	256	1.024	1.216
Design Performance D	198	0.793	0.828	207	0.828	0.887	246	0.983	1.147	250	1	1.176

- * T_{design} = 250°F
 H = 175 Btu/hr
 T_{ambient} = 75°F
 Flow Rate = 6,100 scfm

Figure F-4 - Trade-Offs of Designing Array for Collector Type J, Performance A, and Performance Turns Out to Be B, C, or D* (*H = 175 Btu/hr; $T_{ambient} = 75^{\circ}F$; and $T_{design} = 250^{\circ}F$)

Figure F-5 - Trade-Offs of Designing Array for Collector Type J, Performance B, and Performance Turns Out to Be A, C, or D* (*H = 175 Btu/hr; $T_{ambient} = 75^{\circ}F$; $T_{design} = 250^{\circ}F$)

Figure F-6 - Trade-Offs of Designing Array for Collector Type J, Performance B, and Performance Turns Out to Be A, C, or D* (*H = 175 Btu/hr; $T_{ambient} = 75^\circ \text{F}$; $T_{design} = 250^\circ \text{F}$)

Figure F-7 - Trade-Offs of Designing Array for Collector Type J, Performance B, and Performance Turns Out to Be A, C, or D* (*H = 175 Btu/hr; $T_{ambient} = 75^{\circ}\text{F}$; $T_{design} = 250^{\circ}\text{F}$)

Figure F-7 shows that if the array is designed for the most optimistic performance, and the performance turns out to be worse, the array operates at a greatly reduced cost effectiveness.

This exercise suggests that if the Type J collector were to be used in the final array design, it would be advisable to design for a conservative predicted performance.

Step Five

The final step in determining the array configuration was to evaluate the risks and benefits of a Type J and Hexcel array as compared to a Sunworks and Hexcel array. If we could be certain that Performance A represented the lower limit of performance for collector Type J, then the Type J and Hexcel array might be more attractive. For a slightly greater initial cost (\$10,000), it is likely that the Type J and Hexcel array would operate at a higher cost-effectiveness than a Sunworks and Hexcel array, particularly if the performance turned out to be significantly higher than expected. Obviously, if we could be convinced that the Type J collector had performance characteristics approaching Performance D, then there would be no question that the Type J and Hexcel array was the most cost-effective.

The small amount of data available and the questions concerning the applicability of this data to the Type J collector make it difficult to assume that Performance A is the lower limit of performance. Should the actual performance of the Type J collector turn out to be even worse than Performance A, the consequences of constructing a system using this performance and the Type J collector would be large.

All work to date suggests that the Type J collector has significant potential as a highly cost-effective collector. Lack of clear documentation of its performance, however, prohibits its use. The Sunworks and Hexcel array configuration presented in Table F-I is therefore the configuration that will be used in future design tasks.

APPENDIX G

CALCULATION OF OPTIMAL AREA FOR SUNWORKS COLLECTOR

The optimal area of the Sunworks collector was determined by calculating the area required to heat the airflow of the dehydrator up to the temperature at which the Hexcel collector becomes more cost effective. The crossover temperature was found by deriving the line equations of the CEIs for the two collectors and finding their intersection point. These equations are presented in Table G-I. The CEIs of the Sunworks and Hexcel are equal at a temperature of 157.3°F.

An energy balance equation was used to find the Sunworks area needed to heat the airflow of the dehydrator to 157.3°F. The energy added to the air as it passes through a bank of collectors is:

$$Q = \dot{M} C_p \Delta T = \eta_{avg} H A \quad (1)$$

where

Q = energy added to airflow Btu/hr,

M = mass flow of air lbm/hr,

C_p = specific heat of air Btu/lbm,

ΔT = temperature increase of air through collector °F,

η_{avg} = average efficiency of the collector,

H = seasonal average solar radiation intensity Btu/ft²-hr,

A = area of solar collector.

The area of Sunworks collector which would be most cost effective can be determined by solving equation (1) for A :

$$A = \frac{\dot{M} C_p \Delta T}{\eta_{avg} H} \quad (2)$$

The mass flow through the dehydrator is equal to the airflow requirements of the dehydrator, 6,100 scfm, expressed as a mass flow, or 27,997 lbm/hr. The specific heat of air at standard conditions is 0.24 Btu/lbm. The temperature increase of air through the collector is equal to the output temperature minus the ambient temperature or:

$$157.3^\circ\text{F} - 75^\circ\text{F} = 82.3^\circ\text{F} \quad (3)$$

TABLE G-I

EQUATIONS FOR EFFICIENCY AND CEI VERSUS TEMPERATURE PLOTS

Assumptions:

Average Ambient Temperature During
Dehydration Season = 75°F

Average Total Radiation on Flat Plate
Collector During Dehydration Season = 180 Btu/ft²-hr

Average Beam Radiation on Focusing
Collector During Dehydration Season = 148 Btu/ft²-hr

Sunworks:

$$\eta = 0.71 - 0.00323 (T - 75)$$

$$CEI = 0.032 - 0.000145 (T - 75) \text{ (assumes installed cost of \$22.18/ft}^2\text{)}$$

Hexcel:

$$\eta = 0.705 - 0.001538 (T - 75)$$

$$CEI = 0.0245 - 0.000053 (T - 75) \text{ (assumes installed cost of \$28.82/ft}^2\text{)}$$

η_{avg} for the Sunworks collector was found by substituting the output temperature, 157.3°F, into the Sunworks efficiency equation (Table F-I), and averaging this value with the efficiency at the ambient temperature, 75°F:

$$\eta_{avg} = \frac{\eta_{75} + \eta_{157.3}}{2} = \frac{0.71 + 0.444}{2} = 0.577 \quad (4)$$

The intensity of the seasonal average solar radiation on the Sunworks collector filled at a 10 degree angle, is 180 Btu/ft²--hr. Substituting these values into equation (2) yields:

$$A = \frac{(27,997) (0.24) (82.3)}{(0.577) (180)} = 5,324 \text{ ft}^2$$

APPENDIX H

TRNSYS PROGRAM MODIFICATIONS FOR FOCUSING COLLECTOR

Two modifications of the TRNSYS program have been made in order to simulate the performance of a north-south axis, horizontally mounted, focusing collector. First, the program was modified to derive hourly values of the beam radiation incident on the collector from the hourly total radiation on a horizontal surface. Second, changes were made to account for the end losses as a function of the incidence angle of the beam radiation.

I. Radiation Conversion

Hourly values of the total radiation on a horizontal surface are the only data available from the weather station at Columbia, Missouri. (Columbia, Missouri Radiation data was the best data representative of Lawrence, Kansas, the location of the dehydrator.) Values of the beam radiation incident on the focusing collector were derived from the available data by a four step conversion process. First, the beam radiation on a horizontal surface was derived from the total radiation on a horizontal surface. Second, the direct normal radiation was derived from the beam radiation on a horizontal surface. Third, the beam radiation on the focusing collector was derived from the direct normal radiation. Finally, because in some instances the hourly values of radiation on the focusing collector were above the solar constant, during the early morning and late afternoon hours, it was necessary to add a correction factor using clear day data. The four steps of this conversion are described below.

Step 1. The beam radiation on a horizontal surface is calculated from relationships given by Liu and Jordan.^{1/} The only data required for this calculation are hourly values of the total radiation on a horizontal surface. Using the Liu and Jordan relationships,

$$HD = HT (1.0045 + (2.6313 HT/HEX - 3.5227) HT/HEX + 0.04349) HT/HEX \quad (1)$$

$$\text{and} \quad HB = HT - HD \quad (2)$$

where

HT = the intensity of total radiation on a horizontal surface,
 HD = the intensity of diffuse radiation on a horizontal surface,
 HB = the intensity of beam radiation on a horizontal surface,
 HEX = the intensity of extraterrestrial radiation on a horizontal surface.

^{1/} Liu and Jordan, Solar Energy, IV, November 3, 1960.

Step 2. Hourly values of direct normal radiation can be derived from the hourly values of the beam radiation on a horizontal surface. Figure H-1 shows a surface normal to the incident radiation and a horizontal surface. θ_z is the zenith angle, the angle between the normal to the horizontal surface and a vector pointing toward the sun. θ_z is also the angle between the two surfaces because the angle between the normals to two surfaces is the same as the angle between the surfaces themselves.

The intensity of beam radiation on a surface normal to the incident radiation is equal to the intensity of beam radiation incident on a horizontal surface, divided by the cosine of the zenith angle. Thus:

$$HDN = \frac{HB}{\cos \theta_z} \quad (3)$$

where HD = the intensity of the direct normal radiation.

Step 3. The beam radiation on the focusing collector can be derived from the direct normal radiation. Figure H-2 shows a cross section of the focusing collector. A vector normal to the plane tangent to the apex of the reflector and passing through the collector tube, and a vector from the apex of the reflector pointing toward the sun are drawn on the figure. East-west tracking insures that the vector pointing toward the sun always passes through the collector tube. In other words, the collector is always in focus. However, there can still exist an angle Delta between the incident radiation and the collector plane because there is only one axis tracking. Delta is defined as a function of the latitude, declination and the hour angle by Duffie and Beckman:^{1/}

$$\Delta = \cos^{-1} [(\sin \phi \sin \delta + \cos \phi \cos \delta \cos \omega)^2 + \cos^2 \delta \sin^2 \omega]^{1/2} \quad (4)$$

where

ϕ = the latitude,

δ = the declination,

ω = the hour angle (15° for each hour from solar noon with mornings positive and afternoons negative).

As shown in Figure H-3, the vector pointing toward the sun is normal to the surface on which the direct normal radiation is defined. The plane of the collector is therefore tilted at an angle Delta with respect to the direct normal surface because Delta is the angle between the normals of these two surfaces.

^{1/} Duffie and Beckman, Solar Thermal Processes, John Wiley and Sons, New York, p. 185 (1974).

Figure H-1 - Angle Between Horizontal Surface and
Direct Normal Surface

Figure H-2 - Cross Section of Focusing Collector

Figure H-3 - Angle Between Direct Normal Surface and Surface Tangent to the Apex of the Reflector

Referring to Figure H-3 and using an argument similar to the one used in Step 2, the intensity of the beam radiation on the collector aperture is equal to the intensity of the direct normal radiation times the cosine of delta or

$$HC = HCN (\cos \Delta) \quad (5)$$

where HC = the intensity of beam radiation on the plane of the collector.

Hourly values of HC can be expressed as a function of hourly values of the total radiation on a horizontal surface (HT), the solar constant (HEX), the zenith angle (θ_z), the latitude (ϕ), the declination (δ), and the hour angle (ω). All of these parameters are defined in the TRNSYS program and can be calculated in the program. Modifying the TRNSYS program to calculate HC enables the calculation of hourly values of the beam radiation on a horizontally mounted, north-south oriented focusing collector from data for the total radiation on a horizontal surface. HC is used as the incident radiation in all TRNSYS simulations of the focusing collector. HT, HB and HC from the modified TRNSYS program are shown graphically in Figure 4 for June 21 at a latitude of 40° north.

Step 4. Because in some instances, use of the Liu and Jordan relationship data resulted in values of HC well above the solar constant, it was necessary to introduce a correction factor. Average values over the dehydration season of the clear day direct normal radiation at 40° north latitude for the hours of 6 a.m., 7 a.m., 8 a.m., 4 p.m., 5 p.m., and 6 p.m. were entered into the program. These values are shown in Table H-I. A statement was added which said that HC at any of these hours could not be greater than the corresponding value of the average hourly direct normal radiation (HCN), times the cosin of Delta.

TABLE H-I

AVERAGE OVER DEHYDRATION SEASON, HOURLY, CLEAR DAY, DIRECT
NORMAL RADIATION AT 40° NORTH LATITUDE

<u>Time of Day</u>	<u>Average Radiation (btu/ft²-Hr)</u>
6 a.m., 6 p.m.	116
7 a.m., 5 p.m.	154
8 a.m., 4 p.m.	211

Figure H-4 - TRNSYS Output Showing Radiation Conversion for Focusing Collector

II. End Loss Correction

For some values of Delta in Figure H-2, part of the collector tube will not be illuminated. The TRNSYS program has been modified to account for these end losses. Correction for end losses was made for two Hexcel collectors mounted in series. This represents the actual layout of the focusing collectors in the array. The incident radiation on the focusing collector is adjusted by the ratio of the unshaded length of the absorber to the total length of the reflector, so that

$$HC' = HC \left(\frac{X_H}{L_R} \right) \quad (7)$$

where HC = the intensity of beam radiation on the collector adjusted for end losses,

X_H = unshaded length of absorber,

L_R = length of reflector.

The unshaded length of the absorber is calculated using the method outlined in the SOLSYS manual developed at Sandia Laboratories.^{1/} X_H is a function of Delta and the collector geometry. As shown in the SOLSYS manual, there are three cases for determining X_H :

$$1. \quad L_C \geq L_R + 2L_F \tan |\Delta|,$$

$$X_H = L_R$$

$$2. \quad 2L_F \tan |\Delta| - L_R \leq L_C < L_R + 2L_F \tan |\Delta| \quad (8)$$

$$X_H = \frac{L_C + L_R}{2} - L_F \tan \Delta$$

$$3. \quad L_C < 2L_F \tan |\Delta| - L_R$$
$$X_H = 0$$

where L_R = length of reflector,

L_F = focal length of solar collector.

Values for Delta are calculated using equation (4). Although this equation is different than the equation given for Delta in the SOLSYS manual, it was verified that the two equations result in the same angle. The SOLSYS angle

^{1/} Edenburn, M. W. and N. R. Grandjean, Energy System Simulation Computer Program - SOLSYS (SAND 75-0048), Sandia Laboratories, Albuquerque, New Mexico, pp. 1.2-16 - 1.2-18 (1975).

is given in terms of the azimuth angle and the elevation angle while the Duffie and Beckman angle is given in terms of the latitude, declination and hour angle. These two equations are merely different expressions for the same angle.

Substituting the dimensions of two Hexcel collectors mounted in series into equation (8), $L_R = 38$ ft, $L_C = 39$ ft, $F = 3.0$ ft, yields the conditions and equation necessary to determine X_H :

$$1. 0.1667 \geq \tan |\Delta|$$

$$X_H = 38 \text{ ft}$$

$$2. \tan |\Delta| \leq 12.8333$$

$$\tan |\Delta| > .1667$$

$$X_H = 38.5 - 3 \tan \Delta \quad (9)$$

$$3. 0.1667 \geq \tan |\Delta|$$

$$X_H = 0$$

Substituting the appropriate values for X_H , L_R , and H_C , into equation (7) yields hourly values for the intensity of the beam radiation on the collector, adjusted for end losses.

The modifications as described above have been entered into the TRNSYS program to allow simulation of the performance of the north-south oriented, parabolic, concentrating collector as well as the flat plate collector.

APPENDIX I

INSTRUMENTATION FOR ALFALFA DEHYDRATION SYSTEM

The basic system to be monitored is shown below.

Figure A - Alfalfa Dehydration System

INSTRUMENTATION FOR ALFALFA DEHYDRATION SYSTEM

I. SYSTEM DESCRIPTION

The instrumentation and data acquisition system originally designed around an ERDA-supplied Site Data Acquisition System (SDAS) has been re-designed to comply with ERDA's recent request to Midwest Research Institute. The new system has no SDAS, but is structured on a stand-alone basis to serve the various requirements of the project. The sensors remain unchanged, to allow the option of future SDAS installation. The new Data Acquisition System (DAS) will serve four basic functions:

1. Troubleshoot solar system hardware performance in Phase II.
2. Perform heat balance analysis for verification of solar system performance versus predicted performance in Phase II.
3. Monitor, record, and analyze solar system performance in Phase III.
4. Perform energy analysis and quantitative comparisons with non-solar alfalfa dehydrators (Phase III).

The total system is technically comprised of both the on-site equipment and the computing facilities available at Midwest Research Institute (MRI), in the central offices in Kansas City, Missouri. The equipment located at the alfalfa dehydration site consists of a Doric Digitrend 220 Datalogger (with options), peripherals for hard copies of the data, and the associated sensors for converting the solar system parameters into electrical quantities. This equipment structure is simple, reliable, and cost effective. It serves the aforementioned functions in addition to providing a visual display of the system parameters.

II. SYSTEM PARAMETERS AND RELATIONSHIPS

Figure I-1 depicts the basic solar system and alfalfa dehydrators. The black dots represent sensors, using the following symbol convention.

T's = Temperature measuring sensors
H's = Solar radiation measuring sensors
P's = Pressure measuring sensors
G's = Natural gas consumption sensors
M = Mass flow sensor
Hm = Relative humidity sensor
W = Windspeed sensor
D = Wind direction sensor

The outputs from this program consist of a number of graphs, charts, etc., to fully characterize the system performance. The exact number and types of outputs will be finalized with ERDA monitors prior to submission of the phase III proposal.

IV. SYSTEM COST

The system costs are tabulated in Table A. These costs do not include the computer costs, only the on-site equipment costs.

TABLE I-I

INSTRUMENTATION COSTS FOR
COMMERCIALLY AVAILABLE MONITORING SYSTEM

Sensors	\$ 8,972.85
Datalogger	
40 Point Mainframe	5,250.00
Point Function Select & Skip Pinboard	895.00
High Sensitivity Option	450.00
High Speed A/D Conversion	695.00
Hours Timer/Intervalometer	100.00
PROM	495.00
Dust Cover	160.00
Interface Card for Paper Tape	995.00
Paper Tape Perforator	1,995.00
Paper Tape	86.00
Paper for Internal Printer	165.00
Installation	<u>4,480.99</u>
Total:	\$24,739.84

Figure A - Alfalfa Dehydration System

The solar radiation incident on the collectors is measured by the "H" sensors. For the flat plate collectors, H_1 directly measures the total solar radiation per unit area in the collector plane. For the focusing collectors, two measurements are necessary, since focusing collectors capture only the direct radiation. Both sensors are mounted to track the plane of the focusing collectors. H_2 measures the diffuse solar radiation per unit area, and H_3 measures the total solar radiation per unit area. $H_3 - H_2$ is the direct (or beam) component of the total radiation. The total collectable energy incident on the collector array is given by:

$$QT = (H_1 + H_D) A_p + (H_3 - H_2) \text{ BTU/hour}$$

where $H_3 - H_2$ = Direct (beam) radiation per square foot in the focusing collector plane.

H_1 = Diffuse radiation per square foot in the flat-plate collector plane.

A_p = Flat plate collector area, in square feet

A_f = Focusing collector area, in square feet

The solar radiation measurements are automatically logged once a minute, considerably more often than the other parameters. This allows averaging, or integration, of the solar radiation, to obtain a more accurate computation of the incident radiation over a given time interval. For example, if the other parameters are logged every half hour, the solar radiation information to use with that set of data could be given by

$$H_{avg} = \frac{\sum_{i=1}^{30} H_i \Delta t}{T}$$

where H_i = the solar radiation recorded at the i^{th} logging

Δt = the time between successive loggings (1 minute)

ΔT = the time interval of consideration (30 minutes)

Part of the solar radiation is captured by the collectors, the other portion being the collector losses. The amount of useful energy captured may be modeled by the equation

$$Q_u = \dot{m} C_p (T_o - T_i)$$

where $\dot{m}$ = The mass flow rate of the collecting media (air flowing through the collectors)

C_p = The specific heat of the collecting media

T_o = The temperature of the collector outlet

T_i = The temperature of the collector inlet

C_p is actually dependent on several factors, such as relative humidity, temperature, pressure, etc. It may be accurately computed by mathematical equations, or estimated to a reasonable degree of accuracy by using an average value.

The focusing collectors have adjustment dampers at the outlets, to allow the adjustment of equal mass flow through all of the collectors. This feature permits a simplification in modeling the collectors. The flat plate collectors may be regarded as one large collector whose outlet temperature is the average of the five outlet temperatures actually measured (T_1 - T_5). Alternately, each outlet temperature sensor can represent the outlet temperature of the seven or eight collectors (a section) adjacent to it, and the contributions from each section summed. The focusing collectors have a temperature sensor at each outlet (for calibration of the mass flow distribution). They may be treated in a fashion similar to that of the flat plate collectors, or summed individually.

The heated air from the collectors travels through the air duct to the burner plenum. The air flow (M_1) is measured at a point of non-turbulence, along with pressure (P_2) and temperature (T_{25}) in the air duct. This air velocity is corrected for temperature and pressure to yield standard mass flow (standard $\text{ft}^3/\text{minute}$) by applying an equation of the form

$$V = V_o * \left(\frac{K_1}{K_2} \right) * \left(\frac{C_1}{C_2} \right)$$

where V = the corrected velocity

V_o = The velocity under the standard conditions

K_1 , K_2 , C_1 , C_2 are correction factors which may be extracted from tables or calculated from gas laws.

The total energy that may be theoretically extracted from this air flow, assuming that the air returns to ambient temperature after releasing the energy, is given by:

$$Q_E = \dot{v} \rho C_p (T_o - T_a) \text{ BTU/hour}$$

where $\dot{v}$ = The volumetric flow rate, in standard ft^3/hour

ρ = The density of air at standard conditions, lb/ft^3

C_p = The specific heat of the air $\text{BTU}/\text{lb}-^\circ\text{F}$

T_o = The air duct temperature, $^\circ\text{F}$

T_a = Ambient temperature, $^\circ\text{F}$

Again, C_p is dependent on relative humidity, temperature, and pressure, and may be vigorously computed or estimated by assigning an average value.

The air flows from the air duct into the burner plenum, where it supplements one of the rotary gas dryers with preheated air. The other rotary dryer operates only from gas. Both of the rotary dryer gas supplies are metered and recorded daily by on-site personnel. The number of hours per day that each dryer operates is also recorded. This allows correlations between gas consumptions for the two dryers to be evaluated.

III. SOLAR SYSTEM EVALUATION WITH THE DAS

There are two basic modes of operation of the aggregate DAS. The first mode is for troubleshooting, debugging, and rough evaluation of the solar system in Phase II. The second mode is for the heat balance analysis, monitoring and recording, energy balance analysis, and comparison with non-solar dehydrators required in Phase III.

The first mode uses the on-site equipment and a hand-held programmable calculator, such as the Texas Instruments SR52. The purpose of this mode is to verify basic system performance and hardware compatibility. This may be done using approximations and short cut techniques. The actual procedure is subject to modifications and improvements, but a typical sequence could be:

1. Turn on the system, allow to stabilize.
2. Check system visually and audibly for any obvious problems.
3. Equalize mass flow rates through collectors by adjusting the dampers.
4. Turn on Datalogger system.
5. Check for Datalogger indications of malfunctioning sensors. If so, repair.
6. Activate "single scan" button on Datalogger, obtain printout of all sensor readings.
7. Using programmable calculator, which has been previously programmed for this event, compute the following.
 - a. From readings M_1 , T_{25} , P_2 , HM_1 , and T_{26} , compute Q_E (energy extractable from air duct).
 - b. From the readings $H_1 - H_3$, compute the total solar energy incident on the collector array.
 - c. From this and Q_E , compute the average efficiency of the collector array. Compare this with collector specification curves under the present conditions of collector temperatures, ambient temperatures, and insolation.
 - d. Examine the individual collector temperature sensors for differences. Look for thermal gradients that indicate air leakage, stoppage, etc.

8. Pursue any apparent abnormalities by further detailed investigation of affected areas.

The second mode of operation is necessarily a more detailed mode. For this operation, the data for all of the system parameters are logged periodically, and punched on a paper tape peripheral. This paper tape is collected once a week and brought to the main MRI facilities in Kansas City, Missouri. Here the paper tape is fed into a reader, and into one of a number of possibilities of computer systems. CDC 6500, CDC 6600, UNIVAC 1108, IBM 370, etc., are some examples.

The computer program that manipulates this data is run weekly. It does a number of operations on the data. Some of these are:

1. Integrates the solar radiation data over half hour intervals to provide insolation information.
2. Computes accurate correction factors for the specific heat of air, based on the associated conditions.
3. Models collectors by averaging or other temperature techniques. Flat plate and focusing collectors are treated separately.
4. Tabulates collector efficiencies and losses.
5. Tabulates useful energy delivered through the air duct, in addition to thermal losses.
6. Computes gas consumption in solar-supplemented and stand-alone rotary dryers. This data is correlated with (5) to yield dryer process efficiencies.
7. Tabulates environmental conditions (ambient temperature, pressure, humidity, windspeed and direction, etc.) to correlate their effect on system performance.
8. Performs heat balance analysis to show where all energy losses occur.
9. Draws correlations on gas consumption reductions with varying climatological conditions.
10. Updates a permanent data file.

The outputs from this program consist of a number of graphs, charts, etc., to fully characterize the system performance. The exact number of types of outputs will be finalized with ERDA monitors prior to submission of the phase III proposal.

IV. SYSTEM COST

The system costs are tabulated in Table A. These costs do not include the computer costs, only the on-site equipment costs.

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Hours Timer/Intervalometer	100.00
PROM	495.00
Dust Cover	160.00
Interface Card for Paper Tape	995.00
Paper Tape Perforator	1,995.00
Paper Tape	86.00
Paper for Internal Printer	165.00
Installation	<u>4,480.99</u>
Total:	\$24,739.84

APPENDIX J

EFFECT OF SOLAR HEATING ON NATURAL GAS CONSUMPTION
DURING ALFALFA DRYING

EFFECT OF SOLAR HEATING ON NATURAL GAS CONSUMPTION DURING ALFALFA DRYING

One of the decisions that must be reached concerning the use of solar energy for the dehydration of alfalfa is the amount of air preheating that is most cost-effective. The following analysis was prepared in order to demonstrate that increasing the inlet air temperature reduces the consumption of natural gas in a linear manner. In addition, the partial pressure of water in the inlet gas to the dryer was determined as a function of the inlet air temperature.

For the purpose of this analysis, it was assumed that the natural gas consisted entirely of methane (CH_4). The reaction of methane with oxygen produces both carbon dioxide and water.

The heat of formation for these elements indicates that 345,165 Btus are released for every lbmole of methane consumed.

Solar Air Preheating System

The dehydration of alfalfa using a combination of both methane combustion and solar air preheating consists of many components in actual practice: solar collectors, tracking mechanism (if required), piping, combustion chamber, etc. However, for the purposes of this analysis, it is only necessary to define the variables shown in Figure J-1.

Air that has been preheated using solar collectors can be used in conjunction with energy from the combustion of methane. For any desired energy output of the combustion chamber (E_{out}) and for a desired outlet temperature (T_{out}), it is possible to determine the amount of air to be preheated, and the temperature of preheating. In all cases the references baseline for energy content is 60°F (ambient air temperature).

Reduction in Methane Consumption

The basis for the following analysis is to provide the equivalent heat of burning of sufficient methane to obtain the desired energy output of the combustion chamber (to the dryer). As explained previously, this energy release is accomplished by a combination of air preheating and methane combustion. Obviously, as the incoming air temperature is increased, the amount of methane required is reduced. Thermodynamic first law principles dictate that whatever energy is added by solar preheating does not need to be supplied by methane combustion. Engineering principles modify this by taking into account heat and pressure losses in the transported air. The following analysis considers only the thermodynamic aspects.

Figure J-1 - Solar Air Preheated Alfalfa
Dehydration Schematic

For any desired E_{out} and T_{out} there remains three undefined variables: the amount of methane consumed, the amount of preheated air required, and the temperature of the preheated air. (The latter variable can also be expressed as an amount of excess air required for any given preheat air temperature.) The three equations used to determine these unknowns are:

1. Mass balance on the air.
2. Energy balance on the overall system.
3. Energy balance on the gases leaving the combustion chamber.

In quantitative terms, the above mass and energy balances are reduced to equations 2 through 4.

$$\dot{M}_{air\ in} = \dot{M}_{excess\ air} + \dot{M}_{air\ reacting\ with\ methane} \quad (2)$$

$$E_{out} = E_{combustion} + E_{solar\ heat} \quad (3)$$

$$E_{out} = \sum_{\substack{\text{reaction} \\ \text{products}_i}} \dot{M}_i C_{p_i} dT + \dot{M}_{excess\ air} C_{p_{air}} dT \quad (4)$$

After some manipulation the above equations can be expressed in the following terms.

$$\dot{M}_{air\ in} = \dot{M}_{excess\ air} + \frac{2}{0.21} f \dot{M}_{CH_4} \quad (5)$$

$$E_{out} = f \dot{M}_{CH_4} (345,165 \frac{Btu}{lbmole}) + \dot{M}_{air\ in} [H_{air-1} \quad (6)$$

$$+ H_{H_2O-1} (\frac{0.159313}{18.01534})] - f \dot{M}_{CH_4} H_{CH_4}$$

$$E_{out} = f \dot{M}_{CH_4} \left[H_{CO_2} + \frac{52}{7} H_{N_2} + \frac{2}{21} H_{Ar} + 2 H_{H_2O-2} \right] \quad (7)$$

$$+ \left(\frac{0.159313}{18.01534} \right) \dot{M}_{air, in} H_{H_2O-2} + \dot{M}_{excess, air} H_{air-2}$$

If values are known for E_{out} and T_{out} , all of the variables are defined for any value of T_{air} except $\dot{M}_{air, in}$, $\dot{M}_{excess, air}$, $f \dot{M}_{CH_4}$. All of the enthalpy data was based on the equations for specific heats as shown in Table J-I.

Results of the Analysis

The results of the analysis of the effect of preheating air using solar energy are presented in Figures J-2, 3 and 4. Figure J-2 illustrates the linear decrease in the consumption of methane per unit energy output as a function of the solar air preheating temperature. Although the slope of the line varies with the temperature of the gas leaving the combustion chamber, it is linear in each case.

The amount of air passing through the solar air heater per unit energy output is presented as a function of solar air preheating temperature in Figure J-3. Again, the results are linear, although relatively constant. The unchanging values reflect the fact that the amount of excess air passing through the combustion chamber greatly exceeds the air required for combustion with the methane. [For example, at an outlet temperature of 1,000°F and a solar air preheat temperature of 500°F, the ratio of air to methane is approximately 150:1.]

The amount of excess air passing through the combustion chamber is shown as a function of the solar air preheat temperature in Figure J-4. These values of excess air illustrate that, although the total amount of air passing through the system may be relatively constant, the amount of air required for combustion is not constant. Therefore, the percentage of excess air increases rapidly as the temperature of the solar air preheat increases.

Partial Pressure of Water Vapor In Gas Mixture

The partial pressure of the water vapor in the gas mixture leaving the combustion chamber (entering the dryer) is determined by the mole fraction of water in the stream. Ambient air at a temperature of 60°F and a relative humidity of 50% was assumed, although the amount of water present in the incoming air proved to be a small percentage of the total water in the gas mixture to the dryer. Therefore, the relationship between the partial pressure of the water and the solar air preheat temperature is essentially linear. Figure J-5 presents the results of this calculation.

TABLE J-I

SPECIFIC HEATS AS A FUNCTION OF TEMPERATURE

<u>Component</u>	<u>Specific Heat (Btu/lb-°R), Cp</u>	<u>Ref.</u>
CH ₄	$0.333 + 3.983 \times 10^{-4} T^*$	1
CO ₂	$0.234 + 3.46 \times 10^{-5} T - 14393/T^2$	1
N ₂	$0.232 + 1.98 \times 10^{-5} T$	1
Ar	0.124	1
H ₂ O	$0.456 + 4.6 \times 10^{-6} T - 2.4 \times 10^{-7}/T^2$	1
air**	$7.2926 - 1.4963 \times 10^{-3} T + 1.9260 \times 10^{-6} T^2$ $- 5.1838 \times 10^{-10} T^3 + 5.7471 \times 10^{-15} T^4$	2

* T = Temperature, °R = °F + 459.69

** Specific heat of air is expressed in Btu/lbmole °R

References

1. "A Theoretical Analysis of Rotary Alfalfa Drying,"
Air Resources, Inc., October 1975.
2. Based on NBS Circ. 564 Tables.

Figure J-2 - Gas Consumption as a Function of Solar Air Preheat Temperature

Figure J-3 - Air Usage as a Function of Solar Air Preheat Temperature

Figure J-4 - Excess Air Usage as a Function of Solar Air Preheat Temperature

Figure J-5 - Partial Pressure of Water Vapor in Gas Leaving the Combustion Chamber as a Function of Solar Air Preheat Temperature

Nomenclature

- E_{out} = Energy leaving the combustion chamber, Btus/hr.
- $\dot{M}_{air\ in}$ = Amount of air entering the solar preheater, lbmoles/hr.
- $\dot{M}_{excess\ air}$ = Amount of air leaving the combustion chamber, lbmoles/hr.
- $\dot{M}_{CH_4}$ = Amount of methane consumed, lbmoles/hr.
- f = Fraction of methane required relative to the case where no solar preheating is done.
- H_{air-1} = Enthalpy change to raise air from ambient temperature to T_{air} , Btus/lbmole.
- H_{air-2} = Enthalpy change to raise air from T_{air} to T_{out} , Btus/lbmole.
- H_{H_2O-1} = Enthalpy change to raise water vapor from ambient temperature to T_{air} , Btus/lbmole.
- H_{H_2O-2} = Enthalpy change to raise water vapor from T_{air} to T_{out} , Btus/lbmole.
- H_{CO_2} = Enthalpy change to raise carbon dioxide from ambient temperature to T_{out} , Btus/lbmole.
- H_{N_2} = Enthalpy change to raise nitrogen from ambient temperature to T_{out} , Btus/lbmole.
- H_{Ar} = Enthalpy change to raise argon from ambient temperature to T_{out} , Btus/lbmole.
- H_{CH_4} = Enthalpy change to raise methane from ambient temperature to T_{air} , Btus/lbmole.
- T_{air} = Temperature of solar preheated air, °F.