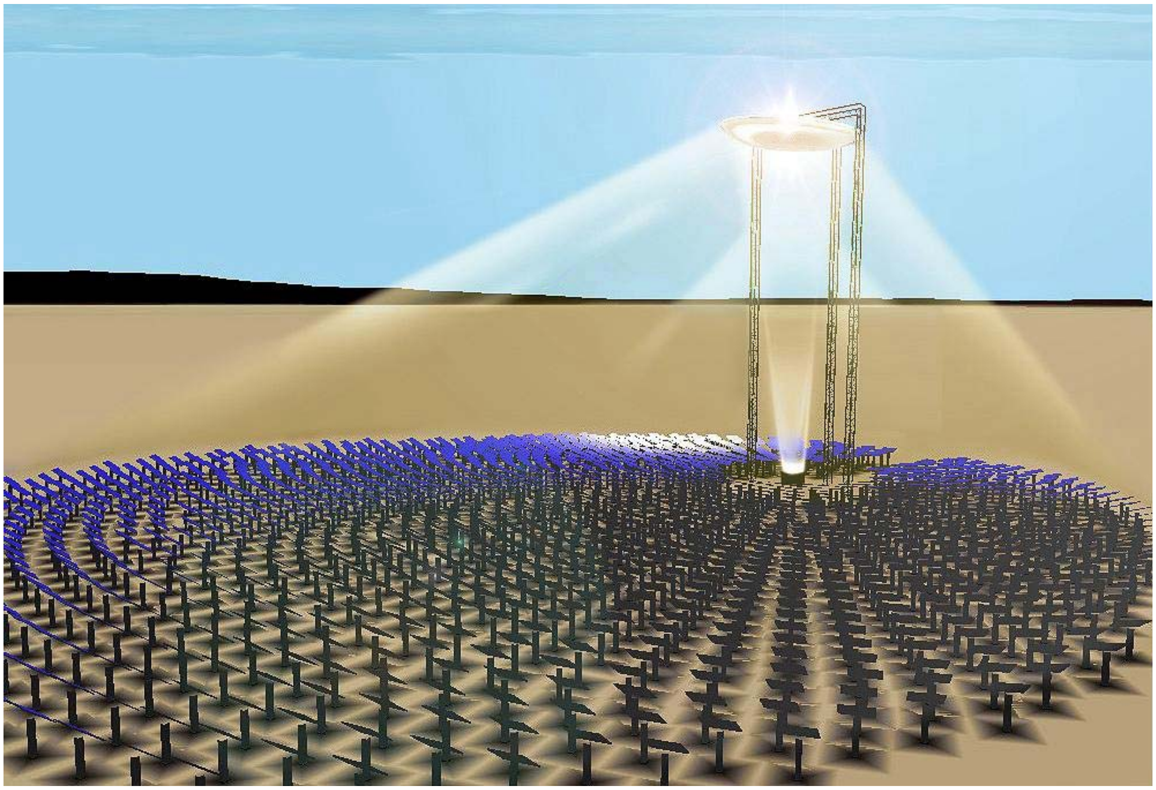
Final Report

Tri-Lateral Noor al Salaam High Concentration Solar Central Receiver Program

James B. Blackmon
Research Professor
Propulsion Research Center
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
Huntsville, Alabama

March 2008



Conducted under DOE Grant Number DE-FC36-02GO12030
NOOR AL SALAAM PROJECT
DOE Golden Field Office
Golden, Colorado
Beth H. Dwyer
Contract Officer

Final Report

Tri-Lateral Noor al Salaam High Concentration Solar Central Receiver Program

James B. Blackmon
Research Professor
Propulsion Research Center
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
Huntsville, Alabama

March 2008

ABSTRACT

This report documents the efforts conducted primarily under the Noor al Salaam ("Light of Peace") program under DOE GRANT NUMBER DE-FC36-02GO12030, together with relevant technical results from a closely related technology development effort, the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver program. These efforts involved preliminary design, development, and test of selected prototype power production subsystems and documentation of an initial version of the system definition for a high concentration solar hybrid/gas electrical power plant to be built in Zaafarana, Egypt as a first step in planned commercialization. A major part of the planned work was halted in 2007 with an amendment in October 2007 requiring that we complete the technical effort by December 31, 2007 and provide a final report to DOE within the following 90 days. This document summarizes the work conducted.

The USISTF program was a 50/50 cost-shared program supported by the Department of Commerce through the U.S./Israel Science and Technology Commission (USISTC). The USISTC was cooperatively developed by President Clinton and the late Prime Minister Rabin of Israel "to encourage technological collaboration" and "support peace in the Middle East through economic development". The program was conducted as a follow-on effort to Israel's Magnet/CONSOLAR Program, which was an advanced development effort to design, fabricate, and test a solar central receiver and secondary optics for a "beam down" central receiver concept. The status of these hardware development programs is reviewed, since they form the basis for the Noor al Salaam program. Descriptions are provided of the integrated system and the major subsystems, including the heliostat, the high temperature air receiver, the power conversion unit, tower and tower reflector, compound parabolic concentrator, and the master control system. One objective of the USISTF program was to conduct marketing research, identify opportunities for use of this technology, and to the extent possible, secure an agreement leading to a pre-commercialization demonstration or prototype plant. This was accomplished with the agreement to conduct the Noor al Salaam program as a tri-lateral project between Egypt, Israel, and the U.S.

The tri-lateral project was led by the University of Alabama in Huntsville (UAH); this included the Egyptian New and Renewable Energy Authority and the Israeli USISTC participants. This project, known was Noor al Salaam, was funded by the U.S. Agency for

International Development (USAID) through the Department of Energy (DOE). The Egyptian activity was under the auspices of the Egyptian Ministry of Energy and Electricity, New and Renewable Energy Authority (NREA) as part of Egypt's plans for renewable energy development. The objective of the Noor al Salaam project was to develop the conditions necessary to obtain funding and construct and operate an approximately 10 to 20 Megawatt hybrid solar/natural gas demonstration power plant in Zaafarana, Egypt that could serve both as a test bed for advanced solar technology evaluations, and as a forerunner to commercial plant designs. This plant, termed Noor Al Salaam, or “Light of Peace”, reached the initial phase of system definition before being curtailed, in part by changes in USAID objectives, coupled with various delays that were beyond the scope of the program to resolve. The background of the USISTF technology development and pre-commercialization effort is provided in this report, together with documentation of the technology developments conducted under the Noor al Salaam program. It should be noted that only a relatively small part of the Noor al Salaam funding was expended over the approximately five years for which UAH was prime contractor before the program was ordered closed (**Reference 1**) so that the remaining funds could be returned to USAID.

INTRODUCTION

In February 1995, the U.S.-Israel Science and Technology Commission (USISTC) selected the team of McDonnell Douglas Aerospace (now a wholly owned subsidiary of The Boeing Company), Ormat Industries, Ltd, and Rotem Industries, Ltd. to develop an innovative, high efficiency, modular solar central receiver power generation system conceived by the Weizmann Institute of Science. The Weizmann Institute of Science (WIS) was a subcontractor to McDonnell Douglas for this effort. Advanced development and fundamental studies of this system were in development under the Israel MAGNET/ and CONSOLAR programs, with Ormat Industries, Ltd and Rotem Industries, Ltd as partners with the Weizmann Institute.

This system offered several technical innovations in solar power generation: (i) a modular design for plant output power ratings ranging from 100's kWe to multi-megawatts for both on-grid and off-grid or remote applications; (ii) “beam down” optics, with a tower-mounted reflector to redirect the solar flux from a field of heliostats to produce high solar concentrations at ground level; (iii) a quartz window volumetric solar receiver capable of supplying high-temperature, high-pressure air directly to a gas turbine, (iv) the ability to operate in a hybrid mode with fossil fuels; (v) compound parabolic concentrators to further concentrate the solar flux prior to entry into the receiver; and (vi) relatively small, low-cost heliostats that are needed for high optical efficiency and high solar flux concentrations at the tower reflector and entrance to the CPCs.

The goal under the USISTF program was to develop and have ready for demonstration and commercialization, solar central receiver power systems based on this new technology.

Major assemblies used for the USISTF integrated test series were provided by the wholly Israeli-funded CONSOLAR program, which was responsible for the development of (i) a very high temperature (1400 C), high pressure (20 atmospheres) air receiver; (ii) a moderate temperature air "peripheral heater" or "pre-heater"; (iii) the compound parabolic concentrator; and (iv) a tower mounted reflector. These assemblies were installed at the

Weizmann Institute of Science and a series of tests were conducted to determine their performance and validate the integrity of the receivers and CPC.

The USISTF product development program initially was for 42 months but was extended to 54 months to allow for completion of the CONSOLAR program, which required additional time to overcome technical challenges associated primarily with the receiver and high temperature piping. The majority of the effort under the USISTF program was ended in December, 2001. The USISTF program encompassed business development, systems engineering, hardware and software production, and subsystem and integrated system testing. The primary goals of this program were: 1) hardware verification of the major subsystems required to design and build central receiver plants (heliostat, receiver, optical path, and hybridized electrical power generation) and 2) acquisition of a customer commitment for an initial plant. A key test objective was operation of the integrated system for power production with a hybrid solar/gas turbine. However, the final tests of the combined hybrid solar/gas turbine were not conducted, although tests of the turbine were run with natural gas, and partial tests of the beam down system were conducted with the CPC and receiver subsystems. Results of these tests are not available at this time.

A System Definition program for a hybrid solar power demonstration plant in Egypt, based on the USISTF technology was then developed and funded, together with a companion program to have collaboration and training efforts conducted with Egyptian solar engineers and managers from NREA. This follow-on program, known as Noor al Salaam, was initially to be led by The Boeing Company, but in 2002, the University of Alabama in Huntsville (UAH) took on the prime contractor responsibilities after Boeing decided not to continue its participation. This program was to involve principals in Egypt and Israel to jointly determine the system design requirements, complete certain technology development tasks, determine the approximate costs and performance of the plant, and initiate the transition to plant construction in Egypt. The plant was to be approximately 10 to 20 Megawatts electric, with a 10 Megawatt thermal solar field as illustrated in **Figure 1**, planned for construction in Zaafarana, Egypt. It was later determined that this program required that a U.S. company serve as prime contractor to complete the Tri-Lateral system definition involving the Israeli and Egyptian organizations, with UAH. For a variety of reasons, covered in Appendix A, which were in part due to events and uncertainties in the Middle East, there was little opportunity to engage both the Israeli and Egyptian principals in this effort. For the remainder of the program, UAH conducted certain technology development tasks and worked with DOE to resolve contractual issues so that the program could move ahead. In August 2007, DOE and USAID determined that the program should be cancelled, due in part to changes in USAID priorities; we received an amendment in November 2007 that de-obligated the remaining funds and provided supplemental funds to complete a final report, together with a subcontract to analyze the optical characteristics of the system, which was already underway.

In the following, the status, system and subsystem design, and future applications of the system are discussed; much of this effort was done under the USISTF program, but parts of it were enhanced during the Noor al Salaam program. Various Appendices are provided for related technology development work, conducted primarily under the Noor al Salaam program, in part to prevent loss of the engineering information and bring the program to a close in accordance with DOE instructions while retaining as much of this information as possible. Copies of relevant DOE, USAID, and UAH documentation regarding contractual and programmatic issues related to this program are provided in **Appendix A**.

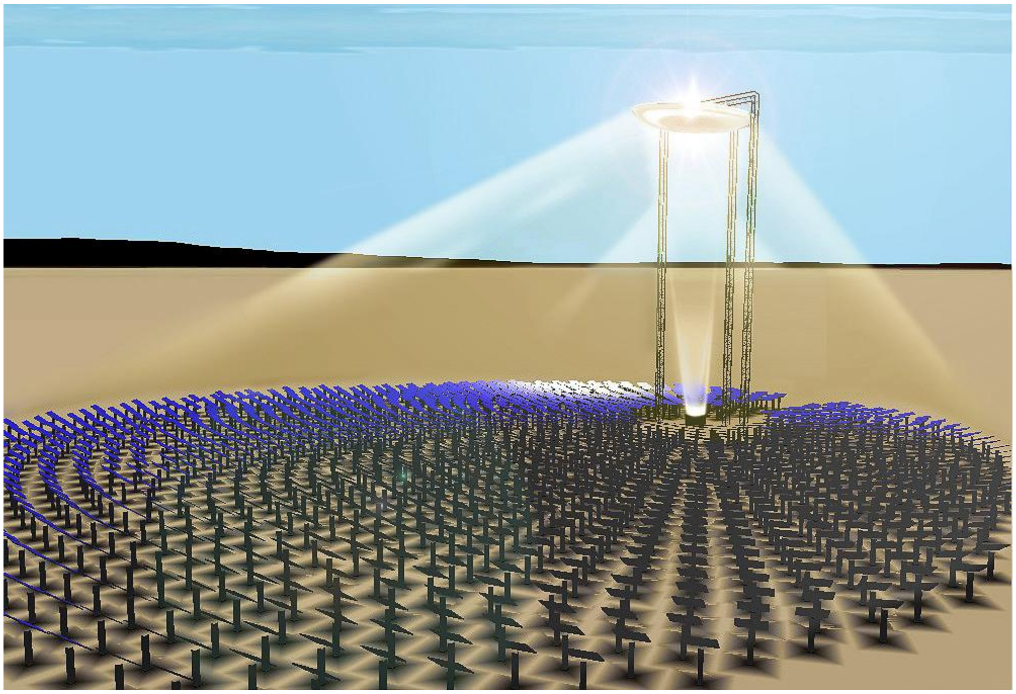


Figure 1- Joint U.S./Egypt/Israel Noor al Salaam High Concentration Solar Central Receiver Demonstration Plant-Zaafarana, Egypt

SYSTEM DESIGN

System Architecture:

The Noor al Salaam concept is illustrated in **Figure 1** for the 10 MW solar thermal power delivered by the heliostat field to the receiver subsystem**.** The basic system concept is covered in the Weizmann Institute patents of **References 2** through **4**. Sunlight from a field of heliostats is reflected to a tower-mounted reflector, which directs this light to a series of compound parabolic concentrators (CPCs) on the ground. There, the light is further concentrated and passes into a series of air receivers. Air from the compressor of a gas turbine flows through the receivers and is heated to moderate to high temperatures. The air then flows to the combustor of the turbine, where natural gas or bio-gas is used to further heat the mixture of air and combustion products prior to flow through the turbine for power production.

There are important potential cost and performance advantages to this system that are associated with the receiver and optics. The volumetric receiver concept (**Reference 4**) developed at the Weizmann Institute of Science and Rotem Industries offers the advantage of accommodating a wide range of incident power levels, temperatures, flow rates, and air pressures, with low pressure losses. By replicating the receiver and positioning multiples of these at the focal zone, with the CPCs, a wide range of power levels are achieved. This modularity also decreases cost, since unique, custom receivers are not needed for specific power levels or designs.

The primary air receivers use a cone shaped quartz window that is kept in compression over all operational conditions, thus reducing the risk fracture of the window by exceeding the ultimate tensile stress. Quartz has a higher compressive strength than conventional steel, and therefore this design concept can provide both high safety factors and efficient transfer of solar energy into the receiver, since the pressures and temperatures in the receiver can be quite high, which improves heat transfer to the air. The concentrated solar radiation is incident on high temperature ceramic fins; the air passes over these fins and is heated to high temperature, but with low flow losses. Reducing the flow losses decreases the loss of pressure ratio in the turbine, which improves turbine efficiency. This type of volumetric receiver can be operated at very high temperature (up to 1700 C in various tests at the Weizmann Institute), very high concentration (2000 to 10000 suns) and high efficiency in part because there is no intervening metal wall. With such direct impingement receivers, there are temperature drops across the pressure vessel wall. These receivers also have no volumetric heating of the air; for high heat transfer rates, high heat transfer coefficients and relatively high velocities are required, and this increases the pressure losses. The ability of the Weizmann volumetric receiver (termed “DIAPR”) to accommodate high temperatures and high concentration ratios, especially at high pressure (of the order of 20 atmospheres for typical turbine compressors) increases the power to volume ratio, which results in relatively small receivers for a given power rating. These relatively small receivers, with relatively simple ceramic walls and fins, supported by a relatively low temperature outer metal pressure vessel, coupled to the truncated cone quartz window can potentially have relatively low hardware cost. In addition, special high temperature metals are not required, and the high temperature ceramic interior can be built at relatively low cost and assembled easily.

The receiver couples to a conventional external burner gas turbine, since the temperatures achieved can be high, of the order of the turbine inlet temperature, and the low flow losses ensure that the turbine pressure ratio, and hence output power, incurs minimal loss. Gas turbines have become a dominant choice for new power generation since they offer high performance, low cost, ease of control for dispatching power as needed, and can be installed in relatively short periods of time. In addition, gas turbine technology continues to advance, with performance increases resulting from increased turbine temperatures possible with advanced materials. This solar receiver design can achieve the high temperatures required for advanced turbines in a solar-only mode, or it can be coupled with fossil fuel (natural gas, preferably) in a gas generator. The latter provides a high degree of operational versatility and higher overall system efficiency, and in principle can be retrofitted to existing gas turbine plants.

The air temperature and flow rate can be selected over a relatively wide range through design of the flow configuration of the piping to achieve optimum conditions for a particular application. Depending on the design approach selected, the high-pressure air from the compressor flows through the receivers in either a series flow path (for maximum outlet temperature) or a parallel flow path, which reduces pressure losses. With compressor outlet temperatures of the order of 300 C to 400 C, it is thus heated to temperatures of the order of 800 C to 1400 C. At these high temperatures, the air can be directly used by the turbine over a wide range of supplemental heating rates with gas to meet the inlet conditions for the turbine. The system can also be used in a stand-alone mode, with essentially no hybrid gas heating. The choice of air temperature is determined by the system design and turbine requirements, but the wide range of acceptable temperatures, coupled with a low pressure loss receiver, makes this approach suitable for integration with gas turbines or combined cycle gas turbines (CCGT), and for retrofits to existing CCGT systems. The aspect was treated in detail under the Noor al Salaam program. This analysis effort is presented in **Appendix B**. This analysis showed that the maximum performance for a hybrid system was achieved by having a flow path, in which the turbine compressor outflow was split such that the compressed air flowed through the outer, inner, and central receivers in a fully parallel path. This minimized the pressure and thermal losses. Since turbine efficiency is a strong function of pressure ratio, this approach, with its minimum flow loss, and with a lower temperature gas into the gas generator, had a theoretical advantage. There was also the practical advantage of dealing with lower temperature gases entering the gas generator. Therefore, no changes were required to conventional gas generators, as would be necessary for high temperature flows at the combustor.

For the near-term market, we selected a relatively large turbine with the majority of the annual energy provided by gas, compared to the solar input. This approach would be used in the Noor al Salaam power plant, in part to provide Egypt with the power needed in the vicinity of Zaafarana, and in part to keep the costs of the solar power system tractable. This hybrid approach provides a lower cost entry into the market since the specific cost of gas turbines decreases with increasing output power. It also offers a wide variety of market opportunities with the emphasis on gas turbine and combined cycle gas turbines (CCGTs) for power generation. The larger turbine improves the solar to electrical energy efficiency, since turbine efficiency increases with power output. It is also more practical for this system to first be constructed with a moderate size solar field, of the order of 10 Megawatts thermal output, to gain experience in system performance and operation before building larger systems. This approach had less risk, and was more likely to be funded, since the solar part of the cost would be lower than for a standalone system. Combining the gas fired system with the solar also allowed the system to come on line more rapidly, and this early use of the fossil powered system reduces the time to break even, and thus improves the return on investment, relative to the longer time required to bring the solar part of the plant on line. We also find that the relatively small solar annual energy fraction, compared to the annual energy from gas, improves the overall financial return for grid supplied, market priced electricity. However, there are other opportunities for solar stand-alone systems, especially in remote areas of developing countries, for which conventional power generation costs are high.

The basic concept of placing a relatively simple reflector on a tower was projected in prior studies to decrease costs associated with piping, valves, controls, and structure that are substantial for a conventional solar central receiver with the receiver mounted on the tower. It also eases the operations and maintenance operations, since the reflector concept is very simple, primarily requiring occasional cleaning. We determined that we can achieve high efficiency optical transfer of the concentrated light from the tower to the compound parabolic concentrators. Some of this work is covered in **Appendix C**, but due to the program being halted, this work could not be completed. The cost of the tower reflector support structure is relatively low, using commercially available geodesic dome structural members to form the required hyperbolic reflector shape (**Appendix D**), and we show that these costs can be more than fully offset by waste heat recovery for uses such as process heat, desalination, or power generation, such as with Organic Rankine Cycle (ORC) turbines.

A solar plant system architecture design was developed for a collector field, tower, tower mounted "beam down" reflector, CPC, and receiver array, and hybrid turbine. The collector field was sized to provide approximately 10 Megawatts thermal at solar noon on the Summer Solstice, for Barstow, CA. An example of a plant layout is shown in **Figure 2**. This plant size was selected in part because it was a reasonable size for demonstration plant applications, and in part because it would be able to use an array of air receivers based on the design developed as part of the CONSOLAR program, with essentially no modifications. The Barstow solar conditions were selected for convenience, and it allows comparison with other approaches that have been studied using that site, and it is representative of solar conditions in preferred locations. The optical aspects of the design were determining factors in the selection of the heliostat size, field layout, CPC size and geometry, tower height, and tower reflector size. The Weizmann WELSOL code was used, with various cost estimating relationships, to develop the essential plant characteristics. An animated graphical ray trace code, termed SolarSim, developed by HiTek Services, Inc. was then used to develop the field layout, for selected heliostat designs, as shown in **Figure 2**. SolarSim was also used to develop detailed flux distributions incident on the tower reflector and CPC aperture; these conditions were used to develop the prototype designs for these subsystems and to develop safe emergency shut down procedures. However, this approach was not a fully system optimization. Therefore, we developed a subcontract with HiTek, Tietronics, and the University of Houston's Professor Lorin Vant Hull to modify and conduct a total system optimization using cost estimating relationships applicable to the beam down central receiver concept. In part, this effort was conducted to ensure that the full optimization capability of RCELL would be available in the future, and that it could be applied to beam down solar power systems. This effort is covered in **Appendix E**.

Heliostat Design

The heliostat design effort conducted under the USISTF program was initiated with a number of programmatic constraints and design requirements. For example, there were time and budget constraints, since it was necessary to design, build, and deliver a heliostat in a relatively short period of time (approximately one year), with a very limited budget. The initial plan under the USISTF program was to build the McDonnell Douglas 57 m^2 heliostat, but for a number of reasons, we decided on a significantly smaller heliostat. From the optical analysis, it was determined that smaller heliostats were needed because conventional, large heliostats (greater than 40 to 50 square meters), had substantial off-axis aberration losses for this application, and thus required a significantly greater total reflector surface area. The heliostat size that provided the minimum total area and expected cost was determined to be in the range of approximately 10 to 20 square meters, based in part on the need for a high concentration ratio at the receiver and a moderately sized tower reflector.

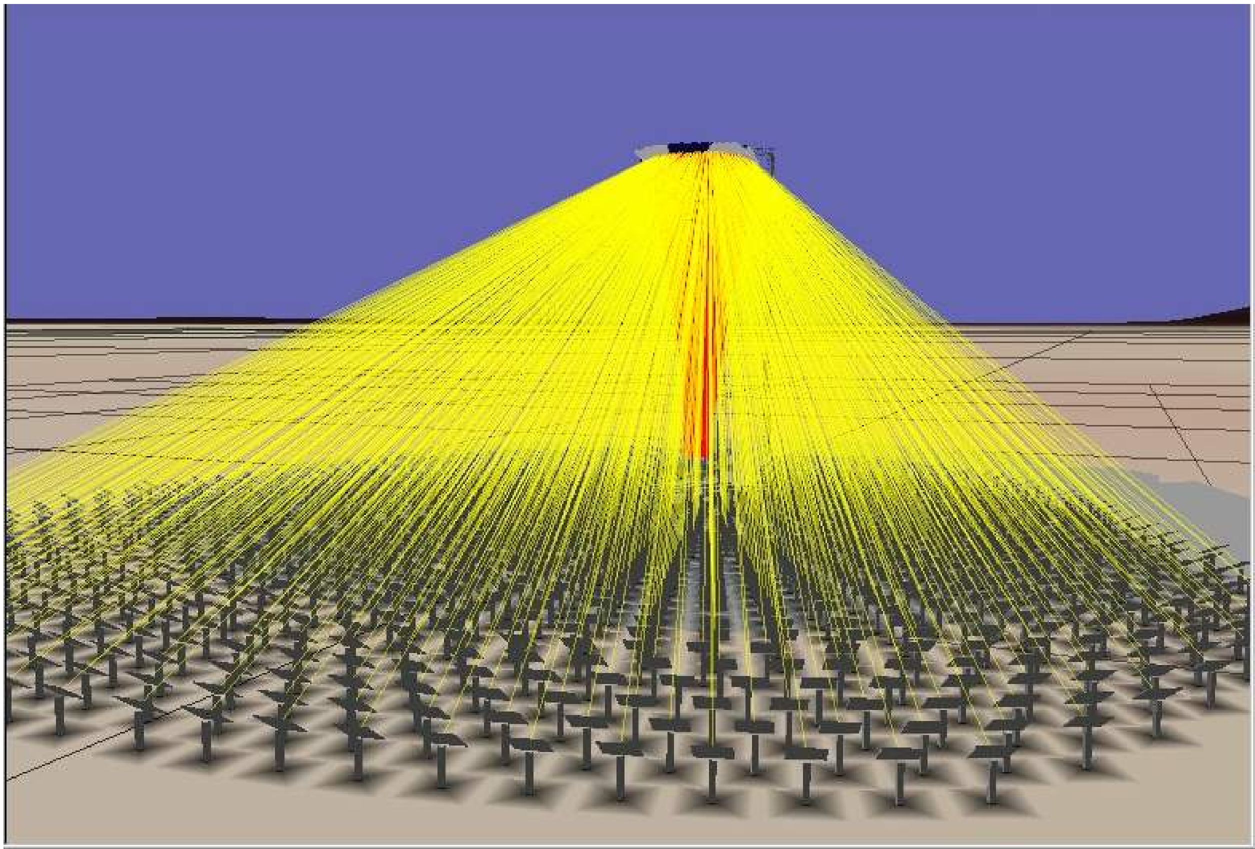


Figure 2 - 10 Megawatt (thermal) Solar Field-SolarSim Animated Graphics Ray Trace

Boeing, working with HiTech Services, Inc., developed an elevation/azimuth heliostat that can be sized between approximately 9 and 21 m^2, with readily available components, with the same basic drive unit. We selected a 9.2 m^2 heliostat area (**Figure 3**), because commercially available, low cost glass could be procured in sizes of approximately 5' by 5'; four of these formed the reflector. However, there were additional reasons for selecting this size, which departs from the trend over the last two decades to build larger heliostats, even as large as 100 to 150 m^2. Recent efforts at DOE for solar central receivers have continued to support large heliostats (**Reference 5**).

However, for the beam down optics system, we determined that there were advantages in terms of optical performance, cost, and development time. The optical performance is significantly better because the off-axis aberration is less, which is especially important for our system with its relatively small receivers and high flux intensity requirements. The drive unit did not require custom parts or a custom design, as would have been required for the larger heliostat, which would have had serious schedule and cost impacts. The larger production number for a given total field reflector area means that the Manufacturing Learning Curve effect should reduce production costs more quickly than with a fewer number of larger heliostats, especially since few custom components are required for the smaller heliostat. This learning curve effect provides a substantial theoretical cost savings. Assuming that the costs per unit area of the small and large heliostat are equal, the cost reduction was approximately 10 to 20%, compared to heliostats of the order of 60 to 100 m^2.

Assuming a 90% to 95% learning curve, the theoretical cost could be reduced by an additional 25% to 50%.

Also, our marketing studies showed that developing countries were projected to have the fastest growth of power in general, and renewable power in particular. We anticipate having heliostat manufacturing plants in these countries, to minimize import duties, taxes, customs issues, and transportation costs. Therefore, we needed a design that could be built in these countries, possibly even in relatively remote areas with limited access by road, with minimal capital investment. The smaller heliostat allowed use of lower cost tooling and a smaller, lower cost factory. Replicating the tooling, such as for the reflector tooling surfaces, would provide an additional benefit in terms of the Manufacturing Learning Curve effect, since this reduces the tooling costs more rapidly than with a fewer number of larger tools. It is also easier to handle the smaller heliostat for fabrication, shipping, installation, remove/replace, and certain types of maintenance (i.e., cleaning, which requires less complex and costly cleaning equipment for small heliostats). Some of this cost savings may be offset by maintenance operations that are relatively independent of size, since there are a larger number of heliostats, but maintenance costs occur throughout the life of the plant, and therefore their net present value is low relative to up-front capital costs. Overall, it was our conclusion that the smaller heliostat was more cost effective and appropriate for our application and for early market entry, especially for developing countries.

We developed and patented an innovative azimuth drive unit (**Reference 6**) that has zero backlash and the ability to absorb shock loads that would be imposed by high wind gusts. It is built of common, mass-produced, off–the-shelf parts, easily obtained at low cost from many manufacturers. The cost uncertainty for later production is reduced since the initial unit is closer in cost to the mass production units, because the majority of the components are already in production. Only the housing is custom, and this is a welded case with minimal machining. The basic approach is a staged chain and sprocket design; the chain and sprocket is the highest efficiency high reduction ratio approach known, and is made of commercially available parts. A pair of sprockets load the chain with a damped spring, such that an imposed load on the heliostat is modulated through the action of this spring, as the tension in the chain increases; this load mitigation can improve life, but it does not allow for backlash within the operational wind speeds. The elevation drive used a modified commercially available linear actuator used primarily for large TV antennas.

The wind profile on the small heliostat produces less theoretical load, since the wind speed is lower near the ground. This wind profile effect either increases the safety factor of the drive unit or allows for lower design loads, for the smaller heliostats. Also, it would be practical and relatively inexpensive to modify fences used for plant security to partially block the wind, further improving safety factor, reducing design load, and minimizing gust effects that degrade tracking performance.

The small heliostat can in principle be used with any size central receiver and could be used for large, relatively low incident flux receivers to tailor the flux distribution more precisely than with large heliostats. This flux profiling could have advantages for start up, preheating, etc.

Figure 3 - Boeing 9.2 M^2 Heliostat

We have built and delivered one complete 9.2m^2 heliostat to Israel. The second unit has been built and tested, except for the second reflector, which is a modified version of the first design. The Noor al Salaam contract cancellation prevented completion of this reflector, which was in the final stages of fabrication at UAH. This reflector design is covered by a patent (**Reference 7**), which discusses the method for building in compressive loads into the reflector, so as to resist higher loads (wind, impact, handling, etc.). Two open loop heliostat controllers were built and tested and each was integrated to the heliostat to conduct tracking tests, but these tests were not completed. We also have the circuit board for the controller. The software acquired with these test controllers included the basic ephemeris data needed for open loop control and provisions for correcting the biases associated with error sources to eliminate drift. Lower cost versions of the controller are foreseen based on the rapid reduction in motor controller and digital signal processor costs, and improvements in processor performance. There are related commercial efforts with this basic approach, and in the future these would be available for a heliostat. Also under the Noor al Salaam effort, we conducted field installation efforts, tested the azimuth drive unit, developed cost savings for the system, and continued field exposure tests of the reflector subsystem. Additional information on the heliostat subsystem and the efforts conducted under Noor al Salaam are provided in the Appendices.

Tower/Tower Reflector:

There were two major objectives for the Tower/Tower Reflector task associated with the CONSOLAR and USISTF programs. The CONSOLAR program required that a tower reflector be installed at the Weizmann Institute. The USISTF program required the design of a tower for a commercial/demonstration plant and the design, development, and test of a tower reflector facet and support structure.

For the CONSOLAR program, Ormat designed and constructed the tower reflector shown in **Figure 4**. This design used high tensile strength chemically treated glass facets that are passively cooled. They were installed on the solar tower at Weizmann's Solar Facility. An access platform was provided for installation and maintenance. Weizmann and Ormat adjusted the facets to meet the required optical performance and flux distribution at the CPC aperture.

Figure 4 - Tower Reflector Installed at Weizmann Institute of Science

For the USISTF program, the tower height and tower reflector size and shape for the baseline plant were determined based on the optical analyses conducted by Weizmann, and further analyzed with the SolarSim code. The tower configuration selected was the three-leg design, shown in **Figure 5 (**see also **Reference 8)**. A trade study of various types of towers was conducted to determine the preferred approach. The guyed three-leg design provided lower cost and better stability than free-standing single towers and could be erected with relative ease. The height of the tower is approximately 70 meters for the 10 Megawatt thermal solar field. The tower design allows the option of raising and lowering the tower reflector on rails. Lowering the tower reflector reduces the loads under severe wind conditions and thus the tower reflector and tower can be designed for a lower load bearing condition to decrease cost. Also, raising and lowering the tower reflector facilitates installation and maintenance. For example, the tower reflector can be assembled at the tower base and erected without the need for large cranes, which would pose difficulties and incur high costs in remote areas. The tower reflector can be lowered for cleaning, inspection, adjustment, etc., which is far more convenient than performing these tasks at the top of the tower.

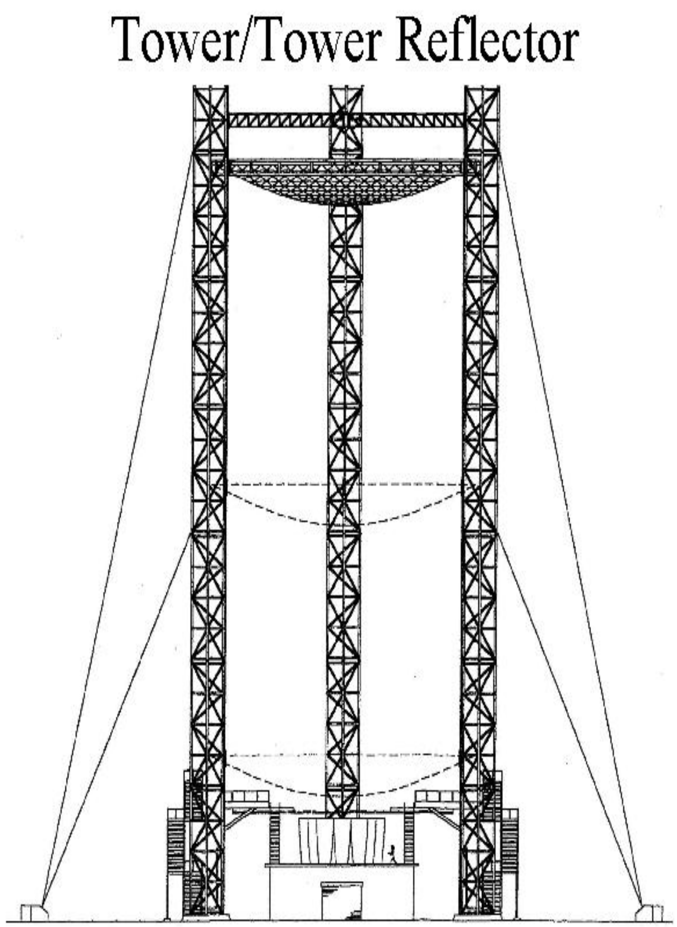


Figure 5 - Tower/Tower Reflector Configuration

The reflector facets are approximately 30" on a side and are equilateral triangles. There are approximately 1800 of these on the roughly 400 square meter tower reflector. The tower reflector structure is a Geometrica, Inc. geodesic dome design, a 14” wide section of which is shown in **Figure 6**. This approach was found to offer low cost, ease of assembly, and has been used throughout the world for extremely large domed enclosures, up to hundreds of meters in diameter, subjected to high wind loads. Virtually any shape can be obtained with their FreeDome design, and we found that this approach would provide the hyperboloidal shape needed at low cost. The assembly of large structures with the Geometrica design is surprisingly easy and fast using low cost labor and hand tools. We have assembled the structure and exposed it, and the reflector, under the Noor al Salaam program.

Figure 6 - Geometrica Geodesic Dome Support Structure Test Article, with Tower Reflector Facet

The patented cooled tower reflector facet design is described in **Reference 9** and **10**. The cooling approach was necessary to avoid excessive temperature and stress due to the incident flux, which can reach a peak of 60 suns. The facet design is shown in **Figure 7**. Under the Noor al Salaam program, we measured the reflector surface, showing that it has a surface slope variation of less than 0.6 mr standard deviation for this early prototype, and thus flux distribution errors due to this slope error would be negligible (of the order of a few inches) at the CPC aperture. This design was installed at NASA MSFC and later at UAH, and as of 2007 has been exposed in the field for over eight years without structural degradation. The tower reflector facet itself was coated with black paint to simulate high thermal loads; the black paint had the effect of simulating the equivalent of about 10 to 20 times the normal solar irradiance, and thus simulated a reflector mounted on the tower. This reflector survived 6 years without any degradation to the glass, but after that, there was impact damage from handling, and some possible evidence of relaxation or strain in the adhesive that provided the compressive load. This, coupled with the impact damage, caused cracking across the surface; although there was no noticeable edge intrusion that caused oxidation or corrosion of the silver during this period, there was one corned that delaminated (See Appendix D). We also conducted thermal tests, as shown in the Appendices, demonstrating that the reflectors can be maintained at temperatures of the order of 50 C.

Figure 7 - Tower Reflector Facet

Receiver

The receiver is the patented DIAPR design (**References 11 to 14**), sized for approximately 0.5 to 1 Megawatt thermal input, with a demonstrated capability to withstand peak temperatures as high as 1700 C, with incident flux intensities of the order of 2000 to over 10000 suns. The early 50 Kw thermal design is described in **Reference 3**. Following a series of tests for several hundred hours at concentrations as high as 4-5 Mw /square meter and associated design and analysis efforts, this design was scaled up to the larger, demonstration/commercial plant size. For this design, the inlet aperture diameter of the quartz window is 44 cm; the window is shown in **Figure 8**. There is a window cooling inlet flow and a primary inlet flow, with a common exit for the mixed streams. The exterior of the pressure vessel and the interface piping is shown in **Figure 9**. The operating pressure is of the order of 20 atmospheres, with flow rates of the order of 1.5 to 3 kg/sec or higher, and air exit air temperatures of the order of 800 to 1400 C, depending on conditions and the design requirements.

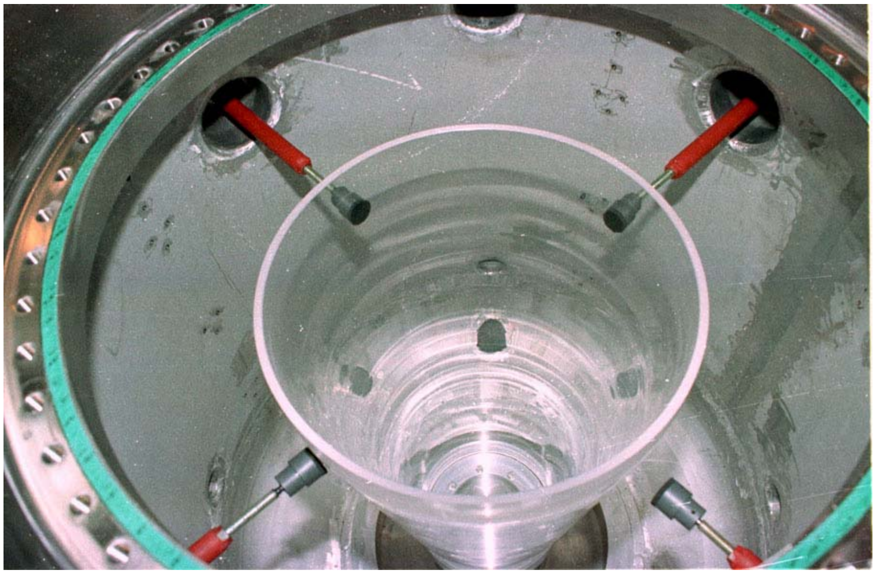


Figure 8 - View of Receiver Window During Installation

A basic advantage of this design approach is that the solar flux enters through a quartz window, which is designed such that there are no tensile stresses; only compressive stresses are present in the window, and quartz in compression is stronger than steel. A further advantage is that the directly irradiated solar absorber is composed of a matrix of ceramic pin heat exchange elements (nicknamed *Porcupine*) that have been shown to endure very high concentrated solar flux, roughly five times that of other volumetric absorbers, such as foam and honeycomb matrices. Under similar test conditions, it has been shown to yield twice the power output of these alternative volumetric approaches. In addition, it is highly resistant to the development of thermal stresses, since the pin elements are free to expand and contract. The system has shown no degradation after hundreds of hours of tests at receiver element temperatures of the order of 1000 to 1700 C and with temperature gradients of several hundred degrees C per centimeter. The design provides both radiation and convection heat transfer which alleviates the development of flow instabilities. The basic elements of the receiver are relatively low cost, since the high temperature elements are composed of ceramic materials that are not exposed to high stresses. This offers a substantial potential cost savings compared to direct impingement high temperature metal receivers. Since solar flux and specific volumetric power level are very high, the size and weight of the receiver is relatively small, which further reduces costs.

Compound Parabolic Concentrator (CPC)

The CPC was designed for the specific conditions at the Weizmann Solar Facility and for the objectives of the CONSOLAR program. It therefore has a size and shape that differ from the CPC that would be used for a demonstration plant, but the essential design features are very similar. The CPC is shown in **Figure 10**. The parabolic shape is approximated by a series of flat facets. The reflectors are bonded to an aluminum

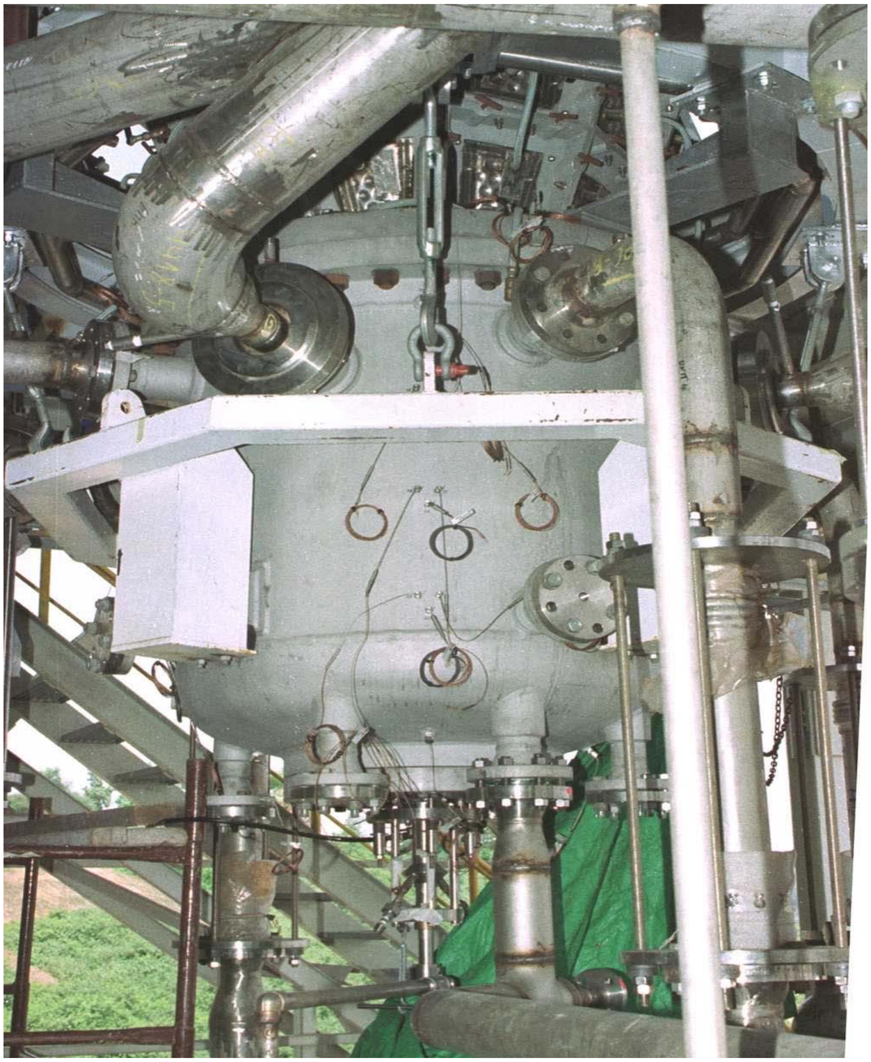


Figure 9 - View of Receiver Installed at Weizmann Institute of Science

support, which is cooled to minimize tensile stresses in the glass; the heat exchangers are seen as dimpled plates attached to the middle of each facet. There is a specially designed transition between the CPC and the receiver inlet aperture; this too is cooled.

Power Conversion Unit

The power conversion unit for the USISTF program uses an Allison turbine, with a power output of approximately 250 Kwe. A number of turbine system modifications were made by Ormat. The turbine combustor was modified to accommodate the combination of flow from the solar receivers and for simultaneous combustion of natural gas. The turbine was coupled to a generator. Ancillary hardware was designed, fabricated, and integrated. The turbine generator was successfully used in natural gas powered tests in mid-2000 to verify that the system is easily synchronized to the electrical grid.

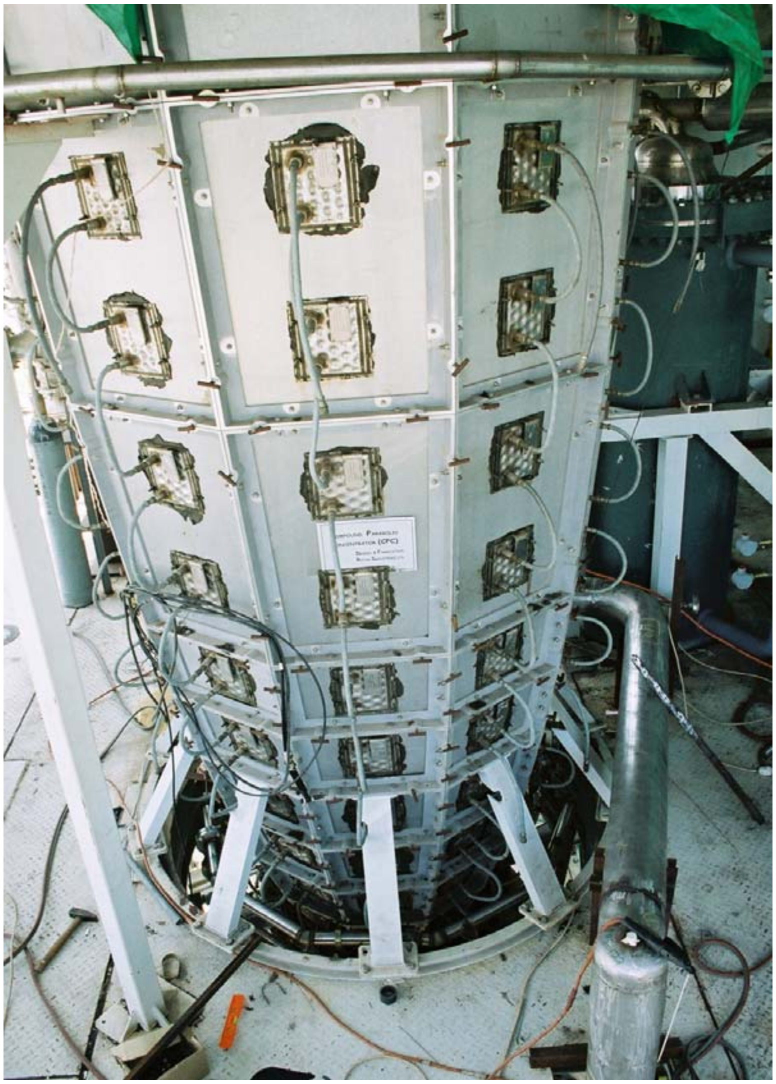


Figure 10 - Compound Parabolic Concentrator Installed at Weizmann Institute of Science

There were different test objectives for the CONSOLAR and USISTF programs. These differences posed some engineering and schedule problems, since flow rates, pressures, and temperatures differed significantly for the CONSOLAR and USISTF programs. However, these problems were solved. The CONSOLAR program included an investigation of the fundamental aspects of achieving very high concentration ratios, very high temperatures, and high pressures. Therefore, the power conversion unit is interfaced to the receiver through a piping system that was designed to allow for simulated solar preheating of the air prior to entry into the receiver, so that the receiver could be tested to very high temperatures, well above 1100 C. An electrical pre-heater was used to heat the airflow in this configuration prior to its flow into the high temperature receiver. The pre-heater, or so-called peripheral heater, was tested separately at the Weizmann Institute; this is for a lower temperature, lower incident flux condition and is based on a metal, direct impingement design.

The difference in requirements for the two programs resulted in differences in the piping configuration and method of achieving the airflow. For example, the CONSOLAR system used a set of compressors for the flow operated in a closed loop. This provides the flow rate and pressure needed. For the USISTF tests, the turbine compressor provided the flow rate. To complicate matters further, it became evident late in the program that our first demonstration plant was most likely to be for the Noor al Salaam plant. We thus found that much would be gained by simulating, within the limits of the capability of the hardware and funding, the types of conditions (air temperature and pressure) needed for the class of turbines being considered for this plant. We therefore made further modifications to the overall system, including the pipe configuration.

An additional aspect of the power conversion system was the selection of turbines for commercial and demonstration plants. Ormat conducted a study of a wide variety of turbines and a number of these were selected as candidates for different types of hybrid solar/gas power plants. In developing a baseline system for the USISTF program, turbines in the range of 10 to 20 Mwe power range were found to offer the type of cost, performance, and capability for hybrid solar gas use needed for anticipated early demonstration commercial plants; in particular, this size-range turbine was selected by NREA as being appropriate for the Noor al Salaam project. The turbine performance, flow-rate, temperature, and pressure conditions were analyzed to ensure that these systems would integrate well with the receiver systems to produce plants that would be suitable for early market entry; several candidates were identified that could be used for Noor al Salaam.

Master Control System (MCS)

For the USISTF program, there were two main objectives for the MCS: (1) develop a system for data acquisition, analysis, and archiving for the tests at the Weizmann Institute, and (2) develop requirements for the MCS for a demonstration/commercial plant. The MCS data system was developed to the point of being ready for integration with the system hardware. An example of an MCS screen that allows for access by "point and click" on a subsystem for more detailed data review is shown in **Figure 11**. One result found in part during the later Noor al Salaam study was that it was advantageous to have a distributed system of more capable heliostat controllers in the field, each providing the pointing angles to approximately ten heliostats. These controllers could also be provided with backup battery power, so that in the event of some sort of system failure, the heliostats could be safely brought to a safe stow condition. An overview of this architecture is in **Appendix K**.

Integrated Subsystem Tests

The basic objective of the CONSOLAR and USISTF programs was to validate the overall system, especially the receiver subsystem and its interface to the turbine, with the following sequence of tests:

- Receiver Test: As part of the CONSOLAR program cold flow check-out tests were conducted, followed by progressively higher temperature and pressure conditions with solar radiation.

- Turbine Test: Plans were made to modify the ducting and interface to the turbine to conduct the power generation tests. This test would then complete the

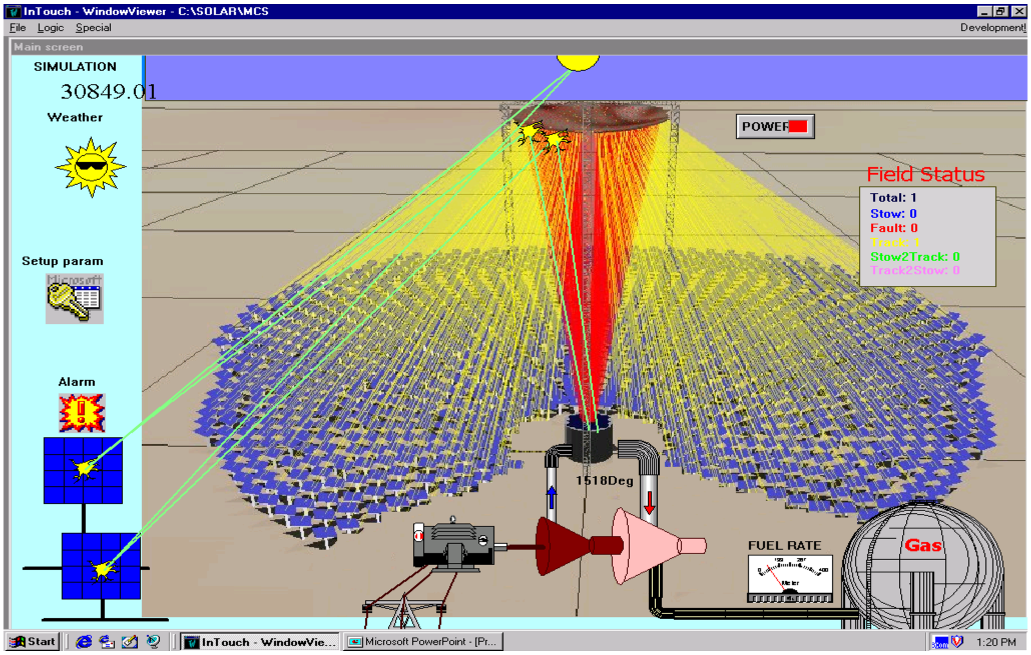


Figure 11 - Master Control System Main Access Screen

integrated receiver/turbine tests for the USISTF program. However, funding limitations have kept this integrated test from being conducted.

A view of the facility that houses the CPC, Receiver, and Power Conversion Unit is shown in **Figure 12**.

Pre-Commercialization Activities

One of the goals of the USISTF program was to study the market for solar power systems and find an opportunity to implement this technology in a demonstration plant. The results of the USISTF program were reviewed by Egypt, and determined to be a potential candidate that deserved consideration as one option for meeting Egypt's goals of developing cost-effective solar power plants. During the latter part of 1999, representatives of Boeing, Egypt's Ministry of Electricity and Energy, and Israel's USISTF team held meetings to determine how to bring this advanced technology to the state of readiness required for commercialization. As a result, a Tri-Lateral agreement was written to jointly develop and explore the technology by means of an approximately 10 to 20 Megawatt solar power demonstration plant, termed *Noor Al Salaam (Light of Peace)*, which could be the precursor to commercialization of this technology.

Figure 12 - View of Test Facility at Weizmann Institute of Science

Plans were then developed between Boeing, Egypt's New and Renewable Energy Authority, and the Israeli USISTF team of Ormat, Rotem, and the Weizmann Institute of Science to seek funding for the project. Working with the U.S. Agency for International Development (USAID), Egyptian authorities, the USISTF, and the Department of Energy, we were able to secure a commitment for funding from USAID for the first phase of this development. During this period, Boeing determined that it would not continue as prime contractor. As a result, a Grant Application for Phase 1 was submitted to DOE by UAH, with funding provided through USAID. This Grant was awarded and initial efforts were begun in 2002. However, various delays and problems with having all participants able to work officially with each other were encountered. There was no final resolution to this problem. In addition, there was a change in USAID priorities and in August 2007 DOE and USAID determined that the program should be terminated (see Appendix A). A rapid effort was conducted to complete the optical evaluation and system optimization task, and to archive the program results in a final report, so that this information can be available for possible future endeavors. However, there was too little time and no budget available to integrate the results from the RCELL optimization with the SolarSim animated graphics code or refine the field layout, as was originally planned.

Various new market opportunities, together with the recognition of the importance of mitigating greenhouse gas emissions, have provided an improvement in conditions that could offer reasonable financial return for solar power plants. These conditions are enhanced with hybrid solar/gas turbine plants, since turbine power systems have high efficiency and low cost, and are becoming a dominant means of developing new power generation plants. In addition to Egypt's long term goals to produce and sell renewable power, there is a potential market opportunity in Spain; the Spanish Royal Decree offers financial incentives for solar power plants. Other possible opportunities were identified in the USISTF study in various developing countries having high solar insolation, as well as in the U.S. desert Southwest. Recent commercial interests to provide Green Power to utilities have resulted in other opportunities, such as in California, Arizona, and a central receiver plant in Israel. There is also renewed interest by DOE in Concentrating Solar Power (CSP). It is this combination of new conditions that allows our advanced system, with its integrated solar/gas turbine configuration, to be considered as a realistic candidate for renewable power production. However, this system must be validated in a demonstration plant. The Noor Al Salaam project was designed to provide the capability to develop and operate such a plant, advance the technology, and validate the overall system performance as a forerunner to commercialization.

Egypt's Ministry of Electricity and Energy had selected Zaafarana, on the Red Sea Coast, as the plant site as shown in **Figure 13**. This site offers high solar irradiance, suitable environmental and topographical conditions, access by road, and it is near the electrical grid and natural gas pipeline.

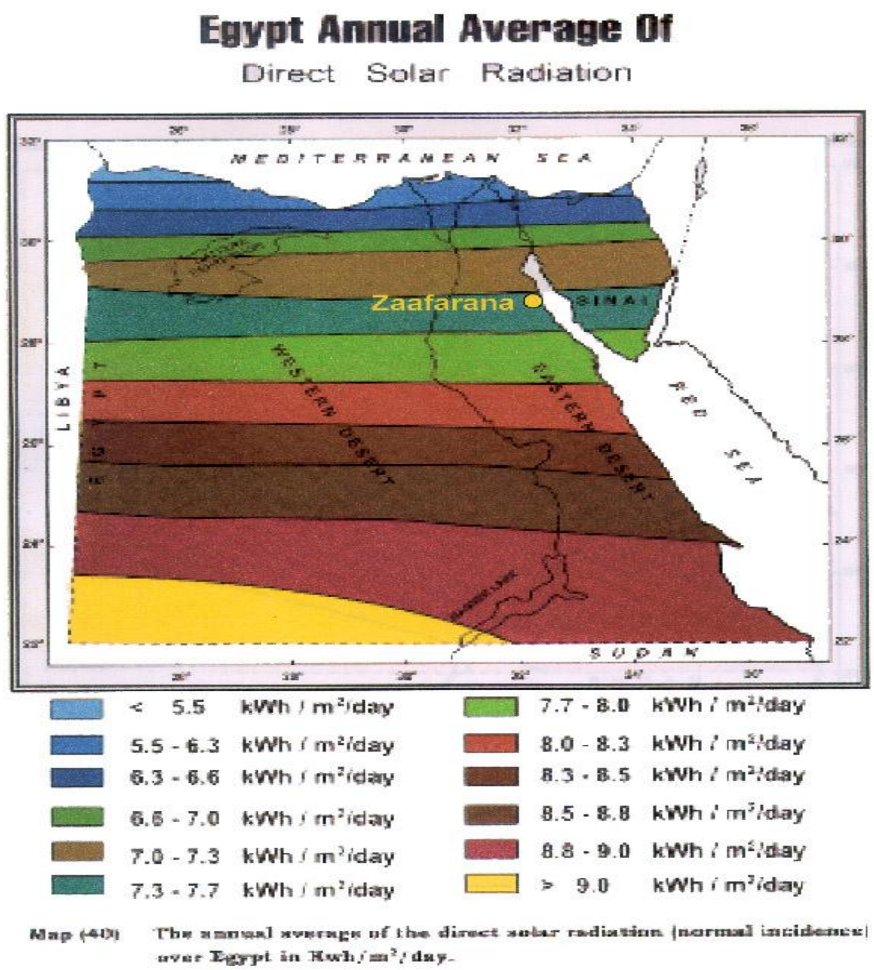


Figure 13 - Map of Region Showing Zaafarana Location and Solar Radiation Levels

We were in the early stages of a Phase 1 study leading to the definition of this hybrid solar power plant when the program was halted and then terminated. Major tasks we were able to at least partially address included:

- Development of an initial System Definition for an approximately 10 to 20 Megawatt electric plant with approximately 10 Megawatts thermal energy from the heliostat field.
- Determination of the system design of the major subsystems.

We were unable to work on the following tasks:

- Development of the various agreements between the participants and acquire the necessary permits, such as an Export License for the technologies
- Determination of sources for In-Country manufacturing, assembly, installation, and test in Egypt.

Technology Risk Mitigation Tasks

UAH was able to conduct certain technology risk mitigation tasks, including additional testing of the receiver, azimuth drive unit, heliostat reflector partial fabrication, etc. These are covered by various appendices to this report and have been briefly summarized as appropriate in the above discussion of the USISTF program and its relationship to the Noor al Salaam program. **Appendix A** contains the contractual documentation for this program. **Appendix B** summarizes a detailed analysis of the thermal and flow system. **Appendix C** covers the optical analyses developed and conducted with SolarSim and RCELL. **Appendix D** covers some efforts on the tower reflector support structure and tower reflector. **Appendix E** covers the initial effort to define a suitable system and cost estimating relationships for the RCELL field optimization study. **Appendix F** covers efforts on the tower reflector subsystem. **Appendix G** covers the additional effort on the heliostat drive unit. **Appendix H** covers the effort for the heliostat reflector. **Appendix I** covers the effort for the heliostat foundation. **Appendix J** summarizes the patents related to this overall technology effort, for both the USISTF and Noor al Salaam programs. **Appendix K** summarizes Master Control System cost estimates and the anticipated architecture. However, substantial changes in related technologies would likely impact these costs and the architecture.

It should be noted, however, that since our technology risk mitigation efforts were halted, much work remains. This report includes the results up to the present time, primarily to avoid losing this information. Even though incomplete, and clearly subject to improvement, we felt it necessary to ensure that this information would be archived, in case it may be of interest later.

System Definition Study, Tri-Lateral Agreements, and RFI Background - Noor al Salaam

Initial efforts to produce a System Definition were developed during the program. UAH also hosted a Tri-Lateral Meeting in April 2005 at which time the Participants agreed to move forward, with agreement on the basic System Definition. Documentation of this meeting is given in **Appendix L**.

It was also determined that UAH would develop a Request for Information (RFI), such that potential Industrial Participants could be invited to submit expressions of interest and background. This information was to be evaluated by the Participants, as agreed to at the April2005 meeting. UAH then developed this RFI and submitted it to an agreed-upon selection of industrial companies. This solicitation was limited to U.S. corporations. The result after much deliberation and planning was that none of the candidates chose to be involved in the Noor al Salaam project at this time. The RFI and related documentation is given in **Appendix M**. **Appendix N** includes a summary of the thermal and calorimeter tests conducted by Rotem and Weizmann on the receiver and CPC. **Appendix O** has the ITAR and Export Control summary required to ensure that the project could be conducted in accordance with these regulations. A draft summary of the System Definition and requirements is given in **Appendix P**.

Conclusion

Our team made progress in the development of the High Concentration Solar Central Receiver, which continued and expanded on the preceding, closely related USISTF program. Under the USISTF program, various modifications were made to the turbine to make it suitable for hybrid solar/gas use. Tests demonstrated that we had a reasonable candidate approach for the Noor al Salaam program by using a turbine with a separate gas generator. All power conversion unit ancillary hardware was built and installed, including the piping, valves, instrumentation, control system, and recuperators. Both the high temperature and peripheral heaters were built, installed, and partially tested at the Weizmann Institute of Science. The turbine generator unit was tested on grid, but not tested in the hybrid mode. With this background information, we were able to model the types of flow options for Noor al Salaam, and from this analysis, select the most efficient. We completed a prototype heliostat design and delivered and installed the basic design at the Weizmann Institute, and continued to test this for performance, integrity, and life and to make design improvements as part of the Noor al Salaam program. We developed a practical approach for the tower and tower reflector, and constructed and tested a novel geodesic dome-type structure. Field exposure and performance tests were then continued under the Noor al Salaam program. Additional systems analyses were also conducted, showing that there are substantial cost benefits from use of the waste heat and showing that the fully parallel flow configuration for the solar heated air provides the maximum thermodynamic efficiency for the turbines, and a moderate temperature entering the gas generator combustor for the turbine. The prototype tower reflector facet was designed and tested, and shown to have good optical characteristics. Long term exposure tests in the field demonstrated that this design was a suitable option. We were granted 17 patents for the basic system, heliostat reflector and drive unit, tower reflector, tower reflector configuration, and optical alignment system and presented and/or published a number of technical papers. One of the major milestones of the USISTF program and later, with the Noor al Salaam program, was achieved with Egypt's agreement to pursue the Noor Al Salaam project under appropriate conditions.

USAID funding, with DOE management oversight, resulted in a grant for the Noor al Salaam Phase 1 System Definition led by the University of Alabama in Huntsville; this change was in large part necessitated by The Boeing Company's decision to relinquish their prime contractor role. Our plan was to move this Tri-Lateral project between the U.S., Egypt, and Israel into turn-key plant construction in Phase 2 after completing the Phase 1 System Definition effort. This required early selection of a U.S. industrial partner or partners to serve as the prime contractor for the team and joint effort to obtain the necessary funding. We completed all tasks associated with soliciting a prime contractor and associated subcontractors, coordinated these efforts with DOE and the principals in Egypt and Israel, and communicated with over a dozen candidates. However, none of these prime contractor candidates chose to participate at that time. In parallel with these programmatic efforts, we accomplished a number of technology risk reduction tasks, including additional development and cost estimates for the heliostat reflector, drive unit, pedestal, and foundation; tower reflector; tower reflector support structure. We also conducted a system definition for the Noor al Salaam plant and system thermal and flow analyses and trade studies. We showed that the waste heat recovery and power production with an Organic Rankine Cycle produced high return and investment. We conducted optical analyses with the SolarSim code and developed a new version of the RCELL code. The new version of the RCELL field layout and cost optimization code can be used with the beam down optical system, using state of the art computers and software. More detailed results of these efforts are covered in the Appendices. Finally, there is a need for additional risk reduction technology developments in the major subsystems, and the need for developing an appropriate leadership role for a prime contractor is paramount.

References:

1. DOE Letter of Instruction to Ms. Gloria Greene, Director, Office of Sponsored Programs "GRANT NUMBER DE-FC36-02GO12030; NOOR AL SALAAM PROJECT", from Beth H. Dwyer, Contracting Officer, dated November 3, 2007. (See also Appendix A)
2. Yogev, A. Solar Energy Plant. Patent Number 5,578,140, granted November 26, 1996.
3. Yogev, A., et al. Patent Number 5,862,799, granted January 1999.
4. Karni, J., Rubin, R., Kribus, A., Doron, P., Fierman, A. and Sagie, D., 1997, "The DIAPR: A High-Pressure, High-Temperature Solar Receiver," *ASME J. of Solar Energy Engineering,* Vol. 119, Feb. 1997.
5. Kolb, Gregory J., Jones, Scott A., Donnelly, Matthew W., Gorman, David, Thomas, Robert, Davenport, Roger, and Lumia, Ron, "Heliostat Cost Reduction Study", Sandia Report SAND2007-3293, June 2007. Available to the public from U.S. Department of Commerce, E-Mail: orders@ntis.fedworld.gov.
6. Blackmon, James B. and Frederick Gant. Solar Power System Drive Unit. Patent Number 6,440,019 B, granted August 27, 2002.
7. Blackmon, James B., et al. Composite Backed Pre-Stressed Mirror for Solar Facet. Patent 6,739,729, granted May 25, 2004.
8. Blackmon, James B., et al. Composite Backed Pre-Stressed Mirror for Solar Facet. Patent 7,309,398, granted December 18, 2007.
9. Blackmon, James B. Geometric Dome Stowable Tower Reflector. Patent Number 6,532,953, granted March 18, 2003.
10. Blackmon, et al, Thermally Controlled Solar Reflector Facet with Heat Recovery. Patent Number 6,708,687, granted March 23, 2004.
11. Blackmon, et al, Thermally Controlled Solar Reflector Facet with Heat Recovery. Patent Number 6,911,110, granted June 28, 2005.
12. Karni, Jacob, et al. Central Solar Receiver. Patent Number 6,516,794, granted February 11, 2003.
13. Karni, Jacob, et al. Central Solar Receiver with a Multi Component Working Medium. Patent Number 5,947,114, granted September 7, 1999.
14. Karni, Jacob, et al. Delivery of Radiation from a First Transparent Medium to a Second Transparent Medium Having a Lower Refraction Index. Patent Number 5,796,892, granted August 18, 1998.
15. Karni, et al. Central Solar Receiver. Patent Number 5,323,764, granted June 28, 1994.

APPENDIX A

DOE, USAID, AND UAH DOCUMENTATION REGARDING CONTRACTUAL AND PROGRAMMATIC ISSUES

مرفق (١)

ANNEX I

TO THE IMPLEMENTING ARRANGEMENT

BETWEEN

**THE MINISTRY OF ELECTRICITY AND ENERGY
OF THE ARAB REPUBLIC OF EGYPT
AND
THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA
FOR COOPERATION IN ENERGY TECHNOLOGY**

IN THE FIELD OF RENEWABLE ENERGY

WHEREAS, the Department of Energy of the United States of America (hereinafter referred to as "DOE") and the Ministry of Electricity and Energy of the Arab Republic of Egypt (hereinafter referred to as "MEE") entered into an Implementing Arrangement for Cooperation in the Field of Energy on July 1, 1999 (hereinafter referred to as the "Agreement");

WHEREAS, the DOE and MEE (hereinafter referred to as the "Parties") recognize the importance of exchanging information, experience and points of view regarding the research, development and demonstration on advanced renewable energy technologies;

The Parties agree to enter into this Annex in accordance with Article VI of the Agreement.

**ARTICLE I
SCOPE**

The Parties agree to cooperate in a manner which will facilitate exchange of information and joint activities in renewable energy technologies. The fields of cooperation may include, but will not be limited to:

1. Cooperation between DOE, the Egyptian New and Renewable Energy Authority (NREA), and the Weizmann Institute of Israel on the demonstration and testing of the Integrated Solar Combined Cycle System (ISCCS) based on Solar Concentration Off-Tower (SCOT) technology in an appropriate site in Egypt.

2. Training of Egyptian engineers at U.S. solar facilities on the operation and maintenance of high temperature solar thermal fields.

3. Exchange of information, visits by experts and training of Egyptian engineers in the following areas:
   - solar thermal power technologies
   - advanced photovoltaic technologies
   - design of photovoltaic systems for grid connection and stand alone applications
   - evaluation of data gathered by sun trackers using different tracking methods and techniques

ARTICLE II
MANAGEMENT

The DOE Assistant Secretary for Renewable Energy and Energy Efficiency shall be responsible for the programmatic aspects of this Annex for DOE. MEE designates the NREA to be responsible for the implementation of this Annex.

Each Party shall designate one Program Coordinator to supervise activities under this Annex. These Program Coordinators shall provide technical management and coordination of the activities under this Annex. Each task undertaken under this Annex shall be described in a work plan approved by the Coordinators, who will designate Co-Project Officers for the task.

ARTICLE III
EXPENSES

Each Party shall bear the costs of its activities under this Annex unless otherwise agreed to in writing.

ARTICLE IV
GENERAL PROVISIONS

Cooperation under this Annex shall be subject to the terms and conditions of the Agreement which are hereby incorporated by reference.

ARTICLE V
ENTRY INTO FORCE AND TERMINATION

This Annex shall enter into force upon signature and shall remain in force for five years, or until termination of the Agreement, whichever comes first. This Annex may be amended or extended by mutual written agreement of the Parties.

"Signed at Cairo, this day 23rd of February, 2000, in two originals, in Arabic and English languages, both texts being equally authentic".

FOR THE MINISTRY OF ELECTRICITY AND ENERGY OF THE ARAB REPUBLIC OF EGYPT

DR. ALI FAHMI EL SAIEDI

[signature]

MINISTER OF ELECTRICITY AND ENERGY

FOR THE DEPARTMENT OF ENERGY OF THE UNITED STATES OF AMERICA

BILL RICHARDSON

[signature]

SECRETARY OF THE DEPARTMENT OF ENERGY

AGR2630224 - 2800575

INTERAGENCY AGREEMENT BETWEEN THE AGENCY FOR INTERNATIONAL DEVELOPMENT AND U.S. DEPARTMENT OF ENERGY

1. Project Name Power Sector Support II	2. Project Number 263-0224
3. Appropriation Symbol 72X1037	4. Budget Plan Code HES69823263KG13
5. Funds N/A	6. Fiscal Year N/A
7. Completion Date September 30, 2002	8. Original X or Amendment No.

9A. Prior Funding · NONE — 9B. Funding Obligated this Document ~~$1,500,000~~ $1,250,000 — 9C. New Total Funding ~~$1,500,000~~ $1,250,000

10. Authority — Section 632(b) of the Foreign Assistance Act of 1961

11. Brief Program Description

a. Detailed assessment of the prospects for moving forward with a 10MW Thermal/Solar demonstration plant in Egypt. The assessment, would address to technical, commercial and financial feasibility of the program and further the prospects for regional cooperation between Egypt, Israel and the United States.

b. Exchange information, visits and training of Egyptian Engineers at DOE solar facilities and at the National Renewable Energy Laboratory in areas such as solar thermal and photovoltaics.

c. Support exchanges, visits and training in the fields of fossil energy and advanced power systems, including fuel cells.

12. Liaison Offices/Additional Representatives

A.	B.
U.S. Department of Energy Moustafa M. Soliman Sr. Program Officer Office of International S&T Cooperation U.S. Department of Energy	U.S. Agency for International Development Raouf N. Youssef Chief Division of Power and Telecommunications (Acts as USAID Project Manager)

13A Signature by Authorized Representative: By: *Linda F. Whitted* NAME: Linda F. Whitted TITLE: Director Office of Resource Management U.S. Department of Energy DATE: March 7, 2000	13B. Signature by Authorized Representative: U.S. Agency for International Development By: *Phillip S. Tresch* NAME: Phillip S. Tresch TITLE: Contracting Officer U.S. Agency for International Development, Egypt DATE: 15 FEBRUARY 2000

14. This Interagency Agreement consits of this facesheet and the following items (if checked):

X Schedule
X Anenx A - Program Description
X Annex B - Financial Plan and Budget
X Annex C - Standard Provisions
X Annex D - Initial Environmental Examination

Note: $250,000 paid by NETL

DOE F 4600.1
(08-93)

U.S. DEPARTMENT OF ENERGY
NOTICE OF FINANCIAL ASSISTANCE AWARD

Under the authority of Public Law ____________________ and subject to legislation, regulations and policies applicable *(cite legislative program title)*:

1. PROJECT TITLE
Noor-Al-Salaam Project

2. INSTRUMENT TYPE
☒ GRANT ☐ COOPERATIVE AGREEMENT

3. RECIPIENT *(Name, address, zip code, area code and telephone no.)*
University of Alabama in Huntsville (UAH)
301 Sparkman Drive, S.W.
Huntsville, AL 35899

4. INSTRUMENT NO. DE-FG36-02GO12030

5. AMENDMENT NO. M002

6. BUDGET PERIOD FROM: 3/12/02 THRU: 9/30/07

7. PROJECT PERIOD FROM: 3/12/02 THRU: 9/30/07

8. RECIPIENT PROJECT DIRECTOR *(Name and telephone no.)*
Dr. James Blackmon
(256) 824-5104

9. RECIPIENT BUSINESS OFFICER: *(Name and telephone no.)*
Valerie Sequist
(256) 824-2656

10. TYPE OF AWARD
☐ NEW ☐ CONTINUATION ☐ RENEWAL
☒ REVISION ☐ SUPPLEMENT

11. DOE PROJECT OFFICER *(Name, address, zip code, telephone no.)*
~~Steve Sargent~~ (303) 275-4912 275-4706
Golden Field Office
1617 Cole Blvd.
Golden, CO 80401 GLENN.DOYLE@
E-Mail: ~~Steve.Sargent~~@go.doe.gov

12. ADMINISTERED FOR DOE BY *(Name, address, zip code, telephone no.)*
Lincoln S. Capstick III (303) 275-4796
Golden Field Office
1617 Cole Blvd.
Golden, CO 80401
E-Mail: Lincoln.Capstick@go.doe.gov

13. RECIPIENT TYPE
☐ STATE GOV'T ☐ INDIAN TRIBAL GOV'T ☐ HOSPITAL ☐ FOR PROFIT ORGANIZATION ☐ C ☐ P ☐ SP ☐ INDIVIDUAL
☐ LOCAL GOV'T ☒ INSTITUTION OF HIGHER EDUCATION ☐ OTHER NONPROFIT ORGANIZATION ☐ OTHER *(Specify)*:

14. ACCOUNTING AND APPROPRIATIONS DATA

a. Appropriation Symbol	b. B & R Number	c. FT/AFP/OC	d. CFA Number

15. EMPLOYER I.D. NUMBER/SSN
TIN/SSN: 63-0520830
DUNS: 94-687-7123

16. BUDGET AND FUNDING INFORMATION

A. CURRENT BUDGET PERIOD INFORMATION		B. CUMULATIVE DOE OBLIGATIONS	
(1) DOE Funds Obligated This Action	$ 0.00	(1) This Budget Period [Total of lines a.(1) and a.(3)]	$ 1,185,285.23
(2) DOE Funds Authorized for Carry Over	$ 0.00		
(3) DOE Funds Previously Obligated in This Budget Period	$ 1,185,285.23	(2) Prior Budget Periods	$
(4) DOE Share of Total Approved Budget	$ 1,185,285.23		
(5) Recipient Share of Total Approved Budget	$ 0.00	(3) Project Period to Date [Total of lines b.(1) and b.(2)]	$ 1,185,285.23
(6) Total Approved Budget	$ 1,185,285.23		

17. TOTAL ESTIMATED COST OF PROJECT $ 1,185,285.23

(This is the current estimated cost of the project. It is not a promise to award nor an authorization to expend funds in this amount.)

18. AWARD/AGREEMENT TERMS AND CONDITIONS
This award/agreement consists of this form plus the following:
a. Special terms and conditions.
b. Applicable program regulations (*specify*) N/A (*Date*)
c. DOE Financial Assistance Rules, 10 CFR 600, as amended.
d. Application/proposal dated March 12, 2002 , ☐ as submitted ☐ with changes as negotiated

19. REMARKS *Note: US Aid funded $1,250,000.00 to DOE/GO for this effort. Of this amount $29,156.21 was moved to Sandia National Laboratory through a reconciling transfer. The amount to Sandia National Laboratory included a 3% administration charge. The remaining amount of $1,220,843.79 was to be used for this grant, however there is a 3% administrative charge thereby leaving $1,185,285.23 to be funded for this award. For purposes of this award, see the "Limitation of Incurred Costs, appendix C.
See Page 2 for additional instructions.

20. EVIDENCE OF RECIPIENT ACCEPTANCE
Valerie Seaquist 11/25/2003
(Signature of Authorized Recipient Official) (Date)
VALERIE SEAQUIST, DIRECTOR
(Name)
OFFICE OF SPONSORED PROGRAMS
(Title)

21. AWARDED BY
Mary Hartford 11/6/03
(Signature) (Date)
Mary Hartford
(Name)
Contracting Officer
(Title)

November 03, 2005

Ms. Gloria Greene, Director
University of Alabama in Huntsville
Office of Sponsored Programs
301 Sparkman Drive, S.W.
Huntsville, AL 35899

SUBJECT: GRANT NUMBER DE-FC36-02GO12030; NOOR AL SALAAM PROJECT

Reference is made to your Research Proposal dated August 26, 2005, as well as our telephone discussions this date, with Andrea Dixon, Jim Blackmon, Glenn Doyle, Pat Saito and ourselves participating. Based on these discussions, we at DOE agreed to authorize certain work before an amendment to the award is accomplished, to clarify some of the current Scope requirements in the award, and to verify our intent as regards an amendment to this award. Accordingly, the following is provided:

(1) UAH is hereby authorized to commence work on the work proposed in your August 26, 2005 Research Proposal, entitled "Noor Al Salaam Phase I System Definition Program; UAH Program Planning and Technology Development," at the estimated cost included in that proposal of $ $93,555. These efforts are within the overall scope of the award, and DOE funding has been obligated to cover the efforts.

(2) UAH is further authorized to commence work on, and issue the Request for Information efforts that are also already described and funded in the current award scope. DOE requires that you provide the RFI, when prepared, to the undersigned or directly to Mr. Doyle for our review and concurrence with its content. This is not an approval but rather a review to ensure that DOE's interests are protected and that the content reflects the award's scope.

Once you have received our concurrence, this letter confirms our discussions that UAH will determine the audience for this RFI, as well as assemble and manage the review committee that selects from any interested respondents. DOE does not have an approval authority for the results. However, again DOE requires that we be provided the opportunity to review the results and discuss them before a selection is made.

(3) Based on our discussions, our agreed upon intent is to amend the award as soon as possible, to include a minimally revised Statement of Objectives (SOO) that includes both tasks for all of the completed as well as future anticipated UAH activities as the

prime Recipient for this award, as well as those tasks for the selected contractor from the RFI. A revised budget in this amendment will estimate all the tasks, in columns by UAH and TBD contractor, such that iterative UAH research proposals are no longer necessary. The parties further agreed that a reporting process for specific tasks would be laid out in the amendment, permitting the deletion of the terms and conditions that currently require these research proposals.

In order to accomplish this, UAH is requested to resubmit an application as we discussed, which provides their proposed SOO and budget, to include support for the as yet to be performed UAH tasks. What obligated funding is not included in the UAH estimate will be the budget for the RFI contractor, and we will renegotiate that estimate at which time there is a novation to the award to make the RFI contractor the prime Recipient.

If you have any questions concerning the above, please direct them to me at (303) 275-4719, or beth.dwyer@go.doe.gov. Feel free to call Mr. Doyle directly as well, at (303) 275-4706.

We look forward to resolving the above issues, and request your application at the earliest reasonable time. Thanks in advance for your attention to this matter.

Sincerely,

Beth H. Dwyer
Contracting Officer

DRAFT

Proposed Statement of Objectives and Budget
Noor al Salaam High Concentration Solar Central Receiver Program
Prepared by
James B. Blackmon
Research Professor
University of Alabama in Huntsville
December 5, 2005
Revised January 5, 2006

In accordance with (IAW) the instructions of the DOE letter of November 7, 2005 and emails from Beth Dwyer (DOE emails of 11/3/2005 and 11/29/05), we provide the requested information in the following. The information includes a" minimally revised Statement of Objectives" for completed tasks and future anticipated tasks for UAH, and tasks for the selected contractor, together with reporting requirements and a budget. For completeness, we include the Statement of Work originally provided to DOE as Appendix A. There are at most only minor changes made to this original SOW.

Relevant instructions are provided below for Item (3) of the letter:

(3) Based on our discussions, our agreed upon intent is to amend the award as soon as possible, to include a minimally revised Statement of Objectives (SOO) that includes both tasks for all of the completed as well as future anticipated UAH activities as the prime Recipient for this award, as well as those tasks for the selected contractor from the RFI. A revised budget in this amendment will estimate all the tasks, in columns by UAH and TBD contractor, such that iterative UAH research proposals are no longer necessary. The parties further agreed that a reporting process for specific tasks would be laid out in the amendment, permitting the deletion of the terms and conditions that currently require these research proposals. In order to accomplish this, UAH is requested to resubmit an application as we discussed, which provides their proposed SOO and budget, to include support for the as yet to be performed UAH tasks. What obligated funding is not included in the UAH estimate will be the budget for the RFI contractor, and we will renegotiate that estimate at which time there is a novation to the award to make the RFI contractor the prime Recipient.

Instructions from the 11/29/05 email state:

> **"…revise the budget into two "phases" with the first being all that is necessary for UAH actual and estimated costs as the prime, and the second being all the estimated costs for the follow-on prime, if you will. The SOO likewise needs to segregate the UAH as prime and the next prime's work.**

For completeness, we include:

I. Total grant funding,
II. Authorized funding to this date,
III. Recently approved funding for the supporting technical tasks (Heliostat and Optimization/Optical Analysis),
IV. Tasks assigned to UAH that have been completed, or essentially completed, with comments/clarifications
V. Anticipated additional UAH effort and funding
VI. Funding to be novated to the selected Industrial Participant (prime contractor).
VII. Summary of results in two columns

Contract Novation:

It should be noted that the original proposal and budget, which had been prepared by Boeing, but was not submitted when Boeing decided to disengage from solar work of this type, had essentially the identical technical and programmatic tasks of the subject Grant, which was awarded to UAH in order to keep the program viable, but with two important exceptions.

First, the Grant included the Egyptian Training effort.

Second, the Grant included the additional tasks required for planning efforts and for the effort to solicit, evaluate, and select a Prime Contractor to conduct the System Definition effort. As a result of the need for these additional tasks, and the lack of additional funds for them, UAH provided as much non-invoiced support as feasible, primarily in student projects related to these tasks. These efforts to conduct certain tasks that had academic value allowed us to conserve funds, such that the management and subcontractor budget now available to the Industrial Participant/Prime Contractor, is comparable to that which was originally budgeted for the Boeing effort and the Ormat, Rotem, Weizmann Institute of Science, and Egyptian New and Renewable Energy Authority (NREA) efforts. The technical effort that was originally to be conducted by Boeing (e.g., heliostat, tower design, tower reflector design and test, and a part of the Master Control Subsystem), has been either in large part completed, or is in the process of being completed, by UAH and its subcontractors, under the Tasks approved by DOE.

Therefore, there is sufficient budget remaining to be novated such that the System Definition effort can be completed by a qualified Industrial Participant/Prime Contractor. It should be noted that UAH does not have a current non-disclosure agreement with Ormat. We therefore do not have up-to-date data on the results of any technical improvements regarding the receiver and power generation system beyond the point reached by the Israeli organizations near the end of the USISTF program and the subcontracts with Boeing. Results up to that period were encouraging, but there may be a need to reconstitute some level of Israeli technical effort, especially for the receiver subsystem, as part of the System Definition. One of the qualifications of the Industrial Participant/Prime Contractor, is that they have the experience and capabilities needed to address these issues for the receiver and power generation subsystems.

In addition, any follow-on efforts to secure funding for subsequent design/build phases for the power plant will be borne by the Prime Contractor. It is further noted that the availability of suitable turbines for solar/natural gas operation (preferably, external gas generator turbines), may be substantially different than during the late 1990s when the program was being conducted. This could also impact the subsequent System Definition.

I. Total Grant Funding:

The original grant for both the Noor al Salaam and Egyptian Training tasks was $1,185,285.

II. Authorized Funding to this Date:

We have identified the total Authorized/Approved funding as part of the original grant as follows: ***ANDREA: I ASSUME WE'LL DOUBLE CHECK THESE. IT'S THE BEST INFORMATION I HAVE AT THIS TIME.***

Egyptian Training: $223,683.30
Pre-Award Planning: $52,866.76
Noor al Salaam
    Effort to seek, evaluate, and select Industrial Participant: $88,855.94

III. Recently Approved Funding for the Supporting Technical Tasks (Heliostat and Optimization/Optical Analysis):

Task 4.1 Heliostat: $18,977.86
Optimization/Optical Analysis: $76,142

IV. Completed Tasks assigned to UAH are summarized below.

UAH has conducted the following tasks, essentially to completion, IAW the SOWs, as of 11/30/05:

1. Completed the Egyptian Training tasks, with documentation provided to DOE and to the Egyptian Ministry of Electricity and Energy-New and Renewable Energy Authority.
2. Completed, or essentially completed, certain tasks, IAW the Statement of Work (see A**ppendix A,** attached) for the Noor al Salaam project, as summarized below, by Task Number. It should be noted that certain aspects of various tasks were in large part completed as student special topics at no cost to the Grant.

Task 1.1 Project Management

Effort was conducted to develop certain agreements with Boeing and the USISTF participants, and especially a Non Disclosure Agreement with Ormat; in addition, we worked to obtain certain technical information, primarily from Ormat, as part of this task and the Pre-Award Planning Task. Limited information has been obtained, including USISTF information provided by Boeing, but other information has not been forthcoming. We also have developed an agreement with Boeing, but the NDA with Ormat, and related information, was not obtained. These activities represented an extensive effort as documented in the background information provided to DOE. It will be necessary for the selected Industrial Participant/Prime Contractor to develop the NDAs, and related, agreements, with the Participants. Additional effort involved day to day management, telecons, emails, etc., as required both internally and externally, with DOE, and the Participants, including the USISTF, NREA, Weizmann Institute of Science, Ormat, Rotem, Boeing, and various subcontractors under the USISTF contract to McDonnell Douglas/Boeing. Effort was also required to restructure the tasks IAW various changes as a result of events over which we had no control, involving planning, scheduling, and conducting the Tri-Lateral meeting with representatives from Egypt and Israel. *No additional costs over that approved are required for this effort.*

Task 1.2 Planning and Conducting Initial Tri-Lateral Meeting

After extensive changes, rework, postponements, etc., this task was essentially completed and resulted in the Tri-lateral meeting and MOA in April 2005. We continue to have limited follow-up telecons and correspondence for clarification and status purposes. *No additional effort or costs over that approved will be required for this task.*

Task 2.1 Preliminary System Description

Draft prepared based on USISTF results. Some additional effort will be required pending results of the Optical Analysis and System Optimization, and any changes in conditions that may occur as the result of changes in conditions and preferences of the Participants, such as plant output power, solar thermal power level (percent solar), etc. *No additional costs over that approved are required for this effort.*

Task 2.2.1 Preparation of List of Candidates

Draft list prepared with addresses, points of contact, etc. Additional effort will be required to prepare the final list as the result of responses to the planned Commerce Business Daily notice. *No additional costs over that approved are required for this effort.*

Task 2.2.2 Coordination with Candidates and Solicitation of Interest/Request for Information

Draft letter, requesting information and interest, White Paper, and other background information prepared and provided to DOE by UAH. Also, developed the peer review team called for in the MOA from the April 2005 Trilateral meeting. Additional effort required for CBD notice, final editing, approvals/coordination, and release to candidate Industrial Participants. *No additional costs over that approved are required for this effort.*

Task 2.3 Optical Analysis and System Optimization

UAH prepared requests for proposals from HiTek Services and Tietronix, and developed final Statements of Work based on inputs. Procurements to be finalized when appropriate internal UAH Account Numbers assigned (late November). Requires UAH technical effort, approved by DOE letter referenced above. *No additional costs over that approved are required for this effort.*

Task 3.1.2 Drive Unit

Partial effort completed by UAH as part of student projects, at no cost to DOE. *Some additional UAH effort will be required to provide analysis and documentation for the Industrial Participant.*

Task 3.1.3 Pedestal

Partial effort completed by UAH as part of student projects, at no cost to DOE. *Some additional UAH effort will be required to provide analysis and documentation for the Industrial Participant.*

Task 3.1.4 Foundation

Partial effort completed by UAH as part of student projects, at no cost to DOE. *Some additional effort will be required to provide documentation for the Industrial Participant.*

Task 4.1.1 Heliostat Reflector Fabrication

Partial effort completed as part of student projects by UAH, at no cost to DOE. *No additional costs over that approved are required for this effort.*

Task 4.1.1.2 Coupon Tests

Partial effort completed by UAH as part of student projects, at no cost to DOE. *No additional costs over that approved are required for this effort.*

Task 4.1.3 Drive Unit Development and Test

Partial effort completed by UAH as part of student projects, at no cost to DOE. *Some additional UAH effort will be required to provide analysis and documentation for the Industrial Participant.*

Task 4.2 Tower Design and Development

Partial effort completed as part of student projects, at no cost to DOE. Original subcontractor (Andrews Tower Company) is no longer available to support the program, due to illness of the president. Continuity of effort and support is available from Nelson Jones, original designer, and inventor of several related technologies, as required by UAH and/or the selected Industrial Participant. *Some additional UAH effort will be required to provide design and documentation for the Industrial Participant, in part as a result of the Optical Analysis and Optimization Task, recently approved by DOE.*

Task 4.3 Tower Reflector Development and Test

Partial effort completed as part of student projects, at no cost to DOE. *Some additional UAH effort will be required to provide analysis and documentation for the Industrial Participant.*

V. Anticipated additional UAH effort and funding are provided below:

The following delineates the additional effort and funding required, which has not previously been approved, to complete UAH tasks as defined in the original grant; these tasks are excerpted from the original grant SOW and retain the same task numbers.

Task 3 – Production, Assembly, and Installation Design - ADDENDUM

This task involves UAH development of two aspects of the Noor al Salam design associated with that part of the technology development that falls under the UAH scope of responsibility. These areas are: heliostat and tower/tower reflector. This effort is necessary in order to determine the initial, non-recurring costs associated with providing the various subsystems, including fabricating, delivering, and installing the subsystems at the site. As required, relevant descriptions will be provided for production floor space, tooling layouts, assembly layouts, material receiving and storage, manufacturing flows, personnel and related skill levels, and processes needed to support the In-Country production, assembly, and installation. Packages of the information needed will be prepared for use by the Industrial Participant in obtaining estimates and quotes from contractors, primarily in Egypt, but as required, in the U.S.

Task 3.1 Heliostat Subsystem

The heliostat overall production, assembly, and installation sequence will be developed to the level of detail necessary to describe the major activities for the following assemblies:

3.1.1 Heliostat Reflector
3.1.2 Drive Unit
3.1.3 Pedestal
3.1.4 Foundation

At this stage of development, the heliostat controller design has been superseded by technology advances and is no longer current. This aspect of the system will be postponed such that a more up-to-date design can be developed and the effort necessary to develop this can be then defined. Additionally, it is likely that the hardware/software for the heliostat controller and the master control system would be the responsibility of the prime contractor (selected Industrial Participant) and would be developed and produced in the U.S. Therefore, this effort is not necessary at this time to support In-Country manufacturing considerations in Egypt.

Task 3.1 Basis of Estimate:

Task 3.1.1 – Heliostat Reflector

Applicable material developed during the heliostat reflector development program will be assembled to provide a tooling description, factory floor layout, process for manufacturing and assembly, estimated production rates for 1500 reflectors, number of personnel and skill levels, time lines, basic parts list, photographs, documentation/drawings.

Task 3.1.1 Sub-Total: 48 hours Professional, 24 hours Technical Support, 4 hours shop support

Task 3.1.2 – Drive Unit

Applicable material developed during the drive unit development program will be assembled to provide a tooling description, factory floor layout, process for

manufacturing and assembly, estimated production rates for 1500 drive units, number of personnel and skill levels, time lines, basic parts list, documentation/drawings.
Task 3.1.2 Sub-Total: 36 hours Professional, 18 hours Technical Support, 4 hours shop support

Task 3.1.3 – Pedestal

Applicable material developed during the pedestal development program will be assembled to provide a tooling description, factory floor layout, process for manufacturing and assembly, estimated production rates for 1500 pedestals, parts list, documentation/drawings.
Task 3.1.3 Sub-Total: 24 hours Professional, 6 hours Technical Support

Task 3.1.4 – Foundation

Applicable material developed during the foundation development program will be assembled to provide an installation description and estimated production rates for 1500 foundations, parts list, documentation/, drawings, etc.
Task 3.1.4 Sub-Total: 16 hours Professional, 4 hours Technical Support

Subtotal, Task 3.1 – 124 hours Professional, 52 hours Technical Support

Task 3.2 Tower/Tower Reflector Subsystem

The tower/tower reflector subsystem consists of the tower structure, the tower reflector support structure, and the tower reflector facets. The manufacturing, assembly, and installation sequence of these assemblies will be developed to the level of detail necessary to describe the major activities. This effort will support the Egyptian In-Country activities. The basic designs of the tower, tower reflector support structure, and tower reflector facets have been developed under the USISTF program, and additional design and test efforts have been conducted as part of a Boeing contract to UAH and as part of various student projects, at no cost to the Grant. The results of this work will be updated to include certain improvements in the design. In addition, the optical analysis of Task 2.3 will determine the tower height and tower reflector size; this information is needed to update the design as well. Supporting information on the production, assembly, and installation sequence was originally planned to be acquired from John Andrews Tower Company and Geometrica to assist Egypt in assessing the installation sequence, personnel, and skill levels required for this subsystem. However, we are no longer able to obtain such tower information from John Andrews Tower Company, in large part due to illness of their president. Much of this work will be conducted by Nelson Jones, the original designer of the tower and tower reflector, and co-holder with Dr. Blackmon of the patent for the Geometric Dome Stowable Tower Reflector.

Task 3.2 – Basis of Estimate:

Task 3.2.1 Tower Structure

Provide drawings and assembly sequences for the tower structure.
Task 3.2.1 Sub-Total: 12 hours Professional, 80 hours Consultant

Task 3.2.2 Tower Reflector Support Structure

Provide drawings and assembly sequences for the tower reflector support structure, in coordination with Geometrica, Inc.
Task 3.2.2 Sub-Total: 16 hours Professional, 48 hours Consultant

Task 3.2.3 Tower Reflector Facets

Provide drawings and photos of tower reflector design with refinements resulting from thermal/optical tests. Describe assembly procedure and initial alignment.
Task 3.2.3 Sub-Total: 16 hours Professional, 36 hours Consultant

Subtotal, Task 3.2 – 44 hours Professional, 164 hours Technical Support

Task 4.0 – Subsystem Design and Development

The effort associated with the UAH responsibilities will be conducted in accordance with the original plan, with the emphasis on refinements to requirements and design and development of the Heliostat, Tower, and Tower Reflector Subsystems. In addition, the requirements and design of the aperture cover and target, and the Digital Image Radiometer Beam Characterization and Alignment subsystem will be developed. Tasks that were part of the original SOW that will be postponed for the selected Industrial Participant and Israeli contractors to conduct include: Master Control, Secondary Concentrator Design, Receiver Design, and Power Conversion Unit requirements and preliminary design. The heliostat controller effort will also be postponed and will be the responsibility of the selected Industrial Participant. Technological advances have rendered the design developed and tested in the late 1990s obsolete, since more advanced, lower cost sensors and processors are now available, and their continued development promises even further improvements.

It is critical that pre-production verification tests be conducted to validate the heliostat design. These activities will include the following.

Task 4.1 Heliostat Development and Test

The heliostat development and test will include completion of the heliostat reflector fabrication, testing of the reflector, and assembly on a refurbished drive unit and pedestal. The drive unit will undergo tests, and the fully assembled heliostat will undergo performance tests. These tasks are delineated in the following.

Note that Task 4.1 is approved per DOE Letter (November 7, 2005) and no additional costs over that approved are required for this effort.

Task 4.1.3 Drive Unit Development and Test

Two azimuth-elevation drive units were fabricated under the USISTF program; one was delivered to Israel with the elevation actuator and tested, but this assembly has since been destroyed due to Value Added Tax and Import Duty requirements. The second drive unit will be disassembled, cleaned, reassembled, and installed on the pedestal. It will be modified with a set of limit switches such that accelerated life tests can be conducted. The drive unit performance will be assessed, including break out voltage and current required to initiate motion, maximum speed under ambient conditions, variations in torque as a function of azimuth angle, and power consumption under simulated operational loads.

The elevation actuator will also be installed on the azimuth drive unit and connected to the reflector facet. It will be modified with a set of limit switches such that accelerated life tests can be conducted. The elevation actuator performance will be assessed, including break out voltage and current required to initiate motion, maximum speed under ambient conditions, and power consumption under simulated operational loads.

Both azimuth and elevation units will then be programmed to undergo accelerated life tests by cycling the units over a substantial range of acceptable angles in azimuth and elevation repeatedly, at relatively high rates, with periodic tests to compare the performance characteristics noted above. We anticipate conducting these tests for at least 100 cycles per day for approximately 4 months, for a total of 12000 cycles; this is the equivalent of over 30 years of daily operation. Issues with wear, changes in performance parameters, maintenance, etc., will be documented. These tests are necessary prior to a commitment to full-scale production; they were originally planned to be conducted as part of the USISTF program, but were not completed in part due to funding limitations.

We will conduct this effort with support from the original subcontractor, HiTek Services, Inc. They will be responsible for adding limit switches, counters, and reversing diode circuits for the zero to 36-volt motor drive circuit and conducting continuity, integrity, and initial operational tests. These limit switches will allow accelerated life tests to be conducted on the drive unit at UAH.

Disassemble, clean and refurbish drive unit (azimuth and elevation) Professional-2 hours, Technical Support, 8 hours
Re-install on pedestal Professional-2 hours, Technical Support, 6 hours
Setup batteries/power supply for continuous tests of both azimuth and elevation drives for continuous, accelerated life tests: Professional-2 hours, Technical Support, 6 hours.
Develop and document test plan: Professional-8 hours, Technical Support-8 hours
Conduct and monitor tests for a period of approximately four months, or as required for 12,000 cycles, or to failure. Professional-8 hours, Technical Support-36 hours
Tear-down, inspect, and document wear, problems encountered, etc. (once per month or 3,000 cycles, whichever occurs first) Professional-16 hours, Technical Support-48 hours
Document results Professional-16 hours, Technical Support-16 hours

Hardware:
Three 12-volt batteries at $50 each, total of $150
Miscellaneous Hardware, $100

Subcontract: $5,000
Miscellaneous UAH Machine Shop Support: 16 hours

Total Task 4.1.3: Professional-42 hours, Technical Support-128 hours, Shop-16 hours, Hardware-$250, Subcontract $5,000

Task 4.2 Tower Design and Development

The tower size will be modified as a result of the optimization analysis of Task 2.3. It will be necessary to modify the tower design as a result of this. Additional loads analysis will be conducted, the tower structure drawings updated, and estimates and/or quotes developed. Part of this effort will be conducted by Nelson Jones, a consultant and co-holder of the patent for the Stowable Tower Reflector, with Dr. Blackmon. Also, Mr. Jones was the design engineer responsible for this effort during the period that McDonnell Douglas/Boeing was conducting the USISTF program; this will ensure continuity of the effort and minimize costs. Part of this effort will be the refinement of the design to allow the tower reflector to be raised or lowered, as required due to high wind conditions. These refinements will include the hardware selection and costs for the motors, brakes, controls, locking mechanisms, and other ancillary hardware.

Consultant: 120 hours
Professional support: 32 hours

Task 4.3 Tower Reflector Development and Test

UAH has a tower reflector facet and a Geometrica geodesic dome structure (approximately 24’ in diameter) as shown in **Figure 4.3.1 and 4.3.2**. Tests have been conducted on this hardware to assess long-term exposure/life issues, structural integrity, and thermal performance of the facet at one-sun, cooled by water. These tests were conducted in part as student projects at UAH at no cost to DOE. Additional tests will be conducted to assess the flow loss (critical to determining the proper layout for the coolant flow of the system on the tower), temperature as a function of higher solar concentrations, and alignment sensitivity and stability. We will also set up the Geometrica support structure, currently located at NASA Marshall Space Flight Center, in the UAH Solar Test Area. (Note that UAH has completed this support structure disassembly, transportation, reassembly, and exposure test as part of student projects at no cost to DOE. We will conduct deflection tests under simulated static loads.

Figure 4.3.1 Tower Reflector Support Structure Assembled at NASA Marshall Space Flight Center

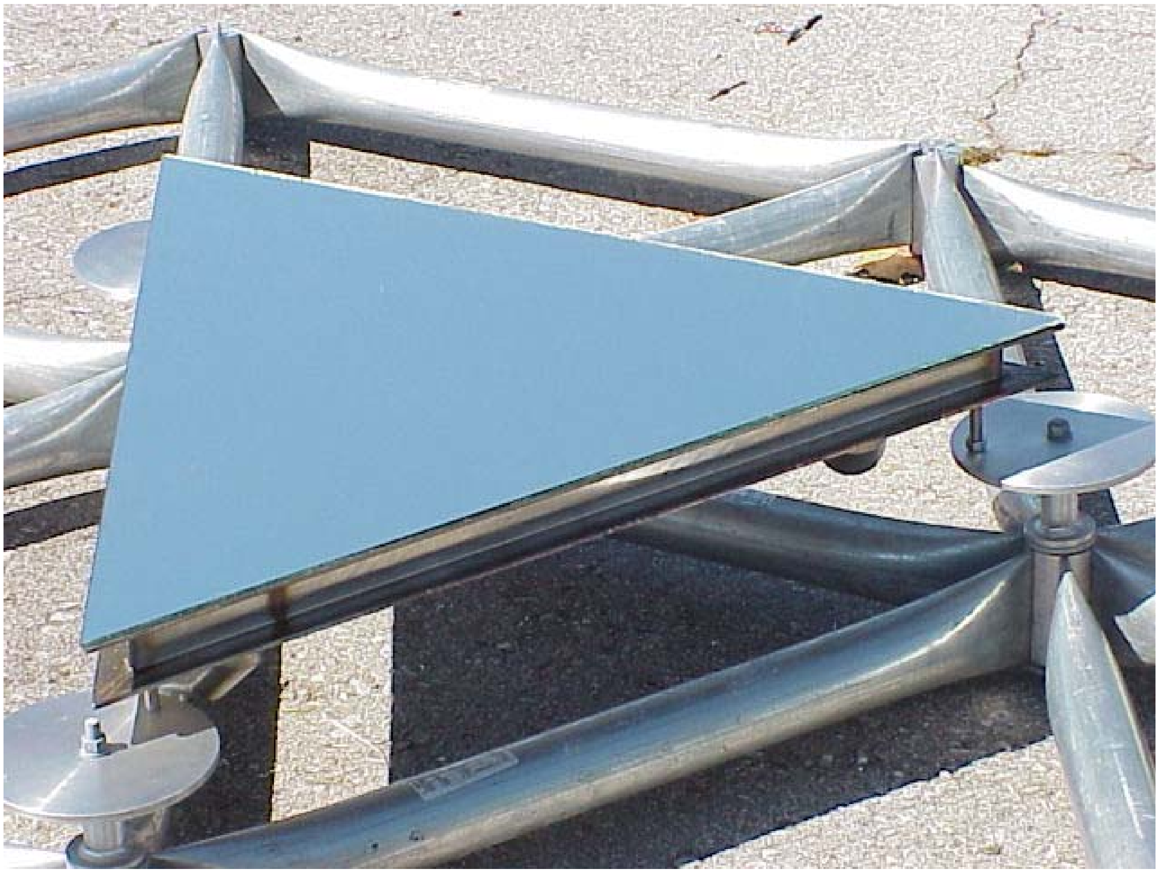


Figure 4.3.2 Tower Reflector Facet Installed on Geometrica Tower Reflector Structure

Task 4.3 Basis of Estimate

Support structure disassembly, transportation to UAH: Professional-4 hours, Technical Support, 8 hours *Completed. No additional funds required.*
Support Structure reassembly at UAH: Professional-2 hours, Technical Support, 8 hours *Completed. No additional funds required.*
Structural deflection tests: Professional-2 hours, Technical Support, 6 hours
Setup for high solar flux tests: Professional-4 hours, Technical Support, 12 hours
Analysis and Documentation: Professional-4 hours, Technical Support, 8 hours

Previous Subtotal: 16 hours Professional, 42 Technical Support
Current Subtotal: 10 hours Professional, 26 hours Technical Support

Task 4.4 Secondary Concentrator

This task is the responsibility of Rotem Industries, Ltd and is not included herein. A TBD level of effort would be funded through the Industrial Participant/Prime Contractor for Rotem technical support.

Task 4.5 Receiver

This task is the responsibility of Rotem Industries, Ltd and is not included herein. A TBD level of effort would be funded through the Industrial Participant/Prime Contractor for Rotem technical support.

Task 4.6 Power Conversion Unit

This task is the responsibility of Ormat Industries, Ltd and is not included herein. A TBD level of effort would be funded through the Industrial Participant/Prime Contractor for Ormat technical support.

Task 4.7 Master Control

This task is the responsibility of UAH but the major part of this effort is not included herein pending selection of the Industrial Participant/Prime Contractor. It is anticipated that this effort will be conducted in the fabrication/installation phase. Also, it is likely that technology advances will make this aspect of the system more cost effective in the time required to complete the System Definition of Phase 1 and initiate the fabrication/installation of Phase 2. However, the activity associated with the definition of the Digital Image Radiometer (DIR) Beam Characterization System (BCS) and the Tower Reflector Alignment System (TRAS) will be conducted by UAH in order to provide this specialized technology to the Industrial Participant/Prime Contractor. This effort includes optical tests of the tower reflector facet alignment as mounted on the Geometrica Dome Tower Reflector Support Structure to validate the approach for obtaining cant angle data on the facets.

Basis of Estimate Task 4.7

Definition of the Digital Image Radiometer (DIR) Beam Characterization System (BCS) and the Tower Reflector Alignment System (TRAS): Professional-16 hours

Modification of tower reflector facet for optical test: Professional-4 hours, Technical Support-2 hours
Simulated optical test with at night with DIR light panel “pin-point” light sources at the distances required for the Tower Reflector in its DIR Alignment position: Professional-4 hours, Technical Support-8 hours.
Documentation: Professional-8 hours, Technical Support-2 hours.

Subtotal Task 4.7: 32 hours Professional, 12 hours Technical Support

Task 5 Balance of Plant

This task will be the responsibility of the selected Industrial Participant/Prime Contractor.

Task 6 Plant Logistics/Operations and Maintenance

This task will be the responsibility of the selected Industrial Participant/Prime Contractor.

Task 7 A&E/Construction Management

This task will be the responsibility of the selected Industrial Participant/Prime Contractor.

Task 8 Cost Analysis

UAH will assemble and document the USISTF cost analysis results such that this information will be in a useful form for the Industrial Participant/Prime Contractor. Results will be organized into Work Breakdown Structure sub-elements and provided, with Basis of Estimates, to facilitate refinement, revision, and to avoid the loss of these important data. It may be necessary to protect certain data such that it cannot be released until after completion of appropriate Non-Disclosure Agreements; these data will be marked proprietary and provided only to DOE.

Basis of Estimate, Task 8
Professional: 80 hours
Technical Support: 40 hours

Task 9 Development of Agreements

This task will be the responsibility of the selected Industrial Participant/Prime Contractor.

Task 10 In-Country Manufacturing, Installation, and O&M Assessment

This task is to be conducted by the Industrial Participant. However, UAH proposes to provide an initial assessment that can be conducted prior to the selection of the Industrial Participant. Part of this task can be cost-effectively conducted in conjunction with the various meetings held with NREA in preparation for the Cairo Conference, and at the Cairo Conference itself. The objective is to:

1. obtain a list of potential Egyptian companies from NREA,
2. engage in discussions with representatives of these companies to explain the scope of the program, the opportunities for manufacturing, installation, and operations and maintenance support,
3. to obtain commitments or expressions of interest,
4. obtain cost data (labor rates, skill levels, etc.) or cost quotes or estimates, as appropriate, and
5. document the findings for transfer to the Industrial Participant

Previous Estimate
Labor: 80 hours Professional, 40 hours Consulting Support, 8 hours Shop Support

This task could not be conducted by UAH since the Tri-Lateral meeting that was to take place in Egypt, was instead conducted at UAH in April 2005. As a result, there was no opportunity to develop the information noted above. This task is now planned to be conducted by the selected Industrial Participant/Prime Contractor in its totality.

The following draft document was in preparation by DOE Headquarters, through Dan F. Melvin's office. UAH provided various inputs and reviewed this working document. The following document is the latest version available prior to its transmittal to Congress. It contains a brief summary of DOE's interest in Noor al Salaam ("DOE will continue to support the Noor Al-Salaam project as it seeks an industrial partner and moves toward deployment.").

Report on the
Agreement with the
Ministry of Energy and Infrastructure of Israel
Concerning Energy Cooperation

Outline of Request

Earlier this year, Congress requested in H.R. 6.316 [check cite, should be jt committee?] that the Secretary of Energy submit to the Committee on Energy and Natural Resources and the Committee on Foreign Relations of the Senate and the Committee on Energy and Commerce and the Committee on International Relations of the House of Representatives this report on cooperation under the Agreement between the U.S. Department of Energy (DOE) and the Israeli Ministry of Energy and Infrastructure (MONI) Concerning Energy Cooperation (the "Agreement") to describe:

> "(1) the ways in which the United States and Israel have cooperated on energy research and development activities under the Agreement;
> (2) projects initiated pursuant to the Agreement; and
> (3) plans for future cooperation and joint projects under the Agreement."

This report is prepared in response to Congress' direction.

Background and history of agreement:

The Department of Energy's (DOE) bilateral cooperation with Israel began in 1984 when DOE signed an agreement with the Israeli Ministry of Energy and Infrastructure (MOEI) for cooperation in energy research and development. Under this agreement, a number of projects were undertaken during the 80's by DOE and Israeli research institutes in the areas of solar energy, wind energy, passive solar, fluidized bed combustion, and shale oil. The agreement was renewed once in 1986 and then expired in 1991.

On February 1, 1996, DOE and the Israeli Ministry of Energy and Infrastructure, since reorganized as the Ministry of National Infrastructure (MONI), signed the Agreement in energy research and development to establish a framework for cooperation. The Agreement facilitates scientific visits to each country's national research facilities and makes possible joint research projects to develop new energy technologies that will provide power for the 21st century. Areas of energy technology cooperation covered by the Agreement include renewable energy; energy efficiency; fossil energy including oil, gas and coal; and electric power production and transmission. Further, the MOU encourages the development of energy projects which are of regional interest and could enhance the Middle East peace process.

When the Secretary of Energy signed the renewal of the Agreement in February 2000, cooperation between DOE and MONI resumed. However, the projects that were begun following the renewal quickly slowed due to the collapse of the Middle East peace process.

Currently, there are three implementing arrangements under the MOU with MONI covering renewable energy, hybrid buses, and high temperature super-conductivity. Current activities under the Agreement have been in the form of meetings between scientists to discuss the development of high temperature super-conductivity, joint demonstration and testing of advanced battery technologies, and joint design and study of combined-cycle solar beam and natural gas technology with the intention to construct a demonstration power plant.

In addition to these activities, DOE co-sponsored a conference on renewable energy in Israel in 2003 titled the "Cooperation for Energy Independence of Democracies in the 21st Century" (further information is available at www.energycooperation.org), which brought together high-ranking officials from six countries, including Israel. The conference was put together with the support of DOE, MONI, and the American Jewish Congress. As a result of this conference, Argonne awarded a contract to Tel Aviv University in the area of … ??? [10/19 DFM call to Harvery Drucker, Argonne NL and Univ. of Chicago]

Implementing Arrangements:

On February 22, 2000, two Implementing Arrangements to the Agreement were signed; one for Cooperation in the Field of Renewable Energy and a second for Cooperation in the Field of Electric and Hybrid Buses. Following the signature of these sub-agreements, a third Implementing Arrangement on Cooperation in the Field of High Temperature Superconductivity was signed on October 23, 2001. The activities undertaken pursuant to these Implementing Arrangements are described in detail below.

Implementation Agreement 1 for Cooperation in the Field of Renewable Energy:

In the area of renewables, DOE has been working with Israel on solar technology. This is a trilateral effort among DOE, the Egyptian New and Renewable Energy Authority (NREA), and the Weizmann Institute of Israel to demonstrate a 10-Megawatt Integrated Solar Combined Cycle Power Plant, named "Noor Al Salaam", or Light of Peace, at an appropriate site in Egypt. The solar If feasible, this project, which combines U.S. heliostat technology built by Boeing and Israel's solar beam down technology with natural gas to power high efficiency combined cycle gas turbines, could have many applications in a region with ample resources of natural gas and solar energy. This activity is supported by DOE, the U.S.-Israel Science and Technology Foundation, the Egyptian NREA, the Boeing Company, Ormat Industries, Ltd., Rotem Industries, Ltd., the University of Alabama at Huntsville, and the Weizmann Institute of Science. A pilot program of this technology is being demonstrated at Israel's Weizmann Institute.

U.S. AID has provided an initial $1 million for a project definition and feasibility study. The University of Alabama at Huntsville is currently seeking a U.S. industrial partner to serve as the prime contractor and systems integrator for the project. The prime contractor will undertake plant definition and then seek funds to support construction. The estimated cost to construct the plant is between $20-30 million. Egypt is willing to provide in kind support for a commercial demonstration of this project that would build a 10 MW thermal (3 MW electric) plant – land, labor, and an electrical grid connection. Recently, Jordan has also indicated that they are interested in participating in this project as well.

Thus far, the partners have received \$2.7 million in support from the U.S.-Israel Science and Technology Foundation. Of these funds, \$1.4 million was contributed to support development of the project in Israel and an additional \$1.3 million was provided to Boeing and McDonald-Douglass with 100% matching by the companies.

Implementation Agreement 2 in the Field of Electric and Hybrid Buses

DOE also has an implementing arrangement with Israel on hybrid bus technology. The objective of this agreement is to compare the advanced zinc-air battery system developed by Electric Fuel Corporation (EFC), a subsidiary of Israel's Arotech Corporation, with other battery systems developed by DOE as they are applied to electric buses used in urban public transportation both in the United States and in Israel. EFC is a U.S. corporation with R&D and manufacturing facilities in Israel and in Auburn, Alabama and is recognized as one of the leaders in zinc-air fuel cell technology and applications.

On November 28, 2001, EFC announced the first on-road demonstration drives of its zero-emission, electric bus using zinc-air fuel cell system. The bus project was funded by EFC, the U.S. Federal Transit Administration, General Electric Corporation, and the Regional Transportation Commission of Nevada. A benefit of this cooperation was the successful testing of General Electric's drive systems and power control as well as benchmarking of the zinc-air battery system in comparison with other battery technologies. Phase III testing concluded that the zinc-air all-electric bus can be introduced commercially and can be economically comparable to diesel-hybrid buses. The report on Phase IV of the FTA's Zero emission zinc-air bus project is expected early in 2006 after which, testing will have been completed.

Implementation Agreement 3 in the Field of High Temperature Superconductivity

The third implementing arrangement with Israel on high temperature superconductivity (HTS) was signed on October 23, 2001. High temperature superconductors are ceramic materials that carry electricity without loss and operate at temperatures that permit the use of inexpensive refrigeration, such as liquid nitrogen. The use of superconductivity can led to great efficiencies in energy-usage by removing the loss of electricity during electricity transmission (grid loss). The energy savings from grid loss increases the power transmission capacity of existing power plants and by making them more productive lessens the need to build additional plants.

The activities under this implementing agreement support the multilateral cooperation in superconductivity under the auspices of the International Energy Agency's Cooperative Programme for Assessing the Impacts of High-Temperature Superconductivity on the Electric Power Sector. The objectives of this cooperation are to better enable each party to keep abreast of progress being made toward applications in the power sector, to catalyze concerted consideration of issues that have not yet been subject to definitive attention by individual participants, and to provide a network and venue that may lay the basis for future international co-operation on joint projects.

The Operating Agent for the IEA HTS Agreement is Argonne National Laboratory. Israel's Tel Aviv University is active in the cooperation at the IEA where it currently holds the Executive Chair. The work program is focused on the exchange of information.

Activities include preparation of essays on outstanding issues; fostering scientific debate and appropriate action by holding workshops and seminars; evaluating and synthesizing the results of on-going work; establishing a contacts register of names, addresses of institutions and published documentation; and promoting international co-operation and planning that may lay the basis for future joint projects, including hardware projects.

Future Directions

The Department of Energy looks forward to working with the Ministry of National Infrastructure in support of these activities. With the renewal of the IEA Implementing Agreement on HTS in the summer of 2005, the partners will pursue new areas of interest including super-conducting fly-wheels and HTS as an energy storage mechanism. DOE will continue to support the Noor Al-Salaam project as it seeks an industrial partner and moves toward deployment. Finally, DOE looks forward to the report on the completion of Phase IV of FTA's testing of the zinc-air battery system.

APPENDIX B

Flow Analysis for the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver System for Potential Application to Noor al Salaam Project

Flow Analysis for the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver System for Potential Application to Noor al Salaam Project

J. Ben Bramblett Kevin R. Nichols James B. Blackmon, Ph. D.
University of Alabama in Huntsville
Propulsion Research Center

Introduction

The U.S./Israel Science and Technology Foundation (USISTF), with sponsorship from the Department of Commerce U.S./Israel Science and Technology Commission, co-funded the development of a High Concentration Solar Central Receiver System, based on high temperature receiver technologies conceived and initially developed in Israel as part of their MAGNET/CONSOLAR program. The USISTC was formed by President Clinton and the late Prime Minister Rabin to promote peace in the Middle East through economic development and to encourage technological collaboration on advanced technologies. The High Concentration Solar Central Receiver program was selected by the USISTC to advance the solar technology conceived by the Weizmann Institute of Science and in part developed by the Israeli MAGNET program by the Institute, together with Ormat Industries, Ltd, and Rotem Industries, Ltd. The USISTF program was led by The Boeing Company, with Ormat and Rotem as associate contractors, and the Weizmann Institute of Science as a subcontractor to Boeing.

The USISTF program involved all of the primary technologies associated with this new solar power system concept. In addition to the further development of heliostats, the tower reflector, and a master control system, it integrated a turbine generator with a special high temperature air receiver as a hybrid solar/gas system to produce 250 kilowatts electricity from solar heated air and natural gas combustion products. This system underwent integration and testing at the Weizmann Institute, with the exception of a full hybrid operation of the turbine with solar heated air. The Weizmann heliostat field is shown in **Figure 1** and the tower mounted reflector is shown in **Figure 2**.

Following the integrated system tests, a demonstration plant was planned for design and construction in Egypt. This project, termed Noor Al Salam (Light of Peace) was for a 10 to 15 Megawatt hybrid solar/natural gas power system, involving a relatively high percentage of natural gas power. It was planned as a joint U.S./Egypt/Israel technology development program. The first phase of this program was funded by the U.S. Agency for International Development, through the Department of Energy. **Figure 3** illustrates such a plant. However, in 2007, the program was cancelled due to changes in objectives for USAID. This report documents an analysis of options for integrating the solar and natural gas powered flows for this hybrid system so as to achieve optimum efficiency. A separate report contains all of the computer program results; this report is approximately 2000 pages in length, and therefore is provided separately to DOE and is not included here.

Figure 1 - Heliostat Field at Weizmann Institute of Science, Rehovot, Israel

Technical Challenge

During the development of the baseline design for the Noor Al Salam program, an issue arose regarding integration of the natural gas with the solar heated air in a hybrid solar/natural gas system. It became necessary to develop a more detailed understanding of the flow configuration impact on the system performance, so that the optimum system could be developed. The basic issue was whether the flow from the compressor should be routed through the solar receivers in parallel or in series, or as a combination. There was also the issue of whether the turbine could be operated without loss of efficiency by having the air flow through the receivers when there was little or no solar irradiance, and the turbine was operated on natural gas alone. In our analysis, we show that there is a significant cost improvement by having a fully parallel flow, and by having a shut off valve such that there is no flow of air from the compressor through the receivers when no solar irradiance is available.

Figure 2 - Tower Mounted Reflector at Weizmann Institute of Science

Results of this effort have shed new light on the flow configuration options and the impacts on system performance. Also, this code is available to conduct further studies of a more detailed nature, to better guide the design of the system.

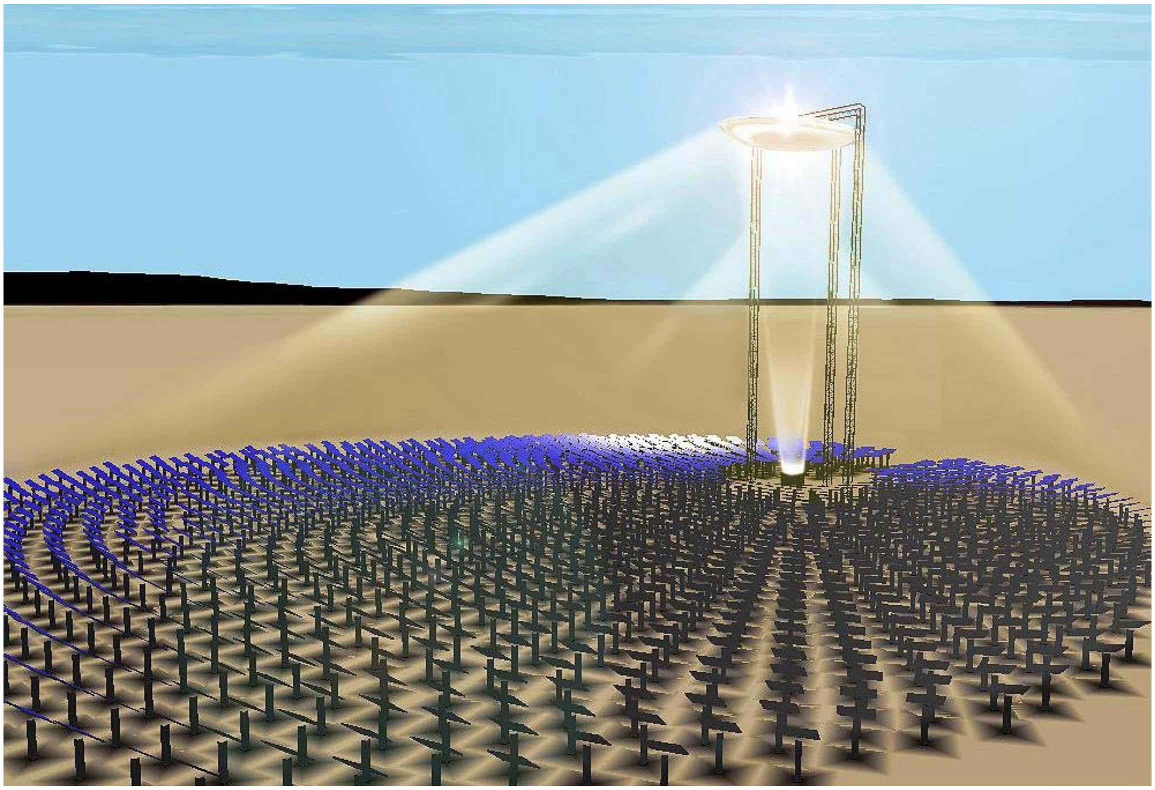


Figure 3 - Planned Noor Al Salam High Concentration Solar Central Receiver-Zaafarana, Egypt.

Technical Discussion

With the original High Concentration Solar Power System, as first proposed for the USISTF study, all of the flow from the compressor would pass through the solar receivers and then be returned to the turbine combustor, where a relatively small percentage of the thermal energy would be provided by burning natural gas. In this configuration, the air temperature needed must be high, in order to be used by gas turbines, and thus the flow proceeds through a series of preheaters, then through intermediate temperature receivers, and finally exits through a high temperature receiver. The supplemental natural gas is used in part to provide fine tuning control of the gas temperature, especially during periods of intermittent clouds. This supplemental power may also be used during the early morning and late evening, when there is less power available from the field due to the cosine effect. Depending on the percentage of power available from the supplemental natural gas, this may result in less net power being produced by the turbine, and thus the turbine could be operated under off-nominal conditions. Below some amount of solar power, it would thus be relatively inefficient to operate the turbine.

Hybrid systems of this type can be operated differently, however, with a much larger percentage of the thermal energy provided by the natural gas, rather than the solar. This situation arises when the solar flux is relatively low, as in the morning and afternoon, or for plants that have large combined cycle gas turbines and relatively small solar thermal inputs. The advisability of passing all of the flow through the receivers becomes questionable in the latter case. Having all of the flow pass through the receivers raises the overall pressure loss, relative to a flow that would be passed directly from the compressor outlet to the combustor inlet for the conventional turbine operated without solar energy.

This increased pressure loss resulting from configuring the turbine to use solar energy would decrease the pressure ratio of the turbine, thus reducing the efficiency and power. Depending on conditions, this effect may or may not be significant.

For a hybrid system with a relatively large amount of power provided by, say, natural gas, having a parallel flow path would allow some part of the flow to pass through the receivers, with the remainder, and most likely majority of the flow, passing directly to the combustor inlet. With this configuration, it would also be necessary to control the flow, in part by adding a flow constriction in the line to the combustor from the compressor, in order to have sufficient flow through the receivers to prevent excessive receiver temperatures. Since the solar power is available only during the day (unless thermal storage is available), the system would operate with additional pressure drop losses and the loss of some of the thermal energy by re-radiation and conduction and convection losses when the system was operated without the solar input. For this situation, it may be necessary to add a more complex flow control and piping system, in order to have the optimum performance and cost. For example, one or more flow control valves would be used so that under night or cloudy conditions no flow would pass through the receivers, but would go directly from the compressor to the combustor inlet. As discussed further in the following, this version of a hybrid system would also benefit from a parallel flow through the receivers, as well as a parallel flow to the combustor.

Other flow related questions must be examined. In the original concept, the flow of the air from the compressor first passed through a series of peripheral heaters, located around a central, high temperature receiver. In this arrangement, one or more sets of peripheral "pre-heaters" increased the temperature of the air such that when it exited the central receiver, the maximum attainable air temperature resulted. The advantage of this approach was that the system could be operated at or near its design point as a "solar-only" power conversion system. Temperatures of the order of 1200 to 1400 C were obtainable in this configuration, and thus high performance gas turbines could be used, in a "solar only" mode, at least near the design point. Even higher temperatures can be obtained with this configuration, if needed. (The design point was typically selected as the maximum solar flux condition, at solar noon, on a specified day, such as the Summer Solstice.)

However, one concern with this approach was that it would require a re-design of the turbine combustor, since the injectors are not designed for inlet air temperatures that exceed something of the order of 800 C. The injector and combustor re-design and qualification effort would be a costly and time-consuming process and it is not yet apparent that turbine manufacturers are interested in doing this for a limited market. Boeing also found in its marketing studies that the solar-only configuration was limited to the relatively far-term market in remote areas. It would be difficult to build early plants in remote areas, and no specific opportunity was found that would result in a demonstration or commercial plant.

The near-term market required the use of substantial percentages of natural gas. This preference for hybrid systems for the near-term market was the result of a number of factors. For example, the markets in Spain, Egypt, and the U.S. for solar power plants favored plants that could provide dispatchable power, which would always be available, even if the solar energy were not available, and could also be controlled. This dispatchable power approach was favored by Egypt for the Noor Al Salam plant, and thus a relatively large turbine was used for the baseline design.

The situation for the Spanish market was more complex. There, the Spanish Royal Decree allowed for a substantial part of the power to be provided by natural gas, but the near-term market preferred a “stand-alone” system. Use of fossil fuel (natural gas) as a supplement was allowed. Up to10% of the solar power could be provided by fossil fuel in order to stabilize and control the air temperature entering the power conversion unit (i.e., turbine). The Decree allowed this 10% to be priced at their subsidized solar market value. Since the power cost associated with the natural gas was a fraction of the cost of the solar thermal part of the system, this 10% produced a significant increase in the return on investment for such hybrid plants. Use of larger turbines, with their lower specific cost, higher efficiency, and moderate combustor entry temperature also improved both the economics and the engineering aspects of the design, at least in principle. However, there were concerns over the fair pricing of such a system, which used both a subsidized solar power price and a current market price for the natural gas (except for the 10% of power allowed, noted above). The situation in Spain is still in a developmental state, and expectations are that there will be changes to the requirements and benefits of subsidized solar power. Since the system we are developing has not yet reached the commercialization stage, we are attempting to design a demonstration plant that has the ability to verify technologies suitable for the entire spectrum of hybrid power, ranging from essentially standalone solar to a gas turbine system with a relatively small amount of solar power.

The requirement for dispatchable power would be achieved most cost effectively by combining the solar plant with a fossil fuel, especially natural gas, and this is easily accomplished with the Israeli design. Alternatively, thermal energy storage could be used, but these systems are relatively costly and not at the point where proven, high temperature systems are available, especially for this new configuration in the near-term. Thermal storage systems are not yet available that could operate at the high temperatures of a gas turbine, without using supplemental heating, and are therefore restricted primarily to steam turbines. A combined cycle gas and steam turbine system or a simple gas turbine system has a substantial efficiency advantage over steam turbines. Therefore, any system that can include a gas turbine can offer performance and cost improvements over a steam turbine system.

There is another effect worth considering. There is an extensive database on turbine performance and cost that shows that efficiency increases with increasing turbine power output, and the cost per kilowatt decreases. Therefore, Boeing showed in its financial analysis that relatively large turbines, with relatively small percentages of solar energy input, provided the best return on investment, especially with subsidized solar plants, in which the solar power commanded a premium price. These larger turbines also provided an important means of mitigating risk, since the system could be operated with a positive return even in the unlikely event that the solar power system failed. The return on investment (ROI) also was improved because the turbine could be brought on-line relatively quickly, and would thus be producing revenue while the solar part of the system was being installed. Since ROI is strongly dependent on the period between the investment and the generation of revenue, having a system that can produce revenue early on has an economic advantage.

When solar power, which is capital intensive, is used without thermal storage, or hybrid fossil fuel, the levelized energy cost (cents per kilowatt hour) becomes relatively high, in part because the capital equipment is idle for a substantial fraction of the year (night time, clouds, etc.). Various mandates also stressed the need for solar power to provide a fraction of the needed growth in power, but no initiative was found in any country for which new sources of power would rely solely on solar.

These cost and marketing issues were important factors in determining that the first plants would likely be hybrid plants, for which both natural gas and solar energy would be needed to best meet the objectives and for which the solar annual energy fraction would be substantially less than that of the natural gas. It was thus important in these plans to ensure that the demonstration plant could provide supporting data for a range of system configurations and methods of operation.

There were other engineering issues related to the configuration for hybrid systems, especially with the series flow, compared to parallel flow. The series flow condition does not necessarily result in the overall optimum power production design over the course of the year, especially if a relatively high percentage of the power is provided by the natural gas. For this case, it is likely preferable to have the flow more in parallel, with a lower outlet temperature from the central receiver, with the flows from different paths joined at the combustor. The resultant temperature is lower, which simplifies the integration with the turbine combustor. The lower temperature results in less loss from conduction, convection, and re-radiation through the piping and receivers. The pressure drop of the flow is less and the turbine pressure and efficiency are thus higher. The total electrical energy generated is also likely higher than for the series flow configuration.

There is a configuration that is a mix of series and parallel flow, in which all the flow from the compressor first passes through the receivers, but these are arranged in a parallel flow path, with the flow first split as it enters the peripheral ("pre-heaters) and then split at the intermediate temperature receivers, and then all the flow passes through the high temperature central receiver.

Each of these flow configuration issues raises additional issues as to how to control the flow. For example, in parallel flows, it is usually necessary to have some means of assuring that the flow rates are essentially equal in the different parallel paths. This necessity to control the flow is even more complicated with the solar receivers, since in some versions, the flow is related to the amount of solar energy incident on the receivers, such that the outlet temperatures can be made constant. This solar flux varies with location in the solar focal zone, and it varies during the day. As a result, some means of actively controlling the flow may be necessary. Alternatively, the outlet temperatures can be allowed to vary with solar flux, and the difference between the inlet temperature compensated by additional natural gas.

A major issue is whether all of the air from the combustor should flow through the receivers, or whether a certain amount should flow directly to the combustor, with a parallel flow from the compressor passing through the receivers. With the latter flow, it may be preferable that the flow progress through the receivers in a parallel configuration, since this results in the same average outlet temperature, but with lower temperatures in the intermediate and high temperature receivers. Alternately, the flow can be partially series and partially parallel, with the final flow passing through the central receiver. The advantage of this approach is that it would allow the high temperature receiver to be verified, and thus provide a data base for operation in the solar only mode.

During night-time, or cloudy conditions, when there is no solar energy, it may also be necessary to stop all flow through the receivers to prevent both heat and pressure losses. This configuration would at least require one or more control valves, or a control valve and one or more orifices, to achieve the appropriate mass flow rates.

Given these issues and various possible system configurations and conditions, it became critical that there be a better understanding of the options for a hybrid solar/natural gas system.

As the first step in this study, we developed a model of the flow based on preliminary pipe sizes, flow rates, and flow configurations as provided by Ormat Industries, Ltd to Boeing. This condition was used in the ABZ Technologies code, using flow loss factor (K-factor) data embedded in the code for the various pipe sizes, bends, plenums, etc. as well as custom flow loss expressions for the metal and DIAPR receivers. Results were then compared with Ormat's results. The model was then made more general, and the first set of runs conducted to understand the impact of the configuration on the flow distribution, flow losses, and hence overall system performance.

In the following, the ABZ Technologies code, the models developed, and preliminary results are presented. It is important to note that one issue has become apparent as the result of the analysis, and that is the question of flow direction control. In some of the early analyses, back flow was noted, but additional pipe lengths were added to increase the resistance and more realistically model the situation; this resulted in the elimination of flow reversals. However, it will be necessary to ensure that such situations cannot occur; this may require additional analyses for the entire range of flow conditions and care in the selection of pipe sizes and configurations.

Flow Analysis

Fluid analysis was done using Design Flow Solutions (DFS) developed by ABZ Incorporated. The code includes DF Branch, which solves problems involving a single flow path, and DF DesigNet, which can solve complex networks. The program contains a database of fluids and hardware. Included in the database are equations and tables that the program uses to evaluate fluid properties. Also included are K-factors, equivalent length, and C_v values and equations for evaluating the flow conditions throughout the system. It also allows for user specified fluids and components. The database also includes specifications of standard pipe characteristics according to ANSI/ASME B36.10 and ANSI/ASME B36.19. A complete description is provided in **Reference 1** of this appendix.

The program is user friendly and easy to learn. All pieces of equipment are entered into what the program's authors call "branches." These are boxes placed onto the design field and represent all pieces of equipment through which the fluid will flow. Each branch can contain any number of components. The braches are connected together with *frictionless lines*. As the name implies, there is no pressure drop associated with them. Their sole function is to indicate to the program how the branches are connected to one another. Arrows designate the flow direction, as determined in the analysis by pressures. This attribute is useful in that it can identify the general flow path, and, in certain instances, designates flow reversals that may not be intended. This situation can then be corrected by adding more realistic components (additional lines with realistic resistance).

Discussion of Model

For this analysis, two models were created. The first model was essentially a duplication of the system developed by Ormat Industries, Ltd. The second was a revised design created to compare with the Ormat system.

The first model was created in the ABZ code based on the system provided by Ormat, but with a number of assumptions and adaptations. The number and type of components were followed verbatim from the description on the spreadsheet provided by Ormat (see **Table 1.**) and our sketch of their configuration, **Figure 4**. In the first Ormat analysis, **Table 1**, no pressure loss was assumed in the receivers. Later, Ormat made assumptions for these losses. After that, additional data and analyses were provided by Rotem such that we could include flow loss effects for the receivers.

Pipe Section No.	Mass Flow Rate	Temperature	Pressure (*)	Power	Nominal Diameter	Item	Pressure Drop	Line Details & Instrumentation	Pressure Drop Coefficient * 10⁴
	kg/s	C	bar	kW	inch		mbar		
1	35.9	390	14.19	---	22	Pipes	9.28	2 meters straight pipe,90 deg-std elbow,Lateral expansion joint,Axial expansion joint	78.45
2	35.9	390	14.18	---	22	PH Inlet Plenum	11.32	5 meters straight pipe,90 deg-std elbow,Lateral expansion joint,2 Axial expansion joint	38.24
3	2.99	390	14.16	---	6	Pipes	15.40	2 meters straight pipe,45 deg-std elbow,Lateral expansion joint, Axial expansion joint,Temperature sensor,Pressure transmiter	33.88
4	2.99	436	14.05	300		Pre-Heater	100.00	DP estimated	
5	2.99	483	14.06	---	8	Pipes	5.06	2 meters straight pipe,45 deg-std elbow,Lateral expansion joint, Axial expansion joint, Temperature sensor,Pressure transmiter	38.77
6	35.9	483	14.05	---	24	PH Outlet Plenum	8.84	5 meters straight pipe,90 deg-std elbow,Lateral expansion joint,2 Axial expansion joint	40.56
7R	5.78	483	14.04	---	10	Pipes	7.26	2 meters straight pipe,45 deg-std elbow,Lateral expansion joint, Axial expansion joint, Temperature sensor,Pressure transmiter	48.15
7H	1.2	483	14.04	---	5	Pipes	8.58	2 meters straight pipe,45 deg-std elbow,Enlarger 5" x 10",Lateral expansion joint, Axial expansion joint, Temperature sensor,Pressure transmiter	40.72
8R	5.98	532	13.94	683		Receiver	100.00	DP estimated	
8H	1.4	836	13.94	1200		High Temp. Receiver	100.00	DP estimated	
9R	5.98	584	13.94	---	12	Pipes	5.04	2 meters straight pipe,45 deg-std elbow,Lateral expansion joint, Axial expansion joint, Temperature sensor,Pressure transmiter	59.54
9H	1.4	1200	13.93	---	8	Pipes	7.92	2 meters straight pipe,45 deg-std elbow,Enlarger 12" x 8",Lateral expansion joint, Axial expansion joint,1 inch inner insulation,Temperature sensor,Pressure transmiter	55.64
10	37.3	607	13.93	---	28	HTR Outlet Plenum	5.67	5 meters straight pipe,90 deg-std elbow,Lateral expansion joint,2 Axial expansion joint	40.40
11	37.3	607	13.93	---	28	Pipes	5.37	4 meters straight pipe,90 deg-std elbow,Lateral expansion joint,2 Axial expansion joint, Temperature sensor,Pressure transmiter	47.81
12	1.4	390	14.19	---	5	Pipes	6.93	2 meters straight pipe,90 deg-std elbow,Lateral expansion joint,Axial expansion joint	27.84
13	1.4	390	14.18	---	5	RCV Cold Inlet Plenum	9.86	5 meters straight pipe,90 deg-std elbow,Lateral expansion joint,2 Axial expansion joint	15.64
14R	0.2	390	14.17	---	2	Pipes	8.36	2 meters straight pipe,45 deg-std elbow,Lateral expansion joint, Axial expansion joint,Temperature sensor,Pressure transmiter	18.50
14H	0.2	390	14.17	---	2	Pipes	8.36	2 meters straight pipe,45 deg-std elbow,Lateral expansion joint, Axial expansion joint,Temperature sensor,Pressure transmiter	18.50
15	37.3	390	1.01	---		---	---		
16	37.68	508	1.04	---		---	---		

(*) Line downstream pressure

Total Pressure Drop between GT compressor outlet and combustor inlet = 273 [mbar]

Table 1 – Schematic of Ormat Flow Configuration Layout

First, we summarize and compare the results obtained for no receiver flow losses. The Ormat description was followed as closely as possible; however, several assumptions had to be made. Many of the components with differing diameters were connected with one another, but the type of connection was not defined. DF DesigNet will not accept direct mating of different sized equipment. As a result, "size changes", either reducers or enlargers, were introduced where appropriate. All size changes were defined as having an included angle of 60^o; that is, the reducer or enlarger had a section slope for the wall of 30^o to the longitudinal axis (60^o included angle). Obviously, these additional pieces of equipment will produce slight additional pressure losses not accounted for in the Ormat analysis. It was also apparent that the pre-heaters had been lumped together in Ormat's analysis, whereas we found it necessary to separate these, and add a section of pipe between each one, to avoid a back flow condition in the ABZ code and to simulate the header that would be required between the outlet from the compressor and the pre-heaters.

Finally, the Ormat spreadsheet evaluated pressure loss using different fluid temperatures and densities that are realistic, given the solar flux incident on the receivers. In the version of the ABZ code we used, all components are interconnected and thus the temperatures and densities cannot be varied from point to point. An attempt to do so could result in an "over specification" of the network. This can lead to difficulty in the program performing as expected or even a misleading answer. (The ABZ code is being extended by the vendor to handle temperature variations, but we do not have that version, but the effect on pressure drop is minor.)

Another assumption was made in the specification of $^r/_d$=3 for all pipe bends, to avoid impractically severe bends in the pipe. Several adaptations were made regarding plenums and descriptions of some of the components. All of the plenums were described as five meters of pipe and a 90^o bend. It was assumed that a plenum was a five-meter pipe with 90^o bends (the number corresponding to the number of pipes exiting the plenum) welded to the side of the pipe at equal distances from one another.

No entries were made for the receivers in our first ABZ model. The goal was to duplicate the results obtained by Ormat – whose program initially did not take into consideration the receivers contribution to pressure loss, since data were not available at that time. But, a precise duplication of results was not practical. Ormat's first analysis obtained a total pressure drop of 73 millibars, whereas we found a value of 353.7 millibars. Both losses correspond to a flow rate of 37.3 kg/sec. The higher loss we found would be expected because it was necessary to add such elements as the expansion and contraction lines and in our analysis, it was necessary to have additional components, as noted above.

Also, there are some questions remaining about the Ormat configuration, in that some of the pipe diameters seem excessive. For example, the pipe exiting the compressor is 22 inches diameter. The pipe at the High Temperature Receiver plenum is 28 inches diameter. Further analysis is needed to ensure that these relatively large sizes are needed and appropriate for the configuration and flow path of the various elements, especially the receivers. Having large diameters such as these could even lead to higher pressure losses, since expanders and contractors would be needed to mate the pipes to the various components, receivers, etc.

Next, the receiver flow loss factors were added, such that the pressure drops and flow rates could be determined more accurately. Ormat's analysis assumed 100 millibars pressure loss for each of the three receivers (pre-heater, receiver, and high temperature receiver). Ormat then obtained a total loss of 273 millibars. We wished to improve on this using more recent data from Rotem as well as our ABZ model, with additional details for the design configuration.

Analyses and test results were provided by Rotem for the flow losses of the metal and DIAPR receivers, as provided in Appendix C. We used the data from Rotem to estimate the K-factor for the metal receiver (i.e., the "pre-heater" or peripheral heater).

The basic approach used was to calculate the K factor for a given flow rate and pressure drop, as reported by Rotem, based on their analysis. The flow equation is:

$$K = \frac{2A\Delta P}{\dot{m}V} \text{ or } \Delta P = \frac{\dot{m}VK}{2A}.$$

With the continuity equation:

$$\dot{m} = \rho VA,$$

and the perfect gas law:

$$\rho = \frac{P}{RT},$$

we can solve to obtain the K as a function of the area of the flow corresponding to a given pressure drop, mass flow rate, and inlet pressure (the pressure drop is small, and thus inlet pressure is representative of the pressure through the receiver); we thus obtain:

$$K = \frac{2A^2\Delta P\frac{(P)}{RT}}{\dot{m}^2}.$$

From Figure 6 of Appendix C, the Hot Stream Pressure Drop as a function of the total Hot Flow Rate gives a table of representative values and the corresponding K-factors of:

Pressure Drop (atm)	**Flow Rate (kg/s)**	**K-factors**
0.025	**0.8**	**24.7**
0.04	**1.0**	**25.25**
0.075	**1.4**	**24.15**
0.15	**2**	**23.67**

With these values, we selected a K-factor of 25 as representative of the DIAPR receiver.

For the pre-heater, or peripheral receivers, which are metallic receivers, we used Rotem's value of the Pre-heater Pressure Drop of 0.2 atm to determine the flow rate to estimate the K-factor. We obtained 0.23 kg/sec at 0.2 atm. From this, we determined the K-factor of these receivers to be 53. We assumed in this calculation that the flow area was 0.32 m (length) times the width of 0.012 meters, for one of the eight trapezoidal areas, approximated here as a rectangle. However, it may be necessary to reconfirm these values with Rotem, to be sure that all values used are correct. Again, we are forced to use K-factors in the ABZ code, rather than simply using the same approach Rotem used for their total pressure drop estimate. It is also worth noting that the K-factor of 53 appears realistic for an orifice, as is used for the metal receivers. However, it would be better to have confirmation from Rotem as to the K-factor for the receivers to conduct the analysis as accurately as possible.

The resulting ABZ code flow schematic is shown in Figure 4, which has K-factors for the receivers included. Note that this schematic has a bypass control valve between the compressor outlet and the combuster inlet, shown on the left hand line of the schematic. When this valve is closed, then all of the flow must pass through the solar receivers. We have also included an On-Off valve, immediately prior to the solar receivers, such that we can prevent any flow through the solar receivers. This valve would be closed for nighttime or for substantial periods of cloud passage.

For our general schematic to apply to the Ormat case, we would have the On-Off Valve open, and our so-called Bypass Valve, closed. Thus, all of the flow from the compressor would pass through the solar receivers, prior to entering the combustor. This case resulted in a total loss for all of the flow through the receivers of 14.87 psi. Ormat obtained a value of 273 millibars, assuming 100 millibars of pressure drop for each receiver. Part of this very substantial difference between our calculations and theirs is due to the much higher pressure drops encountered in the receivers, which we have included, based on the Rotem data, and part is due to the additional flow elements required to make a complete configuration (i.e., we had to include expanders and reducers), as well as the flow losses through the bypass and On-Off valves. The pressure drops through the receivers were substantially higher than 100 millibars, as shown below in Table 2, especially for the pre-heaters.

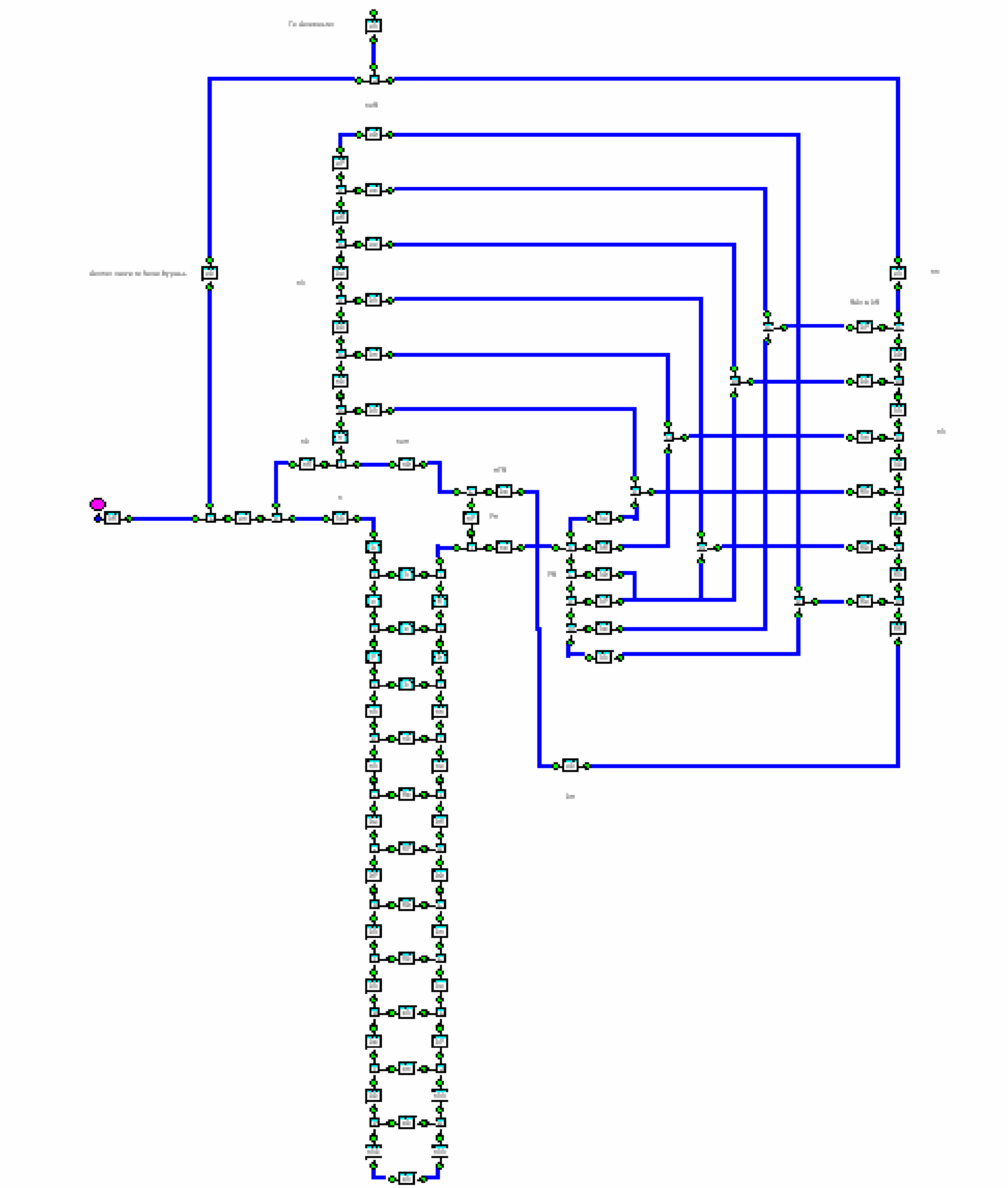


Figure 4 – Ormat Design of Solar Energy System as Modeled in ABZ Code

Table 2 – Flow Losses Based on the ABZ Code

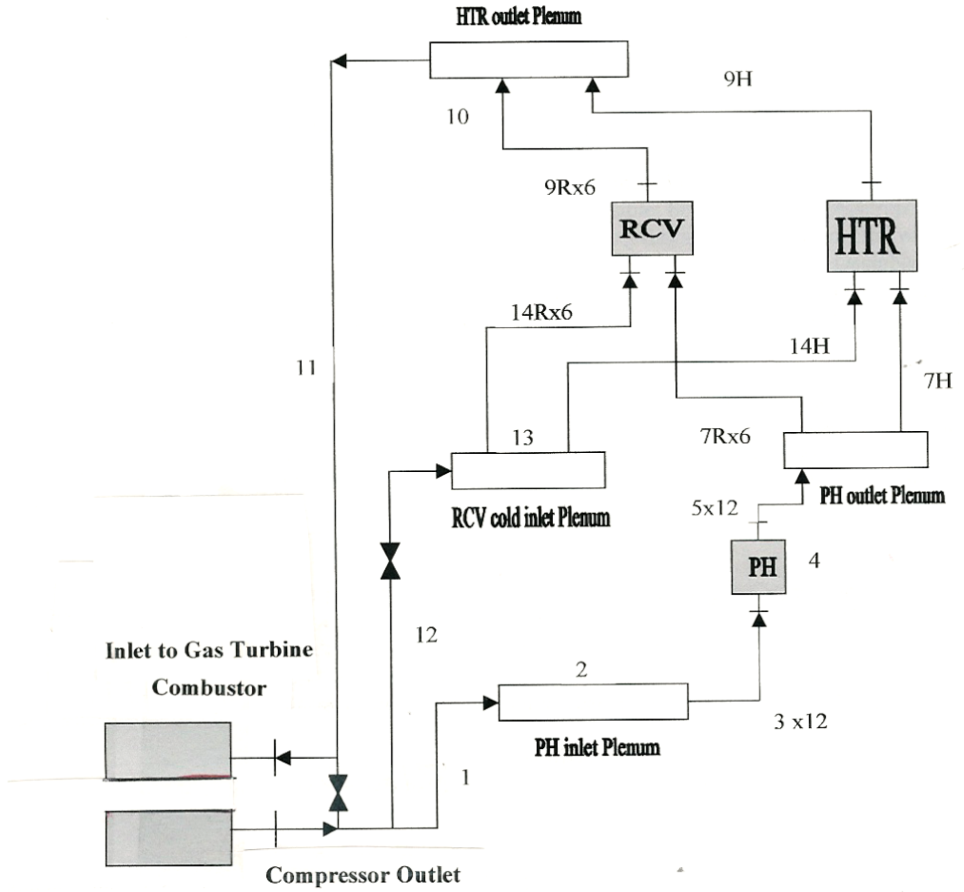
High Temperature Receiver: = 2.13 psi

Receivers:
#1 = 3.47 psi
#2 = 3.84 psi
#3 = 2.27 psi
#4 = 3.19 psi
#5 = 2.49 psi
#6 = 1.74 psi
The average pressure drop is 3.33 psi for these six receivers.

Pre-heaters
#1 = 9.89 psi
#2 = 8.80 psi
#3 = 8.12 psi
#4 = 7.31 psi
#5 = 6.73 psi
#6 = 7.46 psi
#7 = 8.31 psi
#8 = 9.21 psi
#9 = 10.14 psi
#10 = 11.03 psi
#11 = 11.87 psi
#12 = 11.87 psi
The average pressure drop is 9.145 psi.

The ABZ results are shown in Figure 5 for the nominal flow loss conditions and a flow rate of 37.3 kg/sec, and a solar receiver flow inlet pressure of 204 psia (i.e., compressor outlet pressure). Figure 5 is an Excel work sheet that allows the pressure losses for each element to be determined from the code. The spreadsheet also calculates the entering and exiting temperatures, based on the flow rates and the heat flux into the receivers.

It should be noted that there is a valve located downstream from the compressor outlet. Ormat assumes that this is a flow control valve; it is either open or closed. In their analysis, the valve is assumed to be *closed* such that all of the flow passes through the solar receiver system when there is solar insolation. It is presumably open when there is no solar insolation, such that there is only partial flow through the solar receivers.



We next assumed incident solar heat flux into each of the twelve outer, peripheral receivers to be 0.2917 Megawatts, for a total of 3.5 Megawatts. The inner ring of six receivers each had 0.5 Megawatts or 3.0 Megawatts total heat flux. The high temperature receiver was assumed to have 1.0 Megawatts. The total solar power into the receivers is thus 7.5 Megawatts.

With these assumptions, we determined temperatures out of the receivers. The specific heat at constant pressure for air is approximately 1.005 KJ/Kg degree K. With the flow rate and heat flux, the temperature exiting each of the receivers could then be calculated. We determined that the temperature out of the pre-heaters, the receivers and the high temperature receiver as provided in the spreadsheet analysis.

% Open (##)	100
K - Value	1
Cp (j/(kg*K°)	1005
Initial Temperature (C°)	390
Inlet Pressure (psi)	204.5
Outlet Pressure (psi)	202.02
Pressure Change	2.48
Total Temp Out (C°)	291.92917

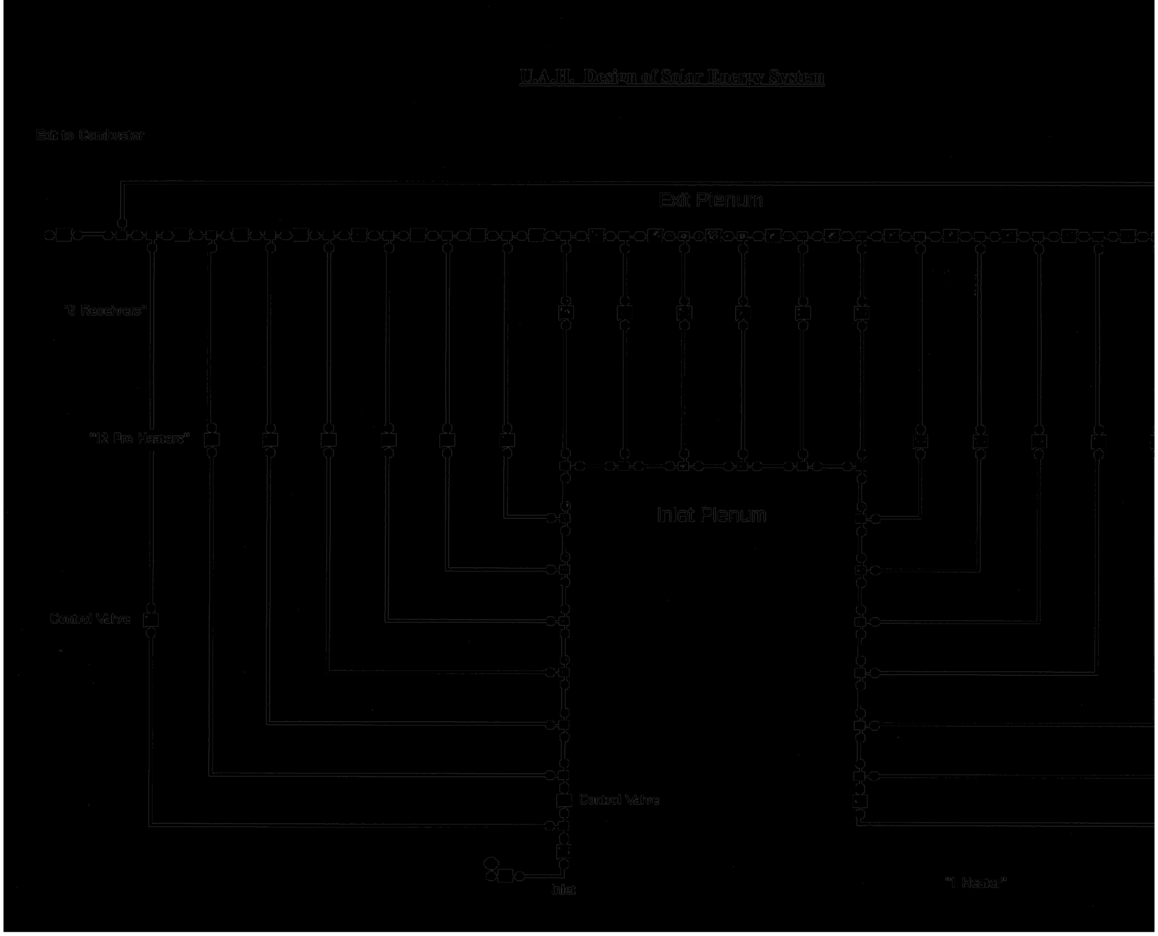
		Thermal Energy	Mass Flow Rate	Inlet Temperature		Outlet Temperature	
	Branch #	Mwatts	kg/s	C°	K°	C°	K°
Pre Heater #1	3	0.2917	2.22	390	663.15	520.7427	793.89268
Pre Heater #2	6	0.2917	2.33	390	663.15	514.5703	787.72028
Pre Heater #3	9	0.2917	1.86	390	663.15	546.0477	819.19772
Pre Heater #4	12	0.2917	1.86	390	663.15	546.0477	819.19772
Pre Heater #5	56	0.2917	1.62	390	663.15	569.1659	842.3159
Pre Heater #6	57	0.2917	1.35	390	663.15	604.9991	878.14908
Pre Heater #7	58	0.2917	1.05	390	663.15	666.4274	939.57739
Pre Heater #8	59	0.2917	0.71	390	663.15	798.8011	1071.9511
Pre Heater #9	60	0.2917	0.85	390	663.15	731.4691	1004.6191
Pre Heater #10	61	0.2917	1.18	390	663.15	635.9735	909.12352
Pre Heater #11	62	0.2917	1.18	390	663.15	635.9735	909.12352
Pre Heater #12	63	0.2917	1.51	390	663.15	582.2177	855.36772
Receiver #1	27	0.5	1.975	545.79812	818.94812	797.7031	1070.8531
Receiver #2	29	0.5	1.975	545.79812	818.94812	797.7031	1070.8531
Receiver #3	31	0.5	1.975	545.79812	818.94812	797.7031	1070.8531
Receiver #4	50	0.5	1.975	545.79812	818.94812	797.7031	1070.8531
Receiver #5	52	0.5	1.975	545.79812	818.94812	797.7031	1070.8531
Receiver #6	54	0.5	1.975	545.79812	818.94812	797.7031	1070.8531
High Temp Receiver	26	1	1.1271012	391.40312	664.55312	1274.221	1547.3708
Flow Control Valve	42		24.34	390	663.15		

Figure 5 – Excel Spreadsheet Results

The second model is presumably a more practical system, which has lower pressure drop and thus higher overall operational efficiency. The proposed system would be purely parallel, in that the flow from the compressor outlet would be split such that separate flow paths connect the outlet to the receivers. We assumed a "1-6-12" configuration. The outer ring is composed twelve peripheral heaters, located on the outskirts of the flux distribution. These may be metal ("TAT" receivers) or DIAPR receivers. There is an inner ring of six DIAPR receivers. These receive a higher flux. At the center is the "high temperature receiver"; this too, is a DIAPR receiver.

The program was used to model a large plenum at the compressor outlet from which the airflow to all receivers would flow. After splitting, the air would travel through pipes to the receivers in 22 inch pipe where it would them be reduced to 10 inches for entrance into the receivers. After exiting, the air would be collected in a long pipe-and-bend plenum much like that used in the first model. The combined flow would then return to the combustion chamber of the turbine, where it would join the flow that enters the combustion chamber directly from the compressor. There, supplemental fuel would be burned to bring the total flow up to the temperature and enthalpy required for the turbine section.

It should be noted that the flow path from the compressor to the receivers, and from the compressor directly to the combustion chamber, requires a restriction in the direct path to ensure that sufficient flow passes through the receivers to avoid excessive temperatures. An important aspect of this analysis was to evaluate the types of conditions and the types of flow control measures needed to have the proper flow rates. As discussed below, we achieved flow control through the selection of modulating valves and pipe diameters and lengths. Part of this was a trial and error process, but we were able to develop a flow control approach that minimized the total flow loss in the system; minimum flow loss is critical to maximizing system efficiency, and annual revenue. A schematic of the fully parallel flow system is shown below.


U.A.H. Design of Solar Energy System
Exit to Combustor
Exit Plenum
"6 Receivers"
"12 Pre Heaters"
Inlet Plenum
Control Valve
Control Valve
Inlet
"1 Heater"

Another adaptation was the specification of the DIAPR and Metal Receivers. Each was inputted as a “User Specified Custom.” For pressure drop calculations a K-factor was assigned to the custom input. The value of this K-factor for the DIAPR receivers was calculated using pressure drop data from “HTR Pressure Drop at Commission Conditions (abbreviated version)” prepared by Rotem Industries.

Evaluation of Pressure Drop on Overall System Performance

The thermal efficiency of an idealized simple gas turbine cycle with a perfect gas can be used to approximate the effect of pressure drop on overall system performance. This performance degradation can then be used to estimate the revenue loss. Comparisons of the revenue loss over the life of the plant with the cost of modifications that decrease the pressure drop can then be made to support a decision as to the preferred approach. In the following analysis, it is concluded that adding a flow control valve (or orifice) and a shutoff valve, with a parallel flow arrangement improves the plant performance and revenue at a cost that is a small fraction of the lost revenue.

There are essentially three basic flow configurations with the beam down optics system. The simplest is to have all of the compressor outflow directed through all of the receivers in an essentially series flow, with all of the flow passing through peripheral receivers and then the central receiver, and then returning to the gas generator, and, with supplemental heating from natural gas, then flowing to the turbine section. The second is similar, but the flow is split, into a series-parallel flow path, with some of the flow passing through the outer receivers, and the remainder going to the central receiver. The third is very different. In this case,

% Open (##)	100
K - Value	1
Cp (j/(kg*K°)	1005
Initial Temperature (C°)	390
Inlet Pressure (psi)	203.05
Outlet Pressure (psi)	202.63
Pressure Change	0.42
Total Temp Out (C°)	590.190037

Report Generator

		Thermal Energy	Mass Flow Rate	Inlet Temperature		Outlet Temperature		Cumulating Mass Flow Rate	Outlet Plenum Temperature	
	Branch #	Mwatts	kg/s	C°	K°	C°	K°	kg/s	C°	K°
Pre Heater #1	16	0.2917	0.61	390	663.15	865.81763	1138.96763	0.61	865.817633	1138.9676
Pre Heater #2	14	0.2917	0.59	390	663.15	881.94704	1155.09704	1.2	873.747927	1146.8979
Pre Heater #3	12	0.2917	0.59	390	663.15	881.94704	1155.09704	1.79	876.450429	1149.6004
Pre Heater #4	11	0.2917	0.59	390	663.15	881.94704	1155.09704	2.38	877.813036	1150.963
Pre Heater #5	10	0.2917	0.59	390	663.15	881.94704	1155.09704	2.97	878.63427	1151.7843
Pre Heater #6	9	0.2917	0.6	390	663.15	873.74793	1146.89793	3.57	877.813036	1150.963
Receiver #1	35	0.5	0.87	390	663.15	961.85338	1235.00338	4.44	894.2804	1167.4304
Receiver #2	22	0.5	0.89	390	663.15	949.00274	1222.15274	5.33	903.417901	1176.5679
Receiver #3	23	0.5	0.91	390	663.15	936.71696	1209.86696	6.24	908.274015	1181.424
Receiver #4	24	0.5	0.93	390	663.15	924.95961	1198.10961	7.17	910.438255	1183.5883
Receiver #5	25	0.5	0.95	390	663.15	913.6973	1186.8473	8.12	910.819548	1183.9695
Receiver #6	26	0.5	1.01	390	663.15	882.58657	1155.73657	9.13	907.696294	1180.8463
Pre Heater #7	8	0.2917	0.72	390	663.15	793.12327	1066.27327	9.85	899.321413	1172.4714
Pre Heater #8	7	0.2917	0.75	390	663.15	776.99834	1050.14834	10.6	890.666479	1163.8165
Pre Heater #9	5	0.2917	0.79	390	663.15	757.40349	1030.55349	11.39	881.42348	1154.5735
Pre Heater #10	4	0.2917	0.82	390	663.15	743.9619	1017.1119	12.21	872.191825	1145.3418
Pre Heater #11	2	0.2917	0.86	390	663.15	727.49855	1000.64855	13.07	862.671075	1135.8211
Pre Heater #12	3	0.2917	0.77	390	663.15	766.94644	1040.09644	13.84	857.345354	1130.4954
High Temp Receiver	41	1	1.53	390	663.15	1040.3431	1313.49306	15.37	875.561781	1148.7118
Flow Control Valve	36		21.91	390	663.15	390	663.15	37.28	590.190037	863.34004

some of the flow passes directly from the compressor to the turbine, through a restricting valve or orifice, and some is passed through the solar receivers, in an essentially all-parallel configuration. A shutoff valve is also provided for the flow to the receivers, so that there is no flow during periods of no sun. The issue is which type of configuration provides the best overall system performance, especially for the Noor Al Salam system, which will most likely have a roughly 10 Megawatt thermal field, but with a roughly 15 Megawatt electric output turbine generator. In this case, the major part of the power is provided by natural gas. At night, the total power is from natural gas. Since the solar power contribution for this system is relatively small, of the order of roughly 3 Megawatts, and this is only of the order of one-third of the time, the total solar energy over the year is roughly one-tenth the total output energy. In this case, it is important to not have the solar energy system degrade the normal natural gas turbine generator system. Therefore, it is important to be able to avoid such degradation effects as occur with flow losses in the additional piping and receivers.

The third configuration accomplishes this in two primary ways. First, there are flow control valves, such that the flow through the solar portion can be closed off, thus avoiding any additional flow loss during periods in which solar power is not available. Second, a valve is provided to slightly increase the flow loss between the compressor outlet and the gas generator such that the flow from the compressor through the solar portion is sufficient to avoid overheating, but not so great as to increase the flow loss for the total system. Since, to first order, thermal efficiency of the turbine cycle is determined only by the pressure ratio, this approach is used to estimate the effect of pressure loss (i.e., a decrease in pressure ratio) on the system performance. *The result is that it is necessary to have low flow loss by not allowing all of the flow to pass through the solar receivers, especially during the non-solar periods.*

Consider a simple gas turbine cycle with a perfect gas. In general, the thermal efficiency is the ideal cycle power divided by the rate of heat addition. Let p_1 and T_1 be the pressure and temperature at the compressor inlet. Let P_2 and T_2 be the compressor outlet conditions (discharge pressure and temperature). Let T_3 be the outlet temperature of the gas generator, and assume there is no loss of pressure in the gas generator. Let P1 be the turbine outlet pressure, and T4 be the turbine exhaust temperature. Mass flow rate is m-dot, and Cp is the specific heat at constant pressure.

The enthalpy change at the turbine is $\dot{m}\, C_p(T_3 - T_4)$; this is the turbine power output. However, to get the net cycle power, we must subtract the power to run the compressor. The compressor power is $\dot{m}\, C_p(T_2\text{-}T_1)$. The rate of heat addition is $\dot{m}\, C_p(T_3\text{-}T_2)$.

Thus, the idealized thermal efficiency is

$$N_{ideal} = \dot{m}\, C_p(T_3 - T_4) - \dot{m}\, C_p(T_2 - T_1)/(\ \dot{m}\, C_p(T_3 - T_2)$$

$$= (T_3 - T_4) - (T_2 - T_1)/(T_3 - T_2)$$

Factoring out the T_3 in the first parenthesis of the numerator, and T_2 in the second, gives

$N_{ideal} = T_3(1 – T_4/T_3) – T_2(1 – T_2/T_1)/(T_3-T_2)$

But, the pressure at stage three is equal to the discharge pressure; i.e., $P_3 = P_2$.

Also, the turbine outlet pressure at stage four, P_4 is identical to the compressor inlet condition, P1. For isentropic conditions, pressure and temperature are related as

$T_a/T_b = (P_a/P_b)^{(g – 1)/g}$, where g is the ratio of specific heats, C_p/C_v.

Thus, we have

$N_{ideal} = T_3(1- (P_1/P_2)^{(g – 1)/g)} – T_2(1 – (P_1/P_2)^{(g-1)/g)}/(T_3 – T_2)$

Factoring out the $1 - (P_1/P_2)^{(g – 1)/g)}$ term in the numerator, and canceling the $T_3 – T_2$ terms gives:

$N_{ideal} = 1 - (P_1/P_2)^{(g –1)/g.}$

For air, gamma is 1.4. For a compressor ratio of, say, 20, the simple gas turbine efficiency is determined to be 57.5%.

As a simple means of estimating the pressure drop effect, relative to the turbine's nominal operating conditions, we can take the derivative of the above expression with respect to pressure, $d(N_{ideal})/dP_2$, to obtain an expression for the change in thermal efficiency with compressor outlet pressure P2.

For small changes in pressure, P2, we have:

Delta $N_{ideal} = (g –1)/g*(1- N_{ideal})$deltaP2/P2.

Since N_{ideal} for $P_2/P_1 = 20$ is 0.575, and g = 1.4, then

Delta $N_{ideal} = (0.4/1.4)(1- N_{ideal})$Delta P_2/P_2. For $P_2 = 20$ atmospheres, and Delta $P_2 = 1$ atmosphere, the decrease in N_{ideal} is

Delta $N_{ideal} = 0.0143(1- N_{ideal})$, or 0.006076; the ideal efficiency is thus 57.5 – 0.607 = 56.89%. Thus, the decrease in efficiency is 57.5/56.89 = 1.0107, or, about a 1.1% decrease.

This 1 atmosphere pressure drop corresponds to the case in which all of the compressor discharge flow passes through the solar receivers, even when there is no solar power; there is no control valve to modulate this flow, or a shutoff valve. Thus, the system will operate with a loss of efficiency of the order of 1.1%. Consider now that the output power is 15 Mwe, with a price of $0.10/kW-hr. The annual output is thus valued at 15,000 Kw*365*24*0.1 = $13.1M/year. A 1.1 % decrease produces a loss of roughly $0.14M per year; over the course of 20 years, this is roughly $2.8M.

We have therefore concluded that it is reasonable to provide the additional flow control valves and piping, in order to maximize the overall system efficiency and revenue, by having a fully parallel flow, with no flow through the system during periods when there is inadequate or no solar irradiance.

Recommendations

This initial analysis indicates that the flow configuration can impact the system performance and revenue, and that a parallel flow configuration offers the advantage of lower flow loss and thus a higher pressure ratio and performance, especially with hybrid systems having a relatively high percentage of power produced by the natural gas, relative to the solar. More detailed results would require better data for the flow loss of the different receivers, better configuration design so that all components could be modeled as to type, size, length, wall roughness, etc. It would also be useful to break the flow up into sections that would allow the differing temperatures and densities to be used. The question of proper sizing and selection of pipe diameters also needs to be addressed, such that the cost and performance (as it relates to the pressure drop and pressure ratio) can be determined and the optimum size selected.

Finally, since flow control valves appear to offer advantages, evaluation of candidate valves should be conducted and these should be used in the analysis to determine the overall effect on pressure drop. The possibility of flow instabilities and imbalances in flow rates between parallel paths that could even result in flow reversals needs to be considered as well. Analyses of flow configurations also need to include a sensitivity analysis, so that the degree of uncertainty in pressure loss can be estimated. Components that are appropriate for the temperature ranges encountered also need to be considered.

The ABZ Technologies model developed for the hybrid solar central receiver would be useful for conducting such analyses; since the developers of the code are now offering additional capabilities, such as "heat exchangers" and varying temperatures, this code could be used with updated subroutines to conduct a detailed analysis of candidate configurations. These results, coupled with cost and expected revenue data, could then be used to select appropriate components.

References:

1. Design Flow Solutions ABZ Incorporated. 4451 Brookfield Corporate Drive, Suite101, Chantilly, VA 20151. Phone: 703-631-7404.
2. Flow Analysis for the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver System and Noor Al Salaam Program. By J. Ben Bramblett, Kevin R. Nichols, and James B. Blackmon. University of Alabama-Huntsville, Propulsion Research Center. This document is a complete compilation of all computer program results and a discussion of the analysis, 1895 pages in length.

Instructions for Using ABZ Code to Save Reports

First of all before you can obtain a file that can be read by the excel program you must set up the ABZ program so it will generate the report. This is done by going to **File** and then down to **Preferences** which will bring you to the "Preferences" screen as shown in Fig.1 below. In this screen make sure that everything that appears here is exactly what you see on your screen. If it is not then change it by pressing each button and the options that are listed below can be selected.

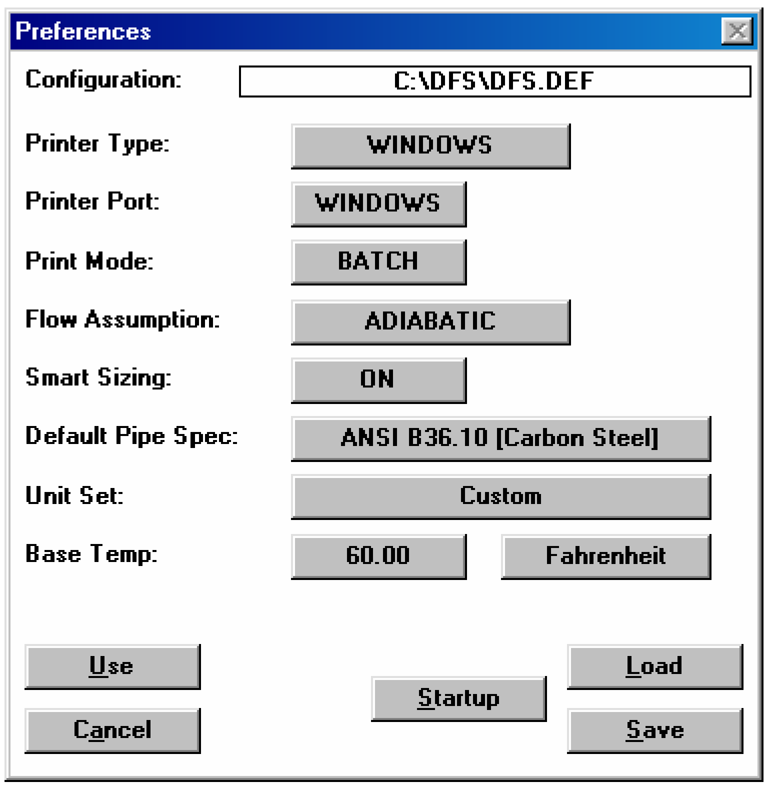


Fig. 1

After you have made all the necessary changes then press the **Use** button and continue.

After you have set up ABZ so you can generate a report, you must then make sure that there is absolutely no branch selected when you do the following or it will only generate a report for the selected branch and not the entire system. If a single branch is selected it will have a red box outline around it. Check the entire system to ensure that there are not any individual branches selected.

In order to obtain a file that can be read within the excel program you must print as though you are going to print directly to the printer by going to **File** and then to **Print** as you would in any typical program. When you do this within the ABZ program you will come to the following screen entitled "Reports". Select the following boxes that contain a check as shown below in Fig. 2.

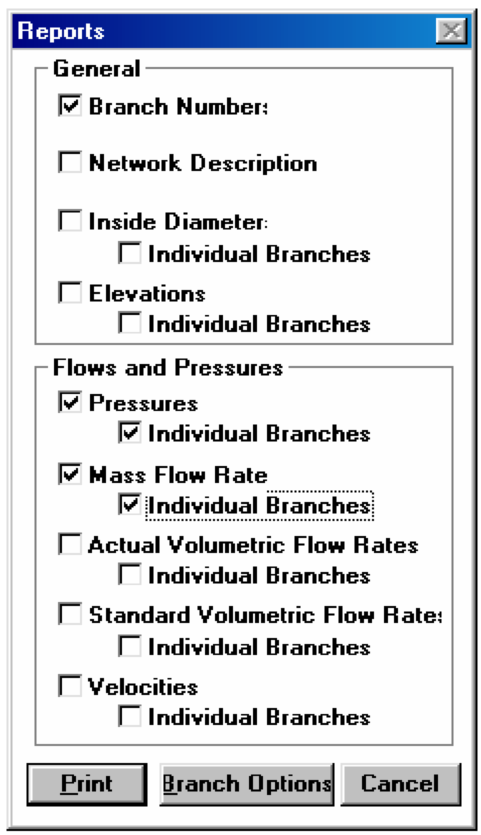


Fig. 2

Before you press the **Print** button in the "Reports" screen as shown in Fig 1. Press the **Branch Options** button. Select the following boxes that contain a check as shown below in Fig 3.

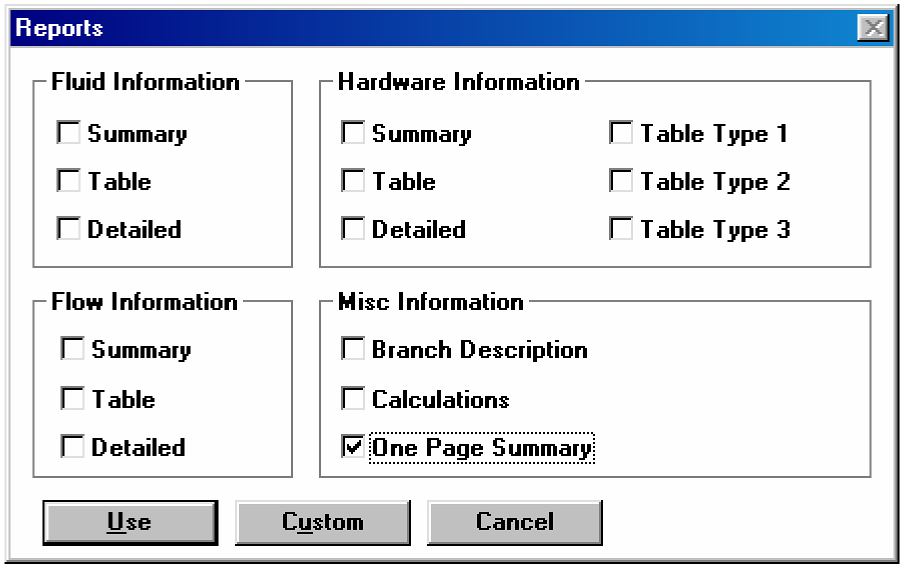


Fig. 3

Now you can press the **Use** button in the "Reports" screen as shown in Fig. 2 and then the **Print** screen as shown in Fig. 1.

The next screen you will see is just to tell you the following in Fig. 4.

Fig. 4

Just press the **OK** button and continue.

Now you need to press the **Exit** button located on the upper tool bar. When you do this, the program will then prompt you to do the following.

Fig. 5

In the "Pending Reports" screen as shown in Fig. 5 above press **No**. After this screen, then the next screen is as follows in Fig. 6.

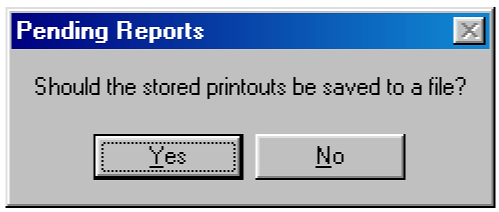


Fig. 6

Press the **Yes** button in the screen as shown above in Fig. 6. This will bring you to the final screen shown below in Fig 7 will allow you to save the report. The report can be saved any where on C: drive . The report should be saved as (DFS##PCT). The ## is where you would put the percent open/closed at which the control valve was set. For example, if the control valve was set at 25% then you would save the program as:
(DFS25PCT) and likewise for any other percentage. When you have finished press the **OK** button and the ABZ program will exit.

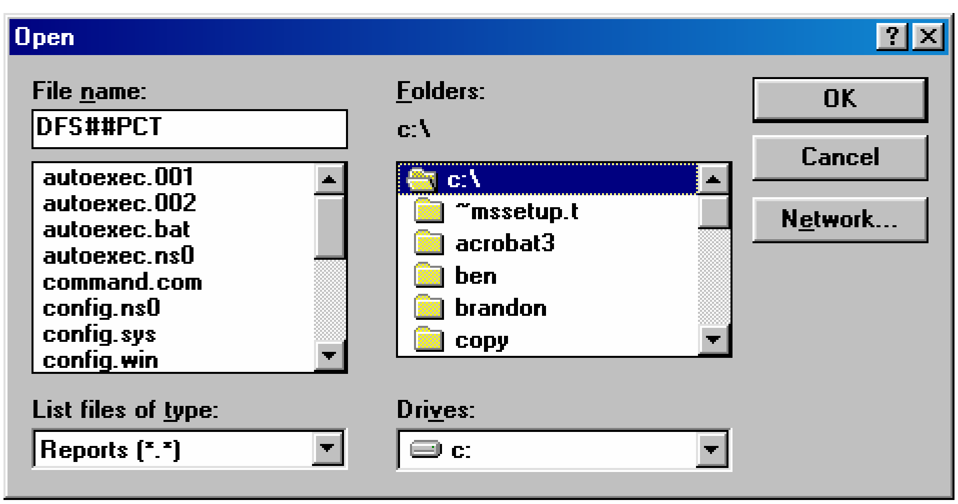


Fig. 7

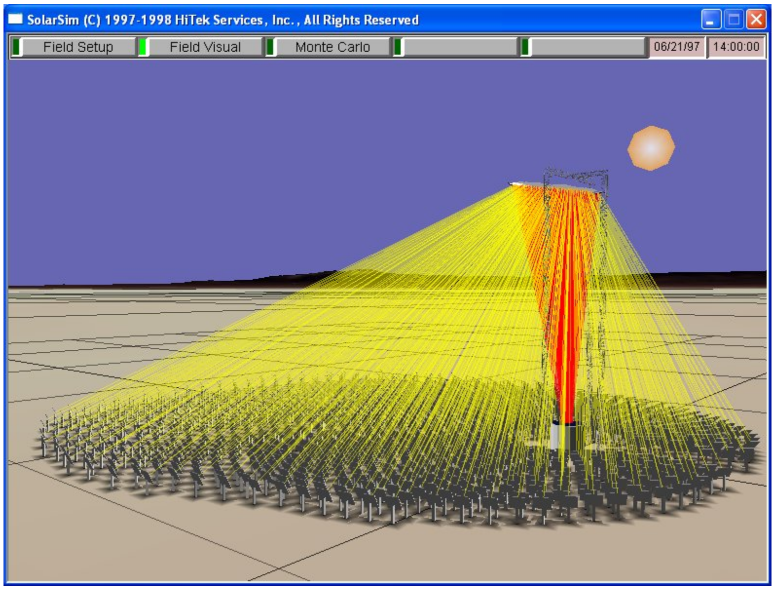
The value of percentages is as follows in Fig. 8 as shown below.

CONTROL VALVE	
% OPEN	K-FACTOR
100	1
50	1.4
25	2
5	5
1	10

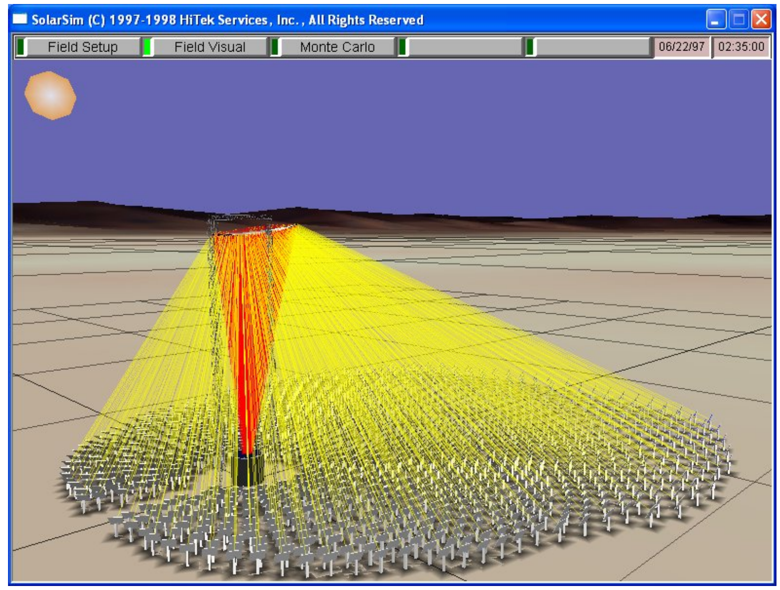
Fig. 8

APPENDIX C
OPTICAL ANALYSIS\

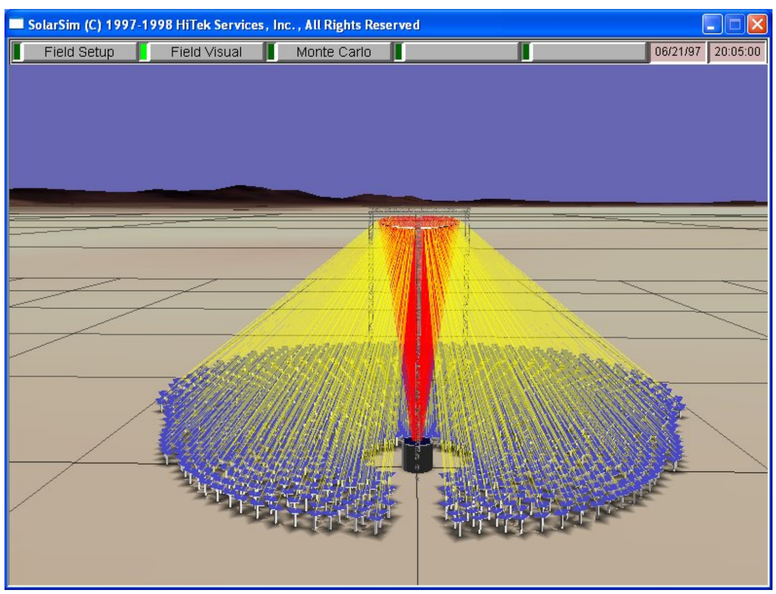
Noor al Salaam Solar Central Receiver Optical Modeling



Sunrise



Sunset



Solar Noon

Prepared by

HiTek Services, Inc.
7234 Hwy. 431 South
Owens Cross Roads, AL 35763
(256) 539-0380

Table of Contents

Background

This report summarizes the optical model performed to support the NAS project at UAH.

Statement of Work

The statement of work is:

1. Port SolarSim™ to a more modern platform (Windows XP™)
2. Verify SolarSim™ Operation
3. Perform Annual Energy Computations at Two Sites
    a. Zafarana, Egypt
    b. Las Vegas, NV

Results

1. **Port SolarSim™**
    a. SolarSim™ was developed in 1997 for use on Silicon Graphics computers
    b. SolarSim™ was ported to Microsoft Windows NT™ in 1998
    c. SolarSim™ was successfully ported to Microsoft Windows XP™ in 2007
2. **Ported SolarSim™ Verified**
    a. The baseline optical simulation for the USISTC central receiver configuration was compared to the solution computed by the ported SolarSim™
    b. The results were the same (within the differences of a Monte Carlo solution)
3. **Annual Energy**
   Zafarana, Egypt

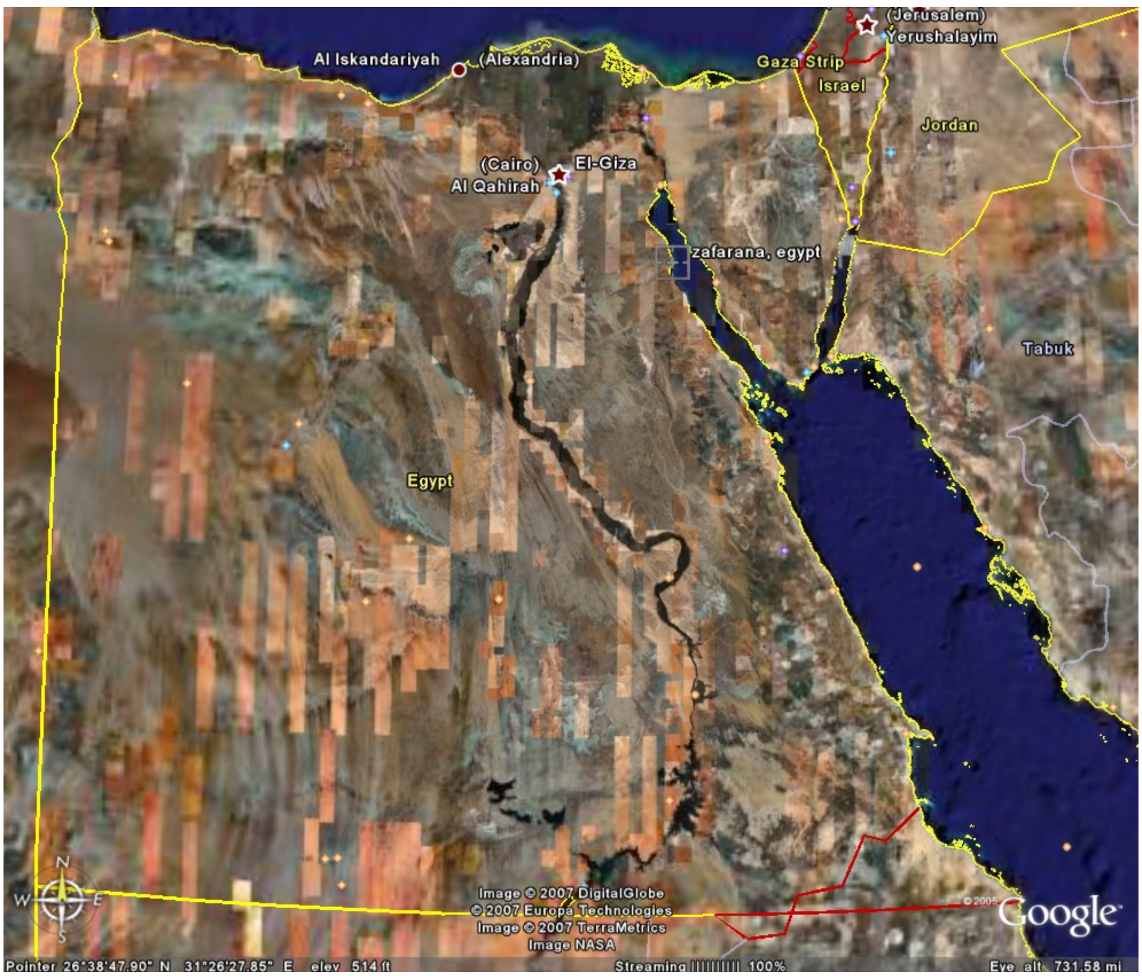
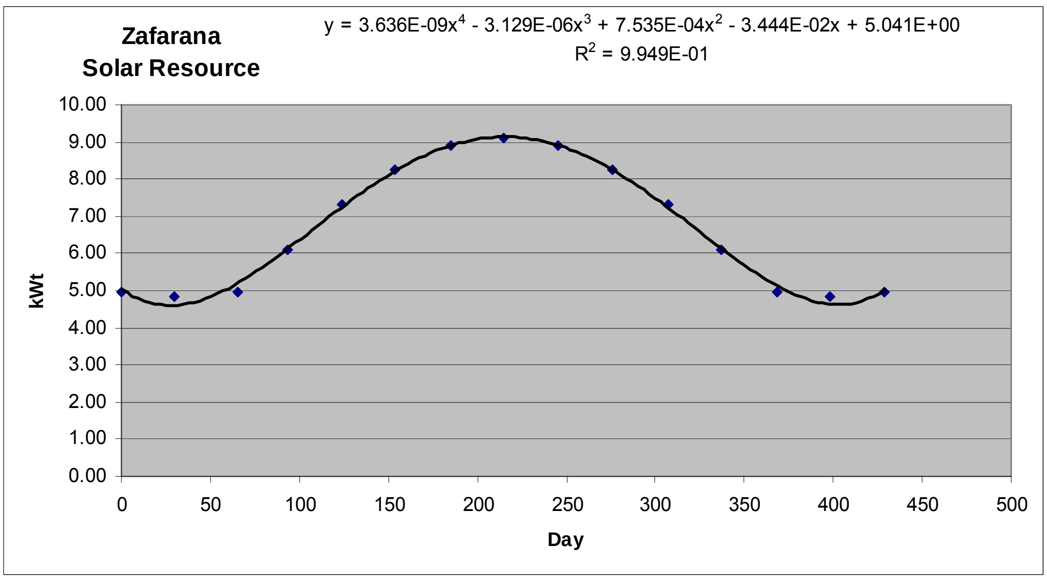


Figure 1 – Google Earth view of Egypt showing the location of Zafarana

Three simulations were completed for each location: (1) to compute the available solar resource, (2) a design point simulation, and (3) an annual energy computation to understand the potential yearly energy harvest. For Zafarana, the simulations were run at 29° 06' N 32° 37' E at sea level.

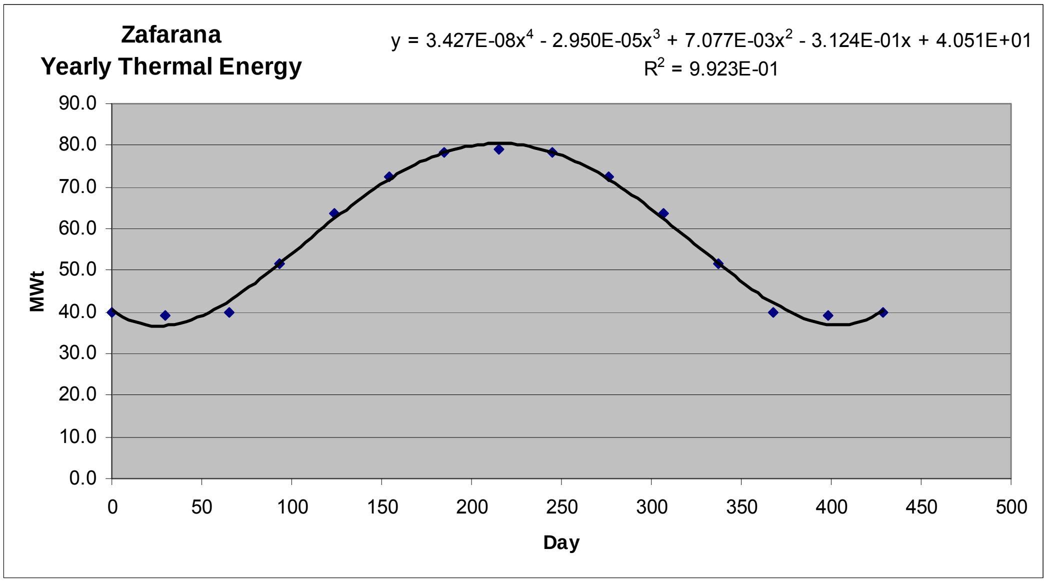
To compute the solar resource computed from SolarSim's sun model, the computed Direct Normal Irradiance (DNI) was integrated during the day, for 12 different days (once per month) and these values were then plotted versus time. A fourth order equation was then curve-fit to the data and that equation was integrated to arrive at a yearly value for the solar resource. Figure 2 below shows the curve fit data and accompanying notes.



1. These points are the SolarSim computed solar resource for Zafarana.
2. The approximate limits of daily integration are when the DNI reaches $250 W/m^2$
3. Integrating the equation above yields 2586 kW_t-hr/m^2/year

Figure 2 – Zafarana's modeled solar resource

The annual thermal energy that is available at the inlet plane to the CPCs was computed using the annual energy simulation. Again, the simulation data was gathered one day each month and that was integrated to get 12 daily values. These values were then plotted and the resulting 4th order curve-fit equation was integrated to yield the yearly thermal energy available at the CPC inlet plane. This data is presented in Figure 3.



1. These points are the SolarSim computed power to the CPC inlet plane.
2. The approximate limits of daily integration are when the DNI reaches 250W/m^2
3. Integrating the equation above yields 22.2 GW_t-hr/year

Figure 3 – Zafarana's modeled annual energy at the CPC inlet plane

The optical efficiency for the system from the sun to the CPC inlet plane was computed for the twelve simulation days using the solar resource and thermal energy data described in Figures 2 and 3. The table in Figure 4 shows the daily data and the overall optical efficiency at Zafarana is 68.4%.

Day	Day	Daily Energy MW-hr_t To Receiver	Daily Optical Efficiency	Sun Hours $I>250W/m_2$	Daily Energy kW-hr_t/m^2 Per Day To Mirror
11/18/1996	0	39.8	63.9%	8.42	4.96
12/18/1996	30	39.1	64.4%	8.00	4.84
1/22/1997	65	39.8	63.9%	8.42	4.96
2/19/1997	93	51.5	67.2%	9.25	6.11
3/22/1997	124	63.6	69.3%	10.30	7.31
4/21/1997	154	72.5	70.0%	11.00	8.25
5/22/1997	185	78.1	69.8%	11.67	8.91
6/21/1997	215	79.1	69.3%	12.00	9.09
7/21/1997	245	78.1	69.8%	11.67	8.91
8/21/1997	276	72.5	70.0%	11.00	8.25
9/21/1997	307	63.6	69.3%	10.30	7.31
10/21/1997	337	51.5	67.2%	9.25	6.11
11/21/1997	368	39.8	63.9%	8.42	4.96
12/21/1997	398	39.1	64.4%	8.00	4.84
1/21/1998	429	39.8	63.9%	8.42	4.96

Figure 4 – Zafarana's average yearly optical efficiency is 68.4% from the sun to the CPC inlet plane

A detailed optical simulation was completed for the design point, solar noon on the summer solstice. Figure 5 shows the field visualization within SolarSim of the heliostat field, tower reflector and the CPC inlet plane. Figure 6 shows the SolarSim input screen where the simulation variables are defined. Please note that these simulations were run using the Test12b heliostat configuration from the previous USISTF work.

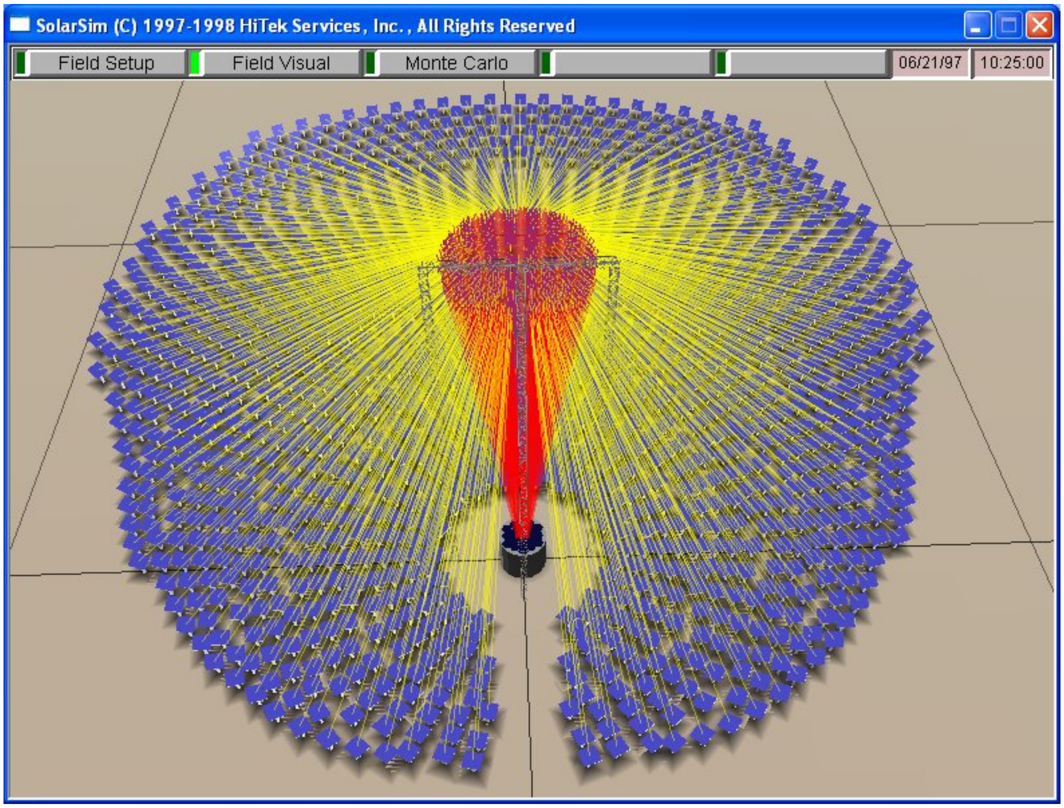


Figure 5 – SolarSim visualization of the heliostat field, tower reflector, and the CPC inlet plane atop the power block. The yellows rays indicated sunlight reflected from a heliostat center and the red rays indicate that ray's reflection off the tower reflector to the CPC inlet plane.

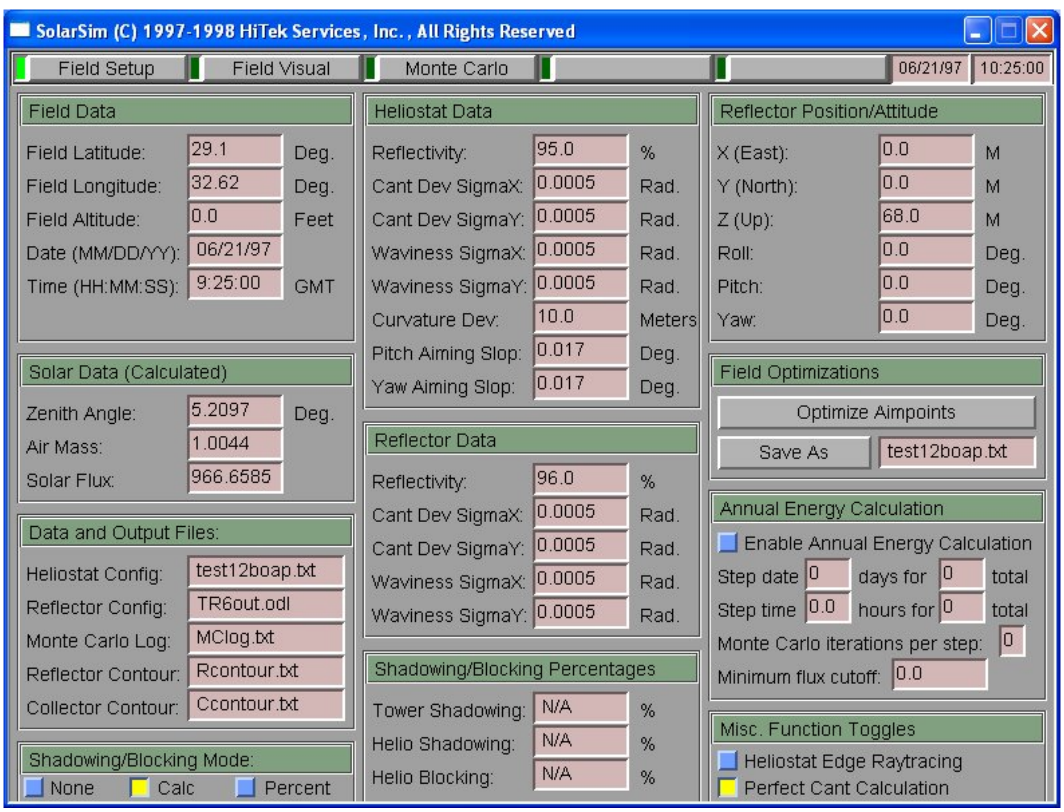


Figure 6 – SolarSim input screen where the simulation variables are defined.

This configuration defines each heliostat as one single 9.2m^2 mirror with 4 different focal lengths used throughout field. Additionally, the individual heliostat aim points were tailored to the triangular-faceted tower reflector defined as "TR6out." Again, this configuration is from the previous USISTF work. Figure 7 shows the results from the optical ray-trace Monte Carlo simulation. Here, the interim results during a particular pass through the simulation are displayed on the upper left hand side of the screen. The iteration-averaged results are shown on the upper right hand side of the screen and show the optical efficiency as 78.82% for the design point time and day.

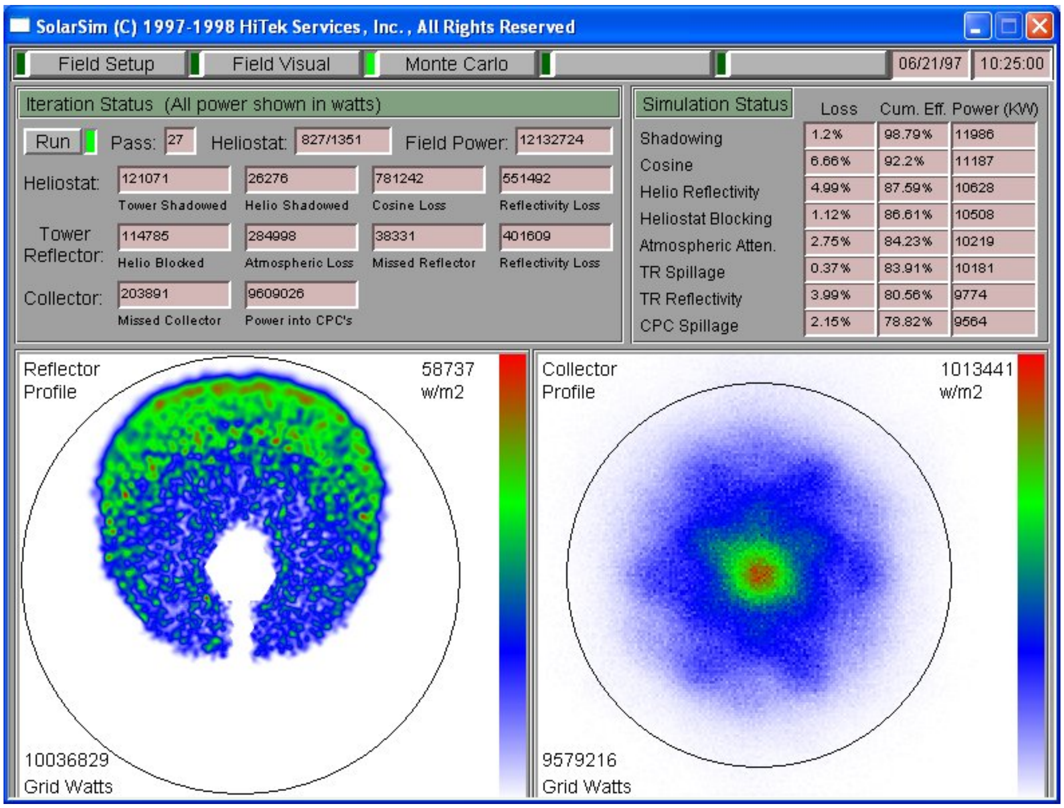


Figure 7 – SolarSim's Monte Carlo Simulation results screen

Las Vegas

The same methodology was employed to run the simulation at Las Vegas, Nevada. Figure 8 shows a satellite view of the greater Las Vegas area. These simulations were run at 36° 18' N 115° 6' W at sea level. Figure 9 shows the plot of the computed solar resource for Las Vegas.

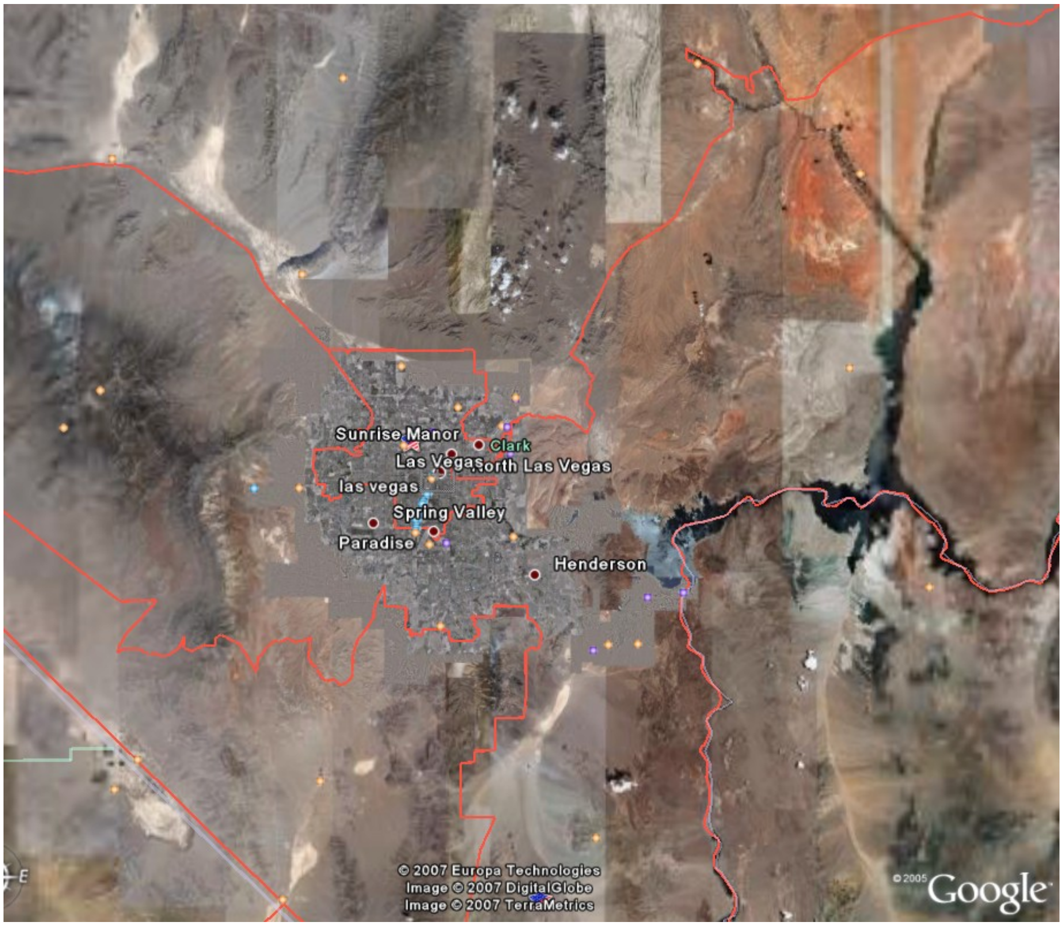
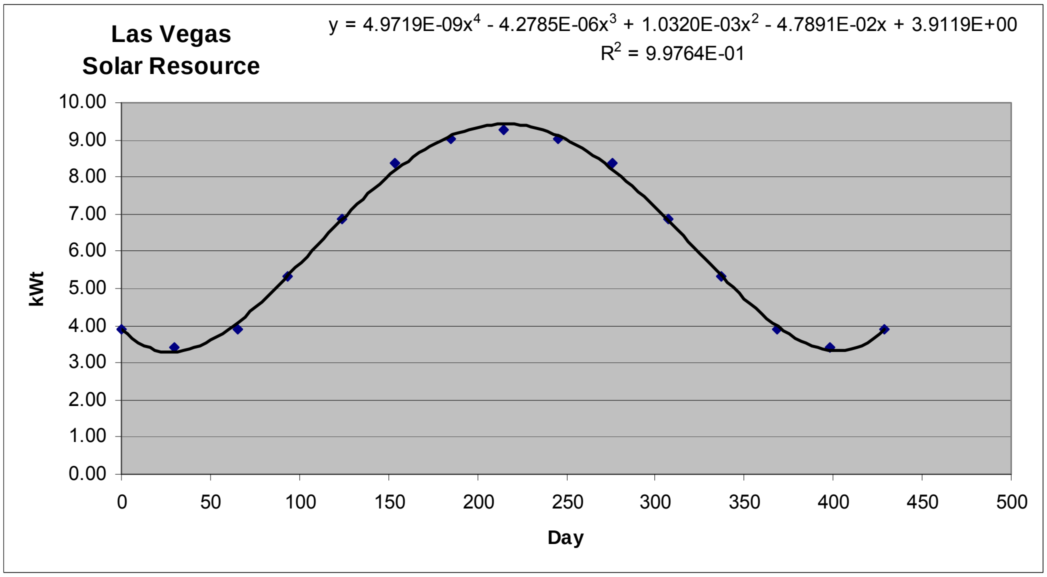


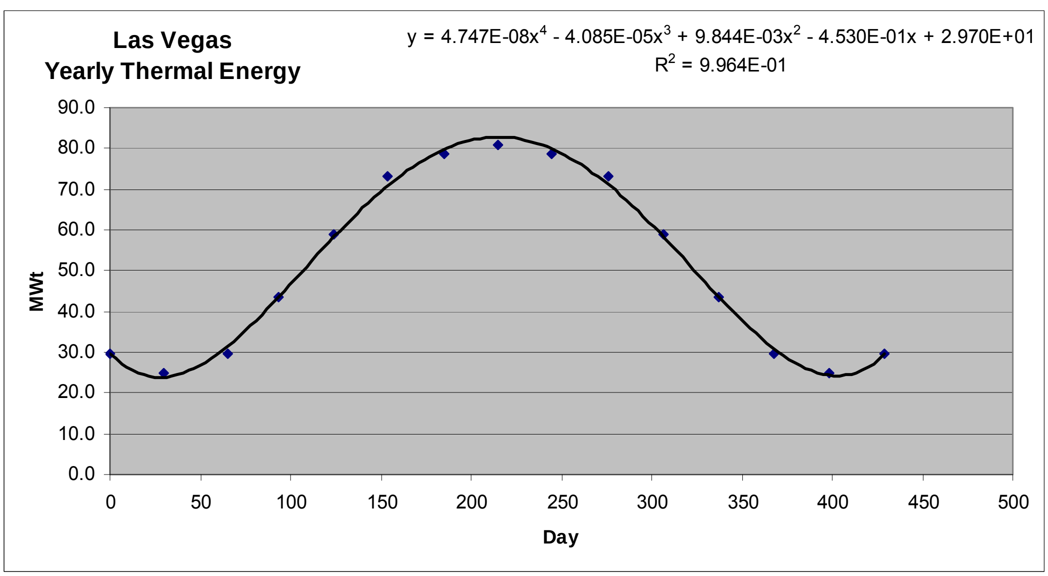
Figure 8 – Google Earth view of the Las Vegas region



1. These points are the SolarSim computed solar resource for Las Vegas.
2. The approximate limits of daily integration are when the DNI reaches 250W/m^2
3. Integrating the equation above yields 2422 kW_t-hr/m^2/year

Figure 9 – Las Vegas's modeled solar resource

The annual energy collected at the inlet plane to the CPCs was computed from the data plotted in Figure 10. The annual energy was computed at 20.5 GW_t-hr/year. Figure 11 shows the tabulated energy collection and solar resource data. From these data, the average optical efficiency (up to the CPC inlet plane) was computed to be 67.3%. Figures 12 and 13 show the SolarSim input screen and Monte Carlo simulation data respectively. The optical efficiency is 77.92% at the design point.



4. These points are the SolarSim computed power to the CPC inlet plane.
5. The approximate limits of daily integration are when the DNI reaches 250W/m^2
6. Integrating the equation above yields 20.5 GW_t-hr/year

Figure 10 – Las Vegas's modeled annual energy at the CPC inlet plane

Day	Day	Daily Energy MW-hr$_t$ To Receiver	Daily Optical Efficiency	Sun Hours I>250W/m$_2$	Daily Energy kW-hr$_t$/m^2 Per Day To Mirror
11/18/1996	0	29.6	60.6%	0.00	3.89
12/18/1996	30	24.8	58.1%	0.00	3.41
1/22/1997	65	29.6	60.6%	0.00	3.89
2/19/1997	93	43.6	65.0%	8.75	5.34
3/22/1997	124	58.8	68.0%	10.00	6.89
4/21/1997	154	73.3	69.7%	11.28	8.38
5/22/1997	185	78.7	69.5%	12.00	9.02
6/21/1997	215	80.7	69.3%	12.33	9.28
7/21/1997	245	78.7	69.5%	12.00	9.02
8/21/1997	276	73.3	69.7%	11.28	8.38
9/21/1997	307	58.8	68.0%	10.00	6.89
10/21/1997	337	43.6	65.0%	8.75	5.34
11/21/1997	368	29.6	60.6%	0.00	3.89
12/21/1997	398	24.8	58.1%	0.00	3.41
1/21/1998	429	29.6	60.6%	0.00	3.89

Figure 11 – Las Vegas's avg. yearly optical efficiency from the sun to the CPC inlet plane is 67.3%

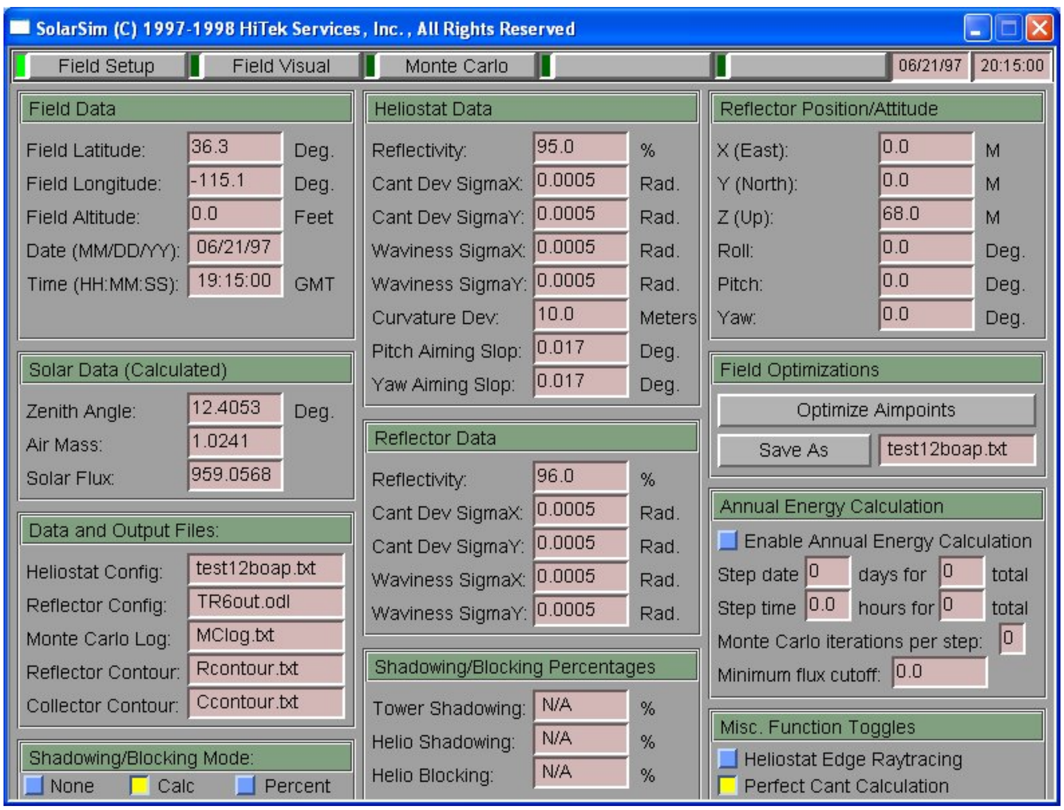


Figure 12 – SolarSim input screen for the Las Vegas simulations

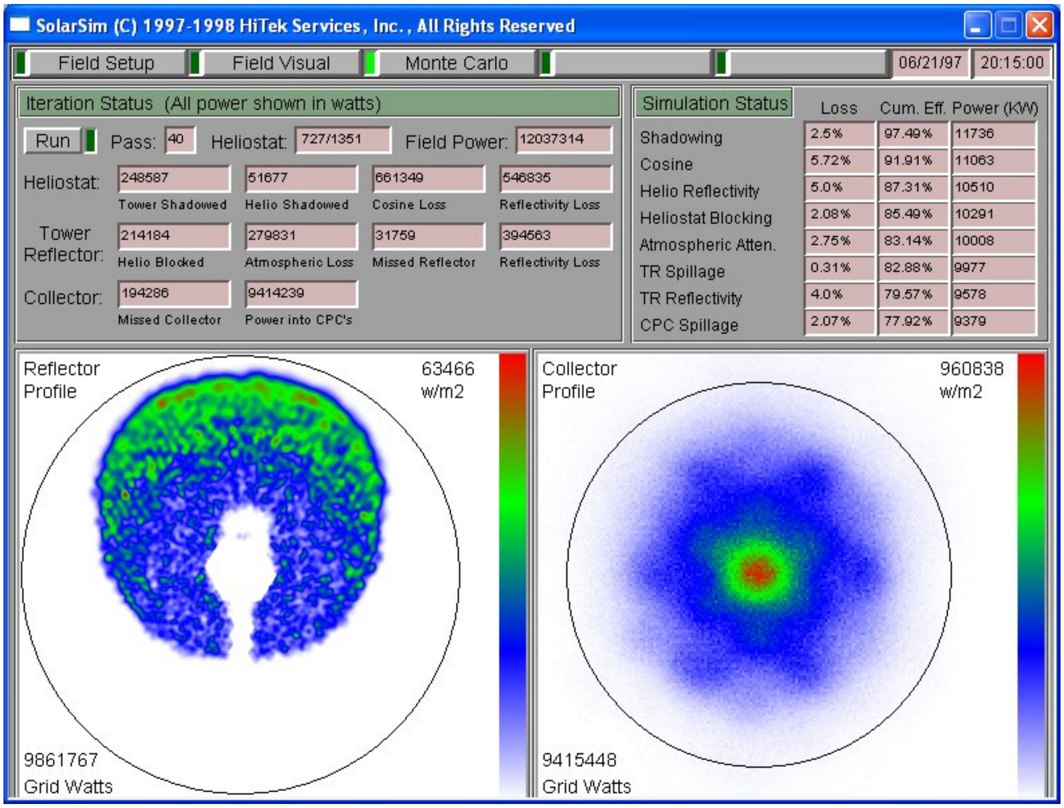


Figure 13 – SolarSim's Monte Carlo Simulation results screen for the design point at Las Vegas

Zafarana – Las Vegas Comparison

The differences in the simulation results for Zafarana and Las Vegas are displayed in Figure 14. As can be seen, the more southerly latitude for Zafarana gives the best simulated results. Of course, the non-simulated effects of weather, pollution, plant outages, etc. will effect a real plant's operation and are not accounted for in this study. As shown, Las Vegas has only 94% of the solar resource of Zafarana and is 1.1% less optically efficient. These lead to the Las Vegas plant having only 92% of the annual energy of the Zafarana plant site.

	Zafarana	Las Vegas		Comments
Latitude	29°	36°		Las Vegas is 7° north
Solar Resource	2586	2423	W/m^2/year	Las Vegas has 94%
Annual Energy To CPCs	22.20	20.47	GW-hr$_t$	Las Vegas has 92%
Average Optical Efficiency	68.4%	67.3%		Las Vegas is 1.1% less

Figure 14 – Comparison of the simulation results for Zafarana and Las Vegas

Tietronix

Final Report

DRAFT

"Application of the UH RCELL Suite of Central Receiver Design Codes to the Development of an Optimized Heliostat Field and Optimized Heliostat Locations for a Beam-Down Facility Using Small Focusing Heliostats "

December 31st, 2007

Prof. Lorin Vant-Hull and Michel Izygon
Tietronix Software, Inc.
1331 Gemini Av., suite 300
Houston, TX 77058
Tel: (281) 461-9300 x256

Background

Over the last several decades the code developed by the solar power team at the University of Houston has been used in the design, operation and evaluation of multiple Solar Thermal Central Receiver Systems. This suite of codes, also known as UH RCELL has been used in support of many feasibility and design studies run by industry (MDAC, Rocketdyne, Black and Veatch, APS, So Cal Ed, PG&E, etc.) In addition, RCELL was the primary optical system design and optimization code used for Solar One and Solar Two. It is a well-accepted opinion that the RCELL code suite is substantially the best option for use in the coming commercialization of Solar Central Receiver Technology.

The RCELL code provides a unique feature compared to other codes such as Sandia's DELSOL and its derivatives. The RCELL optimization process actually optimizes the radial and azimuthal separation of the heliostats in the field, as well as defining the optimum boundary of the field. In fact, the heliostat spacing equations used in the DELSOL code were developed by us using RCELL for a specific site, receiver size, heliostat configuration, and costs for each element. Use of these equations under significantly different conditions must provide a sub-optimal design. The excellent performance codes (MIRVAL and HELIOS, also developed at Sandia) do not provide for optimization of the system, other than by repeated trial and error processes, and require initial input of heliostat locations.

Thus, the University of Houston RCELL suite provides the only practical means to develop true cost-optimum heliostat fields. It was written to satisfy the information requirements of solar system and central receiver designers. These codes have been in continuous development and use for 27 years, and have gone through several generations of FORTRAN and many changes of platform.

Introduction

The initial objective of this project was to provide an optimum design for a Beam Down central receiver project to be located in Egypt. It was also recognized that the current codes would not be operable on the next/current generation of computers, and that many improvements in computer coding have occurred in the past 30 odd years, and that it would be valuable to incorporate these in a reengineered version of the RCELL codes for use in the inevitable resurgence of interest in solar power.

This project has proceeded sporadically over the last few years due to uncertainty in the availability of funding. An initial authority to proceed resulted in the generation of most of the required input parameters, and an identification of the required code in a DEC alpha OpenVMS format. A means to operate this code on a modern PC was developed. A stop work order was received, which was only terminated in November 2007 with instructions to deliver a final report by December 31, 2007. Subsequently we have spent considerable time getting the updated input modules to work with the RC code operating on a DEC alpha emulator based on a PC. Ideally the code would be redeveloped in a modern environment, using concepts and techniques from the FORTRAN code, but taking advantage of the many recent advances in computer speed and memory and in coding technology, to enhance the usablility of the code. However, the current status is adequate for small studies such as this. We are still seeking funding to accomplish the wider task.

The work on this contract has consisted of the following taks:

1) Developing and tabulating on "Input Data Sheets" the input figures and equations corresponding to this specific application of a Beam Down system operating in Egypt.
2) Developing the material to enable simulation of the Beam Down receiver based on a virtual receiver located at the virtual focal point of the field.
3) Devising a means to operate the current version of the code on a modern PC.
4) Implementing the material in 1) and 2) into the operational code
5) Generating an initial series of optimization and performance runs to test the system and to provide improved data for system design.

Each of these elements will be described more fully in the sections which follow.

Task 1: "Input Data Sheets" for the Noor el Salaam Beam Down central receiver system

The RCELL suite of tools was designed to perform a number of functions found necessary in the preliminary design, evaluation, final design, and operation of Central Receiver power plants. The primary functions are:

1. Cellwise basis (NS):
   - Instantaneous performance-shading, blocking, cosine computation (SBC)
   - Annual performance and summary Usually system and panel power efficiency at 7 afternoon times for each of 7 Autumnal months.
2. Cellwise basis (RC);
   - Cost effective optimization of Heliostat spacings
   - Cost effective optimization of Heliostat fields
   - Cost effective optimization of central receiver systems
   - Co-optimization of field and receiver under an allowable flux density constraint, or a required average receiver flux density
3. Individual Heliostat basis (IH);
   - Layout of heliostat files to emulate the optimum Cellwise design
   - Detailed evaluation of receiver flux maps
   - Annual performance summary

To support these functions, a number of detailed models are required. A nominal list of the primary models follows:

- Sun position via Ephemeris (to < 1 deg. error)
- Site dependent insolation model

- Cellwise structure generator
- Individual heliostat structure generator
- Receiver node structure generator (cylinders, flats/apertures)
- Heliostat (rectangular, split rectangular, round)
- Time step generators
- Shading and blocking processor (rectangular or round heliostats, 8 to 24 neighbors, stereographic projections vs. processing of overlapping events)
- Image radius estimator
- Aim point generator, weight functions for aim points
- Image generator - Hermite function approximation
- Receiver flux map / intercept factors
- Receiver temperature and allowable flux model (RC-TEMP)

The RCELL code is based on a variational analysis which defines an optimum performance level which each heliostat in the field is expected to achieve. This performance includes, for each heliostat; the heliostat, land and wiring cost compared to the system cost: as well as insolation weighted annual average shading and blocking losses vs. radial and azimuthal separation; and interception losses vs. location in the field. The result is a definition of heliostat separation everywhere in the field, which is latitude, slope, weather, cost, and optical quality dependant. Essentially, for the specific site the losses due to shading, blocking, cosine, and interception are traded to define the heliostat separation meeting the required performance level. Any region which can not meet the requirement is outside the field boundary. Thus, a cost/performance-optimal system is assured for the specific conditions of each study.

During a solar thermal plant optimization study we perform the following set of activities:

1. Define starting point
    a. Work with UAH to modify the Utility Study inputs to conform to the Beam-down study.
    b. Generate subsystem cost and O&M functions,
        i. land and wire
        ii. heliostat
        iii. tower
        iv. secondary
        v. receiver (perhaps only a power dependant cost in this study)
        vi. fixed costs (permits, computer, control room)
        vii. piping and feed pumps (probably not important here as not to top of tower)
    c. Define subsystem configuration, e.g. heliostat size and optics (e.g. facet focal lengths, shape, canting configuration-on axis?)
    d. Define subsystem performance parameters, e.g. heliostat beam errors, reflectivity, etc.
    e. Determine data for monthly insolation model to allow calculation of diurnal clear-sky insolation at any time of day. Uses long term monthly average values of:

i. Precipitable water
ii. Turbidity
iii. Visual range (for modeling atmospheric attenuation to receiver)
iv. Cloud cover (a multiplier on the clear sky integral to obtain monthly averages)

f. Design point thermal power into the CPC aperture
g. Requires definition of design point (equinox noon?)
h. Design point insolation value (may exceed model value if a very clear day is chosen)
i. Secondary apex height and radius, CPC array aperture, focal height: from preliminary sizing studies.

2. Generate interception data on virtual receiver (projected CPC array through secondary back to initial focal zone.) Use a flat plate receiver at that point
3. Generate an annual cosine, shading, blocking database for the site (requires site latitude, elevation and slope, and a suitable insolation (weather) model).
4. Optimize the heliostat field (boundary and azimuthal and radial separations) for the defined system configuration at power levels of 10, 12.5 and 15 MW thermal
5. Provide results to customer and define an improved system configuration, repeat steps 2 and 4, and, with customer, select a preferred case.
6. Generate table of heliostat positions for the preferred case and provide in electronic format to customer.
7. Provide a 2D and 3D visualization of heliostat field.

A nearly final copy of the input data assembled for use in the RCELL code is attached as an appendix. From this, all the input values were generated. There is considerable documentation back of nearly every number or equation given here. These were developed in conjunction with Jim Blackmon of UHA. Some of the costs were developed years ago on earlier studies, but as are all costs used in RCELL, these are inflated to current dollars by the "Chemical Engineering" plant cost index, published monthly. Consequently the cost effective optimiztion process of RCELL always operates correctly in current year dollars.

Task 2: SIMULATION OF BEAM DOWN CONFIGURATION

The RCELL code is not a ray trace code, and so does not currently have the ability to directly model the passage of the reflected flux from the heliostat field through a secondary optical element, such as a CPC or the Beam Down hyperbola. In many cases this is not a true disadvantage. If the secondary is a simple optical element, such as the Beam Down hyperbola, the primary effect is to magnify (or demagnify) the image formed at the focal plane of the field. Provisions must also be made to deal with the reflection losses at the secondary and any increase in random beam errors resulting from the reflection in a less than ideal optical surface.

Thus, we can optimize the system to provide a desired energy level on a virtual horizontal focal plane located at the defined focal height of the system. As we will see, we can define the required diameter of this plane based on the system geometry, and compute interception and spillage based on this virtual receiver (the defined diameter may require slight modification as the design matures.) The hyperbola acts as an ideal lens (actually more like a shaving mirror), producing an image of the focal plane at a defined height above the ground. This image represents the flux distribution on the array of CPC's forming the receiver.

Each CPC will view the entire illuminated area of the hyperbola and so will intercept a specific portion of the energy which would have reached the virtual receiver, given by the energy plated onto the area of the real image represented by the aperture of each CPC. Alternatively, one can think of projecting the CPC array through the hyperbola onto the virtual receiver. The energy plated onto each (demagnified) virtual CPC image will be the energy intercepted by that CPC. Of course one must deduct the energy absorbed by the hyperbola from the total (esentially multiply (decrease) the reflectivity of each heliostat by the reflectivity of the hyperbola).

The magnification of the virtual image (demagnification of the real 'near ground' image when projected to the virtual focal plane) is given by the system geometry. The hyperbola acts as a 'lens', so image size/image distance equals object size/object distance, where distances are measured from the point of reflection. As a property of the hyperbola is that the ratio of object to image distance remains constant for all rays initially directed at the virtual focal point, we need only deal with the central ray directed at the apex of the hyperbola. In the case we are considering, we have a virtual object a distance F1 above the heliostat field, a hyperbola with apex a distance h below that point, and a real image being formed at an elevation F2 above the heliostat field. The linear magnification is thus:

real image diameter/virtual object diameter) = real image distance/virtual object distance = Linear Magnification = LM = (F1-h-F2)/(h). [EQ 1

Thus, given a value for F2, (distance receiver is above plane of heliostats), we can generate a table of linear image magnification (M) and size of secondary:

if	h/F1 = 0.05	h/F1 =0.1	h/F1 = 0.2	h/F1 = 0.3
and: F2 is zero:	LM = 19	LM = 9;	LM = 4	LM = 2 2/3
F2 is 0.1 F1	LM = 17	LM = 8	LM =3.5	LM =2
F2 is 0.25F1	LM = 13	LM = 6.5	LM =2.75	LM =1.5
~Area of secondary (relative to field)	0.0025	0.01	0.04	0.09

This table suggests that we do not want to make h/F1 too large, or the secondary area becomes excessive, while if F2 increases, the (undesireable) magnification of the real image decreases, allowing higher flux density. One must also remember that each CPC further concentrates the energy impinging on its aperture by $1/\sin^2\theta$ where θ is the opening half-angle of the CPC. In this case, arctan(radius of secondary/distance to apex),

θ = arctan (Rh/F1)/(F1 – h –F2) = arctan R/(F1*M), [EQ 2

where R is the field radius.

If F2 is 0.1 F1 and the field radius is three times F1:

if	h/F1 = 0.05	h/F1 =0.1	h/F1 = 0.2	h/F1 = 0.3	*If R = 4F1* *h/F1 = 0.2*
CPC aperture halfangle	10.0	20.5	40.6	48.4	*48.8*
CPC concentration	33.1	8.1	2.36	1.8	*1.76*
Overal conc.= CPC/LM^2	0.115	0.126	0.192	0.45	*0.144*

Clearly there are many other options, but it is clear that if the area of the secondary is kept reasonably small, the concentration at the virtual receiver will be substantially reduced at the real receiver (the receiver of the CPC, in this case). In the example above, to retain half the concentration the elevated hyperbolic secondary must have an area approximately equal to 10% of the ground area of the field, which may be 30% of the heliostat area. In the final optimization the field radius R, the distance from the virtual focal point to the hyperbola vertex h, and the elevation of the CPC aperture are all variables, albeit subject to reaasonable geometrical constraints.

To ease visualization of the RCELL results, we need to develop a postprocessor routine which produces a scaled flux map on the receiver, using the equations above, showing true dimensions and actual flux density on the CPC aperture plane. To accommodate needs of the cooling/waste-heat collection system, we need also to extend the flux map beyond the actual boundary of the CPC's , showing the spillage flux density.

Additional components of the simulation

It is inevitable that the reflective hyperbolic mirror will not be 'ideal'. It will absorb/scatter some radiation so its reflectivity will be less than unity. This can easily be accomodated as an effective reduction in the reflectivity of the heliostats. In addition, the hyperbola will deviate from the perfect optical figure on both a microscopic scale (surface roughness or ripples) and on a macroscopic scale (approximation by flat triangualr segments and their missalighnment). Presumably all systematic deviations will be corrected for during construction/testing, and remaining errors will be considered randomly distributed, or may be represented by an approximating sigma.

If the lack of perfection of the hyperbola due to random deviations from the perfect optical figure, or microscopic deviations from flatness are represented by a sigma, they can be accommodated by adding the effective sigma (in quadrature) to the heliostat sigma. This sigma only acts on the distance from the hyperbola to the real receiver. Nominally then, to obtain the effective sigma to combine with the heliostat sigma, we can multiply the sigma for the hyperbola by the apex height of the hyperbola above the (real) receiver divided by the total beam path length:

(F1-h-F2)/(F1-h+F1-h-F2) = 1/(2 + F2/ (F1-h-F2)). [EQ 3

If F2 is zero (the real receiver is at the plane of the heliostat field) this reduces to ½. If the real receiver is elevated, it becomes somewhat smaller. Thus we will use $\sigma = (\sigma_h^2 + .25\, \sigma_s^2)^{0.5}$ to encorporate the random errors of the secondary.

Again, F1 is the vitural focal height of the heliostat field (location of the virtual receiver) measured relative to the rotational axis of the heliostats, h is the distance from the virtual focal point to the apex of the hyperbola, and F2 is the height of the actual receiver above the rotational axis of the heliostats, all treated as positive numbers.

As the RCELL code does not directly accommodate the beam-down concept. We can overcome this by using preliminary study results to define the height of the virtual focal plane above the heliostat field and the distance of the apex of the secondary below that point. The image magnification defined by this geometry will allow us to define a demagnified aperture of the defined CPC array, to be located at the initial focal point facing downward. This "virtual receiver" will provide the same interception for each element of the heliostat field as will the actual geometry, and the flux density at the CPC aperture will scale directly as the square of the magnification in the above table (or equation 1. We also will generate a magnified 'real' image of the virtual focal plane to allow direct visualization of the flux maps.

Task 3: Devising a means to operate the current version of the code on a modern PC

The RCELL suite of tools was designed to perform a number of functions found necessary in the preliminary design, evaluation, final design, and operation of Central Receiver power plants. These codes have been in continuous development and use for 25 years, and have gone through several generations of FORTRAN as well as many changes of platform. As for any software that has gone through these changes, its maintenance and operation are getting more and more difficult with the years. The previous full optimization study of a central receiver plant has been done about 5 years ago using a Dec Alpha/Open VMS system operated at the University of Houston. Since then this type of platform is becoming more difficult to find and UH has completely phased them out. We found ourselves with the challenge of operating the suite of code for this study. The different options available to us were the following:

1- Find and acquire a Dec Alpha/Open VMS machine with the associated FORTRAN compiler
2- Port the FORTRAN code to a PC, using one of the currently available Fortran compiler on the PC.
3- Reengineer the code to a modern language (C++ or Java) on a PC or Linux platform.
4- Find, install and assess an OpenVMS emulator on a modern operating system to compile and execute the code.

As one of the secondary goal of this study is to assure the availability and usefulness of the RCELL code suite through the next few years, when they will be required to implement the commercial Central Receiver designs, all of these options need to be weighted with respect to this goal. In the following paragraphs we assess each of the options and describe their advantages and disadvantages.

1- Find and acquire a Dec Alpha/Open VMS machine with the associated FORTRAN compiler: Old Dec Alpha computers can be found for sale on the net on websites such as eBay or Craigslist. Procuring the machine is a good option for operating the code as is, without any modification of the software. It gives a good short to mid term solution, but will not solve the long term problem as the hardware may suffer some problems with time. Also, the operating system (Open VMS) need to be procured and a system administrator needs to be able to install and maintain the system. This type of operating system being rather old, this type of skills is not widely available today. Another disadvantage of this solution is that we do not improve the capability to modify and improve the software, and we do not solve the fragility of the code.
2- Port the FORTRAN code to a PC: A number of FORTRAN compilers are currently available on PC windows or Linux. After a short assessment of the compilers and associated tools we found a couple of primary choices: Silverfrost FTN95, Open Watcom, and Absoft Pro Fortran. Each of these commercial products have their associated IDE and provide multiple options for recognizing VMS Fortran specific extensions. The advantage of this solution is that it should require very little change, if any, of the code. It allows us to alleviate all problems associated with the Dec Alpha platform. It is a good mid term solution that would allow us to use a modern platform while minimizing the cost of porting. It does not solve the fragility of the code and the potential need to add features or improve the code. In the short term it also requires a thorough testing of the code to ensure that the compiler and the associated changes are not causing any effect on the execution and results of the software.
3- Reengineer the code to a modern language (C++ or Java) on a PC or Linux platform: A complete reengineering effort on the suite of code would be the best solution for the long term, as it would ensure that the code will be available for the future needs of the Central Receiver Solar Plant community. Of course this solution is the most expensive and the longest schedule. It would require the development of the complete requirements document, develop a new Object-Oriented Design, and finally implement all of it in a new language such as C++ or Java. This will provide a new lifetime for the software, and should also provide a much improved user interface, performance and added functionality. In fact an initial port of the flux mapping portion of the RCELL code to C++ has already been done for the Solar Two project, in order to provide the real time processing of the Dynamic Aimpoint Processor (DAPS). This activity actually completed a significant portion of the re-engineering task as well as providing firm knowledge of the complications involved and work entailed in completing the re-engineering of the entire RCELL suite of codes. This project has proven the validity of the approach, and is providing a good basis for this reengineering effort. Though, for the short term, this solution is not possible because

of the huge effort needed to reengineer and the large testing effort needed to ensure that the code is providing the same results as the original code.

4- Find, install and assess an OpenVMS emulator on a modern operating system to compile and execute the code. The last option considered is the use of an Open VMS emulator that can be installed on a PC windows or Linux platform. This option is a good short term and mid term solution as it allows to use the code as is, without having to modify it. The machine acts as a Dec Alpha/OpenVMS, without the hardware requirement. It combines the advantages of option 1 and 2, as it provides us with a way to work on a modern hardware platform, with the existing code. It does not provide for a long term solution, does not allow us to correct the fragility problem or the need for improvement of the code.

After having tried to go with option 2, we encountered a number of problems with the code which prevented us to continue with this path. We ended up using the 4th option, by installing an emulator SimH on a Linux platform, then install OpenVMS operating system and OpenVMS FORTRAN compiler. The solution gave us the possibility to use the code as is and generate the runs needed for this study.

Task 4: Implementing the material in 1) and 2) into the operational code

After having installed the emulator solution on the Linux platform we were able to upload the RCELL source files to the emulated OpenVMS, compile, link and execute the code as if we were working on an original Dec Alpha platform. We used the data sheets developed under task 1, and develop the associated input modules files. The code associated with the task 2 requires the initial results of the RC and NS codes.

Task 5: Generating an initial series of optimization and performance runs to test the system and to provide improved data for system design.

APPENDIX 1: **Solar Central Receiver Optical System Study**

Site

Objective: Demonstrate "Beam Down"

Solar Central Rec'r Technologies **Plant Life=20 yrs**

Owner NREA Escalation = 3%

Prime TBD **Discount = 6%**

Prime Contract # **PV Factor => 15**

Site Address Zafarana, Egypt **Escalation for electricity 5%**

Site Location Red Sea Coast, Egypt **PV Factor= =>17.3 @ Disc – Esc = 1%**

I recommend 5% for elec. (fuel costs are going up). And then 17.3 for its PV Factor

Inflation factor (apply to all cost items): IF = 1 for current year, scaled by CEI = CEPI (Chemical Engineering index) plant inflation factor for past years.
The implementation is to multiply any cost figure by CEPI/261.2 [for a 1980 input]. IN 2005 we will set CEPI = 466, giving a multiplier of 466/261.2 = 1.784 in 2005 dollars **(like from Utility Study)_OK JBB**

Latitude 28.75 North Latitude (approx) **Slope of Field = Less than 5%=>0 for now**

Longitude 30.2 degrees East **Uphill direction is to: West**

Elevation 50 – 100 ft above Sea Level: use 25 m

Annual DBI ~ 2700kWh/m^2 **Average daily ~7.4kWh/ m^2 (map 41)**

Atmospheric data below used for Barstow: check Sunsam at site against above

Month	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Visual Range at sealevel=>	50.	50.	50.	50.	42.	42.	35.	35.	35.	42.	50.	50.
Percent Possible Sun	.75	.75	.80	.85	.90	.90	.90	.92	.92	.92	.85	.75
Fraction of cloudless days 0.80 no scheduled maintenance												
10* (10-cloud cover) use PPS instead												
Precipitable water	.73	.65	.72	.87	.99	1.16	1.92	1.97	1.44	.96	.76	.83
Atmospheric turbidity	.006	.006	.006	.006	.017	.018	.035	.034	.035	.018	.006	.006
Climate classification is "tropical and sub tropical desert" for both sites												

See 'the physical elements of geography' for details of such a climate

Minimum Solar Elevation for receiver operation: ε =10 deg

Artificial Horizon? None

Heliostat

Name USISTF

Reflective Area: 100 sqft, no edge seal or open slots, etc.

"Width" x "Height": ____10'__X__10'___: DMIR = √WxH = √10x10 = 10'

Mechanical Limits: (Clear-out Circle+1 foot)/DMIR = (14.142'+1')/10'
= 1.5142 in DMIR's

Height of elevation axis above ground plane: __2m__

Sounds like we should use 0.8 mR to cover all random deviations from a perfect on-axis parabola perfectly focused at the prescribed focal length and exactly pointed.
ADD scaled sigma(TMR) = ? in quadrature => sigma(TMR) * (V-R)/V (=0.1)

Cant distance DNA, Essentially there is a single 10'X10' perfect parabola with random errors. There will be 4 molds with different parabolic curvatures as below to start.

Temp. dependence of focal distance - small

Focusing; groups of 25% of heliostats have common focus and cant

Maybe =VFL X (1.22, 1.56, 1.90, 2.23.)
last = radius of 2.0VFH (=160m),=>boundary @ 2.4VFH=192 m
<297m (for 11cellsx$(1/8)^{1/2}$x80) = 3.89VFH
Use first decent RCELL run at 10 MWt to select new set with 1/4 of helios in each region.

Cost factors

Material cost mostly in 1980 dollars, TO BE INFLATED BY CEPI/261.2
Use data for Egypt from below

Concrete costs in 2005 in Huntsville are quoted as $82.00(CEPI/466) **per cubic yard** ***Use 80% of this for Egypt*** **=> $65.60(CEPI/466) per cubic yard**
Cost of structural steel is $0.54/lb CEPI/261.2) (in both Egypt and the U.S.)
Rebar Cost : Cost of rebar (1980 dollars) was reported as $0.52/lb in the U.S. and $0.49/lb in Egypt =>$0.49/lb (CEPI/261.2) in Egypt).

Heliostat Foundation Cost

Corresponding **concrete** cost for the 0.8 cubic yard foundation installed in **Egypt (80%) was $65.60/cubic yard**), x0.8 cubic yards => $52.48xCEPI/466 **Looks ok to me.**
Total Cost in Egypt, not including concrete: $30.44 x CEPI/466
In Egypt, the total cost per foundation is approximately $82.92(CEPI/466).
Current year (2005), based on costs here in Huntsville corrected to Egypt.

<u>Heliostat</u>

bare cost 100 \$/m2(CEPI/466); range to 150 and 200

Foundation = \$82.94 /helio = \$8.68/ m2 (CEPI/466)

<u>Transportation and installation \$24.74/helio = \$2.59/ m^2 (CEPI/466)</u>

<u>(HLC, UPS, and HC + wiring harness) = \$47.88/ m^2 (CEPI/466)</u>

(17+30+250+100)x1.15/10'x10'helio = (2.10+3.71+30.94+12.37)/m2 = \$49.12/ m2 in 1998 or 2005, (due to Moore's law)

so MCS related costs: = \$49.12/ m2 (CEPI/466)

giving a built and foundationed and installed and wired heliostat cost of (\$100.00+8.68+2.59+49.12) /m^2 (CEPI/466))**= \$(100 + 60.39)/m^2(CEPI/466)**

<u>Operations and maintenance</u>

Present value of operations and maintenance factor:(see also page 1)

Parts and labor =15 (for 20 year life; at discnt – escalation = 3%)

Electricity (esc.+2%) =17.3 (for 20 year life at discount – escalation = 1%)

Heliostat O&M costs => **(\$4.25**/m^2 –year)(CEPI/466)

Wash cost estimate (LVH) 3 men x 50 hours x 26 times/year x \$6/hour = \$23,400/year for the field, or \$15.60/heliostat = \$1.678/ m^2 per year **xCEPI/466**. (Including materials)
With a 20 year plant life, PVF is 15, so the present value cost is \$25.18/m2

Service drive, etc. estimate (JBB) \$10/heliostat-year = \$1.076/ m^2 per year xCEPI/466 => \$16.14/m2 = PV

Drive power estimate (LVH) (2-3000 hours x 2 drives x 50 watts each x \$05/kWh
Looks like about \$12/H/yr, if 50 W continuous. At 20% drive factor, this is \$2.40/H/yr. If you include for the power to operate the electronics, it will still be on order \$5/H/yr =\$0.54 / m^2 per year xCEPI/466 => **\$9.30/ m^2= PV as** PVFelectric = 17.3
assuming the drives are only on 20% of the time

biweekly washing costs of \$15.60/heliostat-year = 1.678/ m^2-year,
service drives @\$10/helio-year = \$1.08/ m^2-year
electrical power to drives and electronics @\$5/helio-yr =\$0.54/ m^2-yr

PVO&M = (15x\$2.76 + 17.3x0.54) = \$50.74(CEPI/466)/ m^2
Effective cost of heliostats =\$(60.39+50.74)+ 100, 150, 200) (CEPI/466))/ m^2
⇨ **So miscellaneous and PVO&M costs exceed \$100 min. bare helio cost**

Fraction of helios operational 0.98
Correction (cell to IH): 3% for Barstow, scaled within code by:
Q = (76m/VFH) x [(100sqft/10.76)/47.38 $m^2]^{0.5}$ =33.66/VFH => 1+.03 Q ~ 1.0126
(To account for loss in mean heliostat efficiency in layout process due to deletes etc.)

Helio reflectivity (clean): 92.5% **Mean dust loss factor: 2%**

Tower Mounted Reflector (TMR) And Tower

TMR width or diameter: (down looking hyperbolic reflector)

The total initial reflector area is essentially a circle, TMR area = 541m2 with 1867 facets: each having an area of 0.29 m2, and a weight of 120 lbs, including the Geometrical struts and hardware

SO R = 13.12 m = 43 ft, and the facet dimensions are a side of 0.8180 m, height of 0.7084 m

Weight of 'Receiver'
(= weight of TMR +10% for support ring and attachment hardware)

= (120lbs/0.29 m^2)*TMRarea * 1.10 ~ 125 tons or 250 kilo-pounds

Reflectivity of TMR (20 year average, including dust effects):__95%_____
Focal height (to virtual focal point) – HT = 80m above heliostat axis (initial value)
Aim strategy Center (X) Belt ( )

TOWER COSTS

THE FOLLOWING EQUATIONS, BASED ON 'TOWER COST ESTIMATING DOCUMENT", WHICH WAS DEVELOPED IN 1980 WITH 1980 DOLLARS, WILL BE USED IN RCELL we assume Egyptian costs for all. **Tower type 3 leg, guyed steel**

Tripod Tower cost (h,wt):
*The analysis predicts tower steel column weights, total steel weight, concrete volume, and rebar weight, given the following parameters: (**note the units used here)***

Weight Receiver: 10 to 8000 KIPS = TMR + support ring, etc.
Lateral Acceleration: 0.05 to 0.6 g = 0.5g: until new data is obtained
Wind Velocity: 70 to 120 mph = 90 mph

Tower Height: 120 to 650 ft

The equations to be used are:

Total Steel Tower Weight
= 2.18(Column Weight) for H_{tower} equal to or greater than 210 ft
= 3.095 (Column Weight) for H_{tower} less than 210 f
[[At **210 ft = 64 m** *there is a factor of 0.7 reduction for taller tower equation*
This will strongly favor taller towers with a discontinuity at 210 ft.
NOT NICE but not a serious problem, as our towers are all likely to be above 64 m
[[probably better to put a stop in the code rather than have it switch costs in secret]]
We have estimated the initial total tower (Column) height to be approximately (5.25/4.75)67 = 74 meters, with the 67 meters being the height to the TMR.]]

Use(1.1 x $H_{\mathbf{TMR}}$ (in m) + 2m)/0.3048 ➔ feet above ground for tower height = $H_{\mathbf{tower}}$ in tower cost calculations above and below
(this is NOT the virtual focal height of 80m vs 67m for the TMR nor is it HT in RCELL)

Weight of 'Receiver'/1000 lb = ($W_{receiver}$) in kilopounds(KIPS)
(= weight of TMR +10% for support ring and attachment hardware) /1000 lbs
= (120lbs/0.29 m^2)*(TMRarea in m^2)*1.10 /1000 =>~250KIPS at 541m2

($W_{receiver}$) ***in kilo-pounds*** *(Acceleration) in g's (Vel) in mph, (H_{tower})* ***in feet***
FOR A SINGLE TOWER, WE HAVE:
Column Weight Steel (Tons) =
$2.6956 \times 10^{-6}(W_{receiver})^{0.2605}(Acceleration)^{0.16675}(Vel)^{1.05556}(H_{tower})^{1.9984}$ *=> ~68tons*

Steel Tower Volume of Foundation Concrete (Cubic Yards) =
$2.4565 \times 10^{-3} (W_{receiver})^{0.09196}(Acceleration)^{0.9547(1.2(1-HT/750)}(Vel)^{2.0523}(H_{tower})^{0.7826}$
=>~1862 cu yds
Steel Tower Foundation Rebar Weight (Tons) =0.0375(Volume of Concrete in one Foundation) [75 lb of rebar/cubic yard of concrete] => ~70 tons

So for all three towers we have 2.18 x Steel + 3 x Concrete + 3 x Rebar
use cost for concrete, steel and rebar from Cost Factors, page 2,

$1080(CEPI/261.2)/ton, $82(CEPI/466)/cu-yd, and $980(CEPI/261.2)/ton

=> $285k + 458k + 367k = $1,110 k for 3 towers, concrete and rebar in 2005 $

assuming the concrete and rebar must also be scaled to 3 towers

Tower Accessory Cost

Total Tower Accessory Cost = TTAC = Obstruction Lighting Costs + Safety Ladder Cost + Lightning Protection Costs + Platform Costs + Painting Cost + Lighting Cost

TTAC(current dollars) = OL + SL+ LP + PL + PA + LI
= TTAC(1980 dollars) *CEPI/261.2
= [$89,000 + $33/ft*3*($H_{tower}$) + $18,000 + $30,000 + $20 (Total: 3 Steel Towers Weight, tons) + $18.70/ft*3*($H_{tower}$)**]** *CEPI/261.2
we need safety ladder and lighting on all 3 towers OK, JBB
Accessory O&M costs (%/year) = 2+0.5+1+0.5+0.2+2
Accessory O&M costs = (2OL + 0.5SL+ 1LP + 0.5PL + 0.2PA + 2LI)/100 $/year
PV Accessory O&M costs = PVF x above = 15 x above
Is there also electrical costs for OL and LI ?
Maybe 4000hrsx20kWx$.05/kWh = $4000/year, x PVFe = 17.3x4000
=>**$51,000X(** CEPI/466) Add to FIXED COSTS

TOWER REFLECTOR COSTS
Tower reflector configuration: hyperbolic, convex down, initial vertex at 68m. ~ 8ft thick
Tower reflector support: $ 100,000 x (diameter/86ft)^2 x CEPI/466
O&M = 1%/year

Tower reflector facets: TRF have area of 0.29 m^2 @ $200 each x CEPI/466

The total initial reflector area is 541 m2, (SO R = 13.12 m = 43 ft) with 1867 facets: each having an area of 0.29 m2. or a side of 0..8180 m, height of 0.7084 m

Tower reflector facet cost = reflector area/0.29 m^2 x $200 x CEPI/466=
$200 **X 1867 x (diameter/86ft)^2 x CEPI/466**

Tower Reflector Facets (TRF)
TRFacet O&M = 1%/year+ ($20 to replace a defective facet + cost of refurbishing a facet) x 5% of facets/year
= (1%x$200 +$20/20 + $60/20) x (CEPI/466)
= ($2 + $1 + $3)x (CEPI/466) = $6X(CEPI/466)/facet-year, so PV = $90/facet
so for all facets, TRF-O&M = $(6/200)*TRFcost = 3%
refurb? GOOD POINT....MOSTLY I THINK refurbishing the facets WOULD BE BONDING EDGES THAT HAVE SEPARATED, MAYBE BEEFING UP THE FIBERGLASS, AND POSSIBLY PUTTING ON REPLACEMENT ALUMINUM/STEEL ATTACHMENT HARDWARE. I'D SUGGEST THAT EACH MIRROR WOULD REQUIRE ABOUT, SAY, 2 - 4 MAN HOURS OF MAINTENANCE, AND MAYBE, SAY, $10 -$20 OF HARDWARE AND MATERIAL COSTS. JBB
Taking the mid points, refurbishing a facet will cost 3hrx$15/hr + $15 = $60

I assume this is a bit lower class labor than the CPC refurb, so used $15/hr

"PREHEATER" SYSTEM

The preheater system is costed to the heliostat plant, but the energy is "given away".
(costed because cooling is required for survival of elements, but heat is low value)
Tower reflector (TR)coolant: water/ethylene glycol (temperatures below ~ 70-210 F)
Tower reflector piping (TRP): @$3/ft => $3/ft (600ft)(TRheight/67m)(CEPI/466)
Feed pump (h,p)+HX(Pth): =[$1800x(TRheight/67m)+$2000(Pth/10MW)](CEPI/466)
Parasitics = [2kWx3000hrs@$0.05/kWhr =$300] x (Pth/10MW)(CEPI/466)/year
PVFe = 17.3
Vertical Increment: Scale = 1+(HT+24)/800m
Bend factor for Piping = 1.5X; included? ___yes___________

RECEIVER "PREHEATER" RELATED COSTS
CPC coolant system & heat exchanger: $5900 (Pth/10MW)(CEPI/466)
Spillage collector and CPC cover: ($30,000 + $30,000) (CEPI/390.6)
Spillage coolant system & HX: $(1400+1300+1000)(spillage/300kW)(CEPI/466)

ESTIMATED O&M on each of above "preheater" elements =5% of cost/year
My guess is 5%, given that it's hot, moderate pressure, remote, etc(JBB).

DIRadiometer $600k for first =>$100k)(CEPI/466)**charged to this plant**
=> a fixed cost CORRECT YEAR OF ESTIMATE = 2005??**2005…cameras and computers keep getting cheaper and better. JBB**

DIAPER Receiver coolant: air @ 500 C max.
1-6-12 hexagonal aperture CPCs in HCP array, 15 ft overall diam. I.e. 3 ft across flats; hexs in 3,4,5,4,3 stack=> space filled HCP array
?1 cm edge effect on CPCs =2.5%of the reflective area
My guess is 2 cm…hard to say…I could be wrong. We'd make it as small as possible, and might extend the glass, with backing, a bit beyond the cooling channel, so it could be 1 cm JBB. I assume this is on EACH CPC, not the combined edge. We will treat it as a reflective loss =>R = 0 .05 + 0.025 t/1cm, t= ? start with 2cm on each CPC => 10% aperture "reflectivity" = loss in beam power prior to absorption. We will NOT deal with thermal losses, nor take advantage of any regained.

[NS grid on CPC aperture] 21+2 for spillage __23 nodes_____
[EW grid on CPC aperture] 21+2 for spillage __23 nodes_____
Orientation (of aperture plane) horizontal, uplooking
Michel: I assume these are convenient, if not OK to reduce as needed to prevent recoding. Start with a circular absorbing area on the "receiver plane" Note these are

on the demagnified aperture (3 ft radius, gives 7 nodes/ft plus 1+1 for spillage). May want to repeat the output on the actual (3 x M = 15 ft to start) aperture for ease of looking, especially later, when M moves from 5.

Secondary Concentrator Receiver aperture (CPC inlet): 8m above helio axis
Absorptivity (effective, for aperture): 0.95?? approx. (including edge effects??)
OK, make it Absorbtivity = 1.0 - .05 - .025 t/1cm, t= ? start with 2cm=> alpha =0.9

Receiver thermal loss: (does not matter if specify 10 MWt onto aperture plane). In fact, we will provide 10MWt <u>through</u> the aperture plane by accounting for R above

Preheat section 12 hexagonal CPC and simple receivers
Diapers 1 + 6 hexagonal CPC and porcupine receivers
Location of preheat: third ring of hcp array + TMR + CPC + spillage apron

RECEIVER AND CPC COST
cost f(Area) 7 installed Diapers = $955,073 x 1.4 x CEPI/389.5; O&M = 5%
cost f(Area) 12 installed Preheaters = $365,088 x 1.4 x CEPI/389.5; O&M = 3%
Rotem had $1,300,000 in 1998. I like 1% better for O&M, sooo
cost f(Area) of CPC's $1,300,000x(CEPI/389.5), O&M = 1%/year
CPC O&M;
[[wash & rinse 50X/year at (2hoursX$20/hr + $6 sln & water) = $2300;
refurbish all CPC mirrors one time @ ((1hrx$20/hr + $1)/sqft glass)x(glass area = 5xinlet =5xPi (1.5ft)**2) x19 = $14,100 over 20 year life => $940/year;
sum = $3240 < 13,000 so 1% is reasonable.]]

I think we could just ratio these by an aperture area and assume geometric similarity. We have often used volume or mass to the 0.8 power, LVH=>A to 0.86 power or L to 0.93. aperture area is fixed for now.

Virtual demagnified receiver aperture: 15 ft X demag. Factor => 15/5=3ft M is a function of Virtual focal height, TMR vertex height, CPC aperture height, plane of elevation axis of heliostats, all stated relative to the 2 m height of the heliostat axis above the ground plane => V=80 , R = 68, A =8, AXIS = 0; are the initial values
M(linear) = (R-A)/(V–R) = (68 – 8)/(80 – 68) = 60/12 = 5.0 =>3ft Dia aperture at VFP
For comparison, (66-8)/(80-66) = 58/14=4.14 if lower TMR 2 m, but TMR diameter up 16%, area and cost up 32%

<u>Field and System here HT = VFP = 80m to start</u>
Cell size (order) N=1, 1/2, 1/3 th DA=HT√N/4, so cell side = .50, .3536, .288 X virtual focal height USE 1/2 TO START => 594 M SQUARE FIELD OK

Size of field in Meters   NS=_368N, 226S_   EW=840/594/485m__297 E&W
In cells   NS=___21_____   EW=____21_____
Tower – in cells   from North____13_____   from West___11______
Array configuration: radial-stagger

Fixed costs: _DIR + MCS + site equipment and buildings + PVlighting electricity
= $100,000(CEPI/466) + *$90,000*(CEPI/389.5) +$155,300*(CEPI/394.3)
+ $51,000 (CEPI/466)

site prep, roads and fences are moved to land costs.
external roads and power transfer line to site assigned to gas turbine plant.

LAND COST COMPONENTS
Land cost: No Costs - - Provided by Egyptian Government
[then add prep costs such as access roads, power connection, etc specific to making site ready to use, estimated below from a 207,500 m^2 **plant in 2001 dollars]**

Site Works: $436,790/5
= $87,358.X (total solar plant area/41,500 m^2) => $2.11/ **m**^{2}(CEPI/394.3)

Roads and Fences: estimated from the field area ratio, re a 5 times larger plant costed at $220,109 ~~{{=> $220,109 /5~~
~~= $44,022 X (total solar plant area/41,500 m^2)(CEPI/394.3) => $1.06}}~~

but PROBABLY should be square root of area ratio: (length of fences and roads) =>$220,109/ 5$^{0.5}$ =>
=$98,435 X (total solar plant area/41,500 m^2)   (CEPI/394.3)
where linear scaling is OK for small changes about the scaled size
= >$2.37/m^2(CEPI/394.3)

LAND COST = $2.11+ $2.37 = $4.48/m2x(total solar plant area-m^2)(CEPI/394.3)
And "total solar plant area" =(#cells within field boundary occupied by heliostats + 1.75(central circle) + 2.75(south road)) x cell area = [# + 4.5] x 0.5 (VFH)^2 /4
(the 4 is for second order cells)

BOP COST SUMMARY ASSUME ALL IN 2001 US DOLLARS = 394.3

Turbine Generator Building AND Receiver substructure; = $61,250)(CEPI/394.3)

Miscellaneous Solar Power System Support Facility: Total:= $43,000**(CEPI/394.3)**
Field Equipment:= $51,100(CEPI/394.3)

This goes to fixed costs: => 61,250+43,000+51,100 = ($155,250) X (CEPI/394.3)
Add to this: O&M =2%

WIRING COSTS
Components of costs from 1978 analysis CEPI/218.8:(per linear meter of wire or trench)

Small power draw, so can just tap off of the central station power transformer

1) **radial power (R) e.g. 110 volt line and data line from center to 15 HLC's**
2) **radial power and data distribution headers (ΔR) [from HLC to nearby circles]**
3) **azimuthal distribution (RΔϕ) [from H to H along a circle]**

(may have distribution transformers in field. ASSUME NOT so do not require high V Power cable to LHC nor transformer costs).

Wiring costs ($/m): 110V power cable = 2.36;
Data Cable =1/2 x 4.20(modern);
Trenching = 1/2x 6.10(Egypt);

⇨ **2.36, 2.10, 3.05, sum = 7.51, all in 1978$ xCEPI/218.8:**

⇨

wiring from tower to 100 H off a LHC Cw1= 7.51/100 =0.0751,
radial wiring from LHC to 14 H on each of 7 arcs

⇨ **Cw2 = (4.46x6DR + 3.05x3DR)/100DR = .3591,**

azimuthal wiring from UPS along arcs to 14 heliostats =>Cw3=7.51;

all X CEPI/218.8

Annual O&M (PVO&M additive to wiring costs within code)
Heliostats are numerous and small so travel time is not important. Include items 1-3 below in O&M/m2

1) ~~**travel costs to circle from tower ($/m of travel x no. of trips/year) I'd assume this is part of the overall maintenance associated with the permanent staff, as noted above, but if you need a rationale, I'll work one up. The idea here is that as the circles get further apart, the cost of getting to them is higher, and RCELL uses this to help keep the field size down, along with cost of land and diminished interception [trades against higher shading and blocking]**~~
2) ~~**? usually set to zero**~~
3) ~~**travel along circle (to wash or service) ($/m of travel x no. of trips/year)**~~

same idea as above

Design Points and Constraints

Design Point Day and Time ___Equinox___Solar Noon
Design Point Insolation _1000 W/m^2 [seems high for sea level and global dim]
Design Point Power 10MWt delivered [assumed to be into the aperture of the CPC after accounting for spillage and edge loses] OK.
Peak Flux Limit on TMR ____Approx. 60 kilowatts/m^2
Peak Flux Limit on CPC aperture __>10,000_ kilowatts/m^2: may be a problem on CPC rims—1-2 cm wide end effects

Land Constraints: if any, such as for transmission lines, oil wells, access roads.
100 ft keep clear circle, 40 ft wide road to south, but is there a 20 ft wide road around the keep clear circle to provide access to field? Sounds like yes to the 20 ft circle, which increases the keep clear circle to 140 ft dia.

140 ft dia = 1.80 of our initial 1/2 order cells at 80m VFH 1 3
4 = a whole cell: :central exclusion at the tower => 1 4 1 => 3 0 3
1 3
40 ft = 12.2m wide road =0.43cell wide exclusion to the south 2 2
add column of 2,2,1,2,2,1,2 to the south border 2 2
1 3

Originator ___Jim Blackmon, Lorin Vant-Hull___ _Date _'05-12-9 to 15
Supplementary Data _some points clarified by LVH_ Date __'06/01/31,02/18
Supplementary Data _LVH updates from JBB 3/23 Date __'06/03/23
Supplementary Data LVH updates from JBB 3/24 Date __'06/03/26
Supplementary Data __JBB reviewed by LVH______ Date __'06/03/27
Stripped version LVH Date '06/03/29
Essentially complete, stripped, LVH approved Date '06/04/26
Tower cost change, LVH JBB approved Date '06/05/01
Approval: design engineer _____________________ Date _________
Approval: code operator _______________________ Date ________

The CEPI inflation factors used in RCELL are:
204.1 = 1977, 218.8 = 1978, 238.7 = 1979,
261.2 = 1980, 297.0 = 1981, 314.0 = 1982,
316.9 = 1983, 322.7 = 1984, 325.3 = 1985,
318.4 = 1986, 323.8 = 1987, 342.5 = 1988,
355.4 = 1989, 357.6 = 1990, 361.3 = 1991,
358.2 = 1992, 359.2 = 1993, 368.1 = 1994,
381.1 = 1995, 381.7 = 1996, 386.5 = 1997,
389.5 = 1998, 390.6 = 1999, 394.1 = 2000,
394.3 = 2001, 395.6 = 2002, 402.0 = 2003,
444.2 = 2004, 466. = 2005

APPENDIX D

TOWER REFLECTOR

Tower Reflector Support Structure and Reflector Facet Field Exposure Test
J.B. Blackmon
November 2007

The tower reflector support structure and one of the reflector facets from the USISTF program was assembled first at NASA MSFC in 1999. Later, this was disassembled and moved to UAH in early 2001. During this period we made occasional observations of the hardware. Until 2006, there was no noticeable effect of exposure to the environment.

The unit was an approximately 14 ft wide Geometrica strut assembly, as shown in **Figure 1** at NASA MSFC and in **Figure 2** at the UAH Solar Test Area. Initially the reflector facet was exposed without any covering, but later, a black plastic covering was placed on this to simulate the relative solar flux incident from the heliostat field. After about one year, the facet was then painted flat black. The effect of this covering and coating was to have a relatively high temperature during the hot summer months. It should be noted that the operational reflector facet would be cooled by a water-ethylene glycol mixture, such that the temperature was maintained well below 200 C, and probably for most of the facets, below 150 C. The unit with the black paint had the equivalent absorption of approximately 0.92 I solar, which in Huntsville is of the order of 1000 W/m2 on a clear day. With a mirror absorptivity of about 0.1, this corresponds to about 9 suns, relative to the installed condition on the tower. Accounting for the reflectivity loss of the heliostats, but assuming that the peak solar irradiance from each heliostat is not superimposed at the tower reflector, this exposure condition corresponds to approximately ten heliostat beams overlapping. With overlap considered, something of the order of several heliostats reflecting sunlight onto the same approximate area of the tower reflector is simulated by this test. However, the temperatures that the reflector facet reached during the clear summer days were of the order of the temperature range for the operational system. This was basically an attempt to provide at least some degree of additional thermal stress on the facet in case there was some type of failure.

We in fact did observe a failure. The facet had been accidentally dropped onto a concrete floor, striking a large steel I-beam during a thermal test. This caused a crack in the mirror. Over the course of about five years, these cracks grew. cracks can be noted over some of the facet area in **Figure 3**. The reflector was assembled using the spool supports and adjusting screws, shown in **Figures 3 and 4**. This corner of **Figure 4** also shows the delamination that occurred in 2006, which appears to have been due at least in part to the facet being dropped and the reflector cracked, since the damage area is in the cracked area. It is also possible that the delamination could be due at least in part to other factors, including insufficient surface cleaning in that area before the adhesive was applied or possibly the built in stress and the expansion and contraction that occurred, especially with the high temperatures with the diurnal cycles over a period of approximately 7 years. The delamination occurred at the stainless steel surface; the adhesive peeled away from the steel, but was intact on the glass, and prevents the glass from being separated into pieces. The delaminated area is only in the one corner, as of November 2007.

Figure 1 – Geometrica Tower Reflector Support Structure with Tower Reflector Facet at NASA MSFC

Figure 2 – Geometrica Tower Reflector Support Structure with Tower Reflector Facet at University of Alabama in Huntsville

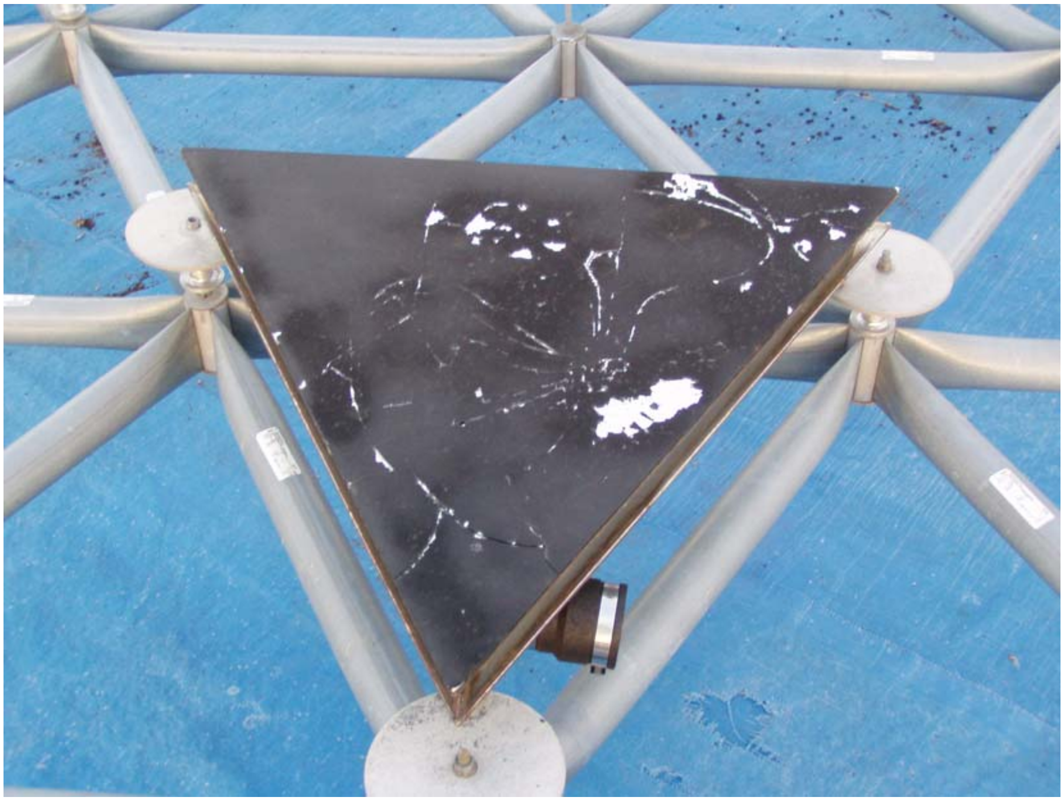


Figure 3 – Reflector facet in 2006, showing cracks that propagated over the course of several years after the facet was dropped and the mirror cracked

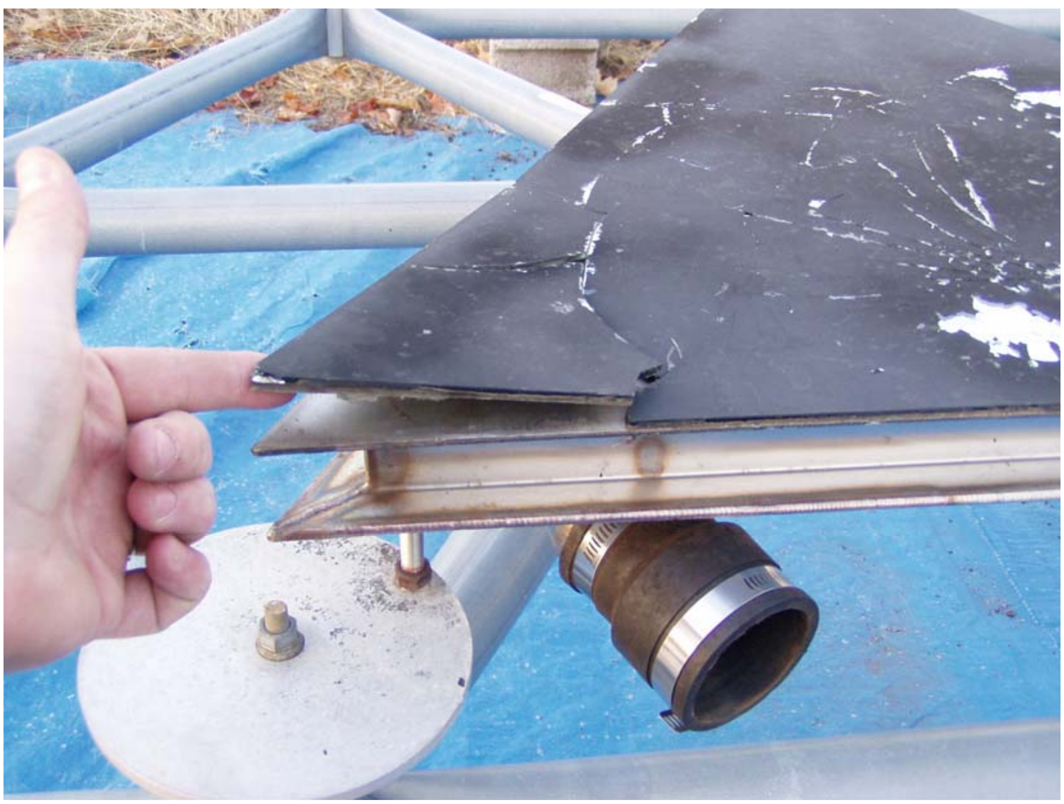


Figure 4 – Delaminated corner, showing adhesive has lifted off of the stainless steel surface

APPENDIX E

RCELL/SOLARSIM COST ESTIMATING RELATIONSHIPS AND RELATED INPUTS

From: SOLARVANTHULL@aol.com
Sent: Monday, June 27, 2005 7:21 PM
To: blackmoj@email.uah.edu
Subject: inputs for beam down

Jim,

In case we want to discuss input needs for the RCELL analysis, here is a copy of some information from a previous study. We also need information to generate a solar model appropriate for the site, which I guess must be between 22 and 30 deg north latitude, and at a height above sea level of ?100 m?. We can accept the Barstow model, or generate a new model for this site. Some modeling info is available on the Web, but it tends to be more in the line of insolation data, rather than precipitable water, aerosol content, %cloud cover, etc our model looks for. We do have available cost models from the Utility Study which are inflated to current costs, but you may need to provide a tower, reflector and receiver costs appropriate for your design. Also heliostat cost and performance data. Initial input on reflector elevation, area, reflectivity, scattering sigma are also needed. Etc. etc........
Talk to you at 9:30 on Tuesday, Michael may call us both to set up a conference call. He understands stuff, and computers also.
See you then,
Lorin

Summary of the conceptual design study results.

The following table is a summary of the current system design.

Parameter	Value
Tower Height	190 m
Receiver Width	15.0 m
Receiver Height	20.5 m
Receiver Area	966 m2
Average Panel Power South Side	0.688 MW/m2
Average Panel Power North Side	0.287 MW/m2
Aim Level Distribution South	0.40, 0.05, 0.10 0.05, 0.40
Aim Level Distribution North	0.45, 0.10 0.00, 0.05, 0.40
Heliostats Number	6100
Heliostats Field Size	826,150 m2
Total Area within Perimeter Road	3.41 km

Future design study.

As mentioned above, this study is a preliminary design study. In the future, when a more detailed set of results is needed, we will continue the design study with the following tasks:

1. Refine any cost model using additional data from the project.
2. Refine the Insolation model based on additional data from the site

3. Add a detailed Allowable Flux curve and study the resulting flux maps for different days/time
4. Perform some panel power runs as well as annual power distribution
5. Perform a sensitivity study, varying the heliostats precision, and focal length.
6. Perform Start-up studies

Appendix A: Cost Model Summary as entered in the RCELL Code

"C" indicates comment lines, which are not operational.

```
C CEI IS "COST ESCALATION INDEX".
C 218.8 = 1978, 238.7 = 1979, 261.2 = 1980
C 297.0 = 1981, 314.0 = 1982, 316.9 = 1983
C 322.7 = 1984, 325.3 = 1985, 320.0 = 1986, 390.0 = 2002
CEI = 390.0
C * COST ESCALATION INDEX FOR 2002$
CFIXD = 2.00E+6
CFIXD = CFIXD*(CEI/390.0)
CL = 0.000
C * 4/Pi*COST OF LAND IN $/M2
CL = CL/390.0*CEI
CLOM = 0.00
C * COST OF LAND O & M IN $/M2
CW(1) = 0.00
C * WIRING EQUIPMENT IN $/M2
CW(1) = CW(1)/316.9*CEI
CW(2) = 0.00
C * WIRING EQUIPMENT O & M IN $/M2
CW(2) = CW(2)/316.9*CEI
CWP(1) = .0412*1.45
C * WIRING COST CONSTANT-PRIMARY FEEDERS
CWP(1) = CWP(1)/316.9*CEI
CWP(2) = .0412*.01*1.45*13.06*0.5 (1+ 0.333)
C * WIRE COST CONST - PRIM FEEDERS O&M
C 13.06=FLIFE AT 6.5%, 0.5*(1+0.33)=effect of reduced cost of labor YYY
CWP(2) = CWP(2)/316.9*CEI
CWR(1) = .4327*1.45
C * WIRE COST CONSTANT-RADIAL HEADERS
CWR(1) = CWR(1)/316.9*CEI
CWR(2) = 0.00
C * WIRE COST CONSTANT RAD HDRS O & M
CWR(2) = CWR(2)/316.9*CEI
CWA(1) = 5.72*1.45
C * WIRE COST CONSTANT-AZIMUTHAL
CWA(1) = CWA(1)/316.9*CEI
CWA(2) = 0.30*13.06
C * WIRE COST-AZIMUTHAL O&M
C (ESTIMATED WASHING COST)
C 13.06 = FLIFE AT 6.5%
```

```
CWA(2) = CWA(2)/316.9*CEI
C
FLIFE = 13.06
C * FINANCIAL LIFE IN YEARS
C (PRESENT VALUE FACTOR)
C 6.5 % REAL INT ==> 13.06
CHL = (110)*(CEI/390.0)
C * HELIO COST IN $/M2
CHOM = (1.32*FLIFE)*(CEI/390.0)
C * HELIO PV OF O & M COST IN $/M2
C
C* COMMON/PVGRP/FLIFE,PRICE,ETAEL,FPV,CHPR
PRICE = .015E3*CEI/390.0
C * COST OF ELECT IN $/MWH
ETAEL = 0.3819
C * EFFICIENCY OF CONVERSION TO ELECT
FPV = FLIFE * PRICE
C * PRESENT VALUE FOR ELECT. PARASITICS.
CHPR = 100.E-6
C * PARASITIC POWER PER HELIOSTAT
100 W DRIVE POWER
CHPR = CHPR*3737./HGLASS
C * HELIOSTAT PARASITICS IN MWHE/M2
C (MULTIPLY BY HOURS OF OPERATION
C AND DIVIDE BY REFLECTIVE AREA OF
C A HELIOSTAT)
C
C
JSALT = 1
C * 0 FOR SODIUM, 1 FOR SALT : 1ST PLANT COSTS
C
THTB = HTX + DMIR/2. - BEL/2. - AEL/2.
C (KEEP IN MIND: BEL AND AEL ARE REC HEIGHT AND DIAM.
C
C TOWER COST DUE TO LARRY STODDARD OF BLACK&VEATCH - 2/24/87
CTOWR = (0.6E6 + 17.72 * THTB**2.392) * (CEI/320.)
C CONCRETE TOWER COST EFFECTIVE
C
IF( THTB .LT. 76. ) CTOWR=(0.201E6+26.5*THTB**2.44)*(CEI/320.)
C STEEL TOWER COST EFFECTIVE
C
C
C CYLINDRICAL RECIEVER COST MODEL
C
C SALT REC. COST MODEL FOR ESKOM
CRECV = 18.0E6+9.0E6*(AEL/13.0)*(BEL/19.5)**0.6
```

```
C
IF(JSALT .EQ. 0) STOP 'SODIUM REC. COST EQN. NEEDED'
C
CRECV = CRECV*(CEI/390.0)
C
C PIPING COST MODEL
C
SCALE = 1.0 + (HTX+66.0)/800.0
SREPOW = SQRT(EQPOWS/390.)
DH = 0.4064*SREPOW
DC = DH
HOT = (1.6*HTX + 1.4*160.*SREPOW)*(0.0+11140.*DH+2846.*DH*DH)
COLD = (1.4*HTX + 0.9*160.*SREPOW)*(494.+6782.*DC)
CVPLUM = HOT + COLD
C HEAT TRACE = 25% PIPING
CVPLUM = 1.25*CVPLUM*(CEI/320.0)
C
C FEED PUMP COST MODEL
C
PSIF = 300.
FHM = PSIF / 2.711
CFPUMP = 1.4E6*( ((HTX+FHM)/(150.+70.))*(EQPOWS/390.) )**0.85
CFPUMP = CFPUMP*(CEI/320.0)
C
CTTOW = CTOWR + CRECV + CVPLUM + CFPUMP
C
TOWOM = 0.002*CTOWR * FLIFE
RECOM = 0.020*CRECV * FLIFE CHANGED TO 0.015 1/9/00
VPOM = 0.010 *CVPLUM * FLIFE
FPOM = 0.050*CFPUMP * FLIFE CHANGED TO 0.02 1/9/00
TOTOM = TOWOM + RECOM + VPOM + FPOM
C FOR ESKOM THE ELECTRICITY COST IS 1.5 CENTS PER KWH INSTEAD OF 5
CENTS/KWH
FPARA = (0.0292*ATPOW * (HTX + 0.75*FHM)/366.)*1.5/5.0
```

Appendix B: Summary Results Page from RCELL Code

```
NGON = 4 ; MAX. NUMBER OF HELIOS./CELL= 266.6 ;
HGLASS/DMIR**2 = 0.9909 ; TOTAL GLASS = 0.82615E+06
6100.6 HELIOS AHELI= 135.4200 ASEG= 135.4200 ; TOTAL LAND =
0.32296E+07
F-LIMIT OPTIMUM ALLOWED M-LIMIT PLANES
044444434444440 000000000000000 000000000000000 00000000
11111111
444444444444444 000000000000000 000000000000000 00000000
11111111
444444434444444 000000222000000 000000222000000 00000000
11111111
```

444444444444444 000034444430000 000034444430000 00000000
11111111
444444434444444 000444444444000 000444434444000 00000000
11111111
444444444444444 002444444444200 002444444444200 30000000
11111111
434443404344434 004444444444400 004443404344400 03000000
11111111
444444444444444 004444444444400 004444444444400 20000000
11111111
444444434444444 004444444444400 004444434444400 00000000
11111111
444444444444444 003444444444300 003444444444300 00000000
11111111
444444444444444 000444444444000 000444444444000 00000000
11111111
444444434444444 000144444441000 000144434441000 00000000
11111111
444444444444444 000003444300000 000003444300000 00000000
11111111
444444444444444 000000000000000 000000000000000 00000000
11111111
044444444444440 000000000000000 000000000000000 00000000
11111111
* * * * NUMBER OF HELIOSTATS PER CELL ; HT = 190.0 FOCAL HEIGHT ; AND APERTURE= 966.04 M2
CYLINDER LENGTH = 22.55 M; DIA. = 15.00 M
REDUCED LENGTH = 20.50 M; DIA. = 15.00 M
NORTH
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 4.5 19.6 25.9 19.6 4.5 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 31.6 58.2 66.3 66.1 66.3 58.2 31.6 0.0 0.0 0.0 0.0
0.0 0.0 0.0 42.4 61.0 75.8 92.2 79.0 92.2 75.8 61.0 42.4 0.0 0.0 0.0
0.0 0.0 22.6 55.4 72.3 94.7 127.4 139.2 127.4 94.7 72.3 55.4 22.6 0.0 0.0
0.0 0.0 43.9 58.1 76.6 80.3 146.5 TOWER 146.5 80.3 76.6 58.1 43.9 0.0 0.0
0.0 0.0 45.0 57.5 74.1 99.7 117.4 146.5 117.4 99.7 74.1 57.5 45.0 0.0 0.0
0.0 0.0 43.4 54.2 66.8 83.5 101.2 80.1 101.2 83.5 66.8 54.2 43.4 0.0 0.0
0.0 0.0 33.6 48.6 58.2 68.2 77.0 80.4 77.0 68.2 58.2 48.6 33.6 0.0 0.0

```
0.0 0.0 1.5 41.4 49.2 55.6 60.7 62.3 60.7 55.6 49.2 41.4 1.5
0.0 0.0
0.0 0.0 0.0 10.1 40.3 44.9 48.4 37.0 48.4 44.9 40.3 10.1 0.0
0.0 0.0
0.0 0.0 0.0 0.0 0.0 25.6 37.6 38.3 37.6 25.6 0.0 0.0 0.0 0.0
0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
SOUTH
BLOSS = 30.100 KW/M2
PERFORMANCE SUMMARY AND COST BREAKDOWN FOR OPTIMIZED COLLECTOR
FIELD -TRIM LINE AT 1.000
EQNOON POWER = 405.165 460.009 IN MW - (SCALED TO 1000.0W/M2)
ANNUAL ENERGY = 887.2214 IN GWH PARAS.= 5.9696 HELIOS 6.1496
FPUMPS
FIXED COSTS = 2.0000 IN $M
COSTS IN $M TOW 5.9545; REC 28.7009; V P 6.8057; PUMP 2.7197
TOTAL TOWER COST= 44.1808; $M FOR 1000.0 EQUINOON POWER
PV O&M COSTS IN $M 0.1555; 7.4967; 0.8888; 1.7759;
SUM PV O&M COSTS= 10.3170;
LAND COST = 0.0000 IN $M; PV OF O&M COST = 0.000 IN $M
WIRING COST = 1.9385 IN $M; PV OF O&M COST = 0.721 IN $M
HELIOSTAT COST = 90.8760 IN $M; PV OF O&M COST = 14.242 IN $M
CAPITAL COST TOT= 138.9953 IN $M;
PV O&M COST TOT= 25.280 IN $M; PV OF PARA COST= 0.907 IN $M
GRAND COST TOTAL= 165.1822 IN $M
FIGURE OF MERIT = 186.179 IN $/MWH , FOR FINPUT= 131.959 ,AND
FSTAR= 175.451
DC(P)/DP= 2.03609E+04 $/MW , EINC/PINC= 1994.25 HOURS AND
DC(E)/DE= 0.52 $/MWH
```

For more explanation on this results page, see SAND88-7029 “The University of Houston Central Receiver Code System: Concepts, Updates, and Start-Up Kits”, C.L.Pitman, L.L. Vant-Hull, March 1989

Appendix C: Glossary

Csa: Mediterranean Climate in Classification of Major Climatic Types According to the Koppen-Geiger-Pohl Scheme
C: Mid-Latitude Climate
s: dry Summer
a :temperature of warmest month 22 degrees Celsius or above
BW: B: Subtropical dry desert
W: wet Summer
%PS: Percent Possible Sun
DBI: Direct Beam Insolation
B500: Measured Turbidity at 500nm
ATF: Atmospheric Turbidity Factor
VR: Visual Range at the Site.

Rain: Rain Condition w for wet d for dry
DMIR: Reference Dimension for heliostat (Square root of height * width)
DREC: Diameter of Receiver
HREC: Height of Receiver
fh: Focal Height of Receiver Centerline (above plane of heliostat elevation axis)
CEI: Cost Escalation Index from Chemical Engineering.

Lorin Vant-Hull
128 N. Red Bud Trail
Elgin, TX 78621, USA

phone: 512-581-9921
e-mail: solarvanthull@aol.com

RECEIVER SUBSYSTEM COSTS FOR COMMERCIAL VERSION OF NOOR AL SALAAM HIGH CONCENTRATION SOLAR CENTRAL RECEIVER POWER PLANT

Rotem provided non-proprietary hardware cost estimates for the receivers. There are 7 so-called High Temperature Receivers (HTR) and 12 Low Temperature Receivers (LTR). From the reference, these costs, in 1998 dollars, are:

Hardware Costs

7 equal HTRs	$955,073
12 equal LTRs	$365,088
Hydraulic Lifting Trolley for HTR/LTR	$30,000
Local Control System	$268,200
Total Receiver Cost	**$1,618,361**

Installation Costs

Installation costs include packaging, shipping, receiving, inspection, and assembly at the site. These costs are not available. As an order of magnitude estimate, we assume 40% of the hardware cost, or 0.4 x $1,618,361 = **$647,344**.

The total receiver installed cost estimate is **$1,618,361 + $647,344 = $2,265,705.**

Reference:

1. Rotem report file ID: C:\data\word\hcscr2.doc

Tower Design Algorithms for Weight and Costs
James B. Blackmon
February 10, 2006
Revised April 3, 2006

Introduction:

We estimated the costs of the tower and tower reflector based on the USISTF High Concentration Solar Central Receiver study, various McDonnell Douglas memoranda, including work done by the author in Egypt in 1980, and a cost escalation table available from Oregon State University (OSU). Results are summarized below, followed by an explanation of the technical approach used. The OSU table is provided below.

Summary:

The equations to determine the weight and cost of the tower are shown to be as follows:

Total Steel Tower Weight = 2.18(Column Weight) for H_{tower} *equal to or greater than 210 ft*

Column Weight Steel $= 2.6956 \times 10^{-6}(W_{receiver})^{0.2605}\,(Acceleration)^{0.16675}(Vel)^{1.05556}(H_{tower})^{1.9984}$

Steel Tower Foundation Concrete Volume (Cubic Yards) $= 2.4565 \times 10^{-3}$
$(W_{receiver})^{0.09196}(Acceleration)^{0.9547(1.2(1-HT/750)}(Vel)^{2.0523}(H_{tower})^{0.7826}$

Steel Tower Foundation Rebar Weight (Tons) = 0.0375(Volume of Foundation Concrete)

Tower Reflector Subsystem Weight = xxxx lbs for weight of facets and Geometrica struts and assembly hardware. Note that in the analysis for the tower foundation and column weight of the steel, the tower reflector subsystem weight is used including the coolant, so that the correct supported weight is used. An accurate value for the subsystem weight is not available at this time since it is dependent on the optical analysis, location, etc. The tower reflector subsystem can be estimated, and includes the support ring and hardware used to lift and lower the tower reflector, as well as the Geometrica struts, assembly hardware, and the tower reflector facets. The facet weight is approximately 25 lbs, including the mounting hardware, hoses, fittings, etc.

Cost of structural steel is $1.28/lb (in both Egypt and the U.S.)

Cost of rebar in Egypt is $1.16/lb or $2320/ton.

Cost of Concrete in Egypt is $258.29/cubic yard.

Total Tower Accessory Cost (2005 dollars) = \$210,900 + \$78.20H_{tower} + \$42,654 + \$71,090 + \$47.39 (Total Tower Weight, tons) + \$44.31H_{tower}

Cost of Tower Reflector Assembly per Unit Area = $1312/m^2.

(Note: The tower reflector Assembly includes hardware costs for the support structure, ring support, and facets, with attachments, hoses, etc., fully assembled, but not including the final fine alignment of the facets.)

For the USISTF study, the baseline area of the tower reflector is 541 m^2. The diameter is 26.2 meters (86.2 ft). For the RCELL analysis, the area would be adjusted to intercept the reflected rays from the heliostat field.

The following Technical Discussion presents results, derivations, validation parameters, and additional notes from studies conducted in 1980 in Egypt and in the U.S., primarily by McDonnell Douglas, but also including Stearns Roger, and Sandia. These notes are included to ensure that worthwhile work conducted at that time is not lost.

Technical Discussion:

In 1980, a series of tower weight and cost studies were conducted for the Egyptian solar central receiver program by McDonnell Douglas, which also involved Stearns Roger and Sandia data, designs, and analyses. This information is summarized below, primarily based on the multiple regression analysis conducted by the author at that time. The approach covered costs for both concrete and steel free-standing towers, and the foundations (concrete and rebar), for conditions including tower supported weight, height, wind speed or wind load, earthquake zone, etc. Costs were based on costs at that time.

These results are applicable to the Noor al Salaam study, with certain limitations. First, the Noor al Salaam tower design that was conducted for the baseline tower height and beam down optic tower reflector, was determined to be a three-leg design with guy wire supports. A free standing tower was found to be more costly, and posed difficulties for the beam down optics. Applying the free standing approach will be conservative, but this level of conservatism may be justified, especially for a design that would presumably be used for other technological and system R&D, which can not be predicted at this time. Having additional design margin, rather than the minimum cost design, should have future benefits to these down-stream solar studies. Hence, we apply the approach based on the multiple regression analysis over 17 Stearns Roger point designs directly to the Noor al Salaam case.

To update the cost, we assume the same fraction of the total cost for the tower and foundation, but we use the updated cost obtained from John Andrews Tower Company, in the year 2000, of $1,000,000 for the tower, with the rails, etc., for raising and lowering the tower reflector, fully installed in Egypt. We have also conducted a cursory “sanity check” against the reported costs for a water tower. The resulting cost and weights are shown to be applicable to the RCELL analysis for determining the optimum field layout, at least to first order, and may be accurate to within 10 to 20%.

From Memorandum A3-226-CS-156, 20 June 1980, we have the following summary, which is copied verbatim; additional work is scanned and included in the Appendix.

The attached multiple regression analysis of the Stearns-Roger tower weights (steel, concrete, and rebar) agrees well with all of the reported point design data and provides design equations which supersede the previous equations.

The analysis predicts tower steel column weights, total steel weight, concrete volume, and rebar weight, given the following parameters:

Weight Receiver: 10 to 8000 KIPS
Lateral Acceleration: 0.05 to 0.6 g
Wind Velocity: 70 to 120 mph
Tower Height: 120 to 650 ft

The equations to be used are:

Total Steel Tower Weight = 2.18(Column Weight) for H_{tower} *equal to or greater than 210 ft*

Total Steel Tower Weight = 3.095 (Column Weight) for H_{tower} *less than 210 ft*

$$\text{Column Weight Steel} = 2.6956 \times 10^{-6} (W_{receiver})^{0.2605} (\text{Acceleration})^{0.16675} (Vel)^{1.05556} (H_{tower})^{1.9984}$$

$$\text{Steel Tower Foundation Concrete Volume (Cubic Yards)} = 2.4565 \times 10^{-3} (W_{receiver})^{0.09196} (\text{Acceleration})^{0.9547(1.2(1-HT/750)} (Vel)^{2.0523} (H_{tower})^{0.7826}$$

Steel Tower Foundation Rebar Weight (Tons) = 0.0375(Volume of Foundation Concrete)

It should be noted that the exponential dependence of concrete volume on lateral ground acceleration raised to a power that is dependent on tower height is necessary for good agreement. Generally, the above equations are in agreement with the 17 point design cases. The maximum errors (for the y values) for the two cases are –12.2% and –13.3% for column weight and –12% for concrete foundation volume (see attached printouts). The curve fit is based on the y=values, which are natural logarithms of the weights and volumes. Thus, the agreement of the equation with the actual weights and volumes will show a greater degree of error, even though the index of determination is reasonably good (0.88 and 0.97, for concrete volume and steel column weight, respectively).

However, it is important to note that the apparent discrepancies exist in the Stearns-Roger data, and specific tower designs can differ significantly from the general designs. Therefore, it will far more accurate to determine the weights for a tower which does not match a specific point design by finding that point design which most closely matches the conditions of interest (receiver weight, accerlaraion, wind velocity, and tower height) and then using the above design equations in a ratio form. For example, if the design parameters of interest are 100 KIP receiver weight, 0.1 g, 90 mph wind, and a 280 ft tower, then these conditions are *most closely matched by Trial Tower design number 1 of Table 1, with a column weight of 444 tons. Thus,*

Column Weight of Tower =
44(100/200)).2605((0.1/0.05)0.16675(90/70)1.05556(280/300)1.9984 = 46.8 tons.

If the multiple regression analysis formula alone is used, the predicted column weight is 54.72 tones, which illustrates the importance of using the nearest point design conditions.

Original Signed by J. B. Blackmon and R.C. Sykes

With this information, we now estimate the total cost based on the John Andrews Tower Company estimate of $1,000,000 for the design of the baseline tower. Note that the USISTF/Noor al Salaam Tower has a set of rails that allow the tower reflector to be assembled and ground level and then raised to the appropriate operational height, lowered to the height required by the Digital Image Radiometer tower reflector alignment system, and completely lowered again to the ground when required for maintenance.
All supporting information from the original memorandum has been scanned and is attached.

The tower cost for the Trial Tower Design Number 1 is $0.543 per pound, for 1980 dollars.

The Foundation Cost is $0.078M. The total cost is $0.204M.

We have several choices for estimating the tower cost to be used in the RCELL code:

1. Assume the value of the dollar, based on the spreadsheet from Oregon State University (reference 1, attached), and assume a year of construction in the future (say, 2010, or 2005).
2. Modify the values from the 1980 memo based on the John Andrews estimate of $1,000,000, and then escalate this to, say, 2005 or 2010, based on his estimate, made in 2000. Use the same ratio of tower and foundation costs, such that his estimate for the point design is compared against the results predicted by the above general equations (not the ratios, since we have no point design weight and cost information for the USISTF baseline design).
3. Use the CEPI index, per Prof. Lorin Vant-Hull's suggestion, since this offers a more accurate estimate of hardware associated with power plants.

The height of the USISTF baseline design is 220 ft (67 meters). The weight of the tower reflector, support structure, and water is determined as described below.

The weight of an individual, equilateral triangle, is 40 lbs. The heat exchanger is 3" thick. The approximate area is ½(Base x Height), where the base is 31", and the height is $15.5(3^{1/2.})$ inches. Thus, the area of each mirror is $½(31)(15.5)3^{1/2}) = 416\ in^2 = 2.89\ ft^2$.

With a thickness of 3", the weight of water is $62.4\ lbs/ft^3(3/12)2.89 = 45$ lbs.

Thus, the total weight of a tower reflector facet is 40 lbs + 45 lbs = 85 lbs. We add to this the weight of the associated tower reflector support structure, which is based on the Geometrica design concept, using galvanized steel tubing, with special crimps at both ends. There are three of these, with special extruded fittings, nuts, bolts, washers, and a spool, which is used to mount the tower reflector facet so that the cant angle can be adjusted. Each tube supports two reflectors, and thus we use one-half the weight of the three for each facet, to determine the total tower reflector support structure weight, and the tower reflector facet weight. (Note: the cant angle adjustment is similar to that successfully used on the McDonnell Douglas Dish Stirling System, which is now owned by Stirling Energy Systems.) The nuts are rotated as required to move the facet up or down in the vicinity of each corner, so as to properly adjust each mirror facet. The corrections are provided for each facet by the DIR.

Since each of the tubes, with the fittings, weighs 15 lbs, and there are three of these, but one half is associated with each facet, then the total weight associated with the facet, water, and all of its support structure, is 85 + 45/2 = 107.5 lbs. To this is added additional weight associated with miscellaneous components, such as the small mirrors mounted on the back of each facet for DIR angle determination, insulation, the hoses for the water flow through the facets, etc. A conservative estimate is assumed of 120 lbs.

The total number of facets has been determined for the baseline design as 1900. Thus, the total supported tower weight is 228,000 lbs or 228 Kips. It is noted that this is close to the receiver weight of 200,000 lbs that was assumed for Trial Tower Design Number 1 in Table 1.

The tower column weight is estimated from the equation,

Column Weight Steel = $2.6956 \times 10^{-6}(W_{receiver})^{0.2605}$
$(Acceleration)^{0.16675}(Vel)^{1.05556}(H_{tower})^{1.9984}$

Assuming that the Wreceiver = 228 KIPS, acceleration is 0.5, wind velocity is 90 mph, and the tower height is 220 ft.

The results for column weight of the steel are:

$2.6956 \times 10\text{-}6\ (4.11)(0.5)^{0.16675}(90)^{1.05556}(220)^{0.2605} = 2.6956 \times 10\text{-}6$
$(4.11)(0.89)(115.56)(47984.1) =$ **54.68 tons**

The total steel tower weight is 3.095(Column Weight) = **169.22 tons**

With the assumption from the 1980 analysis of $0.54/lb for steel, the total cost is **$182,758.**

Steel Tower Foundation Concrete Volume (Cubic Yards) = 2.4565×10^{-3}
$(W_{receiver})^{0.09196}(Acceleration)^{0.9547(1.2(1-HT/750)}(Vel)^{2.0523}(H_{tower})^{0.7826}$

$= 2.4565 \times 10^{-3}\ (228)^{0.09196}(0.5)^{0.9547(1.2(1-HT/750)}(90)^{2.0523}(220)^{0.7826}$

= 2.4565 x 10^{-3} (1.6475)0.57)(10249.2)(68.105) = **<u>1610 cubic yards of concrete</u>**

Steel Tower Foundation Rebar Weight (Tons) = 0.0375(Volume of Foundation Concrete)

= **<u>60.38 tons of rebar</u>**

It should be noted that the concrete volume and hence rebar weight are strong functions of the earthquake induced lateral acceleration. Assuming a value of 0.5 g is near the limit of 0.6 g, and may be overly conservative, but since the design conditions for Zaafarana are not known, or easily obtainable at this time, the conservative value is assumed.

It is assumed from the Stearns Roger data that the U.S. cost of rebar is \$0.52/lb and U.S. concrete is \$181.20/cubic yard. Thus, the total cost of the foundation is:

Concrete Cost = \$182.60/cubic yard (1610 cubic yards) = \$293,986 (from 1980 MDA memos by the author, based on data available at that time.

Corresponding concrete cost for the foundation installed in Egypt was \$109/cubic yard. This would result in a cost of \$175,490.

Rebar Cost = \$0.52 (60.38 x 2000) = \$62,795 (U.S.). Note: cost of rebar was reported as \$0.52/lb in the U.S. and \$0.49/lb in Egypt. Thus, cost of rebar in Egypt would be \$0.49 (60.38)(2000) = \$59,172.

Thus, the total tower cost based on the 1980 analysis is:

U.S. Costs:

Total Tower Cost (Steel + Concrete + Rebar) = \$182,758 **+** \$293,986 + \$\$62,795 = **\$539,539, based on the 1980 cost values.**

Egyptian Costs:

Total Tower Cost (Steel + Concrete + Rebar) = \$182,758 **+** \$175,490 + \$59,172 = **\$417,420, based on the 1980 cost values.**

From the table of dollar values vs. year, provided below, we estimate the conversion factor to bring the dollar value up to 2005 as 0.422. Thus, relative to 2005, these cost estimating relationships predict a U.S. cost of the tower as \$539,539/0.422 = \$1,278,528. Applying this same factor to the Egyptian cost, we get \$417,420/0.422 = \$989,147, for 2005 costs.

John Andrews (President, John Andrews Tower Company, Dallas, TX) determined the cost to be \$1,000,000 in 2000. We can correct his 2000 estimate by dividing by 0.882, giving \$1,000,000/0.882 = \$1,285,473.

However, John Andrews included all tower costs, including accessory or ancillary costs, which we accounted for separately in the 1980 study, and then added on as applicable to the basic tower cost.

Assuming cost estimates from these earlier studies are corrected to 2005 dollar values, and using these cost estimating relationships, we have the following for the various anciallary/accessory costs:

<u>Ancillary/Accessory Costs:</u>

Elevator:

We assume no elevator is required, in part because the tower reflector can be lowered to the working ground level, and thus accessible by stairs. However, elevator costs, in 1980 dollars, are given by the Stearns Roger expression:

Elevator run length (1980 dollars) = 0.8 H_{tower} (the elevator goes to 80% of the tower height).

Elevator Cost (1980 dollars) = +\$64,060 + \$148.675(0.8H_{tower})

Correcting this to 2005, we divide by 0.422, giving

Elevator Cost (2005 dollars) = \$151,801 + \$352.31 (0.8H_{tower})

Obstruction Lighting:

The 1980 study assumed two rings of strobe lights, one at the top of the tower, and one half way up, for a cost of \$89,000. This is corrected to 2005 dollars as

Obstruction Lighting Costs (2005 dollars) = \$210,900.

Stairs:

Stairs are not included, since the tower reflector can be lowered. Stair costs for a 30" wide, structural steel grating treads, are given in the 1980 study as:

Stair Costs (1980 dollars) = \$85.00(0.8H_{tower})

Correcting this to 2005 dollars gives:

Stair Costs (2005 dollars) = \$201.42 (0.8H_{tower})

Safety Ladder:

A safety ladder is assumed, for access to inspect, repair, etc. This cost is given as:

Safety Ladder Cost (1980 dollars) = \$33/ft(H_{tower}), for the full height of the tower, or

Correcting this for 2005 dollars, we have

Safety Ladder Cost (2005 dollars) = \$78.20H_{tower}

Lightning Protection:

Costs from the 1980 study were fixed at \$18,000. Correcting for 2005, we have

Lightning Protection Costs (2005 dollars) = \$42,654.

Platforms:

The 1980 study assumed \$30,000. Correcting for 2005, we have

Platform Costs (2005 dollars) = \$71,090.

Painting:

The 1980 study assumed painting as \$20/ton t of structural steel per coat of paint. Correcting for 2005 dollars, we have

Painting Cost (2005 dollars) = \$47.39 (Total Tower Weight, tons).

Lighting:

Lighting costs from the 1980 study were
Lighting Cost (1980 dollars) = \$18.70H_{tower}

Correcting for 2005 dollars, we have

Lighting Cost (2005 dollars) = \$44.31H_{tower}

Adding all of the applicable cost for the Egyptian tower, we have:

Total Accessory Cost (2005 dollars) = Obstruction Lighting Costs (2005 dollars) + Safety Ladder Cost (2005 dollars) + Lightning Protection Costs (2005 dollars) + Platform Costs (2005 dollars) + Painting Cost (2005 dollars) + Lighting Cost (2005 dollars)

Inserting the appropriate costs, in the same order, we have:

Total Accessory Cost (2005 dollars) = \$210,900 + \$78.20H_{tower} + \$42,654 + \$71,090 + \$47.39 (Total Tower Weight, tons) + \$44.31H_{tower}

For a 220 ft tower, with 169.22 tons of structural steel, we obtain the final Accessory Cost equation and value:

Total Accessory Cost (2005 dollars) = \$210,900 + \$78.20(220) + \$42,654 + \$71,090 + \$47.39 (169.22) + \$44.31(220)

Total Accessory Cost (2005 dollars) = \$359,616.

Thus,

Total Tower Cost, Including Accessories (2005 dollars) = Basic Tower Cost + Total Accessory Cost = \$989,147 + \$359,616 = \$1,348,762. This is compared to the John Andrews estimate, corrected to 2005 dollars, of \$1,285,473.

The projected value is 4.9% higher than the John Andrews estimate, in 2005 dollars. This agreement is sufficient to justify use of the cost estimating relationships provided in the above.

As a "sanity check", certain water tower costs have been determined from recent publications. These were found to be in reasonable agreement with the basic method shown above.

Tower Reflector Weight and Cost

The "receiver" used in the RCELL analysis is the Tower Reflector for the beam down optical system. The for the baseline system, the height of the tower reflector is 67 m. The total reflector area is 541 m^2, with1867 facets, each having an area of 0.29 m^2. The weight of a facet assembly is approximately 40 lbs. Filled with water, the facet weighs approximately 70 lbs. The weight of each of the Geometrica tubular supports is approximately 5 lbs. The extruded corner attachment weight with the aluminum spool support and the bolt, nuts and washers is 3 lbs. The weight of each reflector facet assembly, with one-half the weight of the three corner spools and three tubular supports is 12 lbs. There are 3 x 1867 Geometrica tubular supports and corner attachments for the baseline design. In principle, we can use this information, together with individual item costs or cost estimating relationships, to develop the total cost. However, we have costs for the assembly from Geometrica, and therefore do not have to use these weights with a cost estimating relationship. Geometrica estimated the cost of the tower reflector support structure to be approximately \$50,000 to \$100,000, but "closer to \$50,000" when contacted in 1999. We assume that the baseline cost for 541 m2 is \$75,000 in 1999 dollars, and then use the OSU index to correct this to 2005 dollars. Thus, the cost is \$75,000/0.853 = \$87,925 or, \$162.52/m^2. Installation exercises conducted from 1999 to 2001 indicate that the time to assemble each tubular support to the extruded attachment and spool is typically less than 15 minutes, and only requires one person. However, on occasion, problems are encountered, and we must include the time required to uncrate and position the specially marked tubular supports so that they are precisely pre-positioned. Working conditions in the field in Egypt may reduce the productivity rate, due to high temperatures, delays from being at a remote site, etc. Therefore, we increase the time to 30 minutes per tubular support, and assume there are two workers. Assuming a fully loaded labor rate of $15/hour per worker, the total Geometrica assembly cost is estimated to be:

Assembly cost = 2 x $15 x 1867 = $56010.

The total cost of the assembled Geometrica support structure is then given by:

Cost of Assembled Geometrica Support Structure = $87925 $56010 = $143,935. On a per unit area basis, we have:

Cost of Assembled Geometrica Support Structure per Unit Area = $266/m^2.

The Geometrica Support Structure is mounted to a ring that is supported by clamping metal riders. This system has been designed, but cost estimates have not been obtained. We assume that the ring cost is 30% that of the Geometrica Support Structure.
Cost of Support Ring = $43,180. On a per unit area basis, we have:

Cost of Support Ring per Unit Area = $43,180/541 = $79.82/m^2.

Thus, the total cost of the support structure and support ring is $187,115. On a per Unite Area basis, we have:

Cost of Support Structure and Support Ring per Unit Area = $345.87/m^2.

This value can be used to estimate the cost for the complete tower reflector support structure as its area is changed with height in the RCELL analysis.

The stainless steel tower reflector facet is estimated to be $250, including the primary glass mirror, a small mirror mounted on the top surface to be used for facet alignment, and the cooling hoses and attachments. For the baseline system, this cost is $250 x 1867 = $466,750. Total installation, including uncrating, positioning, initial adjustment, and attachment of cooling hoses is assumed to require 0.7 hour, based on work conducted by the author in assembling the facet onto the Geometrica support structure. An additional 0.3 hour is required to complete the facet final alignment, after data has been determined with the Digital Image Radiometer (DIR) facet alignment system. The cost for the DIR optical evaluation and alignment system, and the data acquisition process, are determined separately.

It is assumed that two workers are required, with a fully loaded labor rate of $15/hour per worker in Egypt. Thus, the total installation cost for the baseline tower reflector is $30/hr x 1867 = $56,010. Thus, the total installed cost of the reflector facet is given by:

Total Installed Cost of the Reflector Facet = $466,750 + $56,010 = $522,760. On a per unit area basis, we have:

Total Installed Cost of the Reflector Facet per Unit Area = $966/m^2

Thus, the total installed cost of the Tower Reflector Support Structure, Support Ring, and the Tower Reflector Facets is given by:

The Tower Reflector Assembly is composed of the Total Installed Cost of Tower Reflector Support Structure, Support Ring, and Tower Reflector Facets, and this cost is given as:

Cost of Tower Reflector Assembly is composed of the Total Installed Cost of Tower Reflector Support Structure, Support Ring, and Tower Reflector Facets = $143,935 + $43,180 + $522,760 = $709,875, for the USISTF baseline system.

On a per Unit Area Basis, the Total Installed Cost of the Tower Reflector Assembly is given as:

Cost of Tower Reflector Assembly per Unit Area = $1312/m^2.

For the baseline design from the USISTF study, the total cost of the tower and tower reflector, fully assembled and installed (but not including the final fine alignment) is determined from the equations for the tower and foundation weights, and the associated costs, and the tower reflector costs.

CPC Spillage Collector and CPC Shutter

From the USISTF Annual Report, 1999, we have the following:

The CPC Spillage Collector and CPC Shutter provide additional performance and operational benefits. The spillage collector can recover the majority of power that does not fall within the CPC aperture, as well as the power that falls on the non-reflective structure that supports the CPC mirrors. A simple surrounding structural heat exchanger is assumed, similar to flat plate solar collectors that can provide moderate temperature heat at temperatures of the order of 100 to 150 C, possibly for an Organic Rankine Cycle (per Ormat turbine generators), or process heat. Another possibility is to use photovoltaic arrays. In all cases, however, the basic approach is to gain additional electrical (or process heat), with positive economic return, which would otherwise be wasted.

The spillage collector has other benefits. It offers protection for the area surrounding the CPC aperture. It provides a base for supporting and protecting the CPC Shutter, which would be positioned underneath the Spillage Collector, since the Shutter would normally be used at night to protect the CPC and receiver from falling debris, sand, dust, insects, etc., and could be used as the BCS target for limited numbers of heliostat beams, as was used at Solar One and Solar Two. The BCS would provide a means for correcting aim points, assessing spillage, determining such factors as individual heliostat flux distributions, tracking accuracy, and response to wind and temperature on the optical path.

From the USISTF Annual Report, 1999, we estimated that the CPC Spillage Collector cost to be $20 to $20 per square foot, with a total area of 1000 square feet, for a total cost of $20,000 to $30,000 in 1999 dollars. We obtained a similar estimate for the Shutter. Thus:

Cost of CPC Spillage Collector = $30,000
Cost of CPC Shutter = $30,000

Pump and Piping Sizing Analysis for Spillage Collector Cooling
Note: 1-6-12 Configuration, with outer Low Temperature
Receivers uncooled (I.e., "TAT" Design), for 7 CPCs
Surrounded by an annular ring that is cooled.

Flow Conditions:

Height of Annular Ring above Ground	30	Ft
Density of water	62.4	lbm/ft^3
Specific heat of water	1	Btu/lbm-F
Outer Diameter of Spillage Collector	26	Ft
Inner Diameter of Spillage Collector	20	
Power Incident on the Tower Reflector	10,000,000	watts
Conversion Factor, watts to Btu/hr	0.292875	watts/Btu/hr
Percentage of Solar Irradiance Absorbed at Spillage Collector	0.03	
Temperature into the Spillage Collector Assembly	70	F
Temperature out of the Spillage Collector Assembly	230	F
Area of the Spillage Collector Annulus	216.66	ft2
Coolant Mass Flow Rate	6402.048656	lbm/hr
Coolant Volumetric Flow Rate	102.5969336	ft3/hr
Coolant Volumetric Flow Rate	13.33760137	gallons/minute
Pipe Diameter assuming a water flow rate of 10 ft/sec	0.060253338	ft
Pipe Diameter assuming a water flow rate of 10 ft/sec	0.723040056	Inch

Power

Pressure Difference to Pump Water up to Spillage Collector	1872	Lb/ft2
Pressure Difference to Pump Water up to Spillage Collector	13	Lb/in2, psi
Power in the Flowing Water	0.097000737	Horsepower
Power in the Flowing Water	0.07236255	Kilowatts
Combined Pump and Motor Efficiency	0.5	
Pump Motor Power	0.1447251	Kilowatts
Pump Motor Power	0.194001474	Horsepower

Spillage Collector Cooling System Cost Estimate

Cost of a Pump and Motor	$1,400
Cost of 1" - 2" Line, 100 Ft @ $3/ft	$300
Miscellaneous Valves, Fittings, Flanges, Brackets, etc.	$1,000
Heat Exchanger	$1,000
Pump/Heat Exchanger System for Tower Reflector	**$3,700**

VersaFlo UPS 3 Speed In-Line Commercial Wet Rotor Circulators - Bronze
Pump HP GPM @ 5' Connection Ph Price for 115v Price for 230v Price for 460v *

UPS 32-40B 1/3 20/30/38 1-1/4" 1 $1414.66 $1415.94 -
UPS 32-40B 1/3 18/25/39 1-1/4" 3 - $1394.12 $1379.01
UPS 32-80B 1/2 42/53/60 1-1/4" 1 $1454.34 $1436.09 -
UPS 32-80B 1/2 47/55/60 1-1/4" 3 - $1451.49 $1448.75
UPS 32-160B 3/4 37/54/68 1-1/2" 1 $1858.41 $1876.73 -
UPS 32-160B 3/4 50/56/70 1-1/2" 3 - $1875.74 $1870.57
UPS 40-40B 1/3 25/41/60 1-1/2" 1 $1737.35 $1736.08 -
UPS 40-40B 1/3 30/38/64 1-1/2" 3 - $1781.92 $1769.29
UPS 40-80/4B 1/2 65/82/102 1-1/2" 1 $1866.42 $1873.58 -
UPS 40-80/4B 1/2 68/80/110 1-1/2" 3 - $1862.15 $1870.43
UPS 40-80/2B 3/4 66/82/98 1-1/2" 1 $1809.61 $1845.74 -
UPS 40-80/2B 3/4 70/80/95 1-1/2" 3 - $1831.84 $1806.90
UPS 40-160B 3/4 59/84/100 1-1/2" 1 $2336.91 $2290.20 -
UPS 40-160B 3/4 65/75/100 1-1/2" 3 - $2298.55 $2304.96
UPS 40-240B 1-1/2 75/97/114 1-1/2" 1 - $2734.59 -
UPS 40-240B 1-1/2 91/102/122 1-1/2" 3 - $2716.79 $2706.82
* 460 V models are 2 speed only - speeds 2 & 3

Excerpted Table from OSU giving value of the dollar from 1960 to 2015

The values for costs in current year dollars (2005) is based on the escalation rates from the Oregon State University study, available on their website. We also estimate costs for manufacturing/installation in Egypt by assuming various reductions relative to U.S. costs, based on engineering judgment and/or past McDonnell Douglas memoranda, etc. This approach allows us to use the OSU table, the 1980 McDonnell Douglas analysis, and the assumption of construction of a system that has been proven and is in effect, in mass production, to determine the tower and tower reflector costs. However, Prof. Vant Hull has recently pointed out that for construction/utility industry equipment, a better estimate is used than the equivalent of a consumer price index, such as is shown in the Oregon State University tables. The OSU values are shown below. The values for various years for construction/utility costs are available from Professor Vant Hull, and these values are used in RCELL. Typically, these values show that costs have not risen as rapidly as for the OSU costs.

1960	0.152	2000	0.882
1961	0.153	2001	0.907
1962	0.155	2002	0.921
1963	0.157	2003	0.942
1964	0.159	2004	0.967
1965	0.161	2005	**1.000**
1966	0.166	2006	1.021
1967	0.171	2007	1.044
1968	0.178	2008	1.068
1969	0.188	2009	1.093
1970	0.199	2010	1.118
1971	0.207	2011	1.142
1972	0.214	2012	1.167
1973	0.227	2013	1.193
1974	0.252	2014	1.219
1975	0.275	2015	1.245
1976	0.291	**See below**	
1977	0.310		
1978	0.334		
1979	0.372		
1980	0.422		
1981	0.465		
1982	0.494		
1983	0.510		
1984	0.532		
1985	0.551		
1986	0.561		
1987	0.582		
1988	0.606		
1989	0.635		
1990	0.669		
1991	0.697		
1992	0.718		
1993	0.740		
1994	0.759		
1995	0.780		
1996	0.803		
1997	0.822		
1998	0.835		
1999	0.853		

CPC COST ESTIMATE FROM ROTEM NON-PROPRIETARY REPORT[1]

The Rotem report provided a cost estimate for the CPC, based on their costs for the hardware designed for the Weizmann Institute Science. There is no known CPC optical design yet developed for the Noor al Salaam plant.

The Rotem data is therefore relevant, and detailed, but without a CPC optical design, a direct application of the costs on a per unit area basis cannot be made at this time.

Therefore, the reported value, in 1998 dollars, is provided below, with a contingency of an additional 50% to allow for the expected increased area of an optical design appropriate to the Noor al Salaam design.

The Rotem costs for the 19 CPC, all of which are for DIAPR receivers, is $914,598, for 1998 dollars.

Packaging, shipping, receiving, inspection, and assembly costs at the site are not available. As an order of magnitude estimate, we assume 40% of the hardware cost, or 0.4 x $914,598 = $365,839.

The total CPC cost estimate is $914,598 + $365,839 = $1,289,437.

This cost is presumed to be for the Rotem subcontract to provide the CPC system, consisting of 19 CPCs, for the 1-6-12 receiver configuration, with 19 DIAPR receivers. There is an option for having the 1-6 configuration with CPCs, and have 12 low temperature receivers of the so-called "TAT" design, which is essentially a lower cost, conventional heat exchanger design that has an entrance aperture and direct impingement of the peripheral solar irradiance. This approach is not included in this cost estimate, in part because the data for this design is not available, and the apparently higher pressure drop associated with this design. Higher pressure drop would reduce the overall pressure ratio of the turbine, and that has an important effect on the efficiency.

A separate report on the air flow path through the receivers has been prepared and is available from UAH.

The Rotem document providing these cost estimates is available in hardcopy only at this time.

Reference:

1. Rotem Report Compound Parabolic Concentrator, file id: c:\data\word\hcscr2.doc

Cost Inputs to RCELL
Notes and Supporting Analysis for Site Works, Concrete Costs, Roads and Fences

James B. Blackmon, Ph.D
Research Professor
University of Alabama in Huntsville
March 23, 2006

Delivered Cost of Concrete, per truck load, 8 cubic yards or greater, is:
<u>$82/cubic yard</u>
(for a delivery distance of about 5 miles, per Alabama Concrete, 3/23/06)

General Site Works (Data from Reference 1):

Civil Works and Erection Cost were estimated from Reference 1 to be $1,706,000 (2001 $U.S.), for a total area of the solar field of 270,320 m^2. The approximate diameter of the Noor al Salaam solar field is 230 m^2, for an area of 41,526 m^2. The ratio of areas is 0.1536. Multiplying this ratio times the above cost gives $262,075. However, the costs for the civil and general site works in Egypt is offset by several factors. First, the plant is a hybrid solar/natural gas plant, and therefore much of the work associated with the site is associated with the large turbine generator. Second, costs in Egypt are substantially less than in the U.S. Third, the requirements for site works are less, in that roads, landscaping, etc., are less. Given these factors, we assume that the site works costs are 1/3 the above, or:

<u>Site Works: $87,358</u>.

Roads, Warehouse, Fence (Data from Reference 1):

Reference 1 has a cost of $1,433,000 for a much larger field area. Multiplying this by the same ratio as above, 0.1536, gives $220,109.

The warehouse costs are included in a separate item.

The roads and fence costs are assumed to be far less, in part because the remote location, and different regulations in Egypt, makes fences unnecessary. To quote from Reference 2:

"Wind fences are expensive, and may not be needed, since the outer part of the collector field does and effective job of protecting the inner field."

Roads may be stabilized with with an acrylic polymer that looks like asphalt, but is much cheaper. To quote from Reference 2, regarding use of this technique at the Kramer Junction Operating Company SEGS plants:

"Roads are treated with an acrylic polymer that looks like asphalt, but is much cheaper. They buy it in bulk when the price drops, and apply it once a year. This is a much cheaper approach than building an asphalt road, and the multiple applications make the surface better over time. From an economic standpoint, this approach has

advantages relative to an upfront capital investment. Egypt would be well-advised to consider this approach."

Weed control is usually a requirement. From Reference 2:

"It is necessary to keep weeds under control. KJC OC uses Krovar or Oust at about $90/acre/year."

However, vegetation can stabilize soil, and it is not clear that it is necessary in a plant in Egypt, even though it is common civil engineering practice.

Given the above, and the far lower labor costs in Egypt, we assume an upfront cost for **Roads and Fences** that is one-fifth the above value estimated from the field area ratio, or $220,109/5 = **$44,022**.

CPC Cooling Pump System Cost Estimate

Cost of a Pump and Motor	$2,300
Cost of 1" - 2" Line, 200 Ft @ $3/ft	$600
Miscellaneous Valves, Fittings, Flanges, Brackets, etc.	$1,000
Heat Exchanger	$2,000
Pump/Heat Exchanger System for Tower Reflector	**$5,900**

Spillage Collector Cooling System Cost Estimate

Cost of a Pump and Motor	$1,400
Cost of 1" - 2" Line, 100 Ft @ $3/ft	$300
Miscellaneous Valves, Fittings, Flanges, Brackets, etc.	$1,000
Heat Exchanger	$1,000
Pump/Heat Exchanger System for Tower Reflector	**$3,700**

Tower Reflector Cooling Pump System Cost Estimate

Cost of a Pump and Motor	$1,800
Cost of 1" - 2" Line, 600 Ft @ $3/ft	$1,800
Miscellaneous Valves, Fittings, Flanges, Brackets, etc.	$1,500
Heat Exchanger	$2,000
Pump/Heat Exchanger System for Tower Reflector	**$7,100**

Turbine Generator Building:

Turbine Generator Building is primarily for the large turbine, used in hybrid mode, integrated with the solar receivers, associated ducting, valves, controls, instrumentation, etc. The building is sized to accommodate the CPC and Low Temperature Receivers with a diameter of the order of 26’, plus access, for a total of about 35’ square. Total area is thus 35 x35 = 1225 ft2. Assume construction costs for a prefab/concrete building and foundation of $50/ft2, for a cost of **$61,250**. The actual building may be larger, due to the larger turbine.

Miscellaneous Solar Power System Support Facility:

There are various support buildings required for solar power generating plants, needed to store and/or process water for cleaning mirrors, store and maintain mirror washing equipment, general maintenance, logistics spares, shipping/receiving, offices, etc.

Only that area estimated to be required for the solar power part of the hybrid system is provided in the following. It is assumed that these facilities are in addition to what would be required for a large remote gas turbine power plant.

Warehouse (30’ x 30’) @ $20/ft2 = $18,000
Shop (30’ x 30’) @ $20/ft2 = $18,000
Office Space (15’ x 15’) @ $20/ft2 = $4500
Miscellaneous Shop Tools and Equipment $2500
Total: $43,000

Field Equipment:

Equipment is required in the field to install and maintain the heliostats, tower, tower reflector, tower reflector facets, CPCs, receivers, etc. Equipment includes the following:

Solar Power System Field Support Equipment

Utility tractor for cleaning mirrors, general purpose	**$25,000**
Tractor accessories (loader, fork lift, grader, back hoe, etc.)	**$10,000**
1000 gallon/day deionized water system	**$1,000**
Water storage tank	**$500**
Water transport tank	**$1,000**
Spray wand system (see Kramer Junction technique)	**$1,000**
ATV for field monitoring	**$6,000**
Scaffolding	**$1,000**
Lifting/rigging equipment	**$1,000**
General electrical and mechanical equipment and supplies	**$5,000**
Subtotal	**$51,500**

Transportation:

Transportation costs for the heliostat delivery is based on the following assumptions:

1. Manufactured/received in Cairo, Egypt
2. Transported approximately 200 miles round trip by 18 wheeler, at $0.50/mile
3. One day per trip, for a driver and helper, at $80/day fully loaded labor rate for the truck and two men
4. Truck stays on site for two full days and then returns
5. 50 complete heliostats per truck (includes pedestals, drive units, reflector assembly)
6. 2000 heliostats total, including spares
7. Time on site is approximately 16 hours, with the heliostats offloaded directly onto the pedestals. Little or no heliostat storage on site. “On-time delivery” assumed, with 25 heliostats installed per day, over the course of 10 months, with approximately weekly deliveries. Higher installation rates can be assumed, but the production rate of the reflector is limited by the cure rate and number of lay up tools. Basic assumption is that the reflectors are the pacing item, and can be made at the rate of 10 per day, with a full 24 hour cure time, over a 10 month period, 5 days per week for 40 weeks, or 2000 heliostats in 40 weeks, delivered 50 heliostats (one truck load) per week to the site. Truck is on site for two full days. Much of the installation is best done at night, to avoid wind gusts and have cooler working conditions.

8. Packaging/Crating/Receiving/Inspection /Inventory Control = $1/heliostat

Transportation Costs = $0.50/mile x 200 miles/trip x 40 trips = $4000, or, $2/heliostat
Delivery Labor Costs = $80/day x 4 days per trip x 40 trips = $12,800, or $6.40/heliostat

Total Delivery Costs per Heliostat = $8.40/heliostat.

Total Transportion and Delivery Costs including Inventory Control = $4.60/heliostat

Heliostat Installation in the Field:

The following primary sequences are assumed to install the heliostat in the field. The truck delivers 50 heliostats to the site. The pedestals are offloaded and installed on the foundation one at a time. The drive units are mounted to the reflector in parallel as the pedestals are removed from the truck. The reflector assembly with the attached elevation and azimuth drive units are lifted off the truck with spreader bars and slings by a crane and positioned above the pedestal. The drive unit is lowered onto the pedestal and attached. Following mechanical installation, a separate electrical assembly, installation, and checkout process is conducted. These times and manpower levels and fully burdened costs are estimated below. It is estimated that 25 heliostats can be installed in one day, and therefore the truck is available for two days. The truck would leave Cairo in the mid-morning, after being loaded, drive to the site, and be available for late afternoon and evening installation for a period of 8 hours, followed by a second day of operation for 8 hours, and then return to Cairo the next day, with one additional day to ensure all operations are completed, and/or to take advantage of night time installation, with lower winds and cooler conditions.

Heliostat Installation in the Field:

Overall installation rate is approximately 25 heliostats per day, with a group of approximately 7 men, or 50 heliostats over a two day period

Labor Category	Labor Rate Fully Burdened $/hr	Hours/Day	Labor Cost Per Day	Number of Days	Cost for Heliostat Installation
Supervisor	8	8	64	100	6400
(Assumes Supervisor has additional administrative duties)					
Mechanical Technician	5	8	40	80	3200
Mechanical Technician Assistant	3	8	24	40	960
Electrical Technician	5	8	40	40	1600
Electrical Technician Assistant	4	8	32	40	1280
Heavy Equipment Operator	4	8	32	40	1280
General Assistant	3	8	24	40	960
	Heliostat Installation Labor Costs, U.S. Dollars =				15680
	Costs per heliostat for installation, 2005 U.S. Dollars Assuming Egyptian Labor Rates				**7.84**

Crane Rental Costs:

It is assumed that a crane capable of lifting a 300 to 400 lb heliostat 8' above ground level will be available on site for heliostat installation for a period of 300 days to ensure full availability during the entire heliostat installation process. It is assumed that the crane rental is $50/day, for a total of $15,000, or $7.50/heliostat.

<u>Total Transportation, Delivery, and Installation Costs per Heliostat = $23.74/heliostat.</u>

References:

1. Molten Salt HTF Project Deliverable 6, Final System Performance and Cost Comparisons, NREL Contreact No. NAA-1-30441—4, Page 4, Kearney and Associations, August 20, 2001.
2. SEGS Acquaintance Program, Conducted by KJC OC, August 5 through August 16, 2002. SEGS 3,4,5,6,&7. Summary Report of Observations Relevant to Egypt's Solar Power Development Plans Based on KJC Plant Operation, Maintenance, and Management. James B. Blackmon, University of Alabama in Huntsville. USAID/DOE Egyptian Training Program.

Solar Power System Field Support Equipment

Utility tractor for cleaning mirrors, general purpose	**$25,000**
Tractor accessories (loader, fork lift, grader, back hoe, etc.)	**$10,000**
1000 gallon/day deionized water system	**$1,000**
Water storage tank	**$500**
Water transport tank	**$1,000**
Spray wand system (see Kramer Junction technique)	**$1,000**
ATV for field monitoring	**$6,000**
Scaffolding	**$1,000**
Lifting/rigging equipment	**$1,000**
General electrical and mechanical equipment and supplies	**$5,000**
Subtotal	**$51,500**

SUMMARY OF NOOR AL SALAAM COSTS
Revised by James B. Blackmon on 3/22/06 in
Telecon with Professor Lorin Vant-Hull

Heliostat cost has not been determined for the small heliostat, and therefore a range of values will be used. We assume the majority of the heliostat will be built in Egypt and therefore assume $100/m2 for 2005 costs. However, this is very approximate, and should be corrected by obtaining quotes from vendors in Egypt, as was planned as part of this study. That effort was curtailed with the program cancellation in November 2007. Also, the total heliostat cost must include heliostat related controller costs and foundation costs.

Heliostat foundation costs, by Blackmon, December 9, 2005

Total Cost in the U.S., not including concrete: $47.60.

Total Cost in Egypt, not including concrete: $30.44

Concrete costs are assumed to be approximately $150.00 per cubic yard. There are approximately 0.8 cubic yards, for a cost of $120.00. We assume concrete costs in Egypt are 20% less, giving a concrete cost total of $96.00

The total cost per foundation in the U.S. is thus approximately $167.60.

In Egypt, the total cost per foundation is approximately $126.44. 2005 DOLLARS

Current year (2005), based on costs in Huntsville.

This is slightly different from the 1980 costs from the MDA study.

Concrete Cost = $182.60/cubic yard (1610 cubic yards) = $293,986 (from 1980 MDA memos by the author, based on data available at that time.
Corresponding concrete cost for the foundation installed in Egypt was $109/cubic yard. This would result in a cost of $175,490. Concrete costs for the foundation for the heliostat, based on the updated values from the MDA memo and more current quotes from Egyptian vendors are needed to complete this, but these values are considered to be reasonable.

Rebar Cost = $0.52 (60.38 x 2000) = $62,795 (U.S.). Note: cost of rebar (1980 dollars) was reported as $0.52/lb in the U.S. and $0.49/lb in Egypt. Thus, cost of rebar in Egypt would be $0.49 (60.38)(2000) = $59,172.

MCS related costs
The following shows an exchange regarding MCS costs.

Jim,

My interpretation of your 1998 $ MCS labor&M cost estimate (which I can't edit but do not really need to) is that most of the items will be fixed costs, which will be **added to** costs of site preparation, HV line to center of plant, site fencing and security post, permits and inducements, etc. I get $89,500 as fixed costs.

Other costs are 100 UPS, 15 HLCs, and 1500 HCs and wiring harness. The last will be added to the individual heliostat cost. The other two will fit into the field wiring scheme. (Blackmon: *That sounds right.)*

The UPS will be assigned 7 to each of the 15 HLCs protecting 14 heliostats each. I see a radial string of 7 UPS each one of which protects 7 HCs to right and to left of it on a single arc, giving blocks of 14 azimuthally by 7 radially surrounding each HLC.(in general, azimuthal separations are larger than radial).

```
o   o   o   o   o   o    o<U> o   o   o   o   o   o   o
                           |
  o   o   o   o   o   o   o| <U>o   o   o   o   o   o   o
                           |
o   o   o   o   o   o    o |<U>o   o   o   o   o   o   o
                           |
  o   o   o   o   o   o HLC<U>o   o   o   o   o   o   o
                           |
o   o   o   o   o   o    o |<U>o   o   o   o   o   o   o
                           |
  o   o   o   o   o   o   o|<U>o   o   o   o   o   o   o
                           |
o   o   o   o   o   o    o |<U>o   o   o   o   o   o   o
                           |
                           ^from tower, also from HLC and transformer to each UPS
(U)
< ,and >. indicate azimuthal lines to 7 helios on arc
```

anyway, you get the idea. Its similar to Barstow. ***(Blackmon: agree)***

Each HLC will be separately wired to the MHFC at the center via a high V transmission line and one or 7? fiber optic cables. This calls for a field transformer at each HLC, which have not been costed. (Blackmon: I am not sure we need a high voltage cable; run distances are short, and power levels are *low. Buried conduit with 120 vac might be ok, or 220 VAC. Buildings run longer distances, but, I'd defer to code requirements, as provided by a construction company.*)

Distributing the cost of these items (HLC, UPS, and HC + wiring harness) to the heliostats results in costs of $(1.83 +2.31+37.66)/m**2 = $41.80/m**2

Converting from 1998$ to current dollars, we have for the MCS related costs:

$41.80/m**2 (CEPI/389.5) ,   to be added to the installed heliostat costs.
And also a fixed cost contribution of:
(Blackmon: $89,500*(CEPI/389.5), to be added to other site related fixed costs looks right.)

COST ESTIMATES FOR COMMERCIAL VERSION OF NOOR AL SALAAM HIGH CONCENTRATION SOLAR CENTRAL RECEIVER MASTER CONTROL SYSTEM (MCS)

The USISTF study considered the MCS options, conducted trade studies, and developed approximate costs for the MCS. This was done primarily in the 1998-1999 time period, and is therefore of only partial value in determining the MCS costs for a plant that is not likely to be designed and built until approximately 2010. The intervening period will have substantial changes in hardware capability, cost, and availability of similar control systems. Therefore, the MCS costs are estimated, and pertinent information is appended to substantiate the estimates. When the Noor al Salaam (NAS) system is considered by the Industrial Participant, overall costs will be determined, including the development costs.

However, for the RCELL optimization, the plant is to be treated as essentially a commercial version of the first plant that will be built in Zaararana, as part of the planned NAS project. Thus, in the RCELL optimization, commercial costs for hardware, fabrication, assembly, installation, checkout, and initial operation will be used, exclusive of development costs. It is assumed that RCELL will use its own internal estimates for trenching, cables, etc.

In the following, estimates are made for the MCS fully installed costs, in current year (2006) dollars, based on the USISTF data, as well as more current engineering estimates.

MCS Control System Architecture

From 4/8/98, page 2, MCS review, the Control System Architecture consists of:

MCS with RS233/422 Serial Communication lines to the following controllers:

1. Heliostat Field (e.g., Local Controllers (approximately 15), Heliostat Controllers (approximately 1500), and UPS modules, approximately 100 28 volt battery units with chargers and electronics)
2. Tower (DIR and CCV safety/observation cameras, instrumentation (temperature, pressure, flow rate, valve status, etc.), lock outs for tower reflector positioning, CPC shutter control, access gate locks, etc.)
3. Turbine (turbine has voltage output and frequency control, and controls percent of natural gas usage relative to solar thermal input. MCS monitors turbine and can cause controlled shutdown and preparation for startup)
4. Receiver (including Compound Parabolic Concentrators) for temperature, flow rate, pressure, valve positions, valve controls (pneumatic, hydraulic, solenoid, etc.)

Additional communication is provided via Ethernet for such activities as MATLAB (or equivalent) system simulations, data analysis, archiving, remote access monitoring by control operators, and an MCS Hot Backup. These activities are conducted on PCs.

The MCS has a central hub for the operators with video monitors for the plant video cameras, and computer monitors, printers, fax/scanners, etc., and other office peripheral equipment.

The Digital Image Radiometer Beam Characterization System is provided, with a digital camera, digitizer, computer and peripherals, radiometers, and access to field data on wind speed, direction, solar irradiance (direct normal, typically with tracking Eppley Pyrheliometers (minimum, 3). The BCS provides data on beam position on the target shutter to enable the MCS to determine tracking errors in order to correct heliostat aim points, and monitor heliostat integrity and performance.

Hardware:

Computer system (updated version of the 1998 300 Mhz Pentium, with all peripherals, including ethernet card(s), serial ports, BPS card, software, monitors, etc.), with redundant back up system.

MATLAB Simulator – Dedicated Computer System similar to the basic MCS

UPS in the field

Heliostat Local Controllers

Heliostat Controllers

Software:

Gensym G2, MATLAB Simulator, compiler, remote site inspection with PCANYWARE or equivalent.

Additional software to be developed:
G2 bridges for the turbine, receiver, heliostat controllers, tower, GPS time, etc.
Visualization simulator
G2 Control Application

Lorin;
I've been reviewing the MCS costs from the USISTF program. Those costs were **in 1998 dollars**. I think we are assuming that we need to use the hardware and installation/startup costs, but not development costs, in RCELL. We only have very approximate numbers for the MCS, but I've compiled these and attached them, with my engineering estimates.

The turbine controls itself (maintains voltage and rpm), but the MCS controls the overall operation of the plant, monitoring, data acquisition/archiving, analysis, etc. The Beam Characterization System is a part of the MCS, and determines the flux distribution on the shutter (these are just above the CPC inlet aperture and can be used as a protective cover and target), for selected heliostat beams (part of alignment procedure), and it is used to adjust the cant angle of the tower reflector facets (each has a small mirror on the back, and is viewed by the DIR from above).

I have made engineering estimates for the labor to install/startup the MCS, including the DIR BCS. Roughly, it's $800K. Please let me know if this looks ok to you.

Thanks, ‘06-03-07
Jim

James B. Blackmon, Ph.D.
Research Professor
Propulsion Research Center
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
(256) 824-5106

COST ESTIMATES FOR COMMERCIAL VERSION OF NOOR AL SALAAM HIGH CONCENTRATION SOLAR CENTRAL RECEIVER MASTER CONTROL SYSTEM (MCS)

The USISTF study considered the MCS options, conducted trade studies, and developed approximate costs for the MCS. This was done primarily in the 1998-1999 time period, and is therefore of only partial value in determining the MCS costs for a plant that is not likely to be designed and built until approximately 2010. The intervening period will have substantial changes in hardware capability, cost, and availability of similar control systems. Therefore, the MCS costs are estimated, and pertinent information is appended to substantiate the estimates. When the Noor al Salaam (NAS) system is considered by the Industrial Participant, overall costs will be determined, including the development costs.

Item	Number Required	Unit Cost 2006 Dollars	Hardware Costs 2006 Dollars	Labor to Install Unit	Labor Subtotal	Item Subtotal
MCS Computer System	2	$3,000	$6,000	$500	$1,000	$7,000
Control Software						
Gensym G2	1	15,000	$15,000	$500	$500	$15,500
MATLAB	1	$3,000	$3,000	$500	$500	$3,500
Remote Site Inspection	1	$500	$500	$100	$100	$600
UPS (28 volt battery, enclosure, charger, slab, etc.)	100	$200	$20,000	$100	$10,000	$30,000
Tower Monitoring System						
Tower Monitoring Cameras	2	1000	$2,000	$500	$1,000	$3,000
			$0	$0	$0	
Lockout/Safety/Access	1	2500	$2,500	$500	$500	$3,000
Tower Reflector Control, Instrumentation	4	500	$2,000	$250	$1,000	$3,000
Turbine Monitoring System						
CPC/Receiver Monitoring Interface						
Control/Instrumentation Interface	1	2500	$2,500	$500	$500	$3,000
Video Monitors	2	1000	$2,000	$500	$1,000	$3,000
Heliostat Control System						
Main Heliostat Field Controller	1	$3,000	$3,000	$500	$500	$3,500
Heliostat Local Controllers	15	$1,200	$18,000	$500	$7,500	$25,500
Heliostat Controllers	1500	$200	$300,000	$50	$75,000	$375,000
Heliostat Wiring	1500	$50	$75,000	$50	$75,000	$150,000
Field Wiring	Part of RCELL					
Digital Image Radiometer Beam Characterization System						
Digital Camera (1 Megapixel) (with lens FOV 120% of CPC)	2	$2,500	$5,000	$500	$1,000	$6,000
Housing/Fittings	2	$1,000	$2,000	$200	$400	$2,400
Cable (500 ft)	500	$2	$1,000	$5	$2,500	$3,500
Computer System (with video digitizer)	1	$3,000	$3,000	$500	$500	$3,500
Radiometers, fittings, cable	5	$500	$2,500	$200	$1,000	$3,500
Software	1	20,000	$20,000	$500	$500	$20,500
Target/Shutter Hardware	1	50,000	$50,000	20,000	$20,000	$70,000
Control/Interface	1	$3,000	$3,000	$2,000	$2,000	$5,000
		Hardware Total	**$485,000**	**Labor Total**	**$180,000**	**$740,000**
Contingency, 15%						**$111,000**
					MCS TOTAL	**$851,000**

From: Jim Blackmon [blackmoj@email.uah.edu]
Sent: Friday, December 09, 2005 5:01 PM
To: Lorin L. Vant-Hull
Subject: DIR BCS Cost Estimate

Lorin;
The DIR BCS development and acquisition cost would be approximately $600K, including all hardware, software, travel, documentation, etc. Installation support would be approximately 3 months on site (Zaafarana), for approximately an additional $60K (labor, per diem, etc.).

James B. Blackmon, Ph.D.
Research Professor
Propulsion Research Center
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
(256) 824-5106

<u>Solar Central Receiver Optical System Study (3-22-06)</u>
Note: this summary is a work in progress, subject to revision.

Site

Objective Demonstrate "Beam Down"
Solar Central Rec'r Technologies **Plant Life=20 yrs**
<u>Owner NREA Escalation= TBD 3%</u>
Prime TBD **Discount= TBD 6%**
Prime Contract # **PV Factor= TBD => 15**
Site Address Zafarana, Egypt **Escalation for electricity 3% ??**
Site Location Red Sea Coast, Egypt **PV Factor= TBD => 15**
Latitude 28.75 North Latitude (approx) **Slope of Field = Less than 5%=>0 for now**
Longitude 30.2 degrees East **Uphill direction is to: West**
Elevation 50 – 100 ft above Sea Level: use 30 m

Month	J	F	M	A	M	J	J	A	S	O	N	D
Visual Range												
Percent possible sun												
10* (10-cloud cover)												
Precipitable water dry												
Atmospheric turbidity clear												

Climate classification is "tropical and sub tropical desert".
See '<u>the physical elements of geography</u>' for details of such a climate
Minimum Solar Elevation for receiver operation: ε =10 deg [use in estimating annual energy, 10 – 15 deg]. Allows RCELL to ignore extreme shading at sunrise/set
Artificial Horizon? None [mountains or whatever]

Heliostat

Name USISTF
Reflective Area: 100 sqft, no edge seal or open slots, etc.
"Width" x "Height": ____10'__X__10'___: DMIR = √WxH = 14.14'
Mechanical Limits: (Clear-out Circle + 1 foot)/DMIR =1 + 1/14.14 = 1.071
Beam Error (Milliradians): 0.?? mr (includes 2 x mechanical, 2 x slope, optical, and 2 x tracking errors in quadrature) => 2x?? ++ 2X0.8mR++ optical beam errors from specified geometry, i.e. parabolic, due to mirror waviness etc ++ 2 x 0.5mR
++ indicates add in quadrature, i.e. as SRSS: ***note: we discussed the rationale for the mirror waviness.*** *Given that the heliostats have a much longer radius of curvature than the Dish Stirling, which we made with 0.8 mr. Slope error, and, given that the composite Dish Stirling mirrors (final versions) had 0.3 mr slope error, we think it's safe to assume that the composite heliostat, with a far larger radius of curvature, should be able to achieve a 0.5 mr slope error. We have assumed a mechanical error of 0.1 to 0.2 mr (preferred, to be*

conservative), but don't think that gravity bending or thermal distortion will be a significant factor for the small heliostats. We treat the optical error as being the difference between the perfect mirror and the actual mirror.

Height of elevation axis above ground plane: ____~7ft??___*Seems reasonable, per discussion.*

Focusing

Cant distance to focal length. On-axis cant?

Focal distance common: 2??-5?? x virtual focal length

Temp. dependence of focal distance small

Cost factors

Heliostat cost _~100?__$/m^2; Transportation and installation _~3.0__$/m^2

Wiring Harness (per Lorin, this is from MCS, HC, etc.) $41.80/m^2

Operations and maintenance

Present value of operations and maintenance factor:(see also page 3)

~15 (for 20 year life at discount – escalation = 3%)

Service drive, etc. ______$/heliostat-year

Electrical power for drives ______$/heliostat-year (2-3000 hours x 2 drives)

Materials to wash and replace mirrors______$/m^2-year

Equipment and labor to wash (if not on page 3) ______$/m^2 –year

Fraction of helios operational 0.98

Correction (cell to IH) 3% for Barstow, scaled by Q = (76m/VFH) x [(100sqft/10.76)/47.38m]$^{0.5}$ => 1+.03 Q ~ 1.015

(To account for loss in mean helio eff. in layout process)

Helio reflectivity (clean): 92.5%

Mean dust loss factor: 2%

Tower Mounted Reflector (TMR) And Tower

TMR width or diameter: Approx. 60' circular

Reflectivity of TMR (20 year average, including dust effects):__________

Focal height (to virtual focal point) – HT __80m??_______

Aim strategy	**Center (X)**	**Belt ( )**
	Hi-lo ( )	**Hi-lo ( )**
	Left-right ( )	**3 point ( )**

Tower type 3 leg, guyed steel

Tower cost (h,wt) 3X?? $1 million x function of relative vertex height and TMR weight

Tower reflector configuration: hyperbolic, convex down, vertex at 67m. ~ 8ft thick

Tower reflector support: 100,000$ x function of diameter

Tower reflector facets: 2000 triangles ~1.8ft wide@ $200 each x (diameter/60ft)^2

Tower reflector coolant: water/ethylene glycol (temperatures below ~ 100 – 120 C)

Coolant flow: l/sec = (1-TMR reflectivity) x 10 MWt /(ΔQ = ?? J/l) /(ΔQ = _____??

Tower reflector piping:

Feed pump (h,p):
Vertical Increment: Scale = 1+(HT+24)/800m
Bend factor for Piping = 1.5X; included? ___________________
DIR Cost (A,p): $600k for first =>$100k charged to this plant => a fixed cost
O&M on each of above [% of cost/year] =??______________________________
O&M- Heliostat - *ATV ($5K-fixed), tractor/fork lift, $20K-fixed, scaffolding $1K-fixed), misc. tools ($1K-fixed), spares 2% of total heliostat cost, solvents ($0.5K/year), fuel/transportation ($2K/year), cleaning solution, cleaning equipment, electrical equipment($3K-fixed), etc.)*
O&M-Tower/Tower Reflector
O&M-Receiver Subsystem
O&M-Secondary Concentrator
O&M-MCS
Lorin deals only with process heat, so O&M on the Power Generation System is not included in RCELL.
DIAPER Receiver
1-6-12 hexagonal aperture CPCs in HCP array, ?1 cm edge effect on all CPCs?
15 ft overall diam.
coolant: air @ 500 C max.
[NS grid on CPC aperture] **21+2 for spillage __23 nodes_____**
[EW grid on CPC aperture] **21+2 for spillage __23 nodes_____**
Orientation (of aperture plane) horizontal
Receiver aperture: 10m?? above ground plane
Absorbtivity (effective, for aperture) 0.95 approx. (including edge effects??)
Receiver thermal loss (does not matter if specify 10 MWt onto aperture plane)
Preheat section 12 simple
Diapers 1 + 6
Location of preheat: third ring of hcp array, plus TMR, plus ??
cost f(Area) Diapers_________ Preheaters____________
cost f(Area) of CPC's for: Diapers_________ Preheaters____________
Virtual demagnified receiver aperture: 15 ft X demag. Factor , a function of Virtual focal height, TMR vertex height, and Receiver aperture height, all stated relative to plane of elevation axis of heliostats

Field and System ____
Cell size (order) N=___1?____th DA=HT√N/4, so cell side = 1/2 virtual focal height
Size of field in Meters NS=________ EW=_________
In cells NS=___21_____ EW=____21_____
Tower – in cells from North____13_____ from West___11______
Array configuration: radial-stagger

Inflation factor (apply to all cost items): IF = 1 for current year, scaled by CEI (Chemical Engineering index) plant inflation factor for past years (like from Utility Study)______________
Fixed costs: _$100k + ??_________
Land cost No Costs-Provided by Egyptian Government [then add prep costs such as access roads, power connection, etc specific to making site ready to use] _______
Wiring costs ($/m)

4) **radial power (R)**
5) **radial power distribution headers (ΔR)**
6) **azimuthal distribution (RΔϕ)**

Annual O&M (PVO&M additive to wiring costs within code)

4) **travel costs to circle from tower ($/m of travel x no. of trips/year)**
5) **?**
6) **travel along circle (to wash or service) ($/m of travel x no. of trips/year)**

Components of wiring costs: (per linear meter of wire or trench)
(may have distribution transformers in field. Then give high V Power cable_______ and low V distribution cable costs__________, and no. of helios/transformer_______ and transformer cost______________)
Data line -__________(if one is used, number of heliostats on a line________)
Trenching___
Installation____

Design Points and Constraints

Design Point Day and Time ___Equinox___Solar Noon______
Design Point Insolation _1000 W/m^2___________
Design Point Power (MWt delivered) __10___[is this at CPC aperture, receiver aperture, or to system output, and what are losses prior to this point]_____
Peak Flux Limit on TMR ____Approx. 60 kilowatts/m^2
Peak Flux Limit on CPC aperture ________ kilowatts/m^2: if it matters
Land Constraints: if any, such as for transmission lines, irrigation ditches, oil wells, access roads. *Central keep out zone is approximately 28 meters.* **This allows space for tower legs, turbine building, CPC aperture, spillage collector, control room,**
Originator ___Jim Blackmon, Lorin Vant-Hull____Date _05-12-9 to 15
Supplementary Data ___________________________ Date __________
Approval: design engineer _____________________ Date _________
Approval: code operator _______________________Date _________

RESULTS/CONCLUSIONS OF THE BEAM DOWN STUDY

As a step in the process of validating the new RCELLL code, which treats the beam-down configuration and uses cost/performance models derived from the USISTF and Noor al Salaam programs, we have developed a preliminary estimate of the basic parameters based on a somewhat similar study we carried out several years ago at 37 degrees N latitude and an elevation of 343 m.

This study employed a flat aperture (of a cavity receiver) which was horizontal. The study was interested in high average flux density over the aperture. We constrained the RCELL optimization to produce a specified design point power into a specified aperture area (thus defining the average flux density into the aperture), and evaluated the resulting optimal heliostat field.

While this study required a considerably higher design point power than the Noor El Salaam beam-down design, it also used a larger heliostat. As a principal of concentrator optics is that there is a complete congruency between systems under scaling, the power level discrepancy is considerably reduced. The heliostat area ratio is 28 m2 vs. 100 sq ft, or a 3.012/1 = 3/1 scaling ratio. Thus, the 66 MWt design point power into the 33 m^2 cavity aperture of that study reduces to 22 MWt into an 11 m^2 aperture, and the 120 m focal height to 120/sqrt3 = 69.3 m focal height to the virtual receiver at Noor El Salaam.

To match the 10 MWt into the CPC aperture requirement of Noor El Salaam requires a further scaling of 2.2 times. The appropriate heliostat size to use with this smaller system to provide complete congruence would be 45.5 sq ft = 6.74 ft square, vs. the 10 ft square heliostat we have contemplated. To accommodate this oversize heliostat, we will scale to 11 MWt but call it 10 MWt effective to allow for the added spillage that may occur.

This final scaling results in a 49 m focal height to the virtual receiver, an aperture area of 5.5 m^2 (radius = 1.323 m), and a power level reduced from 11 to 10 MWt into the aperture of the CPC array fronting the DIAPER receivers (to account for the oversize heliostat.) Also, the field will scale an overall 6 fold, from 169500 m^2 of reflector on 393300 m^2 of land to 28300 m^2 of reflector on 65500 m^2 of land. Adding 5000 m^2 of land to accommodate the central area and a road from the towers to the field boundary gives a total land are of 70,500 m^2 or a 150 m radius field (with the tower slightly displaced from the center toward the equator). The nominal rim angle of this field is 18 degrees (up to the virtual receiver from the boundary of the field).

The reference system was required to produce an average flux density of 2.5 MWt over the 33- m^2 aperture, and generated an average spillage of 18.53%. We would ideally assume these values will be retained in the smaller scaled system with a 5.5 m^2 virtual aperture and a 49 m virtual focal height, but because of the increase in the relative heliostat in the second scaling, it is more appropriate to reduce the average flux attained by the system by 10/11, giving an average flux of 2.27 MWt over the virtual aperture and a total spillage of about 30%. (In a real design, RCELL would accommodate the larger heliostat by distributing the larger loss among shading, blocking, spillage, and a slightly larger field, but we do not have that luxury in this case).

The parameters of this system allow us to estimate the flux distribution over the receiver, assuming it has a circular Gaussian distribution producing an average flux density over the aperture of 2.27 MWth/m^2. For a circular aperture, it can be easily shown that the value of the Gaussian at the rim is just equal to the spillage outside the circle. For the scaled aperture radius of 1.323 m and a value of the Gaussian at that radius of 0.30, we can estimate the effective sigma for the Gaussian distribution over the aperture to be 0.85m. With these conditions, we can estimate the peak flux on the virtual receiver to be about 4 MWt, dropping to 1.2 MWt at the edge.

Now, returning to our beam-down configuration, we can refer to our table of linear magnification to find a typical result on the real receiver (the aperture of the CPC array). For a real receiver aperture at 0.25 F1 (12.25 m above the optical plane of the heliostats) and the hyperbolic secondary at 90% of the virtual focal height or 44m above the optical plane of the heliostats and 4.9 m below the virtual focal plane (h/F1 =0.1), we have a linear magnification of 6.5, and the hyperbolic area of 0.01 of the gross field area, or 705 m^2. This results in a peak flux at the aperture of the real CPC of 0.62 MWt/m^2, an average flux density over that array of 0.35 MW/m2, and a flux density at the lip of the CPC array of 0.18 MWt/m^2

Other cases can be similarly derived.

RESULTS/CONCLUSIONS OF THE BEAM DOWN STUDY
ADDENDUM PROVIDED BY PROFESSOR LORIN VANT-HULL AFTER CONTRACT CLOSE-OUT, APRIL 2008

Because of the fitful nature of the project funding and authorization it was only at the very end of the project that we succeeded in obtaining useful results from RCELL. At this point it was too late to complete a significant search for the best system geometry including the tower mounted reflector (TMR) location, or dimensions, and of the image magnification of the CPC. However, the RCELL results do have considerable bearing on the appropriate design of the system.

The first feature was the size of the optimum field for use with a virtual receiver at the focal height of the system. With a 70 m focal height (in the proposed range), we had to use extreme measures to force RCELL to produce a field in the 10 MW range. Even with the very small (9sqm) receiver used, the small heliostat size and high beam accuracy (0.8 mRad) led to interception factors of 0.9 at 150 m slant range, falling to 0.8 at ~200m. Thus, the converged field tended to fill an area of radius over 190 m, approaching 3 focal heights and producing 30-50 MW, much greater than the design point power of 10 MW. A reasonably sized TMR would have to be placed very near the virtual receiver location to intercept the redirected radiation, and so would produce an extreme de-magnification of the image. Alternatively, it could be made larger, shading more of the field, and also causing the cone angle of the CPC's to increase markedly, decreasing their ability to provide significant re-concentration of the de-magnified image.

To combat these problems and produce a field approximating that resulting from previous analysis, we used a smaller input figure of merit, which tends to separate the heliostats in the field, reducing the power. We also selected a performance factor (called trim ratio in RCELL terminology) to trim the field to the desired dimension. A value around 2.6 was required, meaning the boundary heliostats were 2.6 times more effective than would be a heliostat at the boundary producing the most cost effective central receiver system.

As the field centers tended to be somewhat to the north of the tower, we used a feature of RCELL called RTRIM to center the field. This modified the input figure of merit by 5%x(cos(azimuth)), essentially to tell RCELL we preferred a centered field to reduce receiver costs.

Under these conditions, we found that the entire field was operating in the hexagonal close packed mode, using the mechanical limit of (mirror diagonal plus 30 cm) as the diameter of HCP circles. Thus, there was really little RCELL could do to further optimize the system due to the extreme constraint on the power level for this focal height (required to assure useful operation of the CPC array).

Subject to all these constraints, we did use RCELL to define fields producing 10 MW for focal heights (F1) of 60, 70, and 80 m. As all the fields contain essentially the same number of heliostats, and are of essentially equal density, the field radii are all closely the same, at 91 m, essentially independent of the focal height. In the spreadsheet below, we show the results of computations for several tower heights, field radii, and TMR areas as typical of geometries that would produce 10 MW at the CPC aperture. Note that in each case, the larger field or higher tower produces an increased CPC aperture and a resulting lower concentration at the actual receiver located at its exit aperture.

Nominal Input Data: Focal Height FH=F1	real tower height is F1 + 2 m (2m is helio axis to ground) % of F1 h	F2(m)= VR to TMR h, meters	6 field radius R,m	(8 m above ground) TMR radius r,m	TMR AREA sqm	TMR MAG VRtoCPC	RCELL field radius = field rim angle	RCELL focal height = FH = F1 CPC cone angle	90m CPC Linear Conc.	total linear TMR magnification linear	AREA area	With 9sqm VR aperture sqm
60	0.146	8.760	90	13.140	542.43	5.16	33.69	16.196	3.585	1.440	2.075	18.675
60	0.131	7.884	100	13.140	542.43	5.85	30.96	15.904	3.649	1.603	2.569	23.123
60	0.110	6.570	120	13.140	542.43	7.22	26.57	15.485	3.746	1.927	3.715	33.434
60	0.100	6.000	90	9.000	254.47	8.00	33.69	10.620	5.426	1.474	2.174	19.562
60	0.090	5.400	100	9.000	254.47	9.00	30.96	10.491	5.492	1.639	2.686	24.171
60	0.075	4.500	120	9.000	254.47	11.00	26.57	10.305	5.590	1.968	3.872	34.848
70	0.146	10.220	90	13.140	542.43	5.26	37.87	13.730	4.213	1.249	1.560	14.039
70	0.131	9.198	100	13.140	542.43	5.96	34.99	13.483	4.289	1.389	1.930	17.369
70	0.110	7.665	120	13.140	542.43	7.35	30.26	13.129	4.402	1.669	2.787	25.084
70	0.100	7.000	90	9.000	254.47	8.14	37.87	8.973	6.412	1.270	1.613	14.516
70	0.090	6.300	100	9.000	254.47	9.16	34.99	8.866	6.489	1.412	1.992	17.931
70	0.075	5.250	120	9.000	254.47	11.19	30.26	8.710	6.604	1.695	2.871	25.843
80	0.146	11.680	90	13.140	542.43	5.34	41.63	11.906	4.847	1.101	1.212	10.906
80	0.131	10.512	100	13.140	542.43	6.04	38.66	11.693	4.934	1.224	1.498	13.485
80	0.110	8.760	120	13.140	542.43	7.45	33.69	11.388	5.065	1.470	2.162	19.461
80	0.100	8.000	90	9.000	254.47	8.25	41.63	7.765	7.401	1.115	1.243	11.183
80	0.090	7.200	100	9.000	254.47	9.28	38.66	7.673	7.489	1.239	1.535	13.812
80	0.075	6.000	120	9.000	254.47	11.33	33.69	7.539	7.621	1.487	2.211	19.901

Computation of parameters of TMR and CPC for several tower heights (F1) and heliostat field radii, R, and the consequent magnification of the image at the Virtual Receiver.

While we have now succeeded in running RCELLL with the beam-down configuration and cost/performance models, we do yet have flux maps from the resulting heliostat field. However, we have data from a somewhat similar study we carried out several years ago at 37 degrees N latitude and an elevation of 343 m. We can use the results from this study to obtain a reality check on the expected system design.

That study employed a flat aperture (of a cavity receiver) that was horizontal. The study was interested in high average flux density over the aperture. We constrained the RCELL optimization to produce a specified design point power into a specified aperture area (thus defining the average flux density into the aperture), and evaluated the resulting optimal heliostat field.

While that study required a considerably higher design point power than the Noor El Salaam beam-down design, it also used a larger heliostat. As a principal of concentrator optics is that there is a complete congruency between systems under scaling, the power level discrepancy is considerably reduced. The heliostat area ratio is 28 m^2 vs. 100 sq ft, or a 3.012/1 = 3/1 scaling ratio. Thus, the 66 MWt design point power into the 33 m^2 cavity aperture of that study reduces to 22 MWt into an 11 m^2 aperture, and the 120 m focal height to 120/sqrt3 = 69.3 m focal height to the virtual receiver at Noor El Salaam.

To match the 10 MWt into the CPC aperture requirement of Noor El Salaam requires a further scaling of 2.2 times. The appropriate heliostat size to use with this smaller system to provide complete congruence would be 45.5 sq ft => 6.74 ft square, vs. the 10 ft square heliostat we have contemplated. To accommodate this oversize heliostat, we will scale to 11 MWt but call it 10 MWt effective to allow for the added spillage that may occur.

This final scaling results in a 49 m focal height to the virtual receiver, an aperture area of 5.5 m^2 (radius = 1.323 m), and a power level reduced from 11 to 10 MWt into the aperture of the CPC array fronting the DIAPER receivers (to account for the oversize heliostat.) Also, the field will scale an overall 6 fold, from 169,500 m^2 of reflector on 393,300 m^2 of land to 28,300 m^2 of reflector on 65,500 m^2 of land. Adding 5000 m^2 of land to accommodate the central area and a road from the towers to the field boundary gives a total land are of 70,500 m^2 or a 150 m radius field (with the tower slightly displaced from the center toward the equator). The nominal rim angle of this field is 18 degrees (up to the virtual receiver from the boundary of the field).

The reference system was required to produce an average flux density of 2.5 MWt over the 33- m^2 aperture, and generated an average spillage of 18.53%. We would ideally assume these values will be retained in the smaller scaled system with a 5.5 m^2 virtual aperture and a 49 m virtual focal height, but because of the increase in the relative heliostat in the second scaling, it is more appropriate to reduce the average flux attained by the system by 10/11, giving an average flux of 2.27 MWt over the virtual aperture and a total spillage of about 30%. (In a real design, RCELL would accommodate the larger heliostat by distributing the larger loss among shading, blocking, spillage, and a slightly larger field, but we do not have that luxury in this case).

The parameters of this system allow us to estimate the flux distribution over the receiver, assuming it has a circular Gaussian distribution producing an average flux density over the aperture of 2.27 $MWth/m^2$. For a circular aperture, it can be easily shown that the value of the Gaussian at the rim is just equal to the spillage outside the circle. For the scaled aperture radius of 1.323 m and a value of the Gaussian at that radius of 0.30, we can estimate the effective sigma for the Gaussian distribution over the aperture to be 0.85m. With these conditions, we can estimate the peak flux on the virtual receiver to be about 4 MWt/m^2, dropping to 1.2 MWt at the edge.

Now, returning to our beam-down configuration, we can refer to our table of linear magnification to find a typical result on the real receiver (the aperture of the CPC array). For a real receiver aperture at 0.25 F1 (12.25 m above the optical plane of the heliostats) and the hyperbolic secondary at 90% of the virtual focal height or 44m above the optical plane of the heliostats and 4.9 m below the virtual focal plane (h/F1 =0.1), we have a linear magnification of 6.5, and the hyperbolic area of 0.01 of the gross field area, or 705 m^2. This results in a peak flux density at the aperture of the real CPC of 0.095 MWt/m^2, an average flux density over that array of 0.054 MW/m2, and a flux density at the lip of the CPC array of 0.03 MWt/m^2. This can be combined with the concentration available from the CPC (8.1 from the table below) to project a peak flux at the outlet of the CPC (the DIAPER aperture) on the central DIAPER receiver of ~0.77 MWt/m^2. A respectable, but not particularly high value.

Other cases can be similarly derived.
8888888888888888888888888888888888888888888888888888888

For reference, from the final report appended above: The linear magnification is thus: real image diameter/virtual object diameter = real image distance/virtual object distance = Linear Magnification = LM = (F1-h-F2)/(h). [EQ 1

Thus, given a value for F2, (distance real receiver is above plane of heliostats), we can generate a table of linear image magnification (M) and size of secondary:

if	h/F1 = 0.05	h/F1 =0.1	h/F1 = 0.2	h/F1 = 0.3
and: F2 is zero:	LM = 19	LM = 9;	LM = 4	LM = 2 2/3
F2 is 0.1 F1	LM = 17	LM = 8	LM =3.5	LM =2
F2 is 0.25F1	LM = 13	LM = 6.5	LM =2.75	LM =1.5
~Area of secondary (relative to field)	0.0025	0.01	0.04	0.09

One must also remember that each CPC further concentrates the energy impinging on its aperture by $1/\sin^2\theta$ where θ is the opening half-angle of the CPC. In this case, arctan(radius of secondary/distance to apex),

θ = arctan (Rh/F1)/(F1 – h –F2) = arctan R/(F1*LM), [EQ 2

where R is the field radius.

If F2 is 0.1 F1 and the field radius is three times F1:

if	h/F1 = 0.05	h/F1 =0.1	h/F1 = 0.2	h/F1 = 0.3	*If R = 4F1 h/F1 = 0.2*
CPC aperture halfangle	10.0	20.5	40.6	48.4	*48.8*
CPC concentration	33.1	8.1	2.36	1.8	*1.76*
Overal conc.= CPC/LM^2	0.115	0.126	0.192	0.45	*0.144*

SYSTEM DESIGN CONSIDERATIONS

The Beam-Down central receiver system provides a number of interesting trades. Because of the demagnification of the virtual receiver image by the beam down process, it is not very conducive to very high flux density / very high temperature applications which may require the expensive DIAPER receiver, and also require a very compact and restricted heliostat field. These restrictions have caused RCELL to be forced to operate far from its optimum conditions in order to provide a specific (small) design power with a relatively tall tower and a small diameter field. If one relaxes these constraints and allows the receiver to consist only of the much lower cost "preheaters", the receiver cost will be essentially cut in half (not only is the receiver lower cost, but the CPC will not be subject to the same extreme conditions as when operating with the high flux density DIAPER). This substantially lowers the (tower, TMR, CPC, receiver) costs which the heliostat field must support. Removing the requirement for a small diameter heliostat field (specified in order to reduce the demagnification caused by the TMR) further relieves the constraint on the collector, and we can reconsider the optimization process in RCELL. At this time we do not have the luxury of a new series of runs to define a best field, but in the process to date we have generated a few cases with larger fields. These are not fully optimized, but do show the trend. A case at 70 m FH and other parameters as used in this study showed that 22.8 MWt could be gleaned from a 150 m dia field at an input figure of merit of 169, giving an out figure of merit of 249

$/annual thermal MWhr delivered. When this same array was restricted to deliver 10.5 MWt onto the same virtual receiver, the field diameter shrank to 100 m, the input figure of merit rose to 250, giving an output figure of merit of 373 $/annual thermal MWhr delivered, a 50% increase. If the fully optimized field were achieved the 249 would be reduced substantially for a larger reduction in the cost/unit energy produced. Of course, the TMR dimensions (and cost) would have to be increased to accommodate the larger field, or if h were decreased, the demagnification would increase substantially.

Essentially, removing the constraints associated with achieving an extreamly high flux density/temperature at the real receiver of the beam-down system provides a wide range of system trades, all of which will result in lower cost themal power, albeit at a somewhat reduced temperature and Carnot efficiency for a solar only mode. However, when operated in the hybrid mode, the use of supplemental natural gas will allow the turbine generator to operate at its optimum design condition. Therefore, the work reported here indicates that an economically superior beam down system can be achieved by allowing for lower flux densities and temperatures. The current level of support will not allow evaluation of these options, but this is a useful area of study in the event this system is considered further.

Appendix F

Hydrodynamic and Heat Transfer Analysis of the Tower Reflector Facet for the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver System for Noor Al Salaam

Hydrodynamic and Heat Transfer Analysis of the Tower Reflector Facet for the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver System for Noor Al Salaam

Michael Boland
James B. Blackmon, Ph. D.
University of Alabama-Huntsville
Propulsion Research Center

1.0 Introduction and Summary

The U.S./Israel Science and Technology Foundation (USISTF), with sponsorship from the Department of Commerce U.S./Israel Science and Technology Commission (USISTC), co-funded the development of a High Concentration Solar Central Receiver System, based on high temperature receiver technologies conceived and initially developed in Israel as part of their MAGNET program. The USISTC was formed by President Clinton and the late Prime Minister Rabin to promote peace in the Middle East through economic development and to encourage technological collaboration on advanced technologies. The High Concentration Solar Central Receiver program was selected by the USISTC to advance the solar technology conceived by the Weizmann Institute of Science and in part developed by the Israeli MAGNET program by the Institute, together with Ormat Industries, Ltd, and Rotem Industries, Ltd. The USISTF program was led by The Boeing Company, with Ormat and Rotem as associate contractors, and the Weizmann Institute of Science as a subcontractor to Boeing. Boeing terminated all USISTF program activity at the end of 2000, but efforts have continued into 2007 on the part of the Egyptian and Israeli participants, and the University of Alabama in Huntsville, as part of the Noor al Salaam program.

The USISTF program involved all of the primary technologies associated with this new solar power system concept. In addition to the further development of heliostats, the tower relector, and a master control system, it integrated a turbine generator with a special high temperature air receiver. The objective was to demonstrate a hybrid solar/gas system with an output power level of 250 kilowatts of electricity from solar heated air and natural gas combustion products. This system was partially integrated and tested at Ormat Industries, Ltd. and the Weizmann Institute, in that the turbine generator was operated on grid power, with natural gas, and the receiver was tested in conjunction with the Weizmann field of heliostats (**Figure 1**) and a tower mounted reflector (**Figure 2**). However, the full integrated test program with the turbine generator was not completed.

Following the USISTF program, a joint effort was initiated with support from USAID, with contractual oversight by DOE. This project, termed Noor Al Salam (Light of Peace) WAS for a 10 to 15 Megawatt hybrid solar/natural gas power system, involving a relatively high percentage of natural gas power. The first phase of this program is to be funded by the U.S. Agency for International Development, through the Department of Energy, and involves participants from Egypt and Israel, as well as the U.S. **Figure 3** shows a view of such a plant.

Figure 1 - Heliostat Field at Weizmann Institute of Science, Rehovot, Israel

In the course of the USISTF program and during the development of the baseline design for the Noor Al Salam program, Boeing considered various options for the tower reflector design, including passive mirrors, without any active cooling, and actively cooled mirrors. In the early trade studies, comparisons of cost for high tensile strength, passively cooled mirrors were made relative to actively cooled mirrors using standard float glass. It was found that the actively cooled mirrors offered an opportunity for additional revenue, which offset the cost of the tower reflector, and for this reason, Boeing base-lined this cooled facet design. Other trade studies were conducted for the configuration of the tower reflector, and the selected design was a structure available from Geometrica, Inc., which is low cost, easily assembled with unskilled labor, and can be configured to any reasonable shape, for relatively large areas.

The selected Geometrica configuration is triangular, with interlocking crimped pipe, as shown in **Figures 4** and **5**. With this triangular structural configuration, the facets were formed as equilateral triangles, roughly 30” on a side, as shown in **Figure 5**, for the reflector mounted on the Geometrica structure. One such triangle was fabricated and tested by Boeing for optical performance, and found to provide a surface slope error well within the requirement of 1 milliradian. This facet was installed on the Geometrica structure of 54 triangles, roughly 20’ across, and exposed for a year at the Marshall Space Flight Center**.** A black plastic covering was placed on the mirror to increase the temperature, compared to the mirror. Roughly speaking, the plastic, with an absorptivity of 0.9 to 0.95, compared to glass, with an absorptivity of 0.05 to 0.06, increased the heating effect to correspond to that for a concentrated solar irradiance on the mirror of about 10 to 15 suns, which is approximately the level of a large part of the tower reflector, when irradiated by the heliostat field. (Peak irradiance levels in the central region of illumination may reach as much as 60 suns, depending on conditions.) There was no sign of any form of degradation during the one-year field exposure.

It became necessary to develop a more detailed understanding of the flow and heat transfer characteristics of the facet and the possible improvement in system performance from recovering waste heat from the tower reflector facets and the other sources of waste heat in the system. A flow analysis code developed by ABZ Technologies was obtained by Boeing to conduct this, and other, related studies. The University of Alabama-Huntsville's Propulsion Research Center developed working models for use in

Figure 2 - Tower Mounted Reflector at Weizmann Institute of Science

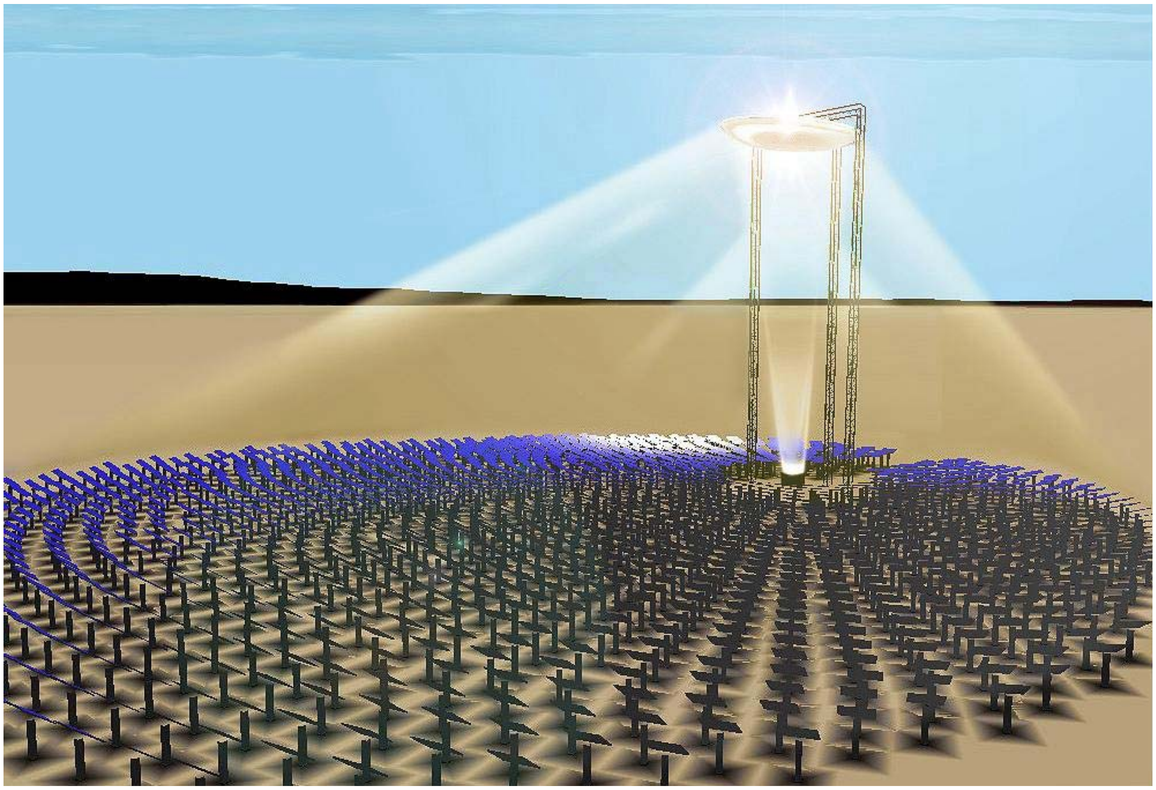


Figure 3 - Planned Noor Al Salam High Concentration Solar Central Receiver-Zaafarana, Egypt.

Figure 4 – Geometrica Structure with Tower Reflector Facet Undergoing Long Term Exposure Test at NASA MSFC

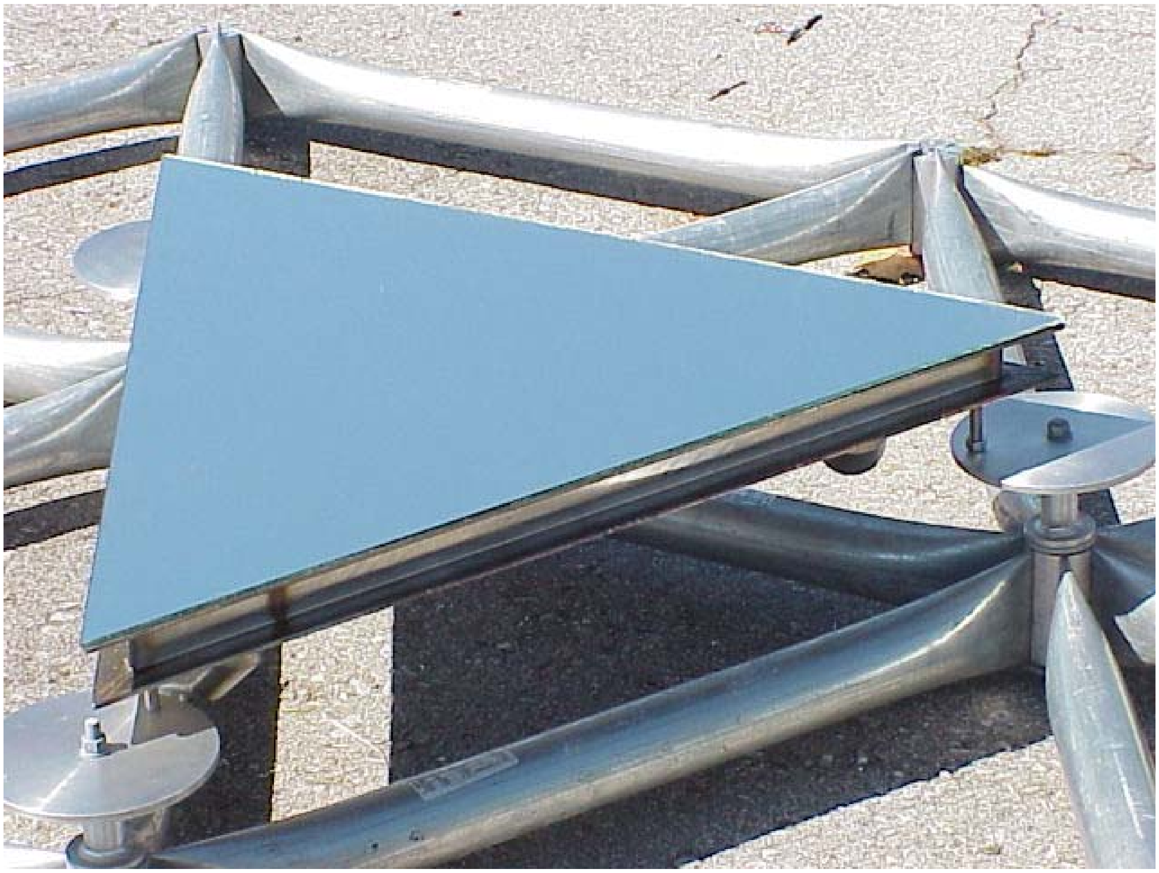


Figure 5 – Tower Reflector Facet Installed on Geometrica Structure at NASA MSFC

analyzing the flow of coolant water through the tower reflector. UAH also conducted an analysis of the temperature of the coolant water, estimated the flow rate needed, sized the piping, determined the additional revenue and return on investment (assuming an Organic Rankine Cycle turbine), developed a flow schematic for a candidate cooling loop, and conducted preliminary tests to assess the actual thermal performance and flow through the facet. Much of this work was conducted as a special study leading to a B.S. in Mechanical Engineering for the principal author, Michael Boland, as part of the requirements for the Special Studies Course, MAE 459. Results of this effort have shed new light on the tower reflector facet design and the impacts on system performance. Also, the codes are now available to conduct further studies of a more detailed nature, to better guide the design of the system. For example, we have developed a working version of the flow schematic as part of the ABZ Technologies code, and have Excel spreadsheets to assess coolant temperature, revenue, cash flow, IRR and ROI.

The conclusions are as follows:

1. The net present value for the waste heat recovery exceeds the estimated cost of the tower reflector facet design and the additional hardware needed for the organic Rankine cycle turbine.

2. The temperature of the facet will not exceed approximately 50 to 60 C, for nominal conditions, and 70 to 80 C for peak conditions, which is well within the long-term temperature limits of the adhesive.
3. The pressure loss through the tower reflector, for the parallel flow case, is modest and poses no problem in terms of stress on the facets. The maximum internal pressure a facet would be exposed to was found to be less than approximately 25 psi.
4. The total pressure required for the flow is also modest, of the order of 125 psi, which poses no difficulty in terms of pumping, piping, etc.
5. Combining the waste heat from the tower reflector with that from the Compound Parabolic Concentrators and the so-called spillage collector surrounding the aperature of the CPCs, results in about 15% additional thermal energy available for process heat or ORC electric power production. With a baseline 10 Megawatt heliostat field, this is approximately 1.7 Megawatts of thermal energy, or, with a 15% efficiency ORC turbine, about 250 Kilowatts of electricity. At $0.10/kw hr, for 2500 hours of solar operation, this results in an additional annual revenue of approximately $66,000.

Additional results related to this study are found in various quarterly reports provided as part of the USISTF program.

2.0 Technical Discussion

The following sections present the analysis and test program conducted as part of this MAE 459 study.

2.1 Heat Transfer Analysis of the Tower Reflector and Tower Reflector Facet

Two analyses were conducted. The first deals with the flow of cooling water (ethylene glycol mixture) through the steel heat exchanger/glass mirror facets in a parallel flow path, and the coupled heat transfer problem for the facets exposed to reflected solar energy from the heliostat field, as well as direct sunlight on the back of the facets. The parallel flow reduces the pressure drop through the facets and ensures that the facets are maintained at a temperature below approximately 70 to 80 C under all conditions. The second analysis is for a glass reflector cooled only by free and forced convection of air and re-radiation, this corresponds to the alternate, non-actively cooled design.

2.1.1 Discussion of System With Coolant Flow

The purpose of this analysis was to determine the amount of coolant flow needed to keep the facets in a safe temperature range, and the amount of "waste heat" that could possibly be harvested and converted into electrical power.

2.1.1.1 First Order Analysis of System With Coolant Flow

The initial step taken was a first order analysis of the system. We knew that roughly 5% of the energy hitting the Tower Reflector (TR) would be absorbed due to a known reflectivity property of glass. From a previous analysis of the Spillage Collector (SC) we knew that an additional 5% of energy would be available to the coolant. Also, a rough guess was made that an additional 5% could be harvested from cooling the CPC's. Each of these components will absorb roughly 500 kW of energy. With this knowledge we were able to determine a mass flow rate of the coolant based upon a known inlet coolant temperature and a desired outlet coolant temperature. The resulting coolant mass flow rate is on the order of 4.2 kg/sec, or about 65 gal/min. This mass flow rate was then used to evaluate the TR in more detail.

The first order analysis of the CPC's is summarized in Table 1 below and the complete first order analysis can be found in **Appendix A**. This first order analysis is also in spreadsheet form to be used in the future.

Energy In (kW)	500
Coolant Temp In (deg C)	30
Desired Coolant Temp Out (deg C)	60
Specific Heat of Coolant @ Temp Out (J/kg K)	3990
Coolant Mass Flow Rate (kg/sec)	4.2

Table 1 – First Order Analysis of Coolant Flow Through the CPC

2.1.1.2 Detailed Analysis of TR With Coolant Flow

The analysis of TR with coolant flow involves considering the energy absorbed and the energy lost to re-radiation and convection

2.1.1.2.1 Convection

Using some typical environmental conditions for the area (95 deg air, wind 5-20 mph, desired surface temp of glass of about 65 deg C) and properties of air at the film temperature we were able to determine the Grashof and Reynolds number. Using the Grashof number divided by the Reynolds number squared (Gr/Re^2) we were able to determine if the convection was forced or free. In cases where the Gr/Re^2 is much less than 1 the convection is considered forced. When much greater than 1, convection is considered free. If Gr/Re^2 is very close to 1 the convection must be considered as mixed. In cases where convection was determined to be mixed, the greater of forced/free calculations were used for energy lost due to convection.

Various possible cases were considered to gain a better understanding of the effects of convection on the system. **Table 2** below shows three of these scenarios. Wind speed is the one variable that was changed to produce examples of free, forced, and mixed convection. Notice how the range in which the convection changes from free to forced is very much in the normal environmental conditions.

In the most common environmental conditions were the wind speed is 10 mph or less the energy lost to convection will be on the order of 100 kW. The basis of this analysis is from a desired surface temperature of the glass to be about 65 deg C. Notice the cells that are shaded gray are the cells that require user input.

Table 2 is from the spreadsheet that was created to be used in the future for more detailed variations. This spreadsheet is located in **Appendix B** and is linked to the evaluation of the entire coolant system. Making changes to this part of the analysis will change the entire system analysis. The calculations performed to build this spreadsheet are contained in **Appendix C**.

Desired Surface Temp of Glass(deg C)	65	65	65
Air Temp (deg C)	35	35	35
Diameter of TR (m)	26.49	26.49	26.49
Area of TR (m^2)	551	551	551
Wind Speed (mph)	5	10	20
Wind Speed (m/s)	2.24	4.47	8.94
Film Temp (K)	323	323	323
Film Temp (K) ^-1	0.003095975	0.003095975	0.003095975
Properties of Air @ Film Temp			
Kinematic Viscosity (m^2/s)	1.84E-05	1.84E-05	1.84E-05
Prandtl Number	0.7035	0.7035	0.7035
Thermal Conductivity (W/m*K)	2.82E-02	2.82E-02	2.82E-02
Thermal Diffusivity (m^2/s)	2.62E-05	2.62E-05	2.62E-05
Grashof Number	5.00E+13	5.00E+13	5.00E+13
Reynolds Number	3.22E+06	6.44E+06	1.29E+07
$Gr_L/(Re_L)^2$	4.83	1.21	0.30
Forced/Free/Mixed Convection	**Free**	**Mixed**	**Forced**
If Forced			
Nusselt Number	4.40E+03	7.66E+03	1.33E+04
Convection Coefficient (W/m^2K)	4.678589401	8.145897277	14.18283093
Q lost to Convection (kW)	**-77**	**-135**	**-234**
If Free			
Characteristic Length (m)	6.6	6.6	6.6
Rayleigh Number	5.49E+11	5.49E+11	5.49E+11
Top Side			
Nusselt Number	1228	1228	1228
Convection Coefficient (W/m^2K)	5.221	5.221	5.221
Q lost to Convection (kW)	-86	-86	-86
Bottom Side			
Nusselt Number	232	232	232
Convection Coefficient (W/m^2K)	0.988	0.988	0.988
Q lost to Convection (kW)	-16	-16	-16
Total if Free	**-103**	**-103**	**-103**

Table 2 – Tower Reflector Convection Analysis

2.1.1.2.2 Radiation

Using absorptivity and emissivity properties along with probable solar energy incident on the top and bottom of the TR a energy analysis was performed on the TR. This analysis involves calculating the energy absorbed and subtracting the energy that is re-radiated. The result will be the net energy absorbed by the TR.

Table 3 below is a summary of this analysis. Like in the previous tables this is from the spreadsheet that is used to evaluate the entire system. **Table 3** highlights the effects of varying absorptivity and emissivity for the steel and glass. Notice that as the emissivity decreases and the absorptivity increases the net energy into the system increases. These are factors to consider in the design. If spending a little extra money on the surfaces will increase the ability to harvest more solar energy through the ORC it may be advisable to do so. While increasing the absorptivity of the glass may not be desirable due to the higher efficiencies of the steam turbine cycle, it may be a good idea to alter the surface finish of the steel, which will only bring in "new" energy to be used in the ORC.

The energy in minus the energy re-radiated was found to be on the order of 850 kW for a likely set of material properties. The radiation analysis can be found in **Appendix D**.

Desired Glass Surface Temp (deg C)	65	65	65
Emissivity of Steel	0.4	0.3	0.2
Emissivity of Glass	0.90	0.90	0.90
Reflectivity of Glass	0.95	0.92	0.9
Absorptivity of Steel	0.4	0.5	0.6
Stefan-Boltzman (W/m^2K^4)	5.67E-08	5.67E-08	5.67E-08
Area of TR (m^2)	551	551	551
Incident Solar Power from Heliostat Field on Tower Reflector (kW)	10000	10000	10000
% of TR Receiving Incident Irradiance *	70%	70%	70%
Solar Irradiance Incident on Top (W/m^2)	1000	1000	1000
Solar Irradiance Incident on Bottom (W/m^2)	25927	25927	25927
Total Energy In (kW)	935	1418	1759
Total Energy Out (kw)	530	489	449
Net Energy In (kW)	**405**	**929**	**1311**
Net Energy Into Coolant From TR	**327**	**794**	**1076**
Temp Change of Coolant In TR (deg C)	19.6	47.7	64.6
Coolant Temp Out (deg C)	**49.6**	**77.7**	**94.6**

* The TR is oversized to account for heliostat tracking errors.

Table 3 – Tower Reflector Radiation Analysis

2.1.1.2.3 Net Energy Into Coolant From TR

The net radiation absorbed minus the energy lost to convection is transferred to the coolant. As seen in **Table 3** above this results in a value on the order of 750 kW for free or mixed convection, and 650 kW for forced convection due to wind.

Using the energy absorbed along with the inlet coolant temperature it was found that the temperature change in the coolant as it flows through the TR is on the order of 40 deg C. This raises the coolant to a temp of about 70 deg C. This temperature rise was based upon the same analysis used in the first order calculations of the CPC. The details of this analysis can be found in the first order analysis of **Appendix A**.

2.1.2 Detailed Analysis of TR With No Coolant Flow

It was necessary to analyze the effects of the system if no coolant flow was present. This could happen when the system is undergoing maintenance. The main purpose of this analysis was to determine how hot the glass surface would get if their was no coolant flow through the TR.

To determine the surface temperature it was necessary to find the amount of energy that is absorbed by the TR and compare it with various surface temperatures in order to find the needed temperature to convect and re-radiate energy at the same rate that its being absorbed. **Table 4** below summarizes these findings. **Table 4** is basically the same as the analysis performed in **Tables 2** and **3** above. In this case however the user has to put in a surface temperature that results in the net energy in due to radiation being equal to the energy lost to convection plus the energy re-radiated. Changing the surface temperature only has an effect on the convection and re-radiation components of the equation. The energy abosorbed is only dependent on the incident energy, and the absorptivity and emissivity properties of the glass and steel. The user simply increases the surface temperature cell until the energy in equals the energy out.

The example in **Table 4** is considered a worst-case type situation and results in the glass surface reaching about 175 deg C. The details of this analysis can be found in **Appendix E**.

Convection

GUESS Surface Temp of Glass(deg C)	**175**	**If Forced**	
Air Temp (deg C)	35	Nusselt Number	9.94E+02
Diameter of TR (m)	26.49	Convection Coefficient (W/m^2K)	1.196889
Area of TR (m^2)	551	**Q lost to Convection (kW)**	**-92**
Wind Speed (mph)	1		
Wind Speed (m/s)	0.45	**If Free**	
Film Temp (K)	378	Characteristic Length (m)	6.6
Film Temp (K) ^-1	0.00264	Rayleigh Number	1.31E+12
Properties of Air @ Film Temp		**Top Side**	
Kinematic Viscosity (m^2/s)	2.36E-05	Nusselt Number	1642
Prandtl Number	0.7	Convection Coefficient (W/m^2K)	7.909
Thermal Conductivity (W/m*K)	3.19E-02	Q lost to Convection (kW)	-610
Thermal Diffusivity (m^2/s)	3.41E-05	**Bottom Side**	
Grashof Number	1.21E+14	Nusselt Number	289
Reynolds Number	5.02E+05	Convection Coefficient (W/m^2K)	1.392
$Gr_L/(Re_L)^2$	481.55	Q lost to Convection (kW)	-107
Forced/Free/Mixed Convection	**Free**	**Total if Free**	**-717**

Radiation

Guess Glass Surface Temp (deg C)	175
Surface Temp of Ground	50
Emissivity of Steel	0.4
Emissivity of Glass	0.90
Emissivity of Ground (sand)	0.90
Reflectivity of Glass	0.92
Absorptivity of Steel	0.5
Stefan-Boltzman (W/m^2K^4)	5.67E-08
Area of TR (m^2)	551
Solar Energy Incident to Top (W/m^2)	1000
Solar Energy Incident to Bottom (W/m^2)	40000
Total Energy In (kW)	2345
Total Energy Out (kw)	1636
Net Energy In (kW)	**709**

Check Guess Value

Change Guess Temp Till = 0	-9

Table 4 – Tower Reflector Analysis With No Coolant Flow

2.1.3 Detailed Analysis of TR With Glass Only

This case was considered to determine how hot a "glass only" facet would get. The analysis was the same as the previous analysis of the TR with no coolant flow. The only difference is that you consider the properties of the paint on the backside of the glass rather than the properties of steel. The results of this analysis are summarized in **Table 5** below. In this situation the glass would routinely be in the 150-160 deg C range.

Tower Reflector (TR)

Convection

GUESS Surface Temp of Glass(deg C)	157	**If Forced**	
Air Temp (deg C)	35	Nusselt Number	9.94E+02
Diameter of TR (m)	26.49	Convection Coefficient (W/m^2K)	1.197
Area of TR (m^2)	551	**Q lost to Convection (kW)**	**-80**
Wind Speed (mph)	1		
Wind Speed (m/s)	0.45	**If Free**	
Film Temp (K)	369	Characteristic Length (m)	6.6
Film Temp (K) ^-1	0.002710027	Rayleigh Number	1.17E+12
Properties of Air @ Film Temp		**Top Side**	
Kinematic Viscosity (m^2/s)	2.36E-05	Nusselt Number	1581
Prandtl Number	0.7	Convection Coefficient (W/m^2K)	7.615
Thermal Conductivity (W/m*K)	3.19E-02	Q lost to Convection (kW)	-512
Thermal Diffusivity (m^2/s)	3.41E-05	**Bottom Side**	
Grashof Number	1.08E+14	Nusselt Number	281
Reynolds Number	5.02E+05	Convection Coefficient (W/m^2K)	1.353
$Gr_L/(Re_L)^2$	429.87	Q lost to Convection (kW)	-91
Forced/Free/Mixed Convection	**Free**	**Total if Free**	**-603**

Radiation

Guess Glass Surface Temp (deg C)	157
Surface Temp of Ground	50
Emissivity of Paint on Top Side of Glass Plate	0.9
Emissivity of Glass	0.90
Emissivity of Ground (sand)	0.90
Reflectivity of Glass	0.92
Absorptivity of Paint	0.8
Stefan-Boltzman (W/m^2K^4)	5.67E-08
Area of TR (m^2)	551
Solar Energy Incident to Top (W/m^2)	1000
Solar Energy Incident to Bottom (W/m^2)	40000
Total Energy In (kW)	2510
Total Energy Out (kw)	1923
Net Energy In (kW)	**587**

Check Guess Value

Change Guess Temp Until = 0	-15

Table 5 – Tower Reflector Analysis With "Glass Only" Facets

2.2 Analysis of the Spillage Collector

The spillage collector was only evaluated on a first order analysis basis.

Based on an average temp of the coolant coming from the TR and the CPC and the assumed energy available to the coolant of 500 kW it was found that the final coolant temp is on the order of 100 deg C. This is ideal for the ORC.

This first order analysis can be found in **Appendix A** and is included in the first order analysis section of the spreadsheet in. The results from the spreadsheet are displayed in **Table 6** below.

Energy In (kW)	500
Coolant Temp In (deg C)	68.8
Mass Flow Rate (kg/sec)	4.2
Specific Heat of Coolant @ Temp In (J/kg K)	3990
Temp Change of Coolant In SC (deg C)	30
Coolant Temp Out (deg C)	98.8

Table 6 – First Order Analysis of the SC

2.3 Energy Available to the ORC From the Coolant

The net energy available to the ORC from the coolant is the sum of three components (TR, CPC's, and SC). This results in about 1700 kW of energy.

Based on various ORC efficiencies it was determined that about 250 kW of energy could be converted to electrical power and sold. This analysis is included in the total system analysis spreadsheet and the results are shown below in **Table 7**. These results will be used later in the financial analysis of the system to determine if using an ORC is financially beneficial.

Energy Availible to ORC (kW)	1327	1794	2076
ORC Efficiency	10%	15%	20%
Total Energy Generated (kW)	133	269	415

Table 7 – Net Power Generated by ORC From Waste Heat

2.4 Flow Analysis

The ABZ Technologies code was used to model a representative fluid loop for the cooling water. There are two principle flow paths, a high pressure and a low-pressure path. The high-pressure path is needed because the tower reflector is at a height of approximately 70 meters. The low-pressure path has a height of the order of 10 meters. The high-pressure path cools the tower reflector facets and then passes through the spillage collector surrounding the compound parabolic concentrators (CPCs) that concentrate the sunlight reflected down from the tower. The high-pressure fluid absorbs approximately 5 % of the incident energy, and reaches an average exit temperature of the order of 65 to 75 C. This coolant water then passes through the spillage collector, where it is further heated, with an additional 2 to 3 % of the thermal energy, and is heated to approximately 90 to 100 C or higher. Similarly, the low pressure coolant water first passes through the CPC support structure/heat exchanger, and absorbs about 5 % of the thermal energy, and then it too passes through the spillage collector, where it is heated by the additional 2 to 3 % of the thermal energy. The two streams of heated water, heated to 80 to 100 C (approximate) then pass through a heat exchanger that boils the organic Rankine cycle liquid to produce vapor to run the ORC turbine and produce electricity. The lower temperature water can then be further cooled in a cooling pond or by a cooling tower. There may be advantages for remote locations by using the cooling pond in conjunction with irrigation, aqua culture, etc., or the hot water may be used in process heat plants.

The schematic used for the ABZ code is shown in **Figures 6, 7,** and **8** below. The schematics display the results of the analysis. The analysis performed to determine some of the code inputs can be found in Appendix F.

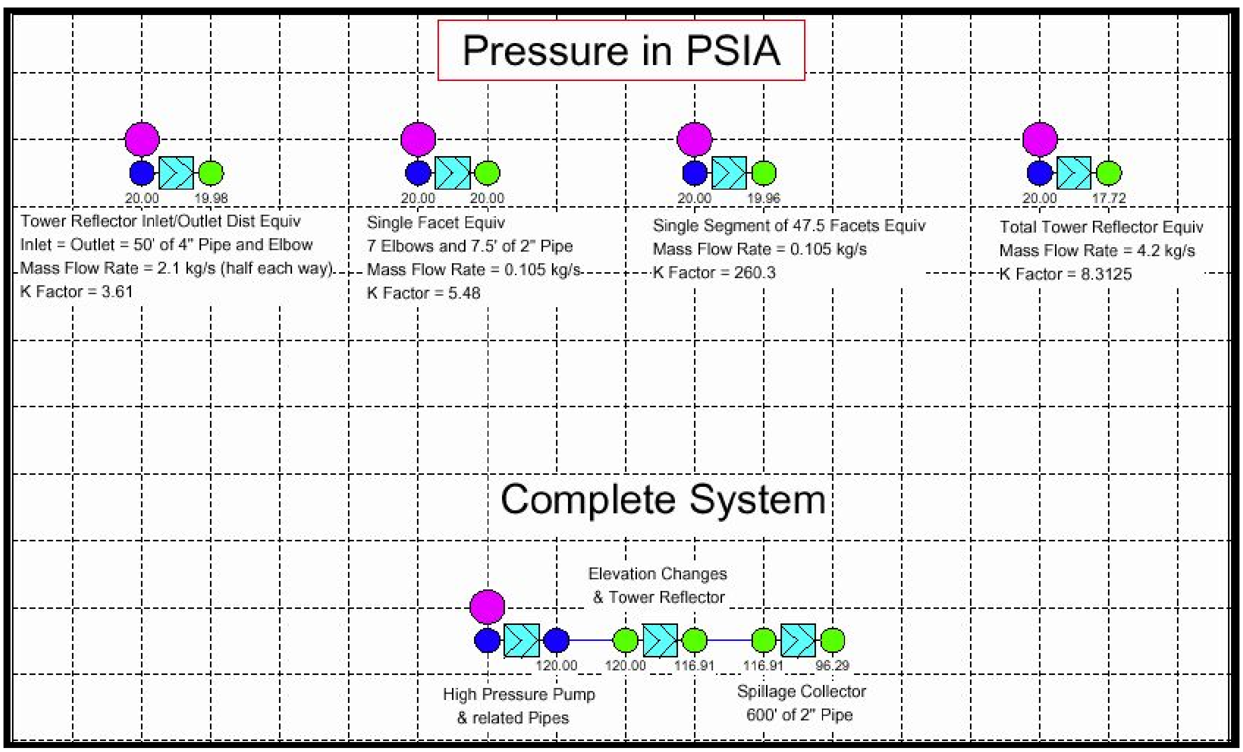


Figure 6 – ABZ Code Pressure Drop Analysis Schematic

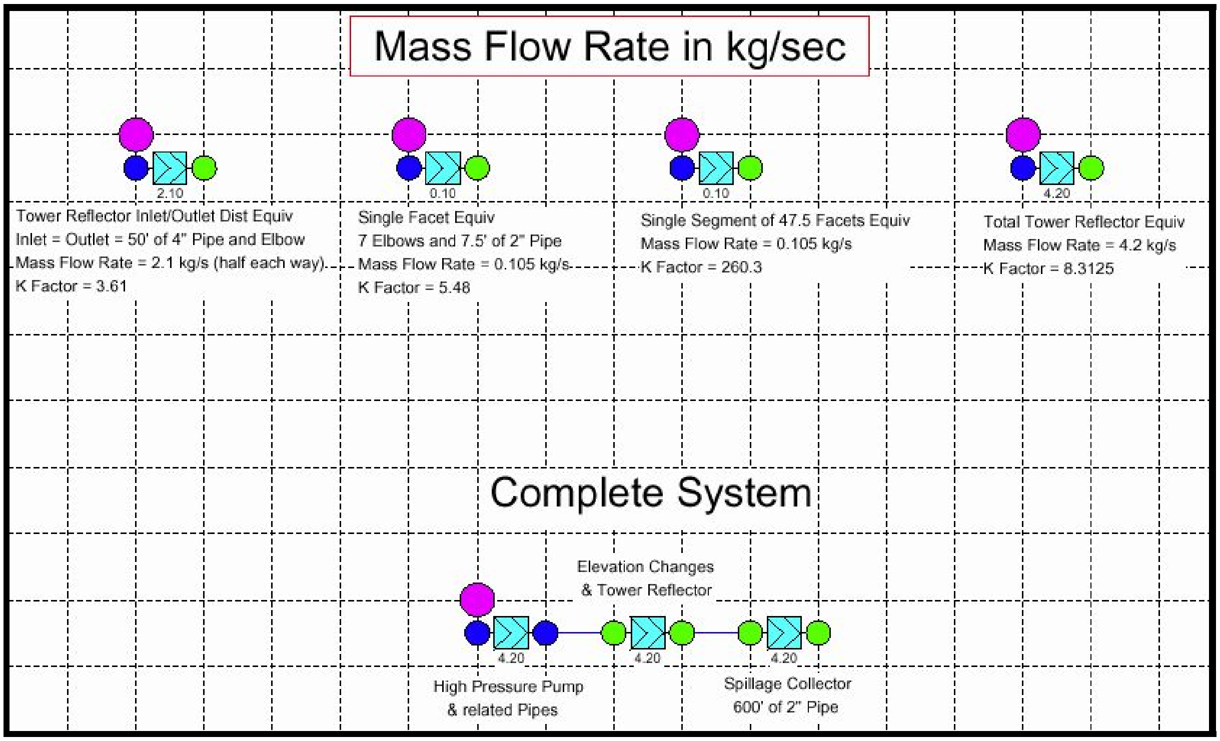


Figure 7 – ABZ Code Mass Flow Rate Analysis Schematic

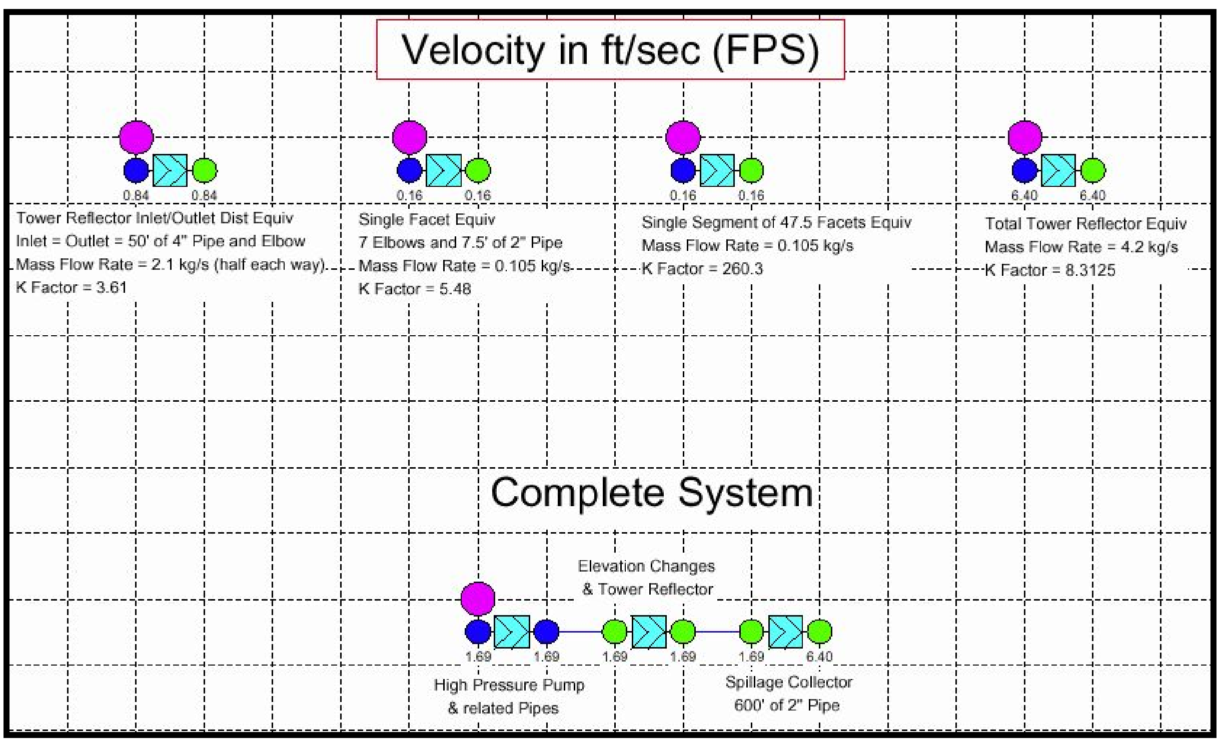


Figure 8 – ABZ Code Flow Velocity Analysis Schematic

2.5 Financial Analysis

Using the results from the analysis discussed in Section 2.3 calculations were performed to determine if converting waste heat into electricity using an ORC is financially feasible.

Variables considered in the financial analysis include ORC efficiency, market price of electrical power, cost of ORC, and capital financing of ORC.

The complete rage of possibilities can be seen in **Appendix G** and a likely scenario is summarized in **Table 8**, and **Figures 9, 10, 11**, and **12** below.

Notice in **Table 8** how much better it is to finance 90% of the capital investement associated with the ORC. These figures assume a low financing charge wish is typical with this type of system.

In **Appendix G** some of the IRR and ROI calculations were in a range that the spreadsheet function could not solve. In all instances these values are negative and would not be considered anyway. The main things to notice in **Appendix G** are the points at a given turbine efficiency and cost that result in the net income, or revenue/kW-hr required to make money. Also notice how lucrative it is if you can sell the "clean solar power" to Spain at the subsidized price their Government is willing to pay to promote this type of technology.

ORC Cost/ kW	**$1000**			
Turbine Efficiency	**15%**			
Turbine Output (kWe)	263			
Annual Energy (kWhr/yr)	766,500			
Revenue/kWhr	**$ 0.05**	**$ 0.07**	**$ 0.10**	**$ 0.26**
Annual Revenue	**$ 38,325.00**	**$ 53,655.00**	**$ 76,650.00**	**$ 199,290.00**
Revenue For 30 Years	$1,149,750.00	$1,609,650.00	$2,299,500.00	$ 5,978,700.00
IRR If Full Paid ORC	**6.5%**	**10.1%**	**15.1%**	**39.9%**
ROI If Full Paid ORC	**7.7%**	**10.7%**	**15.3%**	**39.9%**
IRR If 90% ORC Financed @ 4%	**24.6%**	**55.3%**	**101.3%**	**346.5%**
ROI If 90% ORC Financed @ 4%	**24.6%**	**55.3%**	**101.3%**	**346.5%**

Table 8 – ORC Cost Analysis

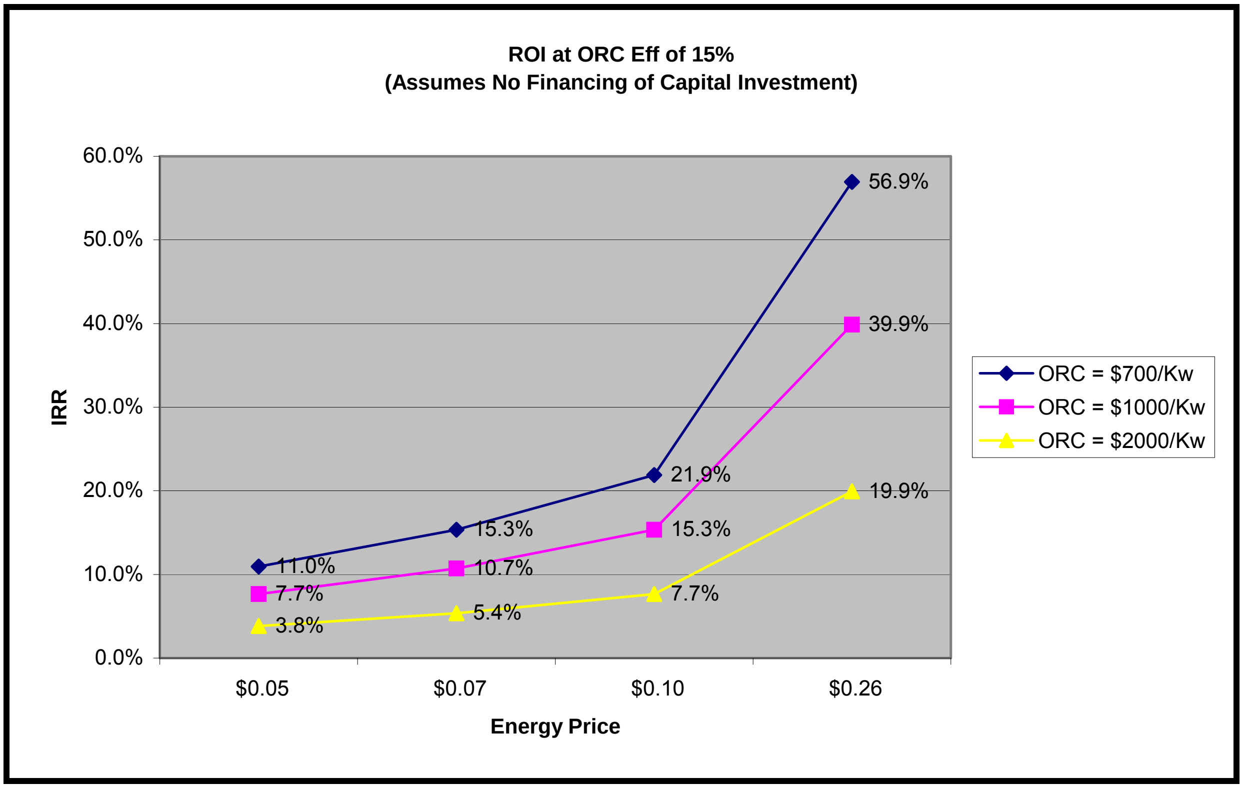


Figure 9 – ROI of ORC Efficiency at 15% and No Financing

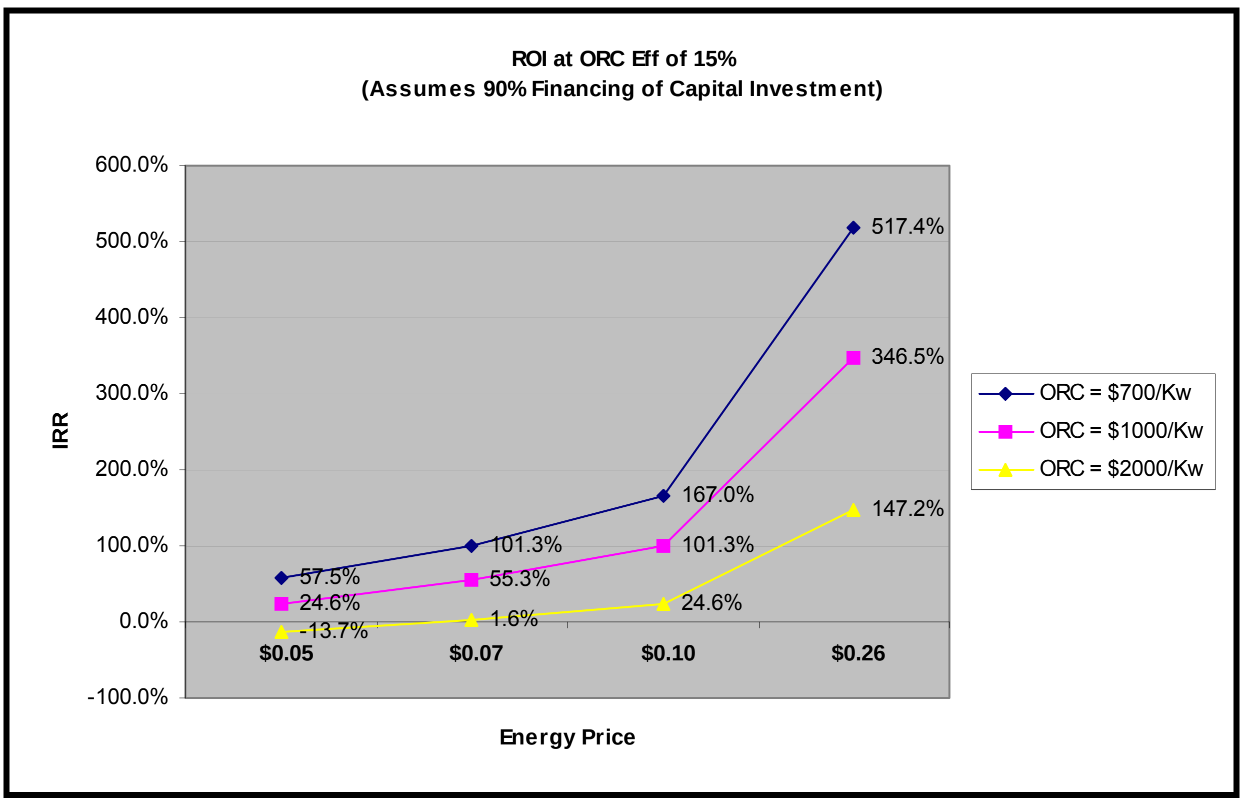


Figure 10– ROI of ORC Efficiency at 15% and 90% Financing

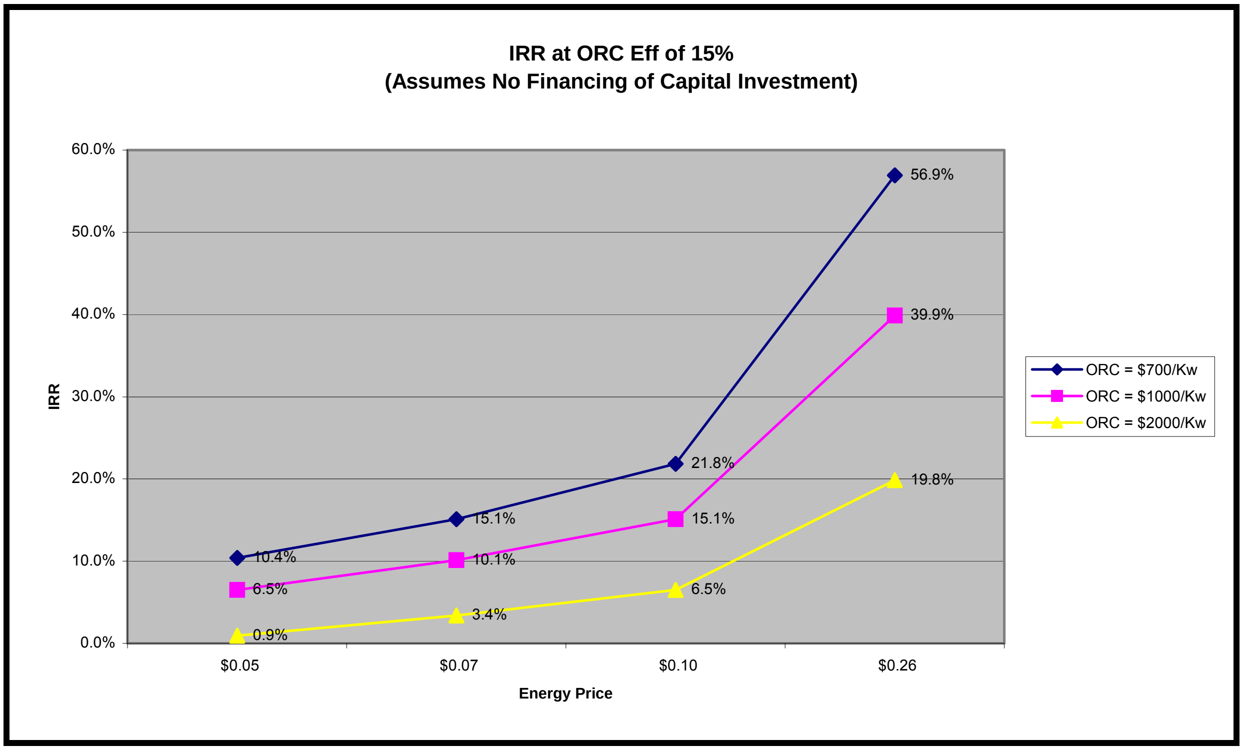
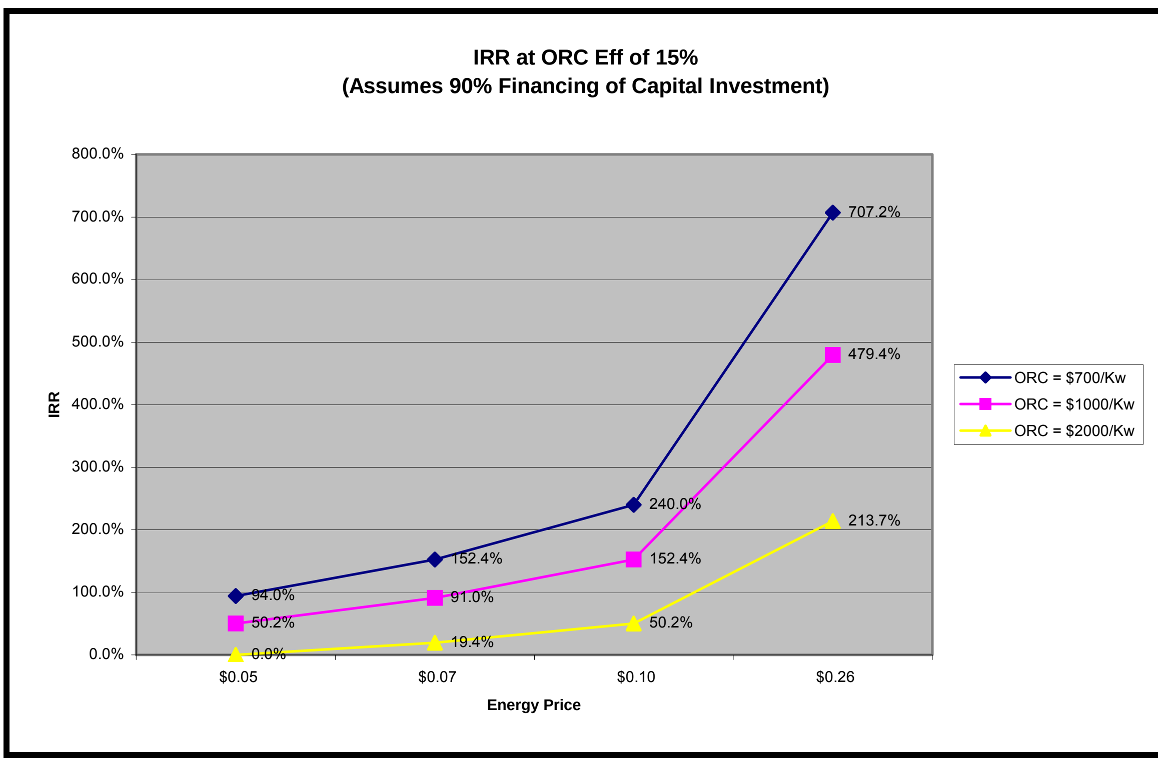


Figure 11 – IRR of ORC Efficiency at 15% and No Financing



Fi

gure 12 – IRR of ORC Efficiency at 15% and 90% Financing

2.6 Test Program

A test set up was completed and proof of concept tests run with the reflector facet. The basic setup is shown in **Figure 13**. The objective was to instrument the reflector facet and obtain initial, rough order of magnitude estimates of the flow loss and effectiveness of the coolant. A data gathering system was used to collect pressure and temperature data. A flow meter was used to determine the volumetric flow rate.

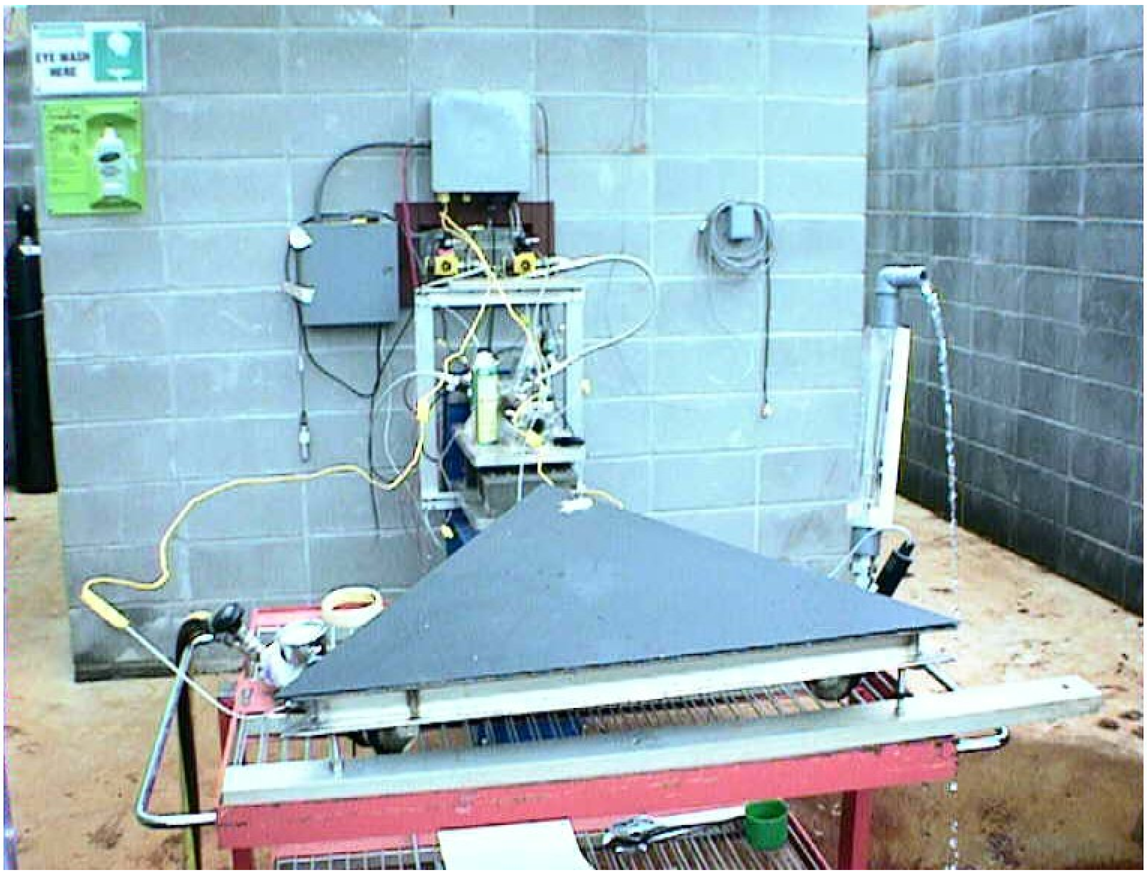


Figure 13 – Facet Test Program Setup

It was beyond the scope of this project to conduct a comprehensive series of tests, but a test was conducted to demonstrate the operation. The collector was tested with incident sunlight, using a black paint on the surface to increase the absorptivity. The absorptivity of the paint is approximately 90%, compared to the absorptivity of the uncoated mirror of approximately 6%. Therefore, a typical incident solar irradiance level of about 800 to 1000 watts/m^2 ("one sun") was the equivalent of about 15 suns. Since the reflector facets installed on the tower reflector will be exposed to solar irradiance levels of this order, and somewhat higher for a concentrated area, the test conditions were appropriate. There is a heliostat and concentrator in the UAH Solar Test Area, and this can be used for more extensive tests at a later time.

One issue that was noted is that if the facet is not filled, there is a much higher temperature than when the air gap at the top is not present. However, with the actual system (termed a "beam down optics" system), the mirrors face down, and the solar irradiance is reflected up from heliostats on the ground (See **Figure 3**). Therefore, this air gap problem would not occur in the actual system. However, the first test was conducted with an air gap, and therefore the results were not relevant since the maximum flow rate produced very little cooling effect. A later "checkout" test was run with the facet filled essentially completely with water.

The basic system appeared to operate well, with the temperature of the reflector maintained in the range of 120 to 150 degrees F, with an inlet temperature of approximately 70 degrees F, for a flow rate of approximately 0.5 gpm of water. Additional tests are recommended to better establish the flow rate, losses, and temperature conditions for comparison with the analysis.

Pump and Piping Sizing Analysis for Tower Reflector Cooling

Flow Conditions:

Height of Tower Mounted Reflector above Ground	230	Ft
Density of water	62.4	lbm/ft^3
specific heat of water	1	Btu/lbm-F
Diameter of Tower Reflector	60	Ft
Power Incident on the Tower Reflector	10,000,000	watts
Conversion Factor, watts to Btu/hr	0.292875	watts/Btu/hr
Percentage of Incident Solar Irradiance Absorbed	0.05	
Temperature into the Tower Reflector Assembly	70	F
Temperature out of the Tower Reflector Assembly	210	F
Area of the Tower Reflector	2826	ft2
Coolant Mass Flow Rate	12194.37839	lbm/hr
Coolant Volumetric Flow Rate	195.4227306	ft3/hr
Coolant Volumetric Flow Rate	25.40495498	gallons/minute
Pipe Diameter assuming a water flow rate of 10 ft/sec	0.083157507	ft
Pipe Diameter assuming a water flow rate of 10 ft/sec	0.997890081	Inch

Power

Pressure Difference to Pump Water up to Tower	14352	Lb/ft2
Pressure Difference to Pump Water up to Tower	99.66666667	Lb/in2, psi
Power in the Flowing Water	1.416518702	Horsepower
Power in the Flowing Water	1.056722952	Kilowatts
Combined Pump and Motor Efficiency	0.5	
Pump Motor Power	2.113445903	Kilowatts
Pump Motor Power	2.833037404	Horsepower

Tower Reflector Cooling Pump System Cost Estimate

Cost of a Pump and Motor	$1,800
Cost of 1" - 2" Line, 600 Ft @ $3/ft	$1,800
Miscellaneous Valves, Fittings, Flanges, Brackets, etc.	$1,500
Heat Exchanger	$2,000
Pump/Heat Exchanger System for Tower Reflector	**$7,100**

High Volume Centrifugal Pumps by Berkeley®

High Volume Centrifugal Pumps by Berkeley®

If your pumping application requires high volume, easy maintenance and long term, reliable service, then Berkeley Pumps are for you. Berkeley pumps are in use worldwide and are known for

Example: By using a 10HP motor and a high flow impeller and pump case we can get 1500GPM of flow at 20' of head. By using the same 10HP motor and a high pressure impeller and pump

Proper efficiency not only extends pump life, it will also save you money!

Choosing the most efficient water pump for your application can be confusing. It can become costly if the wrong pump is chosen, especially when you're choosing a large pump. For this reason,

Single phase pumps available in 3, 5, 7.5, and 10HP

3 - 250 Horse Power pumps available. Flows up to 5400GPM!

New, Lower Prices!

Product Code	HP/Phase	Amps @ 230 v	Inlet/Outlet	GPM @ 20' Head	GPM @ 30' Head	GPM @ 40' Head	GPM @ 50' Head	GPM @ 60' Head	Max. Head	Price	Buy
SCBC30	3 (single phase)	16.5	4"/3"	430	320	80	-	-	-	$1,745.00	

Appendix G
Azimuth Drive Unit Performance Tests
And
Design Improvements for Increasing Performance
and Reducing Manufacturing Costs

Noor al Salaam Heliostat Azimuth Drive Unit Mechanical Tests

Matthew Lynn
James B. Blackmon

Introduction

The Noor al Salaam Heliostat Azimuth Drive Unit is based on a novel sprocket and chain assembly, driven by a gear motor (Reference 1). The proof of concept test article uses commercially available sprockets mounted on a pair of shafts, one of which is formed from a commercially available trailer axle. Since commercially available hardware typically has relatively low eccentricity tolerance requirements, the sprockets can induce variable loads on the chain tension. This series of tests was conducted to investigate the degree of variation in the torque as a function of azimuth angle. The conclusion of these tests is that the variation in torque is substantial, varying from a minimum of about 13 in-lbs to about 70 in-lbs. The solution is to have the sprockets manufactured with a common setup to minimize eccentricity variations of the inner axle shaft hole. This can be done by requiring that the eccentricity specification be defined for procurements, rather than simply procuring a set of off the shelf sprockets.

Objective

The objective is to determine the variation in torque for the azimuth drive unit, and to determine the experimental uncertainty.

Approach

The drive unit was setup with a load cell and lever and torque was applied gradually to produce the data shown in the following figures.

Plotting Formulas for Reading the Excel File

$i := 0..193$ $\qquad$ $j := 0$

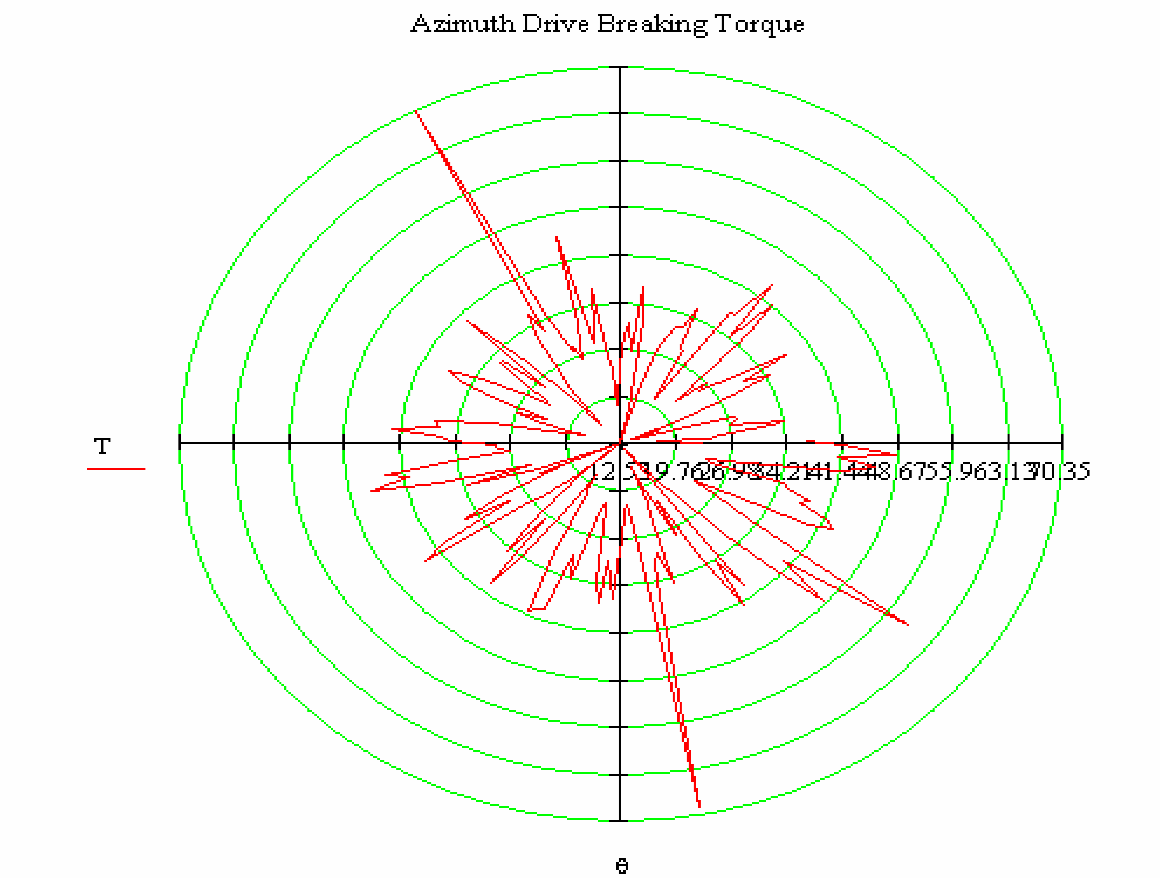
$$\theta_i := \frac{(14 \cdot 10 \cdot 11) \cdot i \cdot 360 \cdot deg}{84 \cdot 84 \cdot 42}$$

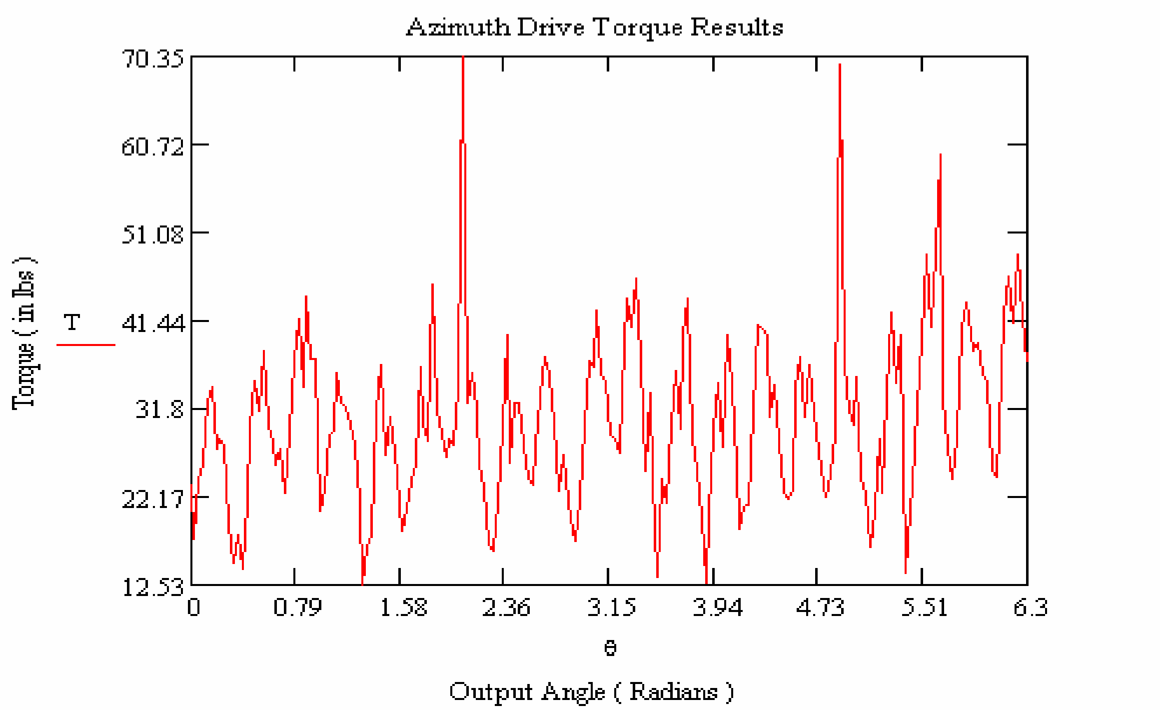
$\theta =$ (deg)

	0
0	0
1	1.871
2	3.741
3	5.612
4	7.483
5	9.354
6	11.224
7	13.095
8	14.966
9	16.837
10	18.707
11	20.578
12	22.449
13	24.32
14	26.19
15	28.061

$T :=$

C:\Documents and S...\Torque.xls


Azimuth Drive Breaking Torque
T
θ


Azimuth Drive Torque Results
70.35
60.72
51.08
41.44
31.8
22.17
12.53
Torque (in lbs)
T
0
0.79
1.58
2.36
3.15
3.94
4.73
5.51
6.3
θ
Output Angle (Radians)

Uncertainty Analysis

Torque = Pulling Force * Distance * sin (ϕ) *sin(α) *sin (β)

Given Information

$E_\phi := .5 \cdot deg$ $E_\beta := 2 \cdot deg$ $E_\alpha := 2 \cdot deg$ $E_d := .01 \cdot in$

$\phi_{max} := 90.5 \cdot deg$ $\beta_{max} := 92 \cdot deg$ $\alpha_{max} := 92 \cdot deg$ $D := 4 \cdot in$

Load Cell Uncertainty Analysis

$Bit_{DAQ} := 12$

$Range_{loadcell} := 100 \cdot lbf$ $Cal_r := .9995$ $P_{min} := 3.132 \cdot lbf$

$$U_{pres} := \frac{.5 \cdot Range_{loadcell}}{2^{Bit_{DAQ}}} \qquad U_{pcal} := \left(1 - Cal_r\right) \cdot lbf \qquad U_{pacc} := .0001 \cdot 100 \cdot lbf$$

$$U_{ptot} := \sqrt{U_{pres}^2 + U_{pcal}^2 + U_{pacc}^2} \qquad U_p := \frac{U_{ptot}}{P_{min}}$$

Distance Uncertainty

$$U_d := \frac{E_d}{D}$$

Angular Uncertainty

$$U_\phi := \frac{1}{\tan\left(\phi_{max}\right)} \qquad U_\beta := \frac{1}{\tan\left(\beta_{max}\right)} \qquad U_\alpha := \frac{1}{\tan\left(\alpha_{max}\right)}$$

Total Uncertainty

$$NormalizedU_{sys} := \sqrt{U_p^2 + U_d^2 + U_\phi^2 + U_\beta^2 + U_\alpha^2}$$

$$NormalizedU_{sys} = 0.05$$

Azimuth Drive Unit Design Improvements for Increasing Performance and Reducing Manufacturing Costs

James B. Blackmon
Professor
Stephen B. Collins
Prototype Development Specialist
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
Huntsville, Alabama

Introduction

The heliostat azimuth drive unit designed and built by McDonnell Douglas and HiTek Services, Inc. under the U.S./Israel Science and Technology Foundation program was examined to determine what changes could be made to improve performance and reduce costs. The following summarizes design revisions identified with the first prototype design. Selected figures of this drive unit are provided below. The supplier, HiTek Services, Inc., has made improvements (primarily in reducing the sprocket eccentricity associated with commercial off –the-shelf sprockets) and produced approximately two-dozen additional azimuth drive units. This drive unit is the baseline system for the Noor al Salaam program, in accordance with the Memorandum of Understanding signed by the USISTF participants.

The drive unit is formed from a staged chain and sprocket with each pair of gear reducing sprockets on two common shafts (see attached figures). The basic design is opposite that of conventional solar drive system configurations, which typically have a large diameter bearing designed for the wind loads. Such bearings are relatively high cost. Instead, in this design a trailer axle type shaft mounted on a pair of bearings is used, such that the pedestal and azimuth drive shaft counteract the moments through these two bearings. Shock loads are mitigated by an adjustable set of chain tensioners. The chains have spring-damper forces exerted by the chain tensioner through a small wheel, sprocket or roller that pushes against the chains laterally to minimize backlash and provide a means of absorbing transient loads, such as wind gusts, thereby reducing the impact loads. This design can be based on commercially available trailer axles, as was done with the prototype, at low cost.

This design was developed, built, and tested. It offers:

1. Low cost, with all but the housing assembled from commercially available off the shelf parts (chains, sprockets, springs, adjusting bolts, bearings, bushings, axle hub, etc.);
2. The chain and sprocket is the highest efficiency gear reduction approach;
3. The assembly is easily assembled by unskilled labor;
4. The major assembly tasks consist of stacking the sprockets, bearings, bushings, etc., onto the shafts, attaching the chain links and bolting the cover in place;

5. The major failure mode is a chain break, and redundancy is built in with two chains on the output stage to minimize the probability of the unit freely rotating;
6. Replacing a chain is relatively easy, with no special equipment required;
7. The system can be adjusted for wear by simply tightening the chain tensioning bolts, without requiring any disassembly.

The azimuth drive is covered by U.S. Patent Reference 1.

The following summarizes optional improvements.

Housing

The housing is made of welded steel plates, shaped to form a lower, essentially rectangular box with two “scarfed” or angled corners at the end opposite the output shaft. On top of this box is a smaller box, which accommodates the output shaft (end of the axle), which is bolted to the top of this box. The box allows for the appropriate movement of the linear actuator. However, it may be practical to build a single rectangular box, thus eliminating the additional weldments and machining.

Assembly

During assembly of the sprockets, located on the two main shafts, with the chains, there is sufficient force exerted on these shafts, drawing them together, that it takes approximately 25 to 50 lbs of lateral force to move these two shafts apart sufficiently to fit the holes that the axle is bolted to. One method of doing this is to have one man separate these by pushing them apart. One can also insert a small lever into the holes and move these such that each bolt can be inserted and screwed in a few turns. Alternatively, we can use shaped bolts and slightly enlarged holes in the top of the housing, such that the bolts could be engaged, and as they were screwed in, would move the axle relative to the bolt hole pattern to have the proper fit.

Axle Hub

The axle hub used is an off-the-shelf trailer axle. This works well, is readily available at very low cost. However, alternatives may exist that can be supplied by other manufacturers (farm equipment, for example) at lower cost, or these may be built at lower cost in Egypt. There may be some cost reduction in using a four-hole pattern, rather than the six-hole pattern currently available off the shelf.

Housing Bolt Holes

The housing is made up of a top and bottom, bolted together along the outer flange. When these two pieces are being assembled, there may be interference that slows the process of inserting the bolts, in part due to the forces exerted by the chain. Although these holes can be moved relative to each other with a small lever (screwdriver or equivalent), another approach is to use countersunk holes on the top, similar to brake drums and tires, which would force the two parts together with the correct final assembly dimensions. The existing design has two locator pins. Larger pins can be used to improve the fit. However, there are no serious impediments to assembly of the housing, and it can be done by one person in a few minutes.

Tension Wheel

A tension wheel is used to impose a side load on the chains. This is a simple disk, but a sprocket could be used. The sprocket would ensure that the chain could not slip off, which is a possible occurrence with the disk.

Chain Tensioner

A chain tensioner is used to exert a side load on the chain, so as to eliminate backlash. The tensioner also allows shock loads from sudden wind gusts to be moderated and dampened out. A sudden, impulsive load on the reflector would cause the reflector to impose a load on the azimuth drive output shaft, which in turn would impose a moment on the chain. The increased tension load would then exert a side load on the tensioner, which would be resisted by the spring. In the current design, only one side of the chain has the tensioner. Thus, the ability to moderate the impulse load is limited to loads in one direction. For the final design, it would be necessary to add a tensioner to the other side as well.

In addition, the design of the tensioner could be modified to operate as a caliper, with a single adjustment for the degree of tension, rather than an adjusting bolt on both sides.

The prototype design has chain tensioners on one side of each chain; in the final design, two would be used, so that impulse loads would be attenuated on both sides (both clockwise and counterclockwise directions). Additional damping can be included with elastomeric materials if necessary.

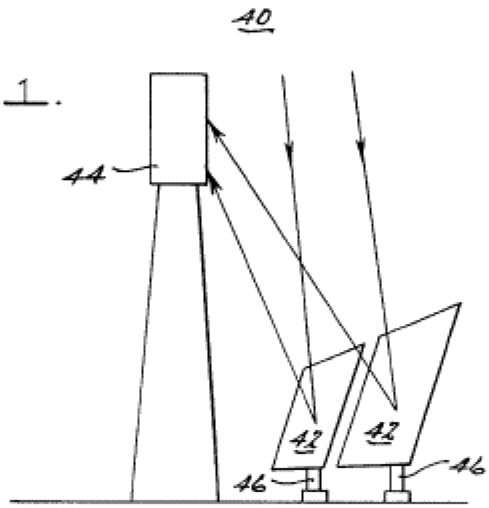
Sprocket Eccentricity

The sprockets procured for the first two prototypes have an eccentricity that causes the torque required to rotate the azimuth drive to vary considerably. We conducted tests as part of a student project to evaluate this variation. The supplier of the drive unit, HiTek Services, Inc., had earlier determined that it was necessary to machine these sprockets with higher tolerances to avoid this torque variation. It is likely that Egyptian manufacturers would be used to make these, rather than buying them “off the shelf”, or they could be procured from the supplier without the center holes, and then these could be drilled for matched sets, to eliminate the tolerance variations.

Reference:

1. James B. Blackmon and Frederick Gant, U.S. Patent Number 6,440,019, Solar Power System Drive Unit, granted August 22, 2002. Assigned to McDonnell Douglas Astronautics (a wholly owned subsidiary of The Boeing Company).

FIG. 1.



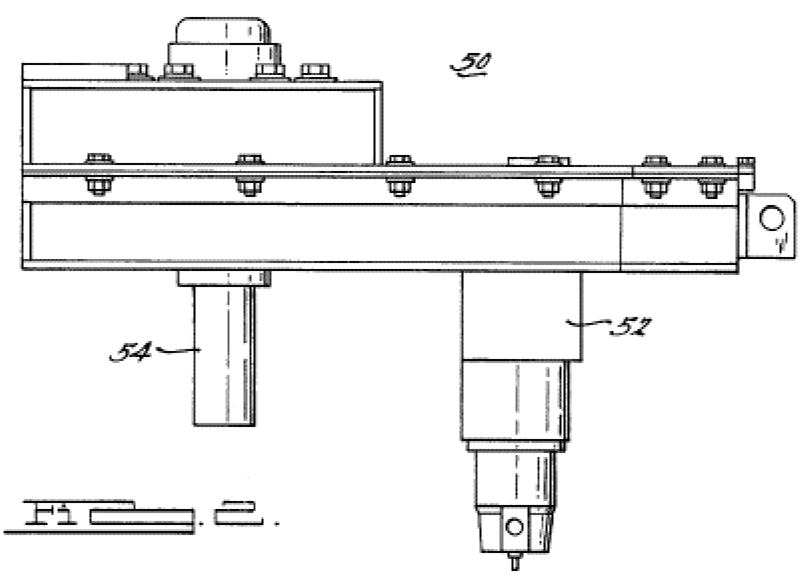


FIG. 2.

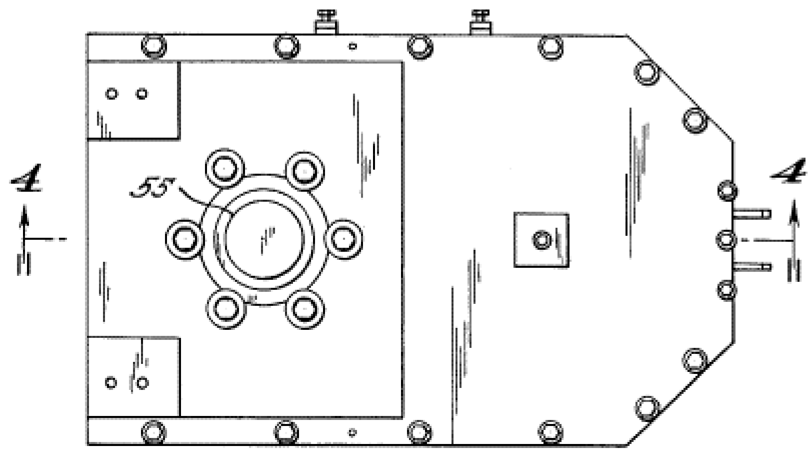
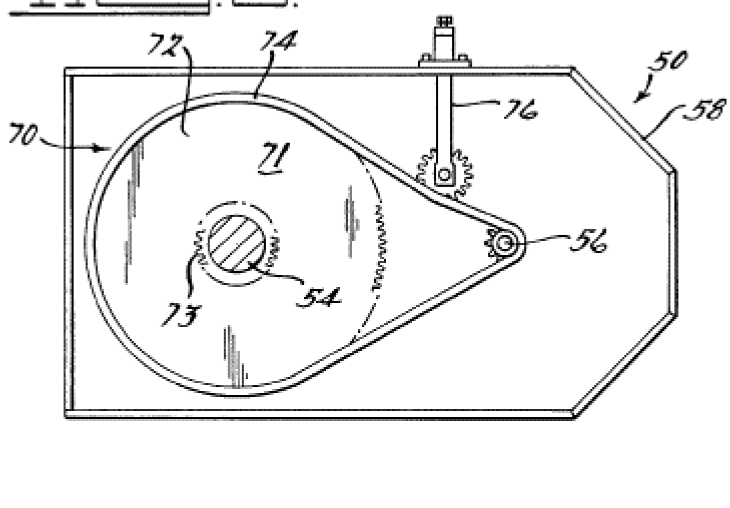


FIG. 3.

FIG. 5.



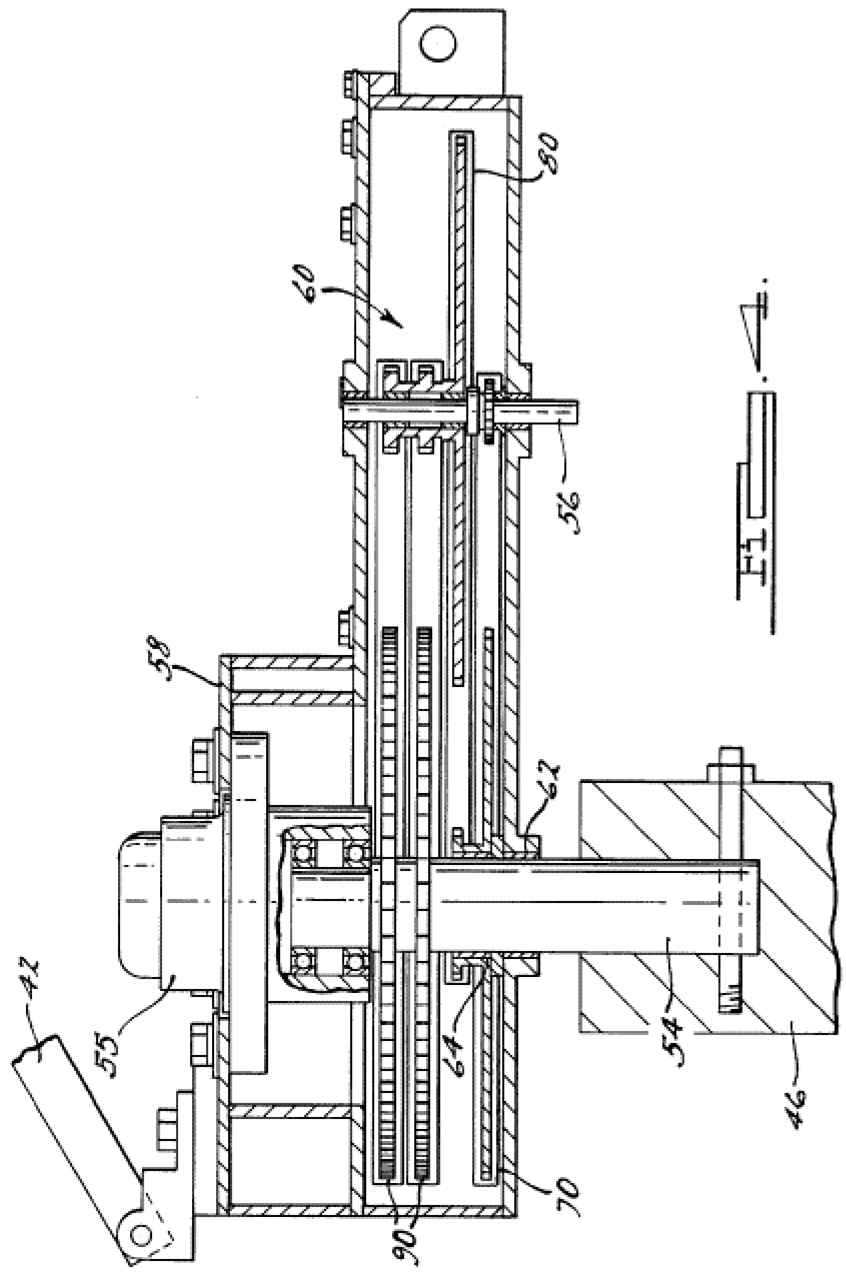


FIG. 4

Appendix H
Heliostat Reflector Fabrication

Heliostat Reflector Fabrication

James B. Blackmon
Kevin Nichols
Ben Bramblett
Morris Morell
University of Alabama in Huntsville

Introduction:

Under the Noor al Salaam program and with Special Studies support from various students, we continued our development of methods for fabricating the heliostat. Part of this effort included constructing ribs and making a heliostat reflector assembly tool. Do to delays in funding, the reflector tool had to be made twice, but was eventually not used due to the program being terminated. We also exposed selected coupons to assess environmental degradation.

Refurbishment and Construction of Heliostat Reflector Fabrication Tooling:

We needed to use the tool from the USISTF program that had been built by HiTek Services to make additional support ribs. This tool had been in storage for several years, and required refurbishment. We also had to refurbish the support frame that can be rolled across the reflectors so that hand lay-up of the fiberglass. These efforts were conducted as part of student projects and were conducted at no cost to DOE.

Process for Fabricating Fiberglass-Backed Heliostat Reflector with 'Built-In" Compressive Loads:

The following procedure covers the steps to produce the heliostat such that the glass reflector does not deform (i.e., lift off of the flat, thick glass forming plane or "tool") and to ensure that some degree of compressive load is imposed on the glass, in a generally uniform, tangential direction. This technique is in conformance with the patent of Reference 1 of this appendix.

Compressive preloading is achieved primarily from two effects: shrinkage of the resin during the cure and curing at a temperature higher than normal operating temperatures. In addition, there may be, and usually is, a temperature gradient, with the mirrored glass having a lower temperature than the resin during the curing process. These effects tend to compress the glass, as described in the related patents.

The desired compressive stresses can be retained only if the mirror shape is controlled so as to not allow bending. Otherwise, the built in stresses could cause the mirror to bend and put part of the mirror surface into tension, thus likely leading to breaking of the mirror. This has been observed when a specimen was fabricated with supporting metal edges, and then the edges were removed; the glass bowed into a convex shape (looking at the mirrored side from the front) and this caused the specimen to break.

The basic concept is that the mirror is formed against the tooling surface, but held down at the edges by a fiberglass fillet around the edges of the mirror (and possibly additional mechanical supports) while its fiberglass backing structure is allowed to cure (typically, under vacuum, which holds the mirror tightly against the tool/forming surface). Then, the rib support structure is bonded to the laminated mirror-backing structure in a separate operation. Separation of the mirror and its laminated fiberglass backing structure from the tool must be avoided until the entire unit, with the glass, backing structure, and rib support structure is completely bonded.

Another factor in our process is that we need to be able to determine the compressive load that will be built in. We anticipate doing this with strain gauges. We may also fiberoptic elements that will enable us to record stress.

The procedure is as follows:

1. Lay carpet padding on a flat floor (e.g., Building 4655, MSFC or UAH Johnson Research Center, the latter requiring a layer of concrete to form a sufficiently flat surface)
2. Place the two thick glass lights (procured from K&M Glass, Huntsville) on the carpet padding; ensure that they are touching along the inner edges and at the same height, with flush edges.
3. Cut plastic (blue and pink) to fit over the entire unit. Carefully roll these and place to the side or hang these from a “clothes line” for ease of access later.
4. Cut bleeder cloth to fit over the entire unit. Carefully roll this and place to the side hang these from a “clothes line” for ease of access later. Note, these sheets are not large enough to cover the entire 10’ by 10’ reflector, and therefore tacky tape will be required to seal it.
5. Cut fiberglass (two layers are needed) to fit over the entire unit. Carefully roll these and place to the side.
6. Clean the glass tool thoroughly with soft rags, window cleaner, and a squeegee.
7. Wax the glass tool, using Rexco Partall Paste #2 (telephone: 1-800-888-1060).
8. Place the four glass sheets face down on the thick (3/4”) glass “tool”.
9. Install strips of metal along the edges of the sheets, position and bond to the thick glass “tool”. The specific design of these strips is TBD. The purpose is to have a reusable means of applying a load to the glass from the top such that it can not bend upwards as the fiberglass cures.
10. Apply a fiberglass “rope” along the outer edges between the glass and the metal strip, to fill the gap and form a robust edge seal.
11. Apply tacky tape to the metal strip around the 10’ by 10’ reflector assembly, making sure that any leaks are sealed, but do not remove the protective strip. This protects the tacky tape from resin in the following process.
12. Place a small (roughly 6” by 6” test sample of glass near the reflector. This will be covered by fiberglass and cured along with the entire unit. The exact means for doing this is TBD. The purpose is to have a coupon for testing later.
13. Cover the four glass mirrors with two layers of fiberglass, with resin applied to the glass, and each layer, by rollers/brushes, etc., as further described in the following:

a. Be sure that the glass pairs line up at the separation between the two thick glass lights.
b. Form a fillet of micro-spheres or chopped-fiber fiberglass and resin around the small separation region (cross-shaped) between the four lights. The purpose of this is to:
    i. Form a sealed edge to minimize or prevent intrusion of water and air that can oxidize or corrode the silver.
    ii. Hold the glass to the thick glass lights after the vacuum is released, so that the unit does not deflect prior to being bonded to the support structure.
c. Roller/brush resin onto the protective backing paint covering the mirrored-glass surface.
d. Immediately place one layer of fiberglass on the mirrored glass and apply sufficient additional resin to ensure good penetration. Note that this process requires great care in positioning the fiberglass such that it does not overlap the edges too much. This process should be practiced first with a dry sample sheet. It may be necessary to apply the fiberglass as separate, roughly 5' by 5' sheets.
e. Immediately apply a second layer of fiberglass and resin.
f. Quickly clean up any resin that gets onto the thick glass support structure that could contaminate the tacky tape. Note that the tacky tape is still protected by its plastic cover.
g. Quickly remove the protective strips from the tacky tape, being careful not to contaminate the tacky tape with any resin.
h. Place the blue perforated plastic sheet across the entire unit.
i. Place the white bleeder cloth over the entire unit.
j. Place the pink plastic (with its vacuum cup fittings) across the entire unit and seal it to the tacky tape. (Note: the pink plastic is roughly 5' wide. It will be necessary to join two or more pieces together with tacky tape to ensure we have a tight seal. This must be done shortly before this process is started so that the correct size is available.)
k. Install the vacuum fittings in the pink plastic sheet.
l. Install the hoses to the vacuum fittings.
m. Start the vacuum pump, inspect for leaks, seal as required.
n. Place electric blankets across the entire unit, cover with sealed/encapsulated wall-insulation.
o. Turn on the electric blankets to maximum. The purpose of the electric blankets is to:
    i. Decrease the cure time
    ii. "Build-in" compressive loads. Since the mirror is cured at, say, 110 to 120 degrees F, when the unit is operated at lower temperatures, there will be substantial additional compressive loads due to the difference between the cure temperature and this lower operational temperature, in addition to the compressive loads built in due to the resin shrinkage. Higher operating temperatures than this will have some tensile stress, but it will be less than for a room-temperature cure.

p. Insert thermometers at various points beneath the blankets to monitor temperature. Record.
q. Monitor and record the stress.
r. Allow the unit to cure overnight.
s. Remove the blankets, plastic sheets and bleeder cloth.
t. Inspect and ensure that the mirrored glass is held down on the thick glass light support surface by the metal strips. If not, force this region down with weights and/or beams and apply additional resin and fiberglass to hold it to the thick glass surface. Allow unit to cure overnight, remove weights and beams, and inspect. Repeat if required. (Preferably, the unit will remain flat, and thus no time will be required to conduct the corrective measures.) The purpose is to ensure that the 10' by 10' mirror maintains a shape that is as flat as practical, by being in intimate contact with the thick glass tool over its entire area.

14. Place the ribs and box ends and main beam onto the thick glass surface. Bond these together with resin and fiberglass cloth to form a monolithic structure.
15. Allow the resin to cure overnight. Note: we may wish to keep the entire unit under "load" (metal strips) for a much longer period, to minimize any post cure distortion.
16. Remove the metal strips.
17. Clean off any residual resin and begin to separate the reflector from the thick glass tool using ship, razor blades, etc.
18. Lift the monolithic structure and then place it back down on the mirror. We have experienced post cure problems in which the reflectors take a "set" that has some distortion built in from loads. We will therefore keep the reflector on the glass structure for a period of approximately 1 to 2 weeks, monitoring its shape daily. The objective is to determine if post cure distortion arises.
19. Once we are satisfied that the shape is correct, install the drive unit "saddle" onto the main beam.
20. Lift and rotate the reflector face up, and place it on the floor.
21. Inspect for surface flatness using various equipment available from the NASA MSFC Space Optics Manufacturing Technology Center.
22. Transport to the heliostat site and install this onto the drive unit, previously installed at UAH in the Solar Test Area.
23. Conduct optical tests to assess flatness.

Miscellaneous Supplies, Tools, and Equipment

- Copy of Fabrication Process
- All Drawings associated with the reflector
- Folder/Binder for all documents pertaining to fabrication and procurement
- Safety Data Sheets
- Wagner Viscosity Meter
- MEKP
- MEKP Dispenser Bottle
- Resin

- Fiberglass
- Thermometers
- Encapsulated insulation
- Electric Blankets
- Carpet padding
- Plastic sheeting
- Brushes and short-nap rollers
- Stirring sticks
- RTV
- Roller handles
- Buckets (disposable)
- Chopped fiber and/or micro-spheres
- Approximately 50' of fiberglass rope
- Buckets (disposable)
- Breathing Masks/filters
- Smocks
- Booties
- Thin disposable gloves
- Scale for measuring resin in buckets
- Rags
- Squeegee
- Window cleaner
- Alcohol
- Acetone
- Tacky Tape
- Miscellaneous glass cleaners, scrub pads, etc.
- Saw horses
- Lifting slings (optional, since the unit can be picked up by 4 men easily)
- Vacuum pump and hoses, extension cord, etc.
- Optical flatness measuring instruments (TBD)
- Drive unit saddle
- Miscellaneous fixtures to mount the reflector on
- Lifting slings, vacuum cups, etc., to lift the reflector and rotate it
- Scale to weigh the completed unit

References:

1. Blackmon, James B. Composite Backed Pre-stressed Mirror for Solar Facet, Patent Number 6,739,729, granted May 25, 2004
2. Blackmon, James B. Composite Backed Pre-stressed Mirror for Solar Facet, Patent Number 7,309,398, granted December 18, 2007

Appendix I
Heliostat Foundation and Installation

Heliostat Installation in the Field:

Overall installation rate is approximately 25 heliostats per day, with a group of approximately 7 men, or 50 heliostats over a two day period

Labor Category	Labor Rate Fully Burdened $/hr	Hours/Day	Labor Cost Per Day	Number of Days	Cost for Heliostat Installation
Supervisor	8	8	64	100	6400
(Assumes Supervisor has additional administrative duties)					
Mechanical Technician	5	8	40	80	3200
Mechanical Technician Assistant	3	8	24	40	960
Electrical Technician	5	8	40	40	1600
Electrical Technician Assistant	4	8	32	40	1280
Heavy Equipment Operator	4	8	32	40	1280
General Assistant	3	8	24	40	960
	Heliostat Installation Labor Costs, U.S. Dollars =				15680
	Costs per heliostat for installation, 2005 U.S. Dollars Assuming Egyptian Labor Rates				**7.84**

Note: The above figures are based on engineering approximations of 2005-2006 labor rates in Egypt. Installation includes lifting and placing the heliostat reflector and drive unit onto the pedestal, securing the J-bolt fittings, and completing the electrical hookup. It is assumed that a spreader support bar is used to distribute the loads such that the heliostat reflector is protected from damage during the lifting operation. It is further assumed that the heliostat is guided onto the J-bolt fittings manually. This activity is similar to that conducted on the McDonnell Douglas heliostat tested at the NWC-China Lake, in 1973-74. This assembly was completed in less than 30 minutes.

Noor al Salaam/USISTF 9.2 m^2 Heliostat Foundation Cost Summary

James B. Blackmon

December 9, 2005

Total cost for U.S. Installation:

Operation	Labor	Material
Rebar Cage	$6.00	$16.00
Auger Hole	$6.00	
Install Rebar cage	$5.60	
Concrete Pouring	$9.00	$3.00
Final Positioning	$2.00	
	$28.60	$19.00

Total Cost, not including concrete: $47.60.

Concrete costs are assumed to be approximately $150.00 per cubic yard. There are approximately 0.8 cubic yards, for a cost of $120.00.

The total cost per foundation is thus approximately $167.60.

Total cost for Egypt Installation:

Operation	Labor	Material
Rebar Cage	$2.40	$12.80
Auger Hole	$2.40	
Install Rebar cage	$2.24	
Concrete Pouring	$3.60	$3.00
Final Positioning	$0.80	
	$11.44	$19.00

Total Cost in the U.S., not including concrete: $47.60.

Total Cost in Egypt, not including concrete: $30.44

Concrete costs are assumed to be approximately $150.00 per cubic yard. There are approximately 0.8 cubic yards, for a cost of $120.00. We assume concrete costs in Egypt are 20% less, giving a concrete cost total of $96.00

The total cost per foundation in the U.S. is thus approximately $167.60.

In Egypt, the total cost per foundation is approximately $126.44.

The total cost difference between Egypt and the U.S. is thus approximately $40, or, the Egyptian costs are roughly 25% less than the U.S. costs. Anecdotal evidence from colleagues in Egypt supports a reduction in costs in Egypt relative to the U.S. that is of the order of 20 to 50%.

Heliostat Foundation – Manufacturing and Installation Cost Estimates

James B. Blackmon
Sean Entrekin
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville

January 31, 2003
Revised May 7, 2003
Revised March 1, 2005
Revised December 9, 2005

The foundation for the heliostats is currently a rebar cage welded to J-bolts, set into a hole 2' in diameter, 4' deep, which can be formed by augering in most situations. The pedestal has a flange that fits onto the J-bolts. This approach is taken for early test units in order to have the versatility of moving the heliostats to different locations or to vary the angle of the pedestal for control system test purposes. In production, a different approach may be found to reduce costs, such as installing a pedestal without a flange directly into the concrete.

The following provides an estimate of the tasks required to prepare the materials needed to fabricate the rebar cage, prepare the hole, and pour the concrete to form the foundation.

Rebar Cage:

A template roughly 3/8" to ¾" plywood, is marked to match the hole pattern. The six holes are then drilled out (approx. 1" diameter). The J-bolts are then installed, double-checked against the pedestal flange to ensure proper fit, and tightened into place. The J-bolts oriented with the L-shaped foot facing outward. A support ring of six lengths of ½" rebar is then MIG welded to the J-bolts. Rebar in 4' lengths is then MIG welded to the J-bolts, and approximately 6" rebar pieces are MIG welded in two rings to stiffen the 4' rebar cage. **Figure 1** shows the completed cage.

The following are times based on actual experience, corrected for certain extraneous periods of non-productivity so that the end result is a reasonable estimate of the actual amount of time required to perform the various tasks under moderate scale production rates with semi-skilled labor. This process was conducted such that it would be representative of the times required if the cage were fabricated in Egypt. Certain tasks are not included, such as procurement, delivery, setup of the materials, clean up, etc. Both a bolt cutter and a chop saw were used to cut the rebar, and the bolt cutter was somewhat faster, especially if a large bolt cutter were used (the one used was barely able to cut through the ½" rebar).

Fabrication Steps

Cut the plywood to approximately 18" to 24" by 18" to 24".	2 min
Measure the plywood template and mark the holes.	1 min
Drill six (6) holes, 1" in diameter.	1 min
Mount the J-bolts for clearance of approx. 1" above flange.	2 min
Set up to weld rebar to J-bolts	2 min

Cut rebar into six 4’ sections	1 min
Alternately, use chop saw (20 to 30 seconds/cut)	2 – 3 min
Cut rebar into 18 6” sections (bolt cutters)	3 min
Alternately, use chop saw (20 to 30 seconds/cut)	6 – 9 min
Tack weld 4’ rebar to J-bolts, approximately 1” welds (15 sec/tack)	1.5 min
Tack weld 6” rebar to J-bolts to form a ring	1.5 min
Tack weld 6” rebar to 4’ rebar, approx 1 ‘ below J-bolts	1.5 min
Tack weld 6” rebar to 4’ rebar, approx 2.5 ‘ below J-bolts	1.5 min
Weld beads along rebar to J-bolt junctures, approx. three 1” beads each	2 min
Weld with reinforcing beads along all rebar-to-rebar joints	4 min
Weld miscellaneous beads along rebar joints as required	2 min
Total	26 min (with bolt

cutter; a total of 30 minutes to 34 minutes is required with table chop saw)

Figure 1 – Rebar Cage

Labor Costs:

Assuming U.S. semi-skilled shop rate ($8/hour) with 50% overhead, the labor cost for one person to construct the rebar cage (using bolt cutters) is approximately 8(26/60)(1.5) = $5.20. With table chop saw, the labor cost is 8(34/60)1.5 = $6.80.

Material costs:

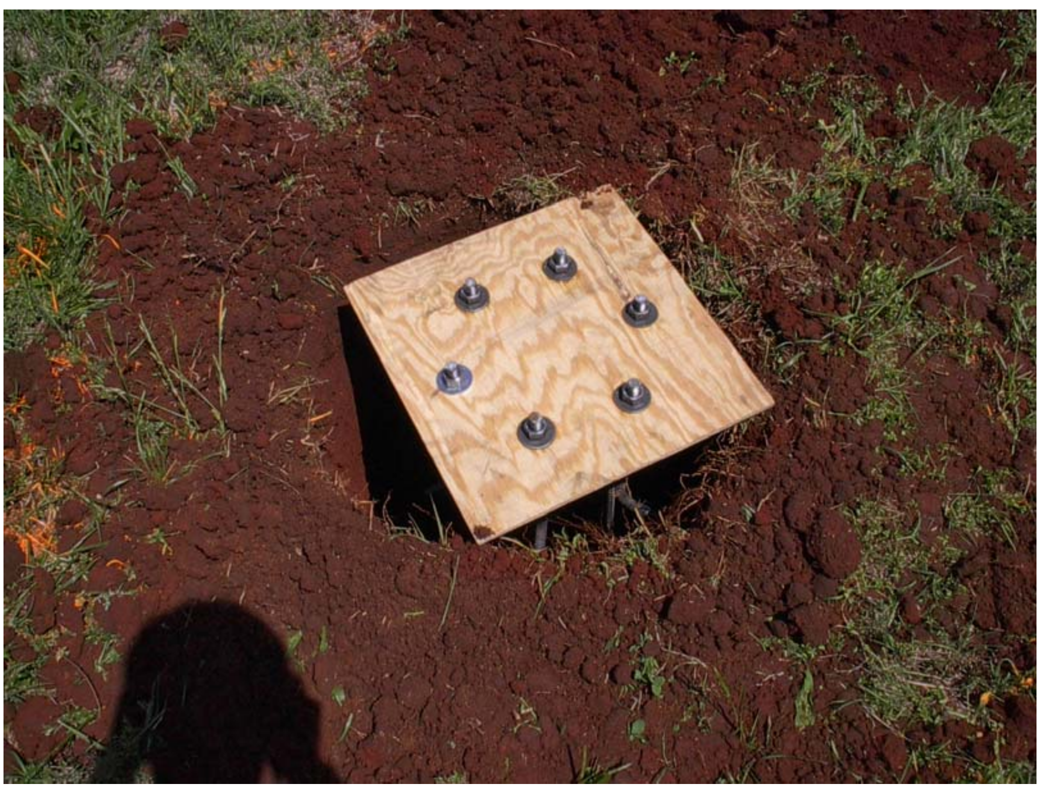
Plywood (2’ by 2’, approx. ½” thick, cut from standard 4’ by 8’ sheet) is 4/32($16/sheet) = $2.00
Rebar (approx. $0.20/ft for ½” diameter) for 24’ (4’ lengths) with 18 6” lengths or 33 ft total = $6.60.
J-bolts, ¾” ten threads per inch, each with two nuts and two washers (approximately $24/box of 20, or $1.20 each, or $7.20.
Welding wire (assume $0.20)

Total Labor: $5.20 to $6.80, but assume $6.00 on average
Total Material: $16.00.

Total for rebar cage: $21.20 to $22.80. Note that with lower rates, such as in Egypt, the labor costs would likely be cut by roughly 60% to approximately $2.40, and the rebar and other material costs are assumed to be 20% less ($12.80), for a total of approximately $15.20 for each rebar cage. With a total of 1500 heliostats, the total cost using U.S. labor estimates is approximately $31,800 to $34,200. With anticipated Egyptian labor rates and material costs, the total cost for 1500 foundations would be roughly $22,800.

Augering of 2 ft diameter, 4 ft deep hole:


15



Rebar Cage Installed with J-Bolts Braced by Plywood

Auger Hole:

The time and costs required to auger the hole includes transportation to the site, equipment attachment, maintenance, rental/depreciation of the tractor, labor cost for two men, and various consumables. These costs are usually determined by contractors, and are strongly site dependent, and may also be impacted by weather conditions. However, we found that the entire setup and augering operation took much less than an hour, and we therefore estimate that for the case in which the soil is amenable to augering, a series of holes could be dug in approximately 15 minutes or less. In our case, the augering only took about 7 minutes. Note, the operation involved stages. The first stage, the hole was dug a few feet, removed, dirt shaken off, hole inspected, and then drilled further. This was then repeated. The depth was approximately 5'.

Assuming 15 minutes, with two men, the cost for semi-skilled labor at $8/hr with 50% overhead would be approximately $6.00 per hole. With Egyptian labor, it is estimated that this would be 60% less, or $2.40 per hole.

We do not include the capital equipment costs, other than indirectly through the overhead rate of 50%.

Install Rebar cage:

Remove from trailer, place into hole 2 men, 1 minute
Protect J-bolts with plastic – 2 men, 1 minute
Steady rebar cage with 2 by 4 or equivalent 2 men, 1 minute
Back truck into position, move chute into position to unload concrete 2 men to aid driver, plus driver, for total of 3 men, 3 minutes.
Pour concrete: 5 minutes
Level rebar cage with large pole, "float" concrete surface to form slight angle for water runoff – 3 minutes
Remove protective plastic after cure and inspect: Supervisor - 1 minute

Total time: Semi-skilled labor: 2 men, 14 minutes. Assuming $8/hour with 50% overhead, the labor cost is approximately 14/60 x $12 x 2 = $5.60.

For Egyptian Labor, this is assumed to be 60% less, or $2.24.

<u>Concrete Pouring Operation</u>

The time to set up and pour the concrete was approximately 15 minutes, with a driver and two helpers. Assuming a cost for semi-skilled labor of $8/hr with 50% overhead, the cost for three men is 15/60 x 3 x 12 = $9/foundation. In addition, there are costs for consumables, which are estimated to be the equivalent of $0.30/mile at 40 miles per hour, for a cost per minute for an idling vehicle of 15/60 x 0.30 x 40 = $3.00/foundation.

We assume that the labor cost in Egypt will be 60% less, for a labor cost of $3.60.

Final Positioning/Cleanup/Inspection

The final positioning, clean up and inspection required 2 men for 5 minutes. The cost is estimated to be 5/60 x 2 x 12 = $2.00/foundation. It is assumed that the cost for this operation would be 60% less in Egypt, or $0.80 per foundation.

Total cost for U.S. Installation:

Operation	Labor	Material
Rebar Cage	$6.00	$16.00
Auger Hole	$6.00	
Install Rebar cage	$5.60	
Concrete Pouring	$9.00	$3.00
Final Positioning	$2.00	
	$28.60	$19.00

Total Cost, not including concrete: $47.60.

Concrete costs are assumed to be approximately $150.00 per cubic yard. There are approximately 0.8 cubic yards, for a cost of $120.00.

The total cost per foundation is thus approximately $167.60.

Total cost for Egypt Installation:

Operation	Labor	Material
Rebar Cage	$2.40	$12.80
Auger Hole	$2.40	
Install Rebar cage	$2.24	
Concrete Pouring	$3.60	$3.00
Final Positioning	$0.80	
	$11.44	$19.00

Total Cost in the U.S., not including concrete: $47.60.

Total Cost in Egypt, not including concrete: $30.44

Concrete costs are assumed to be approximately $150.00 per cubic yard. There are approximately 0.8 cubic yards, for a cost of $120.00. We assume concrete costs in Egypt are 20% less, giving a concrete cost total of $96.00

<u>The total cost per foundation in the U.S. is thus approximately $167.60.</u>

<u>In Egypt, the total cost per foundation is approximately $126.44.</u>

The total cost difference between Egypt and the U.S. is thus approximately $40, or, the Egyptian costs are roughly 25% less than the U.S. costs. Anecdotal evidence from colleagues in Egypt supports a reduction in costs in Egypt relative to the U.S. that is of the order of 20 to 50%.

. Appendix J
Patents related to overall technology effort, for both the USISTF and Noor al Salaam programs.

PATENTS ASSOCIATED WITH NOOR AL SALAM/USISTF PROGRAMS

1. **Solar Energy Plant. Amnon Yogev, Vladimir Krupkin, and Michael Epstein. Patent Number 5,578,140, Dated November 26, 1996.**
2. **Central Solar Receiver. Jacob Karni and Avi Kribus. Patent Number 5,323,764, dated June 28, 1994**
3. **Central Receiver with a Multi-component Working Medium. Avi Kribus, Pinchas Doron, and Jacob Karni. Patent Number 5,947,114, dated September 7, 1999.**
4. **Delivery of Radiation from a First Transparent Medium to a Second Transparent Medium Having a Lower Refractive Index. Jacob Karni, Harald Ries, Akiba Segal, Vladimir Krupkin, and Amnon Yogev. Patent Number 5,796,892, dated August 18, 1998.**
5. **Central Solar Receiver. Jacob Karni, Pinchas Doron, and Moshe Danino. Patent Number US 6,516,794 B2, dated February 11, 2003**
6. **Control of a Heliostat Field in a Solar Energy Plant. Amnon Yogev and Vladimir Krupkin. Patent Number 5,862,799, dated January 26, 1999.**
7. **Solar Power System Drive Unit. James B. Blackmon and Frederick Gant. Patent Number 6,440,019, dated August 29, 2002.**
8. **Light Weight Reflector Facet. James B. Blackmon and K.W. Stone. Patent Number 5,751,503, dated May 12, 1998.**
9. **Light Weight Reflector Facet. James B. Blackmon, K.W. Stone, and S.W. Kusek. Patent Number 5,956,191, dated September 21, 1999.**
10. **Geometric Dome Stowable Tower Reflector. James B. Blackmon with Nelson E. Jones. Patent Number 6,532,953 B1, dated March 18, 2003.**
11. **Digital Image System and Method for Determining Surface Reflective and Refractive Characteristics of Objects. James B. Blackmon and K.W. Stone. Patent Number 5,477,332, dated December 19,1995.**
12. **Digital Image System for Determining Relative Position and Motion of In-Flight Vehicles. James B. Blackmon with K. W. Stone. Patent Number 5,493,392, dated February 20, 1996.**
13. **Alignment System and Method for Dish Concentrators. James B. Blackmon and K.W. Stone. Patent Number 5,982,481, dated November 9, 1999.**
14. **Thermally Controlled Solar Reflector Facet with Heat Recovery. James B. Blackmon. Patent Number 6,708,687, dated March 23, 2004.**
15. **Thermally Controlled Solar Reflector Facet with Heat Recovery. James B. Blackmon. Patent Number 6,911,110, dated June 28, 2005.**
16. **Composite Backed Prestressed Mirror for Solar Facet. James B. Blackmon. Patent Number 6,739,729, dated May 25, 2004.**
17. **Composite Backed Prestressed Mirror for Solar Facet. James B. Blackmon. Patent Number 7,309,398, dated December 18, 2007.**

Note: The original funding agreement contained "March-in Rights", relative to the patents, as follows:

Section K

"Notwithstanding the patent rights acquired by Participants by mutual agreement or pursuant to Section J.1., the Government of the United States and Israel shall each receive the right to require the owner or the exclusive licensee of the owner of any subject invention to grant to a responsible applicant or applicants a license upon terms that are deemed reasonable, under the circumstances, in a prior written agreement by the Government of the owner; and subject to the prior written agreement of the Government of the owner, if either government determines that, within its country, (a) such action is necessary because the owner or the exclusive licensee of the owner has not commercialized the subject invention within a reasonable time, or (b) such action is necessary to alleviate health and safety needs which have not reasonably satisfied by the owner or the exclusive licensee of the owner."

Appendix K

COST ESTIMATES FOR COMMERCIAL VERSION OF NOOR AL SALAAM HIGH CONCENTRATION SOLAR CENTRAL RECEIVER MASTER CONTROL SYSTEM (MCS)

COST ESTIMATES FOR COMMERCIAL VERSION OF NOOR AL SALAAM HIGH CONCENTRATION SOLAR CENTRAL RECEIVER MASTER CONTROL SYSTEM (MCS)

James B. Blackmon, Ph.D.
Research Professor
Propulsion Research Center
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville

The USISTF study considered the MCS options, conducted trade studies, and developed approximate costs for the MCS. This was done primarily in the 1998-1999 time period, and is therefore of only partial value in determining the MCS costs for a plant that is not likely to be designed and built until approximately 2010 or beyond. Technology advances will have produced substantial changes in hardware capability, cost, and availability of control systems. Therefore, the MCS costs are estimated, and pertinent information is appended to substantiate the estimates. When the Noor al Salaam (NAS) system is considered by the Industrial Participant, overall costs would be determined, including the development costs.

However, for the RCELL optimization, the plant is to be treated as essentially a commercial version of the first plant that will be built in Zaafarana, as part of the planned NAS project. Thus, in the RCELL optimization, commercial costs for hardware, fabrication, assembly, installation, checkout, and initial operation will be used, exclusive of development costs. It is assumed that RCELL will use its own internal estimates for trenching, cables, etc.

In the following, estimates are made for the MCS fully installed costs, in current year (2006) dollars, based on the USISTF data, as well as more current engineering estimates.

MCS Control System Architecture

From 4/8/98, page 2, MCS review, the Control System Architecture consists of:

MCS with RS233/422 Serial Communication lines to the following controllers:

5. Heliostat Field (e.g., Local Controllers (approximately 15), Heliostat Controllers (approximately 1500), and UPS modules, approximately 100 28 volt battery units with chargers and electronics)
6. Tower (DIR and CCV safety/observation cameras, instrumentation (temperature, pressure, flow rate, valve status, etc.), lock outs for tower reflector positioning, CPC shutter control, access gate locks, etc.)
7. Turbine (turbine has voltage output and frequency control, and controls percent of natural gas usage relative to solar thermal input. MCS monitors turbine and can cause controlled shutdown and preparation for startup)
8. Receiver (including Compound Parabolic Concentrators) for temperature, flow rate, pressure, valve positions, valve controls (pneumatic, hydraulic, solenoid, etc.)

Additional communication is provided via Ethernet for such activities as MATLAB (or equivalent) system simulations, data analysis, archiving, remote access monitoring by control operators, and an MCS Hot Backup. These activities are conducted on PCs.

The MCS has a central hub for the operators with video monitors for the plant video cameras, and computer monitors, printers, fax/scanners, etc., and other office peripheral equipment.

The Digital Image Radiometer Beam Characterization System is provided, with a digital camera, digitizer, computer and peripherals, radiometers, and access to field data on wind speed, direction, solar irradiance (direct normal, typically with tracking Eppley Pyrheliometers (minimum, 3). The BCS provides data on beam position on the target shutter to enable the MCS to determine tracking errors in order to correct heliostat aim points, and monitor heliostat integrity and performance.

Hardware:

Computer system (updated version of the 1998 300 Mhz Pentium, with all peripherals, including ethernet card(s), serial ports, BPS card, software, monitors, etc.), with redundant back up system.

MATLAB Simulator – Dedicated Computer System similar to the basic MCS

UPS in the field

Heliostat Local Controllers

Heliostat Controllers

Software:

Gensym G2, MATLAB Simulator, compiler, remote site inspection with PCANYWARE or equivalent.

Additional software to be developed:
G2 bridges for the turbine, receiver, heliostat controllers, tower, GPS time, etc.
Visualization simulator
G2 Control Application

MCS Labor and Material Cost Estimate

Item	Number Required	Unit Cost 2006 Dollars	Hardware Costs 2006 Dollars	Labor to Install Unit	Labor Subtotal	Item Subtotal
MCS Computer System	2	$3,000	$6,000	$500	$1,000	$7,000
Control Software						
Gensym G2	1	15,000	$15,000	$500	$500	$15,500
MATLAB	1	$3,000	$3,000	$500	$500	$3,500
Remote Site Inspection	1	$500	$500	$100	$100	$600
UPS (28 volt battery, enclosure, charger, slab, etc.)	100	$200	$20,000	$100	$10,000	$30,000
Tower Monitoring System						
Tower Monitoring Cameras	2	1000	$2,000	$500	$1,000	$3,000
			$0	$0	$0	
Lockout/Safety/Access	1	2500	$2,500	$500	$500	$3,000
Tower Reflector Control, Instrumentation	4	500	$2,000	$250	$1,000	$3,000
Turbine Monitoring System						
CPC/Receiver Monitoring Interface						
Control/Instrumentation Interface	1	2500	$2,500	$500	$500	$3,000
Video Monitors	2	1000	$2,000	$500	$1,000	$3,000
Heliostat Control System						
Main Heliostat Field Controller	1	$3,000	$3,000	$500	$500	$3,500
Heliostat Local Controllers	15	$1,200	$18,000	$500	$7,500	$25,500
Heliostat Controllers	1500	$200	$300,000	$50	$75,000	$375,000
Heliostat Wiring	1500	$50	$75,000	$50	$75,000	$150,000
Field Wiring	Part of RCELL					
Digital Image Radiometer Beam Characterization System						
Digital Camera (1 Megapixel) (with lens FOV 120% of CPC)	2	$2,500	$5,000	$500	$1,000	$6,000
Housing/Fittings	2	$1,000	$2,000	$200	$400	$2,400
Cable (500 ft)	500	$2	$1,000	$5	$2,500	$3,500
Computer System (with video digitizer)	1	$3,000	$3,000	$500	$500	$3,500
Radiometers, fittings, cable	5	$500	$2,500	$200	$1,000	$3,500
Software	1	20,000	$20,000	$500	$500	$20,500
Target/Shutter						
Hardware	1	50,000	$50,000	20,000	$20,000	$70,000
Control/Interface	1	$3,000	$3,000	$2,000	$2,000	$5,000
		Hardware Total	**$485,000**	**Labor Total**	**$180,000**	**$740,000**
Contingency, 15%						**$111,000**
					MCS TOTAL	**$851,000**

Appendix L
April 2005 Tri-Lateral Meeting

A meeting was held at UAH in April 2005 in part to address how the Tri-Lateral Agreement could be implemented to move the Noor al Salaam program forward. As a result of these discussions by representatives from Egypt (NREA), Israel (Weizmann Institute of Science), DOE, and the USISTF program, we agreed that UAH would develop a plan to solicit inputs on capabilities and expressions of interest from potential industrial participants. The Tri-Lateral Agreement and other related documents are provided below, together with the documentation associated with this meeting.

Mr. Arnold Brenner April 28, 2005
Director
U.S.-Israel Science and Technology Foundation
1130 17th Street N.W., Suite 312
Washington D.C. 20036

Re: Memorandum of Understanding-Noor al Salaam Project

Dear Arnie;

I've enclosed the original memorandum that was signed by all of the participants, after some minor changes made to your draft, shortly after you had to leave. I know you want to sign this as well. Please sign and return it to me. Meanwhile, I will be working with DOE to complete the process of finding the right prime contractor. I've also enclosed some pertinent information from previous meetings and agreements with DOE for your records.

It's of course important that the USISTF have a representative on the peer group I will be forming. Please let me know who you would like, and of course, if you have the time, we'd all welcome having you serve.

Thanks again for your support and interest for the NAS project. Our meetings went quite well, and the Egyptian delegates were also pleased with the remainder of the trip to NREL and Kramer Junction, etc. I'm pleased that all of your surgeries are out of the way, and successful!

Best wishes,

James B. Blackmon, Ph.D.
Research Professor
Department of Mechanical and Aerospace Engineering
Propulsion Research Center
University of Alabama in Huntsville
Telephone: (256) 824-5106; FAX: (256) 824-7205
E-mail: blackmoj@email.uah.edu

Memorandum of Understanding

April 11, 2005

The consensus of the assembled participants, i.e., NREA, DOE, USISTF, UAH, Weizmann Institute of Science, etc., is that the original USISTF/McDonnell Douglas/Ormat/Rotem solar energy project known as the "Noor al Salaam" project, should continue with UAH leading a taskforce of the assembled members to identify, evaluate, and select a prime contractor (or a subcontractor of UAH) to complete Phase I, which includes preparations for the implementation of Phase II of the project, as defined in accordance with the original DOE Implementing Arrangement and the Agreement in Principle to Conduct a Joint Concentrated Solar Power Demonstration Project Between Participants in the United States, Egypt, and Israel (1999) and its appendix for sharing tasks between the three parties, and the UAH Statement of Work (grant number TBD).

As part of the selection process, Dr. James B. Blackmon of the University of Alabama in Huntsville will assemble a peer group, which will consist of representatives from the US, Egypt, and Israel. This peer group will assess the criteria for the selection of the prime contractor. The Prime Contractor selection criteria will follow the scope of work defined in the original grant and the RFI dated June 30, 2004 by UAH, and the Annex I of the "Implementing Arrangement between the Ministry of Electricity and Energy of the Arab Republic of Egypt and the Department of Energy of the United States of America for Cooperation in Energy Technology". Final selection of the Prime Contractor will be conducted in accordance with the Energy Acquisition Regulations.

Witnessed by:

Mr. Samir Hassan
NREA

Mr. Arnold Brenner
USISTF

4/2/05

Dan Melvin
DOE

Dr. Jacob Karni
Weizmann Institute of Science

4/2/05

James B. Blackmon, Ph.D.
University of Alabama in Huntsville

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)
and
Noor Al Salaam Tri-Lateral Hybrid Solar/Gas Power Project System Definition Program

Egyptian Ministry of Electricity and Energy
Egyptian New and Renewable Energy Authority (NREA)
U.S./Israel Science and Technology Foundation
U.S. Department of Energy - Headquarters
DOE National Renewable Energy Laboratory
DOE Golden Field Office
Florida Power and Light-Energy
Weizmann Institute of Science
University of Alabama in Huntsville

Days 1 and 2 (Saturday and Sunday, April 9 and 10, 2005) – Delegation travels from Cairo via Atlanta to Huntsville. Met at Airport by UAH Representatives. Facilitated Check-In at Hotel, with Rest/Free-Time for Visitors, including Shopping, Dinner, etc., if desired.

Day 2 (Sunday, April 10, 2005)

Mid Afternoon – Optional Tour of Huntsville Area/Points of Interest

5:30 to 6:00 PM – Tour of UAH Campus and Solar Test Area

6:30 to 8:30 – Hosted Dinner for NREA Delegation and Guests

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)
and
Noor Al Salaam Tri-Lateral Hybrid Solar/Gas Power Project System Definition Program (Cont'd)

<u>Day 3 (8:00 AM to 5:00 PM – Monday, April 11, 2005) - Plenary Session - UAH Technology Hall, Room S105</u>

8:00 to 8:30 AM – Coffee Break and Pre-Meeting Introductions

8:30 to 8:45 AM - Overview of Meeting Agenda/Sign In Sheet/General Remarks

8:45 to 9:15 AM - Introductions/Opening Remarks:

Dr. Ron Greenwood –Vice President of Research, UAH
Dr. Mark Bower – Chairman, Department of Mechanical and Aerospace Engineering
Dr. Clark Hawk – Director, Propulsion Research Center
Mr. Dan Melvin – Department of Energy - Headquarters
Mr. Glenn Doyle – DOE National Renewable EnergyLaboratory (NREL)
Mr. Arnold Brenner - Executive Director, U.S./Israel Science and Technology Foundation (USISTF)
Mr. Emara Kassem – Egyptian Ministry of Electricity and Energy
Mr. Samir Hassan - Executive Chairman, New and Renewable Energy Authority
Dr. Jacob Karni – Professor and Director of Weizmann Institute of Science Energy Center

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)
and
Noor Al Salaam Tri-Lateral Hybrid Solar/Gas Power Project System Definition Program (Cont'd)

<u>Presentations:</u>

9:15 to 9:45 Overview of U.S. Department of Energy Renewable Energy Programs – Dan Melvin, DOE
and Glenn Doyle, NREL

9:45 to 10:00 Break

10:00 to 10:30 AM - Overview of Egyptian Renewable Energy Projects and Plans – NREA

10:30 to 10:45 AM – Top Level Overview of Egyptian Collaboration/Training and Noor al Salaam Tri-Lateral Project – Jim Blackmon, UAH

10:45 to 11:30 – Overview of U.S./Israel Science and Technology Program – Jim Blackmon, UAH

11:30 to 12:30 PM - Lunch at Beville Center for delegation and representatives

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)
and
Noor Al Salaam Tri-Lateral Hybrid Solar/Gas Power Project System Definition Program (Cont'd)

12:45 to 1:00 - UAH-USISTF-Noor Al Salaam Technology Development – Jim Blackmon, UAH

1:00 to 2:00 PM - Noor al Salaam Contractual Issues

Open Discussion with All Participants, Facilitated by Jim Blackmon, UAH

- **UAH Noor Al Salaam System Definition Contract and Statement of Work:**
  - **Summary of Original Proposal to DOE**
  - **Tri-Lateral Statement of Work and Division of Responsibilities**
  - **Contractual Issues and Constraints**

- **Request for Information/Interest from Candidate Industrial Participants**
- **Transfer of Roles – UAH to Selected Prime Contractor**
- **ITAR-EAR Issues**

Break: 2:00 to 2:15 PM

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit) and Noor Al Salaam Tri-Lateral Hybrid Solar/Gas Power Project System Definition Program (Cont'd)

2:15 to 4:30 PM - Initial Tri-Lateral Planning Discussions – Noor al Salaam Project. All Participants, Facilitated by Jim Blackmon, UAH

- **History, Background, Agreements, and Plans**
  - **Review of Objectives**
  - **Organization**
  - **Business Development/Funding Issues**

- **General Discussion of Issues, Recommendations, Next Steps – All Participants.**

4:30 to 5:00 PM - Agreements/Assignments of Tasks/Action Items. Other New Business

6:00 PM – Dinner

AGENDA
Planning and Work Shops for Egyptian Technical Interchange
(Fourth Visit)

Day 4 (Tuesday, April 12, 2005)

8:30 to 9:00 – Follow Up Discussions on Noor al Salaam – All Participants

9:00 to 9:30 AM - Overview of KJC SEGS (Solar Trough) Plant – Kramer Junction, California – UAH

9:30 to 10:00 AM – Overview of DOE Solar Thermal Water Dissociation Program – UAH and Weizmann Institute of Science

POINT OF ORDER:
CHECKS MUST BE PICKED UP AT ACCOUNTS PAYABLE AT 10:00 AM AND CASHED AT CREDIT UNION

11:30 Depart UAH for Huntsville Airport (Approximate)

11:45 to 1:00 - Lunch at Airport

1:30 Departure for Denver via Atlanta

6:00 PM Drive to Golden, Colorado, Check In at Hotel, Dinner.

AGENDA
Planning and Work Shops for Egyptian Technical Interchange
(Fourth Visit)

Day 5 – (Wednesday, April 13, 2005) –

DOE New and Renewable Energy Laboratory (NREL), Golden, Colorado

8:00 AM to 5:00 PM – Meetings with NREL Key Personnel

Specific Agenda to be determined by NREL/Golden Field Office, including such discussion topics as:

- **Background on Egypt's Plans for Renewable Energy Systems**
  - **Overview of Egypt's Power Requirements**
  - **Potential Applications (e.g., Remote Areas, Agriculture, Domestic Grid Power, Green Power Sales, etc.)**
  - **Potential for Securing Funding for Projects**
  - **Status of Egyptian Solar Power Projects and Plans**
  - **Egypt's Solar Trough Status**
  - **Egypt's planned Solar Trough Bidder's Conference, other International Meetings of Interest (e.g., 2nd International Conference on Thermal Engineering Theory and Applications (ICTEA06), others as appropriate)**

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)

Day 5 – (Wednesday, April 13, 2005) – Cont'd

- **DOE/NREL/Sandia Renewable Energy Technology Development**
  - o **Photovoltaic R & D**
  - o **Wind Energy**
  - o **Solar Thermal Power Systems**

- **DOE-NREA Opportunities for Cooperation**
  - **NREL Renewable Energy System Design Software Codes**

  - **DOE/ISC/NREA Accreditation Process**

  - **Potential Collaborations**
    - o **Establishing Means for Furthering Collaboration**
    - o **Personnel Exchanges**
    - o **Validation/Enhancement of Environmental Data**
    - o **Advanced Technologies and Systems**

- **Other, TBD**

- **Tours of NREL Test Facility, as time permits**

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)

<u>Day 6 – (Thursday, April 14, 2005)</u>

NREL, Golden, Colorado to Los Angeles, Kramer Junction Facility, Mojave Desert, California

8:30 AM - Depart Golden, Colorado for Denver Airport (Staples)

11:30 AM – Depart Denver for Los Angeles
12:52 AM - Arrive Los Angeles
2:00 to 5:00 PM - Drive to Barstow, California, Hotel Check In

6:30 to 8:30 PM - Dinner

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)

<u>Day 7 – (Friday, April 15, 2005)</u>

Depart from Barstow to Kramer Junction approximately 8:00 am.

Meet with management of Florida Power and Light-Energy Kramer Junction facility, approximately 9:00 AM to early afternoon:

Introduction (Organization/History, etc.)

Plant Operational Performance/ Lessons Learned

Methods of Improving Performance

General Discussion

Tour

Mid afternoon to approximately 5:30 PM Optional Tour of Kern Wind Energy Facility or Solar 1 and Solar 2 Central Receiver Plant (TBD)

AGENDA
Planning and Work Shops for Egyptian Technical Interchange (Fourth Visit)

<u>Day 8 – (Saturday, April 16, 2005)</u>
Drive to Los Angeles Saturday morning

Informal Discussions at Hotel

Free time (Sight-Seeing/Shopping, etc.)

<u>Day 9 –(Sunday, April 17, 2005)</u>

8:30 - Depart for Airport

11:15 - Depart Los Angeles (LAX) for Cairo via Atlanta (6:25 PM arrival).
9:35 PM – Depart Atlanta for Cairo via Paris
6:10 PM – Arrive Cairo

Note: Dr. Blackmon will take the delegation to Los Angeles Airport (LAX) for departure flight to Cairo via Atlanta. He will stay in Los Angeles for other UAH business.

Top Level Overview
Egyptian New and Renewable Energy Authority
Collaboration/Training Program
And
Noor al Salaam Program

James B. Blackmon

April 2005

- **Introduction**
  - **DOE Golden Field Office awarded a Grant, funded by USAID, to the University of Alabama in Huntsville (UAH), in association with the Egyptian New and Renewable Energy Authority for:**
    - **Phase I Training at Off-Site Facilities in the U.S. and Technical Interchanges in Egypt and the U.S.**
    - **Phase II System Definition Study (High Concentration Solar Central Receiver-Noor Al Salaam (Light of Peace) Project)**
      - **Tri-Lateral Program (U.S./Egypt/Israel) to jointly develop an advanced hybrid solar central receiver prototype/demonstration plant in Egypt**

Top Level Overview
Egyptian New and Renewable Energy Authority
Collaboration/Training Program
And
Noor al Salaam Program

Training/Collaboration Tasks Conducted to Date Include:

First Visit – ASES and NREL

- **ASES Annual Meeting, Reno, Nevada**
    - **Technical Sessions**
    - **Tours (Sacramento Municipal Utility District-Solar Power, private and commercial PV systems, Geothermal, Wind, etc.)**
    - **Technical Paper Presentation on the NREA Program by Dr. Rakha (NREA)**
    - **Meetings with Industry Representatives**

- **NREL Technical Interchange Meetings**
    - **PV and Solar Thermal Technology/Research**
    - **Codes**
    - **Test Sites**
    - **Accreditation**
    - **Future Collaboration**

Top Level Overview
Egyptian New and Renewable Energy Authority
Collaboration/Training Program
And
Noor al Salaam Program

Second Visit - Kramer Junction Corporation (World's Largest Solar Trough Power Plant)

- **2 weeks of Plant Operation Training/Technical Meetings**
- **Draft report on operation, maintenance, organization, financial, etc.**

- **Visit to the University of Las Vegas Solar Facility**
    - **Dish Stirling Concentrators (SAIC/STM and SES)**

<u>Third Visit - Sandia National Laboratories Technical Interchange, Arizona Public Service STAR Facility, and Stirling Energy Systems</u>

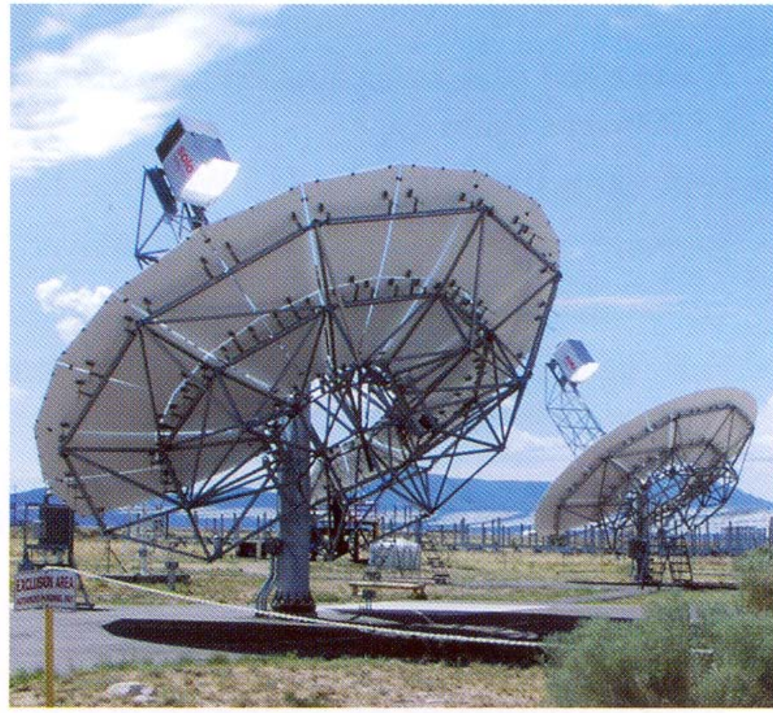
- **Familiarization with Technical Areas of R&D**
- **Briefings on Egypt's Renewable Energy Plans**
- **Establish technical points of contact**
- **Explore Opportunities for Collaboration**

Top Level Overview
Egyptian New and Renewable Energy Authority
Collaboration/Training Program
And
Noor al Salaam Program

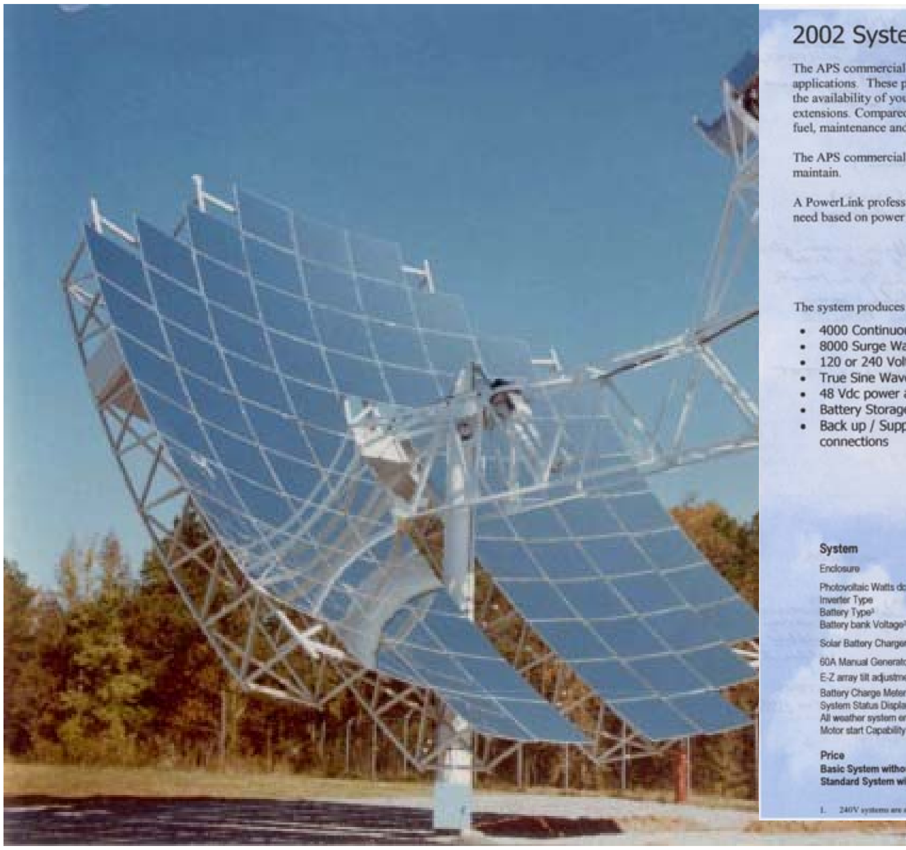
Results to Date:

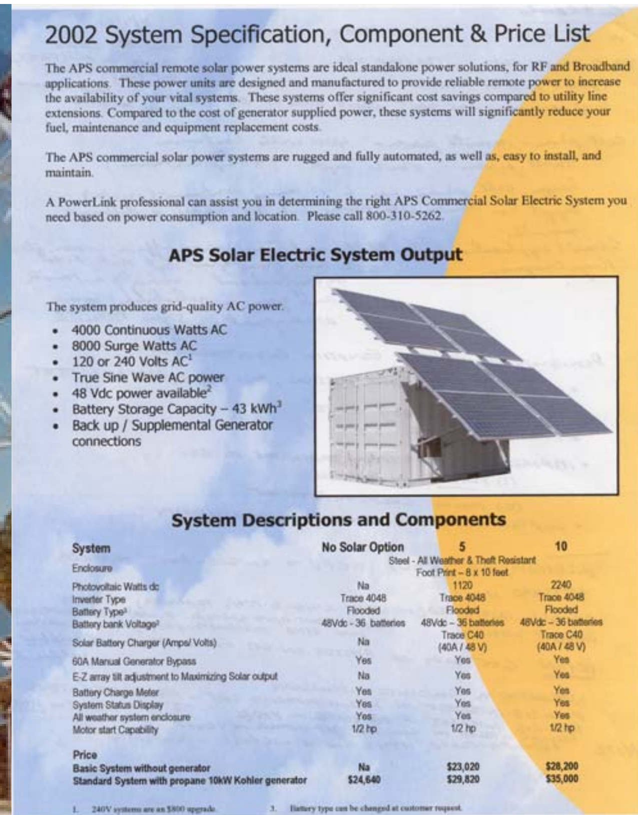
- **Developed potential future collaborations between Egypt and the U.S. including:**
  - **Resource Assessment,**
  - **Training and Standards,**
  - **System and Human Capacity Development,**
  - **Economic Analysis and Strategic Planning,**
  - **Science and Technology Development,**
  - **Low Cost Manufacturing and Economic Development,**
  - **Provision of Test Hardware, Instrumentation, Codes**
  -
- **Draft Reports of Efforts to Date**
  - **Compilations of Relevant Information, Technical Papers, etc. for NREA Library**
  - **Documentation of work conducted**
  -
- **Networking with Counterparts throughout the Solar Industry/Research Community**

Sun•Lab staff continually operate, test, and n
advanced concentrating solar power systems
make this technology a competitive form of e
generation.



The Mod 1 (foreground) and Mod 2 (background) Remote Power Systems at Sandia's National Solar Thermal Test Facility in Albuquerque, NM.





2002 System Specification, Component & Price List

The APS commercial remote solar power systems are ideal standalone power solutions, for RF and Broadband applications. These power units are designed and manufactured to provide reliable remote power to increase the availability of your vital systems. These systems offer significant cost savings compared to utility line extensions. Compared to the cost of generator supplied power, these systems will significantly reduce your fuel, maintenance and equipment replacement costs.

The APS commercial solar power systems are rugged and fully automated, as well as, easy to install, and maintain.

A PowerLink professional can assist you in determining the right APS Commercial Solar Electric System you need based on power consumption and location. Please call 800-310-5262.

APS Solar Electric System Output

The system produces grid-quality AC power.

- 4000 Continuous Watts AC
- 8000 Surge Watts AC
- 120 or 240 Volts AC[1]
- True Sine Wave AC power
- 48 Vdc power available[2]
- Battery Storage Capacity – 43 kWh[3]
- Back up / Supplemental Generator connections

System Descriptions and Components

System	No Solar Option	5	10
Enclosure	Steel - All Weather & Theft Resistant Foot Print – 8 x 10 feet		
Photovoltaic Watts dc	Na	1120	2240
Inverter Type	Trace 4048	Trace 4048	Trace 4048
Battery Type[3]	Flooded	Flooded	Flooded
Battery bank Voltage[2]	48Vdc - 36 batteries	48Vdc – 36 batteries	48Vdc – 36 batteries
Solar Battery Charger (Amps/ Volts)	Na	Trace C40 (40A / 48 V)	Trace C40 (40A / 48 V)
60A Manual Generator Bypass	Yes	Yes	Yes
E-Z array tilt adjustment to Maximizing Solar output	Na	Yes	Yes
Battery Charge Meter	Yes	Yes	Yes
System Status Display	Yes	Yes	Yes
All weather system enclosure	Yes	Yes	Yes
Motor start Capability	1/2 hp	1/2 hp	1/2 hp
Price			
Basic System without generator	**Na**	**$23,020**	**$28,200**
Standard System with propane 10kW Kohler generator	**$24,640**	**$29,820**	**$35,000**

1. 240V systems are an $800 upgrade.
3. Battery type can be changed at customer request.

Stirling Energy Systems 25 Kilowatt Electric Dish Stirling Solar Power System Concentrator – World's record for net solar electric efficiency in the field (Developed by McDonnell Douglas, 1982-1984)

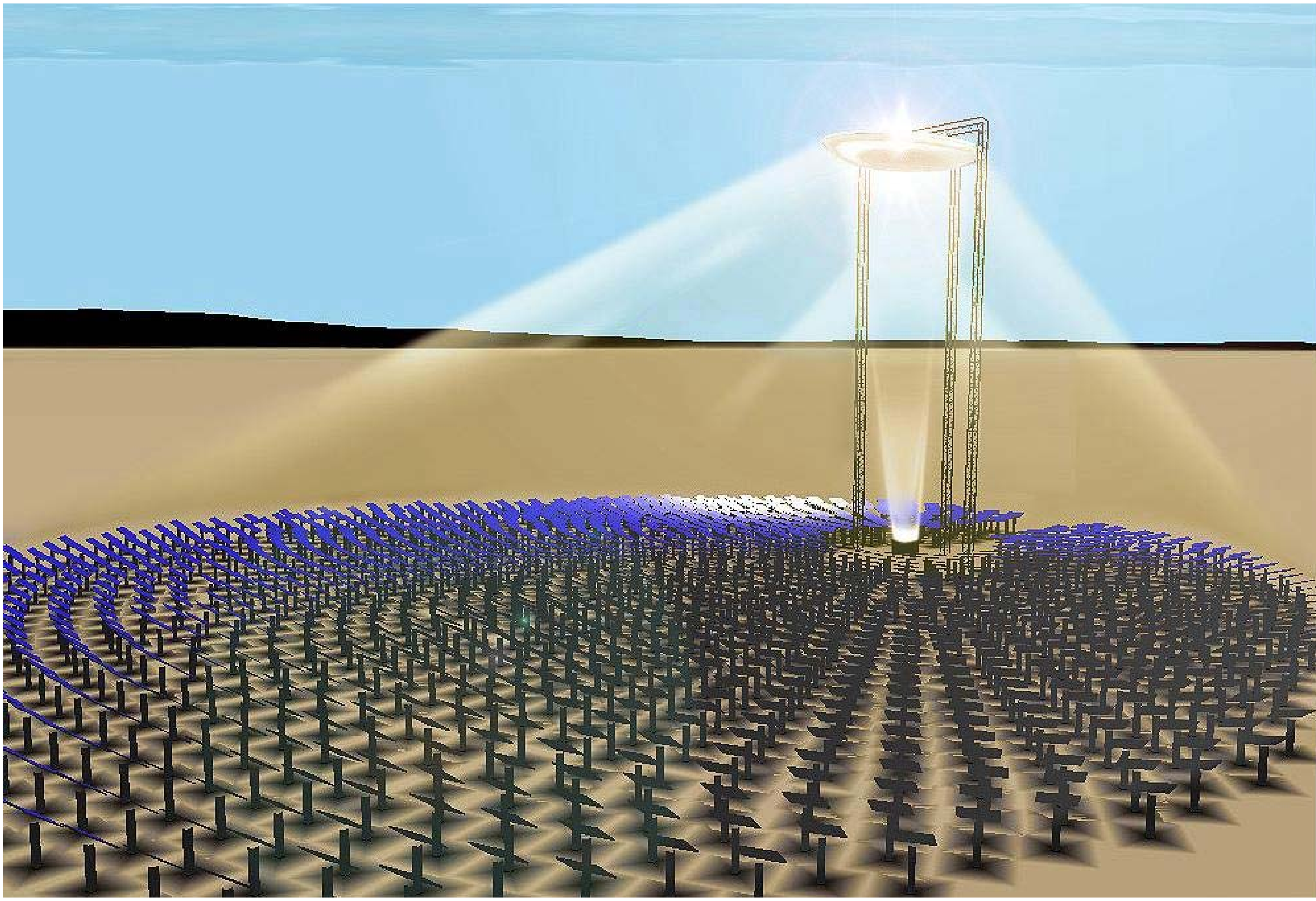
APS Remote Solar Power System (Commercially Available)

Top Level Overview
Egyptian New and Renewable Energy Authority
Collaboration/Training Program
And
Noor al Salaam Program

- **Noor al Salaam Program**
  - <u>**Noor al Salaam System Definition Study to be conducted as a joint effort between NREA, Ormat Industries, Ltd, Rotem Industries, Ltd., Weizmann Institute of Science, UAH, and a Prime Contractor/Industrial Participants Team to-be-determined**</u>

  - **Effort led by UAH**

- **Maintain Program Continuity**
- **Address contractual issues (agreements, data rights, etc.)**
- **Evaluate Potential Industrial Participant(s)**
- **Conduct Technology Development**



Noor al Salaam (“Light of Peace”) High Concentration Solar Central Receiver-Zaafarana, Egypt – A Tri-Lateral Program (U.S., Egypt, Israel)

Top Level Overview
Egyptian New and Renewable Energy Authority
Collaboration/Training Program
And
Noor al Salaam Program

<u>Fourth Visit: Egyptian Ministry/NREA Delegation Technical Interchanges (April 2005)</u>

- **Briefings/Tours of NREL and Kramer Junction**
- **Noor al Salaam Discussions**
  - **Egyptian Ministry of Electricity and Energy**
  - **Egyptian New and Renewable Energy Authority (NREA)**
  - **Department of Energy (DOE)**
  - **U.S./Israel Science and Technology Foundation (USISTF)**
  - **Weizmann Institute Science**
  - **University of Alabama in Huntsville**

Status of the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver Program

James B. Blackmon
Research Professor
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
Huntsville, Alabama
April 2005

INTRODUCTION

- **February 1995 - U.S.-Israel Science and Technology Commission (USISTC) selected McDonnell Douglas Aerospace (now a wholly owned subsidiary of The Boeing Company), Ormat Industries, Ltd, Rotem Industries, Ltd., and the Weizmann Institute of Science (WIS) to develop an innovative, high efficiency, modular solar central receiver power generation system conceived by the Weizmann Institute of Science.**

- **Advanced development and fundamental studies of this system were in development under the Israel CONSOLAR program, with Ormat Industries, Ltd, Rotem Industries, Ltd, and the Weizmann Institute.**

- **Project was conducted until December, 2001**

- **Related efforts have continued at UAH to the present**

- **The goal under the USISTF program was to develop and have ready for demonstration and commercialization, solar central receiver power systems based on this new technology.**

Status of the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver Program (Cont'd)

- **Technical innovations include:**

- **modular design for plant output power ratings ranging from 100's kWe to multi-megawatts for both on-grid and off-grid or remote applications;**
- **"beam down" optics, with a tower mounted reflector to redirect the solar flux from a field of heliostats to produce high solar concentrations at ground level;**
- **a quartz window solar receiver capable of supplying high-temperature, high-pressure air directly to a gas turbine,**
- **ability to operate in a hybrid mode with fossil fuels;**
- **compound parabolic concentrators to further concentrate the solar flux prior to entry into the receiver;**
- **heliostats sized for high optical performance and high solar flux concentrations at the tower reflector and entrance to the CPCs**
- **Low cost heliostat design with minimal upfront investment in tooling**
- **Maximum use of high production rate low cost components in the drive unit design**
- **Innovative tower design, tower reflector support structure, and tower reflector facets**
- **Capability of capturing waste heat and solar spillage power for moderate temperature (co-generation) applications**

Status of the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver Program (Cont'd)

- **Major assemblies for the USISTF integrated test series were provided by the wholly Israeli-funded CONSOLAR program**
- **CONSOLAR developed:**
    - **A very high temperature (1400 C), high pressure (20 atmospheres) air receiver;**

- **A moderate temperature air "peripheral heater" or "pre-heater";**

- **A compound parabolic concentrator; and**

- **A passively cooled tower mounted reflector.**

- **Assemblies have been installed at the Weizmann Institute of Science and have undergone a series of tests to determine their performance and validate the integrity of the receivers and CPC.**

Status of the U.S./Israel Science and Technology Foundation (USISTF) High Concentration Solar Central Receiver Program (Cont'd)

Contractual Objectives and Status:

- **Program initially was for 42 months but was extended to 54 months to allow for completion of the CONSOLAR program, which required additional time to overcome technical challenges associated primarily with the receiver and high temperature piping.**
- **Majority of the USISTF program was ended in December, 2001.**
- **USISTF program encompassed business development, systems engineering, hardware and software production, and subsystem and integrated system testing.**
- **Objectives were:**
    - **Hardware verification of the major subsystems required to design and build central receiver plants**

(heliostat, receiver, optical path, and hybridized electrical power generation)

  - **Acquisition of a customer commitment for an initial plant.**
  - **Operation of the integrated system for power production with a hybrid solar/gas turbine.**

- **Follow-on study being conducted under a DOE Grant to the University of Alabama in Huntsville (UAH) for application to a 10 to 15 Megawatt demonstration plant, as illustrated in Figure 1, planned for construction in Zaafarana, Egypt.**
- **A U.S. company will be selected to serve as prime contractor for continuation of the Tri-Lateral system definition study, involving the Egyptian, Israeli, and U.S. organizations.**

Joint U.S./Egypt/Israel High Concentration Solar Central Receiver Demonstration Plant-Zaafarana, Egypt

SYSTEM DESIGN

System Considerations:

- **selected a relatively large turbine with the majority of the annual energy provided by gas, compared to the solar input.**
- **lower cost entry into the market since the specific cost of gas turbines decreases with increasing output power**
- **offers a wide variety of market opportunities with the emphasis on gas turbine and CCGTs for power generation.**
- **larger turbine improves the solar to electrical energy efficiency, since turbine efficiency increases with power output.**
- **more practical for Noor al Salaam system to first be constructed with a moderate size solar field, of the order of 10 Megawatts output, to gain experience in system performance and operation before building larger systems.**
- **relatively small solar annual energy fraction, compared to the annual energy from gas, improves the overall financial return for grid supplied, market priced electricity at current gas prices.**
- **However, there are other opportunities for solar stand-alone systems, especially in remote areas of developing countries, for which conventional power generation costs are high.**

SYSTEM DESIGN (Cont'd)

System Architecture:

- **Sunlight from a field of heliostats is reflected to a tower-mounted reflector, which directs this light to a series of compound parabolic concentrators (CPCs) on the ground.**
- **Light is further concentrated and passes into a series of air receivers.**
- **Air from the compressor of a gas turbine flows through the receivers and is heated to high temperature.**
- **Air then flows to the combustor of the turbine, where natural gas or bio-gas is used to further heat the mixture of air and combustion products prior to flow through the turbine for power production.**
- **Important performance and cost advantages:**
  - **Receiver concept developed at the Weizmann Institute of Science and Rotem Industries offers a major advantage in that it can accommodate a wide range of incident power level, temperature, flow rate, and air pressure.**
  - **By replicating the receiver and positioning multiples of these at the focal zone, with the CPCs, a wide range of power levels are achieved.**
  - **This modularity also decreases cost, since unique, custom receivers are not needed for specific power levels or designs.**

SYSTEM DESIGN (Cont'd)

- **Primary air receivers use a cone shaped quartz window kept in compression over all operational conditions.**
  - **Quartz has a higher compressive strength than steel**
  - **high safety factors**
  - **efficient transfer of solar energy into the receiver**
  - **concentrated solar radiation is incident on high temperature ceramic fins**
  - **air passes over these fins and is heated to high temperature, but with very low flow losses.**
  - **volumetric receiver can be operated at very high temperature (up to 1700 C), very high concentrations (2000 to 10000 suns) and high efficiency**
  - **no intervening metal wall, as with direct impingement receivers**
  - **special high temperature metals are not required**
  - **ability to accommodate high temperatures and high concentration ratios increases the power to volume ratio, which results in relatively small receivers for a given power rating, which reduces hardware cost**
  - **high temperature ceramic interior can be built at relatively low cost**
  - **receiver couples to a conventional external burner gas turbine**

SYSTEM DESIGN (Cont'd)

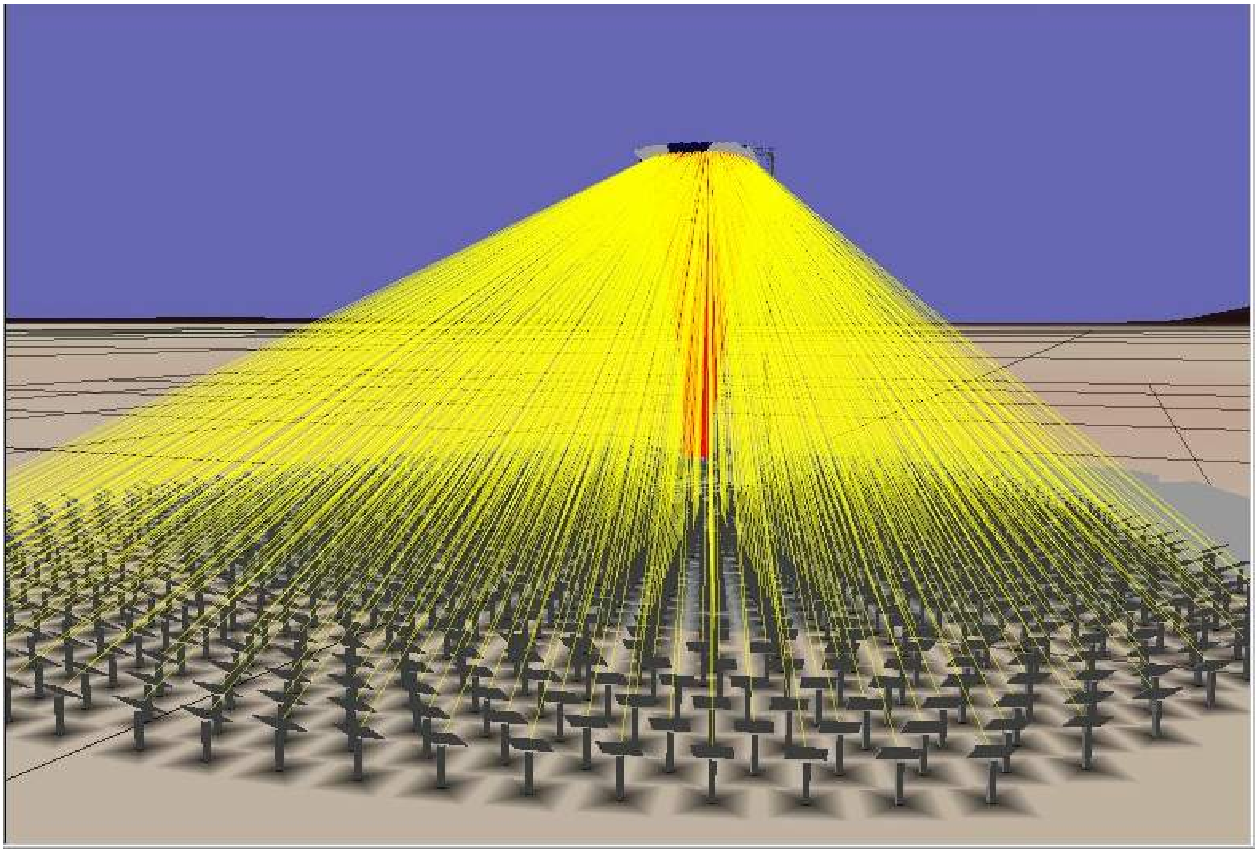
- **Gas turbines have become the dominant choice for new power generation**
  - **high performance,**
  - **low cost,**
  - **ease of control for dispatching power as needed,**
  - **installed in relatively short periods of time.**
  - **technology continues to advance, with performance increases resulting from increased turbine temperatures possible with advanced materials.**
  - **solar receiver design can achieve the high temperatures required for advanced turbines.**
  - **air temperature and flow rate can be selected over a relatively wide range through design of the flow configuration of the piping to achieve optimum conditions for a particular application.**
  - **high-pressure air from the compressor flows through the receivers in either a series flow path (for maximum outlet temperature) or a parallel flow path, which reduces pressure losses.**
  - **system can also be used in a stand-alone mode, with essentially no hybrid gas heating, for remote applications**
  - **choice of air temperature is determined by the system design and turbine requirements**
  - **suitable for integration with gas turbines or combined cycle gas turbines (CCGT), and for retrofits to existing CCGT systems.**

SYSTEM DESIGN (Cont'd)

- **placing a relatively simple reflector on a tower decreases costs associated with piping, valves, controls, and structure that are substantial for a conventional solar central receiver with the receiver mounted on the tower.**
- **eases the operations and maintenance operations, since the reflector concept is very simple, primarily requiring only an occasional cleaning.**
- **achieves high efficiency optical transfer of the concentrated light from the tower to the compound parabolic concentrators.**
- **cost of the tower reflector is relatively low, using commercially available geodesic dome structural members to form the required hyperbolic reflector shape**
- **tower reflector costs completely offset by waste heat recovery for uses such as process heat, desalination, or power generation with Organic Rankine Cycle (ORC) turbines**

SYSTEM DESIGN (Cont'd)

- **system architecture design was developed for a collector field, tower, tower mounted "beam down" reflector, CPC, receiver array, and hybrid turbine.**
- **collector field was sized to provide approximately 10 Megawatts thermal at solar noon on the Summer Solstice, for Barstow, CA.**
- **plant size was selected in part because it was a reasonable size for demonstration plant applications, and in part because it would be able to use an array of air receivers based on the design developed as part of the CONSOLAR program, with essentially no modifications.**
- **Barstow conditions were selected for convenience.**
- **optical aspects of the design were determining factors in the selection of the heliostat size, field layout, CPC size and geometry, tower height, and tower reflector size. The Weizmann WELSOL code was used, with various cost estimating relationships, to develop the essential plant characteristics.**
- **animated graphical ray trace code, termed SolarSim, developed by HiTek Services, Inc. was then used to develop the field layout, for selected heliostat designs**
- **SolarSim was also used to develop detailed flux distributions incident on the tower reflector and CPC aperture; these conditions were used to develop the prototype designs for these subsystems and to develop safe emergency shut down procedures.**



10 Megawatt (thermal) Solar Field-SolarSim Animated Graphics Ray Trace

Heliostat Design

- **effort was initiated with a number of programmatic constraints and design requirements**
- **necessary to design, build, and deliver a heliostat in a relatively short period of time (approximately one year), with a very limited budget.**
- **initial plan under the USISTF program was to build the McDonnell Douglas 57 m2 heliostat, but for a number of reasons, we decided on a significantly smaller heliostat.**

- **From the optical analysis, it was determined that smaller heliostats were needed because conventional, large heliostats (greater than 40 to 50 square meters), had substantial off-axis aberration losses for this application, and thus required a significantly greater total reflector surface area.**
- **heliostat size that provided the minimum total area and expected cost was determined to be in the range of approximately 10 to 20 square meters, based in part on the need for a high concentration ratio at the receiver and a moderately sized tower reflector.**
- **Boeing, working with HiTech Services, Inc., developed an elevation/azimuth heliostat that can be sized between approximately 9 and 21 m2, with readily available components, with the same basic drive unit.**
- **We selected a 9.2 m2 heliostat area, because commercially available, low cost glass could be procured in sizes of approximately 5' by 5'; four of these formed the reflector.**

Heliostat Design (Cont'd)

- **There were additional reasons for selecting this size**
  - **departs from the trend over the last two decades to build larger helostats, even as large as 100 to 150 m2.**
  - **advantages in terms of optical performance, cost, and development time.**
  - **optical performance is significantly better because the off axis aberration is less, which is especially important for our system with its relatively small receivers and high flux intensity requirements.**
  - **wind profile produces less load, since the wind speed is lower near the ground.**
  - **This increases the safety factor of the drive unit or allows for lower design loads, for the smaller heliostats.**
  - **practical and relatively inexpensive to modify fences used for plant security to partially block the wind, further improving safety factor, reducing design load, and minimizing gust effects that degrade tracking performance.**

- **drive unit did not require custom parts or a custom design, as would have been required for the larger heliostat, which would have had serious schedule and cost impacts.**

<u>Heliostat Design (Cont'd)</u>

- **larger production number for a given total field reflector area means that the Manufacturing Learning Curve effect should reduce production costs more quickly than with a fewer number of larger heliostats, especially since few custom components are required for the smaller heliostat.**
- **learning curve effect provides a substantial theoretical cost savings. Assuming that the costs per unit area of the small and large heliostat are equal, the cost reduction was approximately 10 to 20%, compared to heliostats of the order of 60 to 100 m2.**
- **Assuming a 90% to 95% learning curve, the theoretical cost could be reduced by an additional 25% to 50%.**
- **our marketing studies showed that developing countries were projected to have the fastest growth of power in general, and renewable power in particular.**
- **anticipate having heliostat manufacturing plants in these countries, to minimize import duties, taxes, customs issues, and transportation costs.**
- **Therefore, we needed a design that could be built in these countries, possibly even in relatively remote areas with limited access by road, with minimal capital investment.**
- **The smaller heliostat allowed use of lower cost tooling and a smaller, lower cost factory.**
- **Replicating the tooling, such as for the reflector tooling surfaces, would provide an additional benefit in terms of the Manufacturing Learning Curve effect, since this reduces the tooling costs more rapidly than with a fewer number of larger tools.**
- **It is also easier to handle the smaller heliostat for fabrication, shipping, installation, remove/replace, and certain types of maintenance (i.e., cleaning, which requires less complex and costly cleaning equipment for small heliostats).**
- **Some of this cost savings may be offset by maintenance operations that are relatively independent of size, since there are a larger number of heliostats, but maintenance costs occur**

throughout the life of the plant, and therefore their net present value is low relative to up-front capital costs.

Heliostat Design (Cont'd)

- **Overall, it was our conclusion that the smaller heliostat was more cost effective and appropriate for our application and for early market entry, especially for developing countries.**

- **Developed an innovative drive unit**
  - **zero backlash within the operational wind speed**
  - **ability to absorb shock loads that would be imposed by high wind gusts.**
  - **built of common, off–the-shelf parts, easily obtained at low cost from many manufacturers.**
  - **cost uncertainty for later production is reduced because the majority of the components are already in production and therefore the initial unit is closer in cost to the mass production units,.**
  - **Only the housing is custom, and this is a welded case with minimal machining.**

- **Built and delivered one complete 9.2m2 heliostat to Israel.**
- **second unit has been built and tested, except for the second reflector, which is a modified version of the first design.**
- **Two open loop heliostat controllers have been built and tested and each has been integrated to the heliostat to conduct tracking tests.**
- **The software includes the basic ephemeris data needed for open loop control and provisions for correcting the biases associated with error sources to eliminate drift.**
- **Lower cost versions of the controller are foreseen based on the rapid reduction in motor controller and digital signal processor costs, and improvements in processor performance.**

Boeing 9.2 M2 Heliostat

Tower/Tower Reflector

- **CONSOLAR program required that a tower reflector be installed at the Weizmann Institute.**
- **USISTF program required the design of a tower for a commercial/demonstration plant and the design, development, and test of a tower reflector facet and support structure.**
- **For CONSOLAR, Ormat designed and constructed the tower reflector.**
    - **high tensile strength chemically treated glass facets**
    - **passively cooled.**
    - **installed on the solar tower at Weizmann's Solar Facility.**
    - **access platform is provided for installation and maintenance.**
    - **Weizmann and Ormat adjusted the facets to meet the required optical performance and flux distribution at the CPC aperture.**

Tower/Tower Reflector (Cont'd)

Tower

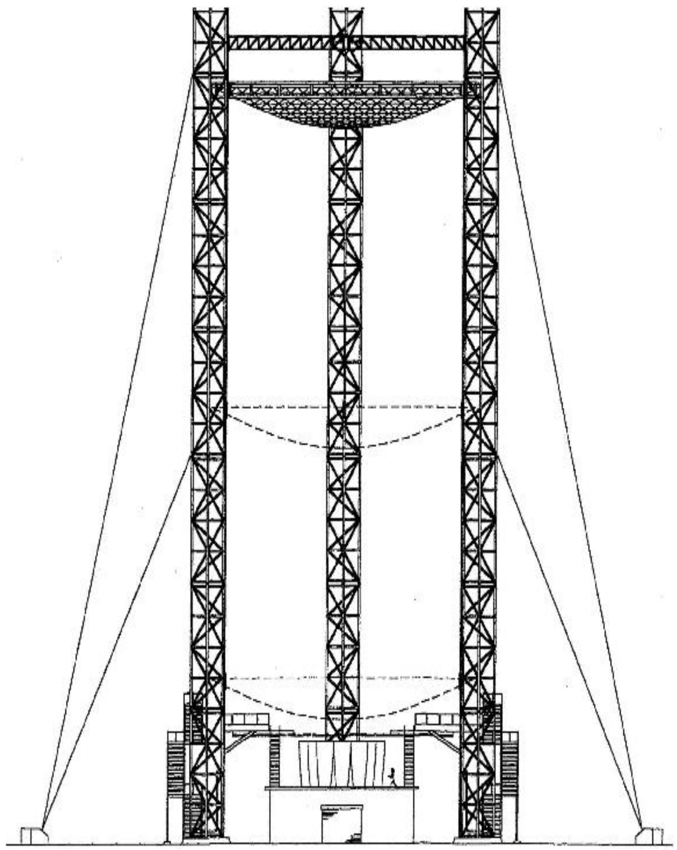
- **USISTF tower height and tower reflector size and shape based on the optical analyses conducted by Weizmann, and further analyzed by HiTek with the SolarSim code.**

- **Guyed three-leg design selected based on trade study of various types of towers**
- **lower cost and better stability than free-standing single towers and could be erected with relative ease.**
- **70 meters height for the 10 Megawatt thermal field.**
- **design allows the option of raising and lowering the tower reflector on rails.**
- **Lowering the tower reflector reduces the loads under severe wind conditions and thus the tower reflector and tower can be designed for a lower load bearing condition to decrease cost.**
- **raising and lowering the tower reflector facilitates installation and maintenance.**
    - **tower reflector can be assembled at the tower base and erected without the need for large cranes, which would pose difficulties and incur high costs in remote areas.**
    - **The tower reflector can be lowered for cleaning, inspection, adjustment, etc., which is far more convenient than performing these tasks at the top of the tower.**
    - **Allows us of Digital Image Radiometer for accurate facet alignment.**

Tower Reflector/Facets

- **400 square meter tower reflector with approximately 1800 facets (equilateral triangles 30" on a side)**
- **tower reflector structure is a Geometrica, Inc. geodesic dome design**
- **offers low cost, ease of assembly, and has been used throughout the world for extremely large domed enclosures, up to hundreds of meters in diameter, subjected to high wind loads.**
- **Virtually any shape can be obtained with their FreeDome design,**
- **assembly of large structures with the Geometrica design is surprisingly easy and fast using low cost labor and hand tools (Video available demonstrating assembly of very large structures)**
- **reflector facets designed to be cooled, with heat recovery**
    - **necessary to avoid excessive temperature and stress due to the incident flux (peak of 60 suns)**
- **measurements of the reflector surface show less than 0.6 mr standard deviation for an early prototype, and thus flux distribution errors due to this slope error will be negligible at the CPC aperture.**

Tower/Tower Reflector



Geometrica Geodesic Dome Support Structure Test Article, with Tower Reflector Facet

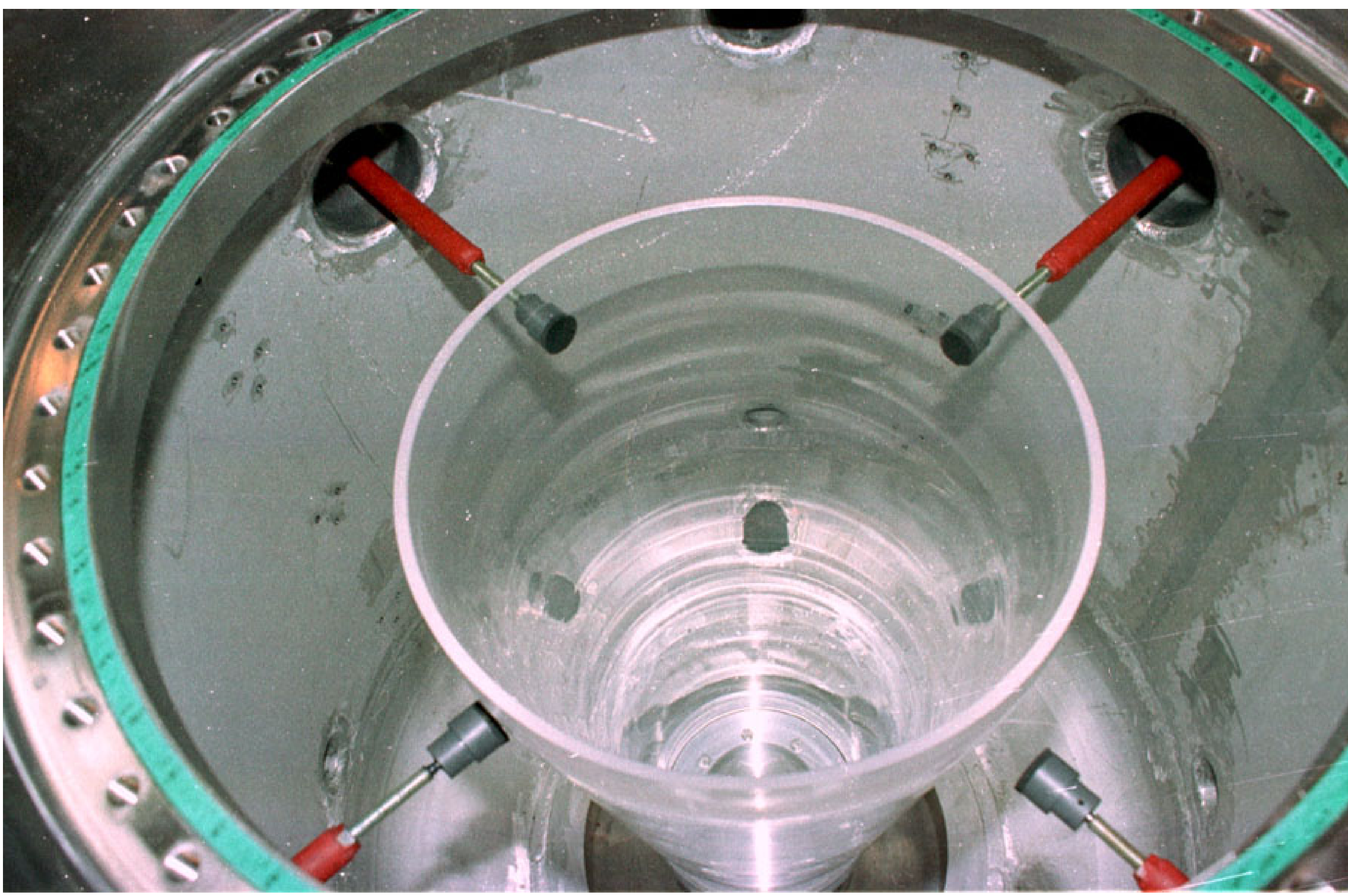
Tower Reflector Facet

Receiver

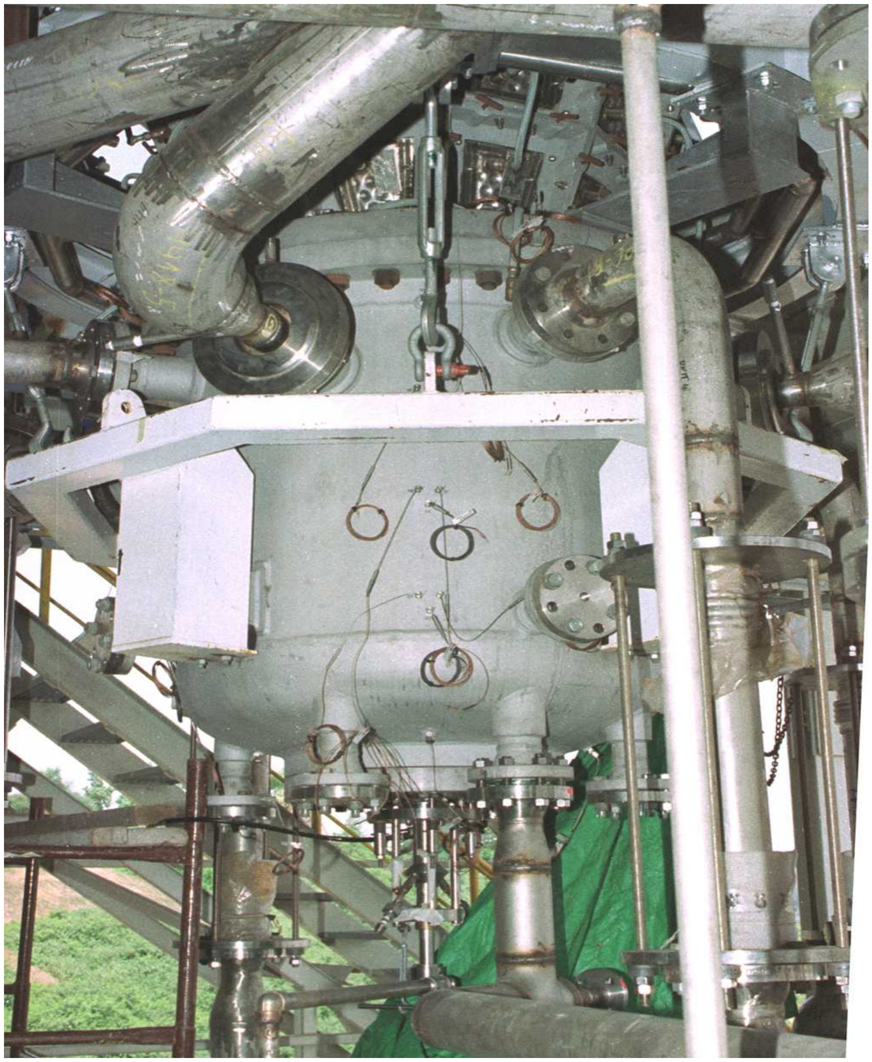
- **Patented DIAPR design, sized for approximately 0.5 to 1 Megawatt thermal input, with a demonstrated capability to withstand peak temperatures as high as 1700 C, with incident flux intensities of the order of 2000 to over 10000 suns.**
- **50 Kw thermal design tested for several hundred hours at concentrations as high as 4-5 Mw /square meter**
- **scaled-up to the larger, demonstration/commercial plant size (quartz window is 44 cm)**
- **operating pressure 20 atmospheres, with flow rates of the order of 1.5 to 3 kg/sec or higher, and air exit air temperatures of the order of 800 to 1400 C, depending on conditions and the design requirements.**
- **no tensile stresses; only compressive stresses are present in the window, and quartz in compression is stronger than steel.**

- **directly irradiated solar absorber is composed of a matrix of ceramic pin heat exchange elements (nicknamed *Porcupine*) that have been shown to endure very high concentrated solar flux, roughly five times that of other volumetric absorbers, such as foam and honeycomb matrices.**
- **Under similar test conditions, it has been shown to yield twice the power output of these alternative volumetric approaches.**
- **highly resistant to the development of thermal stresses, since the pin elements are free to expand and contract.**
- **no degradation after hundreds of hours of tests at receiver element temperatures of the order of 1000 to 1700 C and with temperature gradients of several hundred degrees C per centimeter.**
- **basic elements of the receiver are relatively low cost, since the high temperature elements are composed of ceramic materials that are not exposed to high stresses.**

View of Receiver Window During Installation



View of Receiver Installed at Weizmann Institute of Science

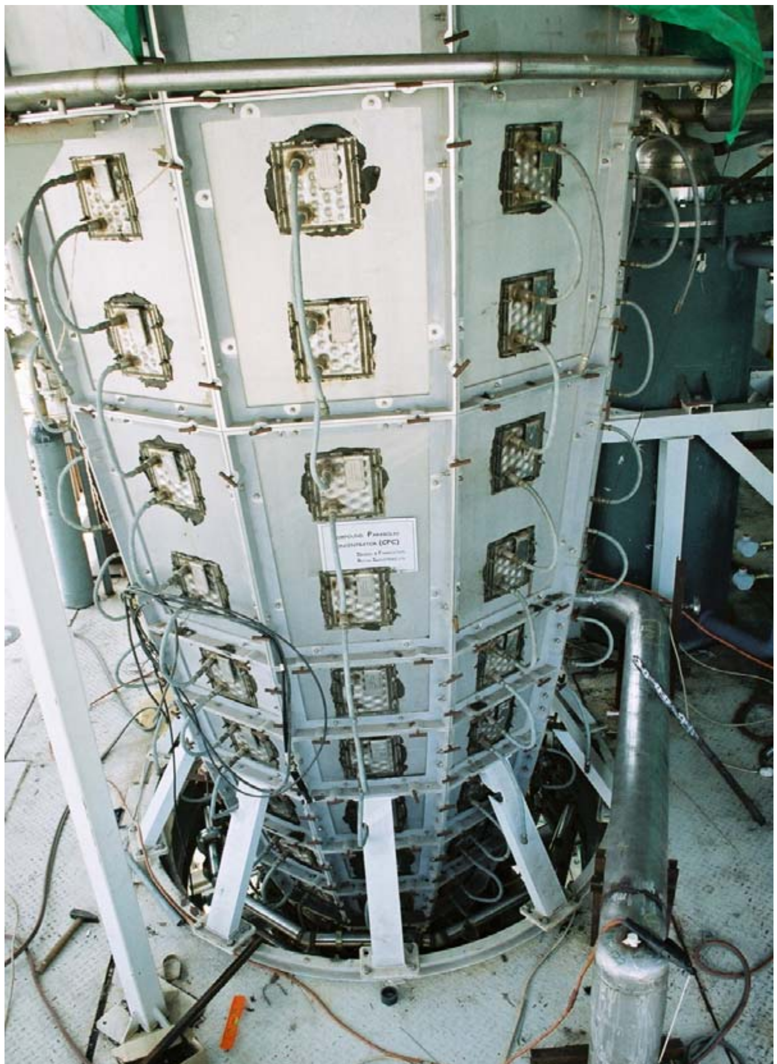


Compound Parabolic Concentrator (CPC)

- **CPC designed for the specific conditions at the Weizmann Solar Facility**
- **Different size and shape would be used for Noor al Salaam, but design features are similar**
- **Parabolic shape is approximated by a series of flat facets.**
- **Reflectors bonded to an aluminum support, which is cooled to minimize tensile stresses in the glass**

- **Heat exchangers are seen as dimpled plates attached to the middle of each facet.**
- **There is a specially designed transition between the CPC and the receiver inlet aperture; this too is cooled.**

Compound Parabolic Concentrator Installed at Weizmann Institute of Science



Power Conversion Unit

- **Gas turbine, with a power output of approximately 250 Kwe.**
- **A number of turbine system modifications were made by Ormat.**

- **he turbine combustor has been modified to accommodate the combination of flow from the solar receivers and for simultaneous combustion of natural gas.**
- **The turbine is coupled to a generator.**
- **Ancillary hardware was designed, fabricated, and integrated, such as the gear drive coupling the turbine and generator, the oil cooler, skid, etc.**
- **The turbine generator was successfully used in natural gas powered tests in mid-2000 to verify that the system is easily synchronized to the electrical grid.**

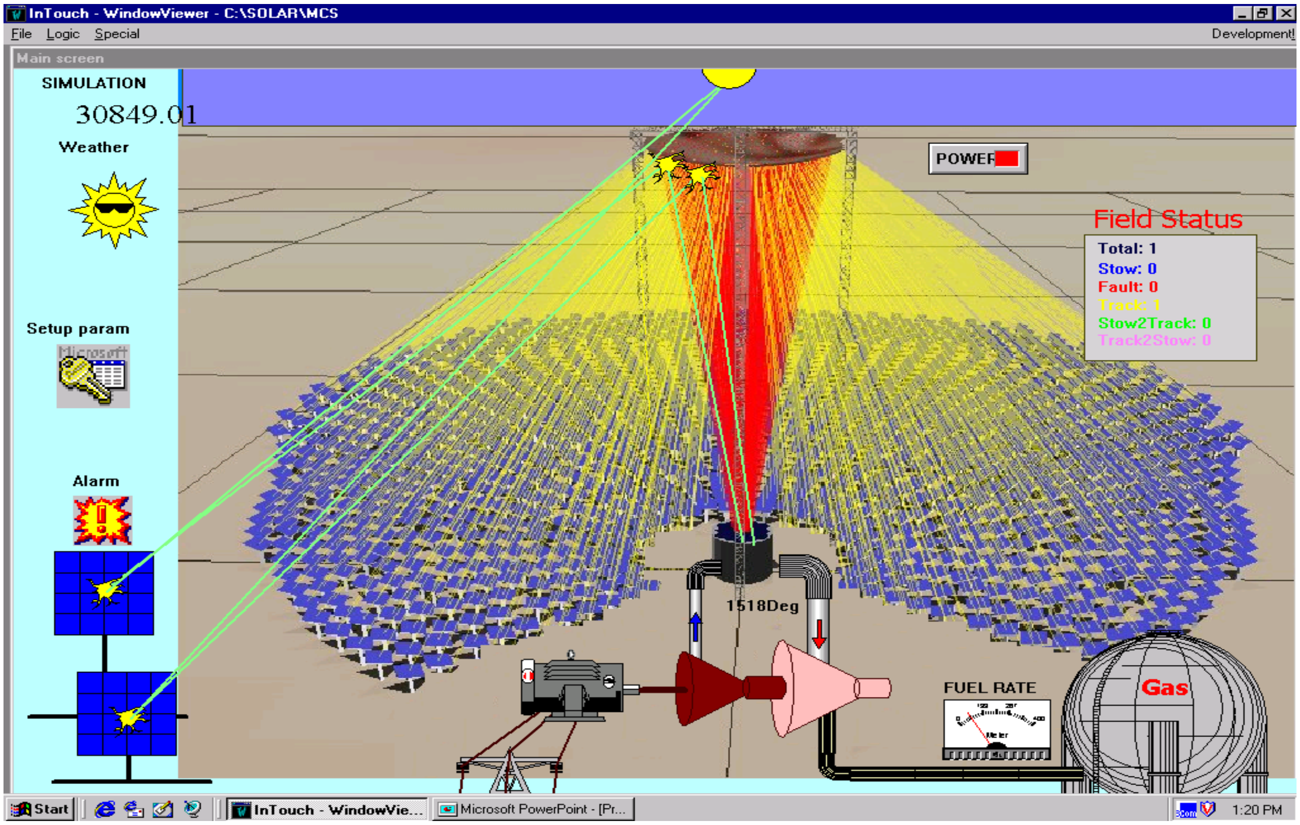
View of Power Conversion Unit (Allison Turbine, Generator,

and Ancillary Hardware)

Master Control System (MCS)

- **For the USISTF program, there were two main objectives for the MCS:**
  - **develop a system for data acquisition, analysis, and archiving for the tests at the Weizmann Institute, and**
  - **develop requirements for the MCS for a demonstration/commercial plant. The MCS data system was developed to the point of being ready for integration with the system hardware. An example of an MCS screen that allows**

for access by "point and click" on a subsystem for more detailed data review is shown below.



<u>Integrated Subsystem Tests</u>

The basic objective of the CONSOLAR and USISTF programs was to validate the overall system, especially the receiver subsystem and its interface to the turbine, with the following sequence of tests:

- **Receiver Test: As part of the CONSOLAR program cold flow check-out tests were conducted, followed by progressively higher temperature and pressure conditions with solar radiation.**
- **Turbine Test: Plans were made to modify the ducting and interface to the turbine to conduct the power generation tests. This test would then complete the integrated receiver/turbine tests for the USISTF program. However, funding limitations have kept this integrated test from being conducted.**
- **A view of the facility that houses the CPC, Receiver, and Power Conversion Unit is shown below.**

View of Test Facility at Weizmann Institute of Science

Conclusion

- **Completed a prototype heliostat design**
- **Developed a practical approach for the tower and tower reflector**
- **Constructed and tested a novel geodesic dome-type structure**
- **Prototype tower reflector facet has been designed and tested, and shown to have good optical characteristics**
- **Various modifications have been made to the turbine to make it suitable for hybrid solar/gas use.**
- **All power conversion unit ancillary hardware has been built and installed, including the piping, valves, instrumentation, control system, and recuperators.**
- **Both the high temperature and peripheral heaters have been built, installed, and tested at the Weizmann Institute of Science.**
- **The turbine generator unit has been tested on grid, but not yet tested in the hybrid mode.**
- **One of the major milestones of the USISTF program was achieved with Egypt's decision to pursue the Noor Al Salam project.**
- **Our plan is to move this Tri-Lateral project between Egypt, Israel, and the U.S. into turn-key plant construction Phase 2 after completing the Phase 1 effort**
- **This will involve early selection of a U.S. industrial partner to serve as the prime contractor.**

UAH-USISTF-Noor Al Salaam Technology Development

- **Pre-Production Heliostat Reflector Fabrication (Kevin Losser, Kevin Nichols, Ben Bramblett)**
    - **Fabricated 10 Fiberglass Channels and Supporting Box Caps**
    - **Developed Process for "Building In" Compressive Loads to Strengthen the Glass**
        - **Lower cost than tempered/chemically treated glass**
        - **Intrinsic part of the fabrication process**
    - **Developed Approach for Prevention of Silver Oxidation and Corrosion**
        - **Tested under outdoor conditions for over 6 years, with no penetration**
    - **In process of developing edge bonding between low cost polyester and polyurethane**
        - **Resin Industry has no experience in this.**
        - **New approaches being developed now**
- **Tower Reflector Facet (Dr. Marlow Moser, Mike Boland)**
    - **Conducted thermal management tests, verifying cooling under realistic conditions, with minimal pressure drop through the facet**
    - **Long term exposure tests verify facet integrity**
- **Heliostat Drive Unit (Dr. Marlow Moser, Steve Collins, Brad Johnson, Matthew Lynn, other undergraduates)**
    - **Conducted various drive unit performance tests**
    - **Developed design improvements for low cost manufacturing**
    - **HiTek Services has developed a "Mark 2" version, and produced approximately two dozen**
    - **Conducted torque tests resulting in recommendation for reducing eccentricity of the sprockets**
- **Economic Evaluation of Waste Heat and Spillage Collector Co-Generation (Mike Boland)**
    - **Thermal Analysis shows that an additional 15 to 20% of the solar energy can be collected at the Tower Reflector, CPC, and Spillage Collector surrounding the receivers, with a substantial economic benefit, including use in Organic Rankine Cycle Turbines (e.g., Ormat's)**

UAH-USISTF-Noor Al Salaam Technology Development (Cont'd)

- **Design Tools**
  - **System Flow Analysis (ABZ Technologies "Crane Corporation Code") – Kevin Nichols, Ben Bramblett**
    - **Developed detailed flow schematic sand determined the flow losses for series flow, series/parallel flow, and full parallel flow**
    - **Analysis showed significant overall system performance improvement with full parallel flow, with higher pressure ratio in the turbine, less heat loss, and ability to operate turbine at night, without any additional loss by flow through solar flow loop.**
  - **Optical Analysis (Steve Kusek, HiTek Services, Inc. SolarSim Code)**
    - **Unique Tool, with only known capability to conduct animated graphics ray tracing, for detailed analysis and observation of the heliostat field at any time of the day, any location on the earth, under any solar conditions.**
    - **Extremely useful approach for determining the flux distribution on the tower reflector, receiver, and for off-nominal conditions**
    - **Important capability for assessing safe operation of the plant (e.g., startup, shutdown, emergency response, etc.)**
  - **RCELL (Prof. Lorin Vant Hull, University of Houston, and Tietronics)**
    - **Legacy code used to develop Solar 1 and Solar 2**
    - **Only known full optimization code for detailed heliostat field layout, integrated with receiver, to maximize plant overall cost effectiveness**
    - **Planned modernization as part of on-going NAS effort under DOE Grant to UAH**

UAH-USISTF-Noor Al Salaam Research and Development

- **Related Work at UAH Propulsion Research Center and Department of Mechanical and Aerospace Engineering (1970s to the Present)**
    - **Solar Thermal Test Bed Developed During the 1970s (Industrial and Residential)**

    - **Developed the Solar Test Facility**
        - **Heliostat**
        - **Dish Concentrator**
        - **Vacuum Chamber**

    - **Solar Thermal Rocket Research**

    - **High Temperature Optical Properties of Carbon-Carbon Exposed to Concentrated Solar Irradiation**

    - **Solid State Heat Pipe and Ultra Low Thermal Conductivity Integrated Structures**

- **Related Work at NASA Marshall Space Flight Center in Solar Energy**
        - **Extensive residential and Industrial Research Program Conducted in the 1970s and 1980s**

        - **Operational Solar Heliostat and Concentrator**

Extensive solar Thermal rocket Design, Analysis, and Test Conducted for over 20 years

Overview of Noor Al Salaam Program

TECHNICAL SUMMARY

UAH Areas of Responsibility-DOE Grant

James B. Blackmon
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville

Noor al Salaam General Requirements and System Architecture

- **High Level Requirements**

- **Heliostat Subsystem**
    - **General**
    - **Reflector**
    - **Drive Unit**
    - **Foundation/Pedestal**
- **Tower Subsystem Design**
    - **Tower Design**
    - **Tower Reflector Structure Design**
    - **Tower Reflector Facet Design**
    - **Test Results/Component Development**

- **Ancillary Hardware**
    - **Spillage Collector/Target/Enclosure**
    - **Thermal Management/Waste Heat Recovery System**

- **DIR Beam Characterization System**

Draft High Level Requirements:

1. **Provide substantial power from gas turbine burning natural gas, with solar supplement**

2. **Provide hybrid solar and gas power under normal operational conditions**

3. **Provide option of producing power during night-time and inclement weather conditions, using natural gas (or alternatives) and possibly future thermal storage (advanced technology);**

4. **Serve as both a power plant and as a research and development facility to evaluate system performance;**

5. **Select turbine with potential for combined cycle, if practical;**

6. **Offer versatility in plant design to allow for adding advanced technologies for evaluation.**

Basic characteristics:

1. **Per the SOW, plant architecture is based on USISTF program:**

    a. **Beam down optics (tower mounted reflector)**

    b. **Volumetric air receiver with secondary optics at the base of the tower**

    c. **Spillage collector, waste heat recovery capability**

d. **Field of heliostats sized to provide high optical quality and low off-axis aberration**

2. **Reflected energy from the heliostat field of 10 Megawatts thermal (or greater) at solar noon on the Summer Solstice for the solar conditions at Zaafarana.**

3. **Optical system will have the concentration ratio, efficiency, configuration, and size appropriate for commercial solar hybrid systems in this size range.**

4. **Receiver will be sized such that it can accommodate larger systems by addition of modules.**

5. **Flow path will be configured for versatile verification testing of the receiver, as well as optimum system life cycle cost performance.**

Noor al Salam General Requirements and System Architecture

Basic requirements (Continued):

6. **A 10 to 20 Mwe simple gas turbine will be used, with the ability to be interfaced to a Rankine bottoming cycle (steam and/or organic) at some later time to operate as a Combined Cycle Gas Turbine.**

7. **Turbine will have external gas generator to simplify integration of the solar heated air.**

8. **System will incorporate design flexibility to later add promising near term technology options such as:**

a. **Spillage thermal energy collection (for other ancillary uses);**
b. **Larger tower reflector area (of the order of 10% to 15%);**
c. **Additional heliostats (of the order of 10% to 15% additional area);**
d. **Steam injection to the turbine;**
e. **Absorption cooling for turbine inlet air temperature control; and**
f. **Such other subsystems as shall provide for potential improvements by use of additional hardware or revisions to the operation.**

9. **System versatility accommodates other advanced technologies such as:**

   a. **high temperature phase change thermal storage**
   b. **concentrating photovoltaics or solar thermal collectors for spillage collection;**
   c. **biogas use with the turbine;**
   d. **synthetic fuel formation using solar energy;**
   e. **expert system control of the plant with minimal human operator requirements;**
   f. **expert system communication to remote operators**
   g. **real time performance monitoring and access to detailed subsystem data**
   h. **internet access for access by researchers throughout the world;**
   i. **advanced heat exchangers;**
   j. **advanced technology receivers;**
   k. **Organic Rankine systems for waste hear recovery and power production: and**
   l. **ancillary applications such as desalination and water purification using waste heat.**

General Note

m. **The Noor al Salaam plant would be the largest solar research and power plant facility for high concentration technologies in the world**
n. **Much of the USISTF design and related technology is patented, thus affording competitive advantage to participants**

Noor al Salam General Requirements and System Architecture

Purpose of NAS system versatility is to:

- **Provide Egypt, the commercial partners, and solar researchers throughout the world with a first class facility for advancing the state of the art, while helping to meet Egypt's goals for renewable power production.**

- **Recommendation - Noor al Salaam to be designed such that it does not preclude eventual use of additional capabilities, such as:**

  - **the building housing the turbine would be located, sized, and designed to accommodate the bottoming cycle;**

  - **sufficient space and access would be provided for a phase change thermal storage system;**

  - **the office building would be over-sized and configured to allow for growth in number of personnel;**

  - **options for ducting the compressor outlet through the receivers would be provided, such that partial or full parallel flow can be used;**

  - **tower design would allow for positioning the tower reflector at various heights, with additional reflector facets, ability to cant reflector to reflect concentrated sunlight onto test areas adjacent to the CPC aperture;**

Noor al Salam General Requirements and System Architecture

- **tower design would allow for additional hardware to be mounted at varying positions (reflectors, receivers, etc.);**

- **design would include ability to vary the flux distribution at the CPC aperture;**

- **heliostat field would be configured such that additional heliostats can be added;**

- **CPC aperture area would be configured so that the cover could be used to not only protect the CPC/receivers, but also serve as a target for one or more beams, for optical beam characterization purposes;**

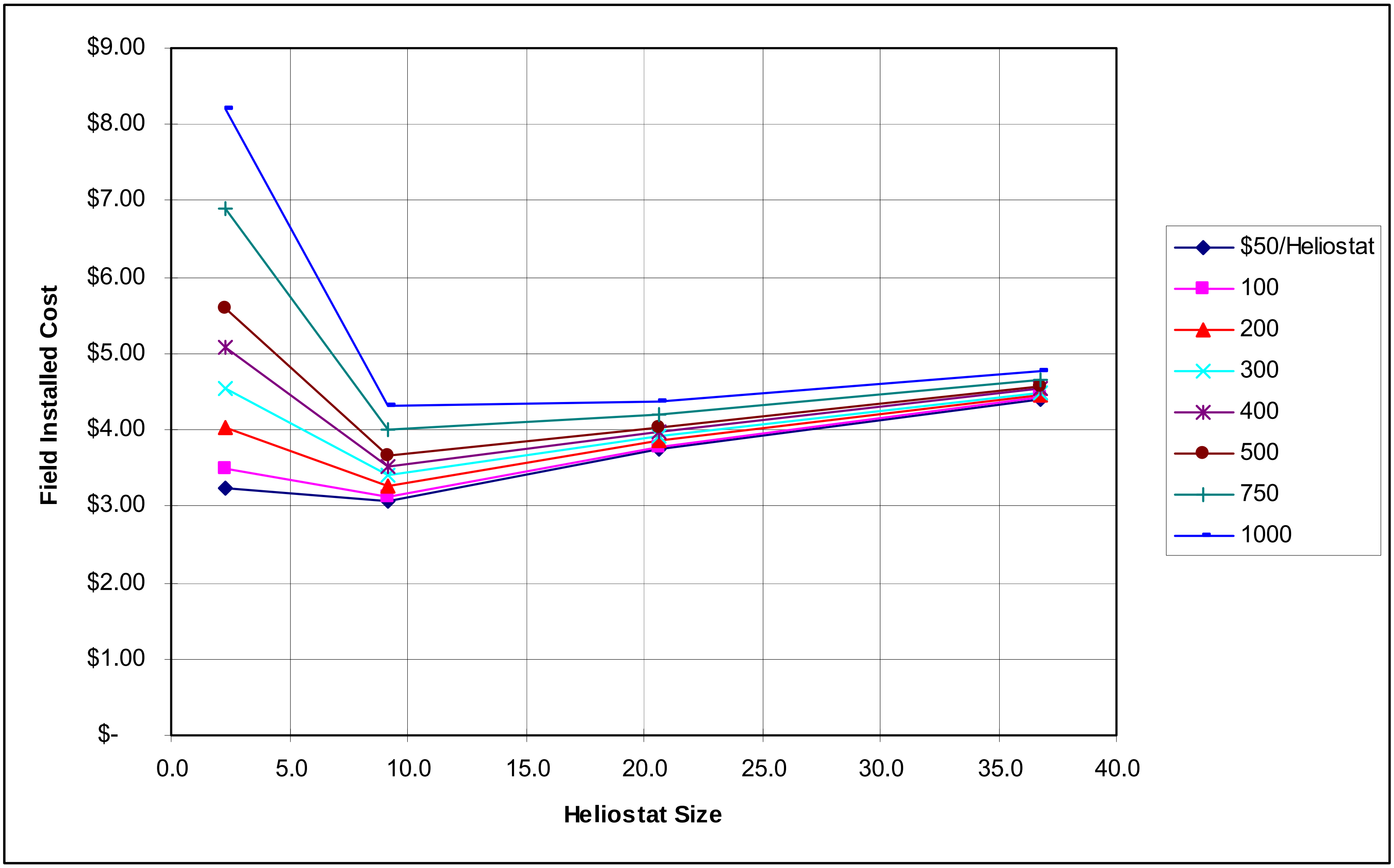
- **area beneath the tower would be sized to accommodate additional subsystems and components.**

Heliostat Design

General

Design Requirements:
(Based on over 30 years of similar requirements for various DOE programs)

- **Operate (Track) during wind speeds of 35 mph**
- **Operate (slew) during wind speeds of up to 50 mph**
- **Position heliostat into stow during wind speeds above 50 mph**
- **Support wind loads generated at 90 mph**
- **Obtain and maintain positional accuracy of 1.5 mRad in winds up to 10mph and 2.0 mRad in winds up to 35 mph**
- **Be self-locking under back-driving conditions, even with motor removed for maintenance**
- **Sustain a 30 year life under outdoor conditions with low cost maintenance**
- **Optimized to provide high optical efficiency and minimum overall cost of the subsystems**


$9.00
$8.00
$7.00
$6.00
$5.00
$4.00
$3.00
$2.00
$1.00
$-
Field Installed Cost
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Heliostat Size
$50/Heliostat
100
200
300
400
500
750
1000

Heliostat Design

Drive Unit

Manufacturability Requirements:
(Based on low cost manufacturing in Egypt with minimum investment in special tools, facilities, etc.)

- **Majority of components available off the shelf**
- **Minimum or no custom components required**
- **Housing formed from welded plate stock**
- **Easily assembled with low-cost manual labor**
- **Minimal special tooling investment required**
- **Fabricated with standard machine shop tools**
    - **(Shears, breaks, mills, lathes, etc.)**
- **Production in Egypt of essentially entire azimuth drive unit**
- **Off the shelf procurement of elevation drive unit (e.g., tracking TV Dish actuator)**

Heliostat Design (Cont'd)

<u>Drive Unit</u>

Design Features:

- **Compact dual shaft multistage gear reduction**
- **High efficiency chain/sprocket drive**
- **Easily assembled and repaired**
- **Fail operational mode with dual output drive chain**
- **Self – locking in elevation and azimuth**
- **Low cost, off the shelf, commercially available chains, sprockets, bearings, gear motor**
- **Proven hermetic seal under long term exposure (Alabama, five years, rain, temperature extremes, etc.)**
- **Patented design protects commercial partners and enhances competitive position.**

Heliostat Design (Cont'd)

<u>Reflector</u>

Design Requirements:

- **Similar to Drive Unit Requirements and Typical DOE Requirements**

Manufacturability Requirements:

- **Minimum Investment in Tooling Required**
- **Hand lay-up of fiberglass with semi-skilled labor**
- **Five curved reflector tools with one reflector per day produce the needed number of heliostats in approximately one year**
- **Fabrication proven with first reflector; additional work in progress on second, improved reflector**

<u>Reflector</u>

Design Features:

- **Very high compressive loads "built-in" to the glass to resist breakage**
- **Sealed edges using combination of low cost resins**
- **High optical efficiency with very low off-axis aberration achieved by:**
  - **use of five radii of curvature and**
  - **approximately 10 m^2 area heliostat for high optical performance**

Heliostat Design (Cont’d)

Foundation/Pedestal

Design Requirements:

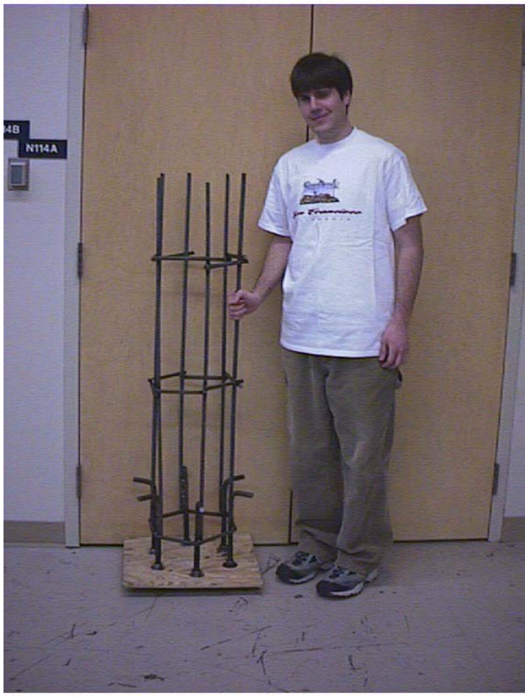
- **Similar to Drive Unit Requirements and Typical DOE Requirements**

Manufacturability Requirements:

- **Minimum Investment in Tooling Required**
- **Pedestal Fabrication from Commercially Available Steel Pipe, Welded Flange**
- **Foundation Formed from Rebar Cage, J-Bolts, Concrete**
- **Augered Hole Assumed Appropriate for Zaafarana (to be verified, depends on type of soil, bearing strength, etc.)**

Design Features:

- **Rebar cage easily formed with low-cost labor (cut pieces of rebar hand assembled and arc welded)**
- **Tractor Mounted Auger easily forms hole**
- **Four foundations formed and installed (Three in Alabama, one at Weizmann Institute)**
- **Pedestal with Drive Unit Quickly Erectable by Two – Three Men without Special Assembly Equipment**


N114A

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements:

•Environmental conditions include winds and gusts, temperature extremes, rain, snow, hail, air pollutants, animal and insect exposure, and earthquake conditions

- **Wind velocities: $V_h = V(10m) \times [H(h)/H(10m)]^{0.15}$•Operational: 0 - 50 mph (at 68 m height) - 35 mph at 10m**
- **Survival: 120 mph (at 68m height) - 90mph at 10m**
- **Sandstorm environment**
- **Air temperature range: -30C to 55C**
- **Rain: Max for 24 hours: 75mm**
- **Ice: Freezing rain may deposit ice in a layer up to 50mm thick**
- **Hail: 25mm diameter, e.g.=0.9, 20m/s any direction**
- **Snow: Max 24 hour rate: 0.3m (1 ft); max loading 250Pa (5 lbs/ft^2)**
- **Earthquake: seismic zone: TBD**
- **Corrosive environments: TBD**

•Solar Irradiance:

- **Peak incident flux from heliostats: TBD (30-50 kW/m^2 , steady state)**
- **Backside of reflector exposed to 1 sun**

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements (Continued):

• Reflectivity

- **Under normal operational usage with periodic cleaning, the average reflectivity shall be at least TBD. Clean new facet reflectivity should exceed TBD within a 1-mrad cone integrated over the incident spectrum (Air Mass 1.5). Surface degradation rate shall be minimized consistent with a 30 year mirror life**

• Surface waviness shall be < TBD mrad (expect less than 1 mr, based on prototype performance)
• Reflective Surface Deflections under operational wind load: Facets and their supports shall be designed to prevent reflective surface deflections from exceeding TBD mrad

- **Alignment:**
  - **Digital Image Radiometer Video System, Mounted on Tower, with Backside Flat Glass Reflectors on Facets**

- **Thermal Management**
  - **Cooling of Tower Reflector Facets with Option for Waste Heat Recovery and Sale**

- **Assembly**
  - **Easily assembled in remote areas without special equipment**

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements (Continued):

Manufacturability Requirements:

- **Fabrication with Low Cost ToolingFabrication from Commercially Available Stock High Optical Performance Achievable Without High Cost Tooling or Processing**

Design Characteristics:

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements (Continued):

- **Welded Stainless Steel FacetsGlass Bonded to Stainless Steel Heat Exchanger Heat Recovery Offers Option for Offsetting Tower Cost with Sale of Power (Process Heat, Organic Rankine Cycle, etc.)Successfully Tested at High Heat Flux and Exposed in the Field for FourYearsEasily Aligned to Meet Required Flux Distribution at**

the Aperture of the CPCs (Similar to Proven 25 Kwe Dish Stirling

Concentrator with Patented Digital Image Radiometer Alignment System)

Tower Support Structure and Adjustable Cant Angle Facet (Covered with Black Plastic to Maximize Solar Heating Effects)

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements (Continued):

- **Ancillary Hardware**
  - **Spillage Collector/Waste Heat Recovery/Target/Enclosure:**
  - **A movable pair of panels can be moved across the CPC aperture to**
    protect the CPCs and Receivers from rain, dust, debris, etc.

- **This enclosure also serves as a Digital Image Radiometer Beam Characterization System (BCS) target.**

- **Waste Heat Recovery System:**

    - **The tower reflector facets, CPCs, and the Spillage Collector/Target Enclosure are cooled with a water/ethylene glycol mixture.**

    - **The heat recovered can be used in an Organic Rankine Cycle to produce additional power, or**

    - **used with heat exchangers to provide process heat, at approximately 80 to 120C or higher, depending on detailed design conditions.**

DIGITAL IMAGE RADIOMETER (DIR) BEAM CHARACTERIZATION AND ALIGNMENT SYSTEM

- **DIR is a patented method for aligning mirrors and determining the flux distribution of solar radiation incident on a target**

- **DIR hardware includes a modified video camera, lens, digitizer, computer, and pinpoint light source panel.**

- **Camera and light source panel is mounted above the tower reflector. Reflected light from the mirrors on the back of each panel is analyzed to determine the angular error of each facet, and the corrections required.**

- **DIR is a proven system used to rapidly align the McDonnell Douglas/SES Dish Concentrator to within +- 0.1 milliradians. Higher resolution CCD cameras and smaller LED high intensity light sources now available will further improve accuracy, leading to alignment error measurements easily less than +-0.025 milliradians. However, _-0.1 milliradians is sufficient for most solar power optical systems.**



NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

- **Noor al Salam - Phase 1 was developed as a Tri-Lateral effort between principles in Egypt, Israel, and the U.S. to develop a System Definition for a 10 to 20 Megawatt Hybrid Solar Central Receiver.**

- **Noor Al Salam Phase 1 System Definition Grant participants:**

  University of Alabama in Huntsville (prime contractor)
  Ormat Industries, Ltd.,
  Rotem Industries, Ltd.,
  Weizmann Institute of Science,
  Egyptian New and Renewable Energy Authority (NREA)

- **Participants met at Boeing-Huntsville, August 3, 2000 and agreed on scope and roles; proposal was completed for Phase 1 effort in December 2000.**

- **Participants recognized:**

  - **Extensive collaboration needed, as a valued part of the original purpose "promoting peace and economic development in the region"**

  - **Program would likely face difficulties above and beyond the control of the Participants**

Therefore, program was organized such that it could continue, even if such difficulties occurred.

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

- **Originally, Boeing would have conducted the Phase 1 System Definition and Phase 2 plant construction and manufacturing, with other Participants as sub-contractors**

- **With Boeing's decision to discontinue its participation (early in 2001), UAH became the prime contractor for Phase 1 System Definition**

- **Grant was awarded to UAH in 2002**

- **Events occurred that posed impediments to conducting the program in complete accordance with the original Grant**

  - **Non Disclosure Agreements were not completed allowing UAH access to certain data**
  - **Information returned to Boeing and Ormat**
  - **Boeing Intellectual Property returned to UAH with a Proprietary Information Agreement (PIA)**

- **These events allowed only a part of the program to be conducted, primarily involving:**

  - **Effort to Seek, Evaluate, and Recommend Industrial Participant to replace Boeing**
  - **Continuation of certain UAH technology development tasks (heliostat, tower reflector, analysis, etc.)**

- **Grant was revised in order to deal with these factors, as discussed at length with DOE (April 1, 2003).**

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

Selected tasks from the original Grant, plus the effort to bring a Prime Contractor on board, were recommended and approved by DOE:

First:

- **Select and transition responsibility for managing the full, Tri-Lateral Noor Al Salam program from UAH to an Industrial Participant (Prime Contractor) in Phase 1.**
    - **Hold meetings with representatives from NREA, Weizmann, USISTF, and DOE to initiate NAS plans**
    - **Industrial Participant would serve as prime contractor on the program and would lead Phase 2 effort to build the plant in Egypt.**

Second:

- **Complete certain technology development tasks**
    - **Provides background needed for Industrial Participant**
    - **Supports schedule and milestone deliverables for full Tri-Lateral program**
    - **Maintains capability to conduct the technical support tasks**

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

Industrial Participant Selection and Evaluation

- **Request for Information (Draft) was completed and stands ready to be distributed as appropriate**

- **Reviewed by Boeing (Rocketdyne North American, Mike McDowell) and approved for release (no Boeing proprietary information in document)**

- **Contacts made with candidate Industrial Participants, including:**

  Summa Technologies (Ron Hackney)
  Lockheed Missiles and Space Company (Dave Christensen)
  Nexant (Bechtel) (Bill Gould)
  Duke Solar (John Myles)
  Others (Black and Veatch, Fluor Daniel, etc.)

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

UAH Supporting Program Planning and Technology Development Tasks for the resulting ADDENDUM Statement of Work:

System Engineering and Integration - ADDENDUM

Supports System Definition Document.

Formal System Definition Document would be developed by the Industrial Participant in cooperation with NREA and Israeli Participants.

Preliminary System Description - ADDENDUM

Develop preliminary version of overall system description as the baseline for control of subsystem design activities. Based primarily on prior USISTF results.

Preliminary system description would be provided to DOE, and through DOE, to NREA and the Israeli Participants.

Revisions would be incorporated as appropriate.

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

Evaluation of Candidate Industrial Partners - ADDENDUM

UAH Will Seek, Evaluate, and Recommend Industrial Partner to:

1. **provide assistance and/or lead the System Definition Program (Phase 1).**
2. **Acquire funding for Phase 2**
3. **Lead Phase 2.**
4. **Participate with NREA and Israeli Participants early in Phase 1**
5. **Address issues regarding potential vendors, and other policy and procedural issues leading to Phase 2.**

A joint NDA will be required between companies having an interest in considering this opportunity in greater detail with UAH, Ormat, Rotem, the Weizmann Institute of Science, and NREA.

UAH will, as part of this process, receive information and permission from Boeing for release of certain information developed by Boeing under the previous USISTF cost-shared program

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

Evaluation Factors:

1. **The capability and scope that would be provided either as a prime contractor or as a supporting subcontractor, in such areas as civil engineering; architectural and engineering; plant construction; subsystem design, fabrication, and test; Egyptian In-Country manufacturing; plant integration; optical analysis; inspection and checkout; operation; etc.**
2. **Experience in conducting business in the Middle East, especially in Israel and Egypt. As appropriate, a list of past contracts will be requested, with summary descriptions of the scope, duration, purpose, customers, etc.**
3. **Corporate presence in one or both of these countries, including a description of the in-country representatives, offices, plants, manufacturing and/or engineering facilities, relevant on-going contracts with companies or government organizations in one or more of these countries, names and addresses for points of contact, etc.**
4. **Experience in the technologies involved, both at a corporate level and in the assignment of personnel with the appropriate capability and experience. Biographies of key personnel or equivalent experience/capabilities that would be assigned for the Phase 1 and Phase 2 effort would be requested.**
5. **Ability and interest in supporting the establishment of such agreements between the Participants as would be required to conduct the Phase 1 effort and continue this into Phase 2, as well as subsequent commercialization efforts.**
6. **Ability and interest in participating in a planned one-week conference in Cairo or in Huntsville regarding solar power plants and technologies; the conference is likely to be held in 2003; there may also be a pre-meeting in 2003 at which the participation of the industrial partner(s) or candidates would be welcomed.**

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

7. **Ability and interest in providing cost-sharing of the Phase 1 effort, including management support at the appropriate level, other indirect funds, capital equipment, new business development funds, legal and financial analysis support, Independent Research and Development funds, travel funds, etc. The total level of effort that would be committed to Phase 1 to support the System Definition and the development of the System Definition Document, including level and type of cost-sharing, would be an important evaluation factor.**
8. **Ability to conduct on its own, or to secure the Egyptian in-country companies required to conduct, such tasks as civil engineering, architectural and engineering, plant construction, subsystem manufacturing, plant integration, checkout, and operation, etc.**
9. **A major objective of the Phase 1 System Definition is to determine the extent to which Egyptian companies will have the interest and ability to conduct the work required for the Phase 2 plant construction. The means by which this effort will be conducted will be requested.**
10. **Providing the training necessary for Egyptian personnel to operate and maintain the plant is important to its success. The means by which this effort will be conducted will be requested.**
11. **Ability and interest to support the pursuit of funds for Phase 2 from government and private sources is critical. The means by which this effort will be conducted will be requested.**
12. **Ability and interest to operate the plant and/or be available for consulting during the plant startup, checkout, and modification.**
13. **Ability and interest to support the evaluation of the plant in terms of reliability, performance, O&M costs, life-expectancy, and improvements. A substantial level of sustaining engineering is expected for Phase 2, since this is a first of a kind plant with opportunities for substantial revision and testing to determine the performance parameters.**

14. **Ability and interest to support the commercialization efforts that would follow a successful Phase 2.**

15. **Willingness to provide the universities involved in the development of this project with subsequent research and development contracts as appropriate for continued technological advances, including funds for consultation, grants, student projects, etc. The universities involved would include the University of Alabama in Huntsville, the University of Houston, and the Weizmann Institute of Science, and very likely one or more universities in Egypt. This effort would ensure a degree of continuity from the inception of the concept at the Weizmann Institute through its development at UAH and its future advanced development and experimentation with one or more Egyptian academic institutions.**
16. **Consideration of legal and/or financial restrictions and conditions such as exit criteria, program duration, financial return "hurdle rates", liability limitations, etc., that would compel the company to withdraw from the program at Phase 1, Phase 2, or subsequent commercialization efforts.**

Optical Analysis and System Optimization - ADDENDUM

- **Achieve a true optimization capability for layout of the heliostat field**
- **Supported by a subcontract to Tietronix Software and Professor Lorin Vant-Hull of the University of Houston, to modify RCELL System Optimization Optical Analysis Code**
- **Use the SolarSim code to assess the flux distributions**

NOOR AL SALAM - Phase 1 System Definition Program UAH Program Planning and Technology Development

Production, Assembly, and Installation Design - ADDENDUM

Determine the initial, non-recurring costs associated with providing the various heliostat and tower reflector subsystems

Heliostat Subsystem

The heliostat overall production, assembly, and installation sequence will be developed to the level of detail necessary to describe the major activities for the following assemblies:

- **Heliostat Reflector**
- **Drive Unit**
- **Pedestal**
- **Foundation**

Tower/Tower Reflector Subsystem

- **Manufacturing, assembly, and installation sequence of these assemblies will be developed to the level of detail necessary to describe the major activities.**

- **This effort will support the Egyptian In-Country activities.**

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

Subsystem Design and Development

Tasks that were part of the original SOW that will be postponed for the selected Industrial Participant and Israeli contractors to conduct include:

- **Master Control,**
- **Secondary Concentrator Design,**
- **Receiver Design, and**
- **Power Conversion Unit requirements and preliminary design.**
- **The heliostat controller effort will also be postponed and will be the responsibility of the selected Industrial Participant.**

UAH responsibilities will be conducted in accordance with the original plan, with the emphasis on refinements to requirements and design and development of:

- **Heliostat,**
- **Tower,**
- **Tower Reflector Subsystems.**
- **Aperture cover and target, and**
- **Digital Image Radiometer Beam Characterization and Alignment**

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

Heliostat Development and Test

- **Completion of the heliostat reflector fabrication**
- **Testing of the reflector**
- **Assembly on a refurbished drive unit and pedestal**
- **Drive unit tests**
- **Performance tests of assembled heliostat**

NOOR AL SALAM - Phase 1 System Definition Program
UAH Program Planning and Technology Development

Tower Reflector Development and Test

UAH has a tower reflector facet and a Geometrica geodesic dome structure. Tests will be conducted on this hardware to assess long-term exposure/life issues, structural integrity, and thermal performance of the facet at one-sun, cooled by water.

Additional tests will be conducted to assess the flow loss (critical to determining the proper layout for the coolant flow of the system on the tower), temperature as a function of higher solar concentrations, and alignment sensitivity and stability.

We will also set up the Geometrica support structure, currently located at NASA Marshall Space Flight Center, in the UAH Solar Test Area.

We will conduct deflection tests under simulated static loads. Note: essentially all of these tasks have been completed by UAH PRC students at no cost to the government.

Review of ITAR/EAR Export Control Issues Related to Noor al Salam Project

James B. Blackmon
February 13, 2004

**Both ITAR and EAR Export Control regulations and documents were reviewed to ensure compliance with the Noor al Salam project.
The United States Munitions List (USML) – 22 DFR 121 was reviewed to ensure compliance with all ITAR-related Export Control laws and regulations. Only one category (Category XIII) relates in any way to the Noor al Salam project under the DOE Grant (Pre-Award Planning and Egyptian Engineer Training_DOE fg36-02g)12030). The category description for subheading (f) is given below in its entirety.
Category XIII -- Auxiliary Military Equipment**

(f) Energy conversion devices for producing electrical energy from nuclear, thermal, or solar energy, or from chemical reaction which are specifically designed or modified for military application.

The EAR Commerce Control List (CCL –15 CFR 774) was reviewed. There is no category that relates to the solar power aspects of the Noor al Salam project . However, Category 1 – Materials, Chemicals, Micro-organisms and Toxins, was reviewed and no area was found that related to the subject technologies.

Review of ITAR/EAR Export Control Issues Related to Noor al Salam Project (Cont'd)

Conclusion

The production of electrical energy from solar energy that is the subject of the Grant (Pre-Award Planning and Egyptian Engineer Training DOE fg36-02g)12030) is not specifically designed or modified for military application. The purpose of this Grant is to conduct a System Definition for a 10 to 20 Megawatt solar central receiver plant in Egypt, as a forerunner to commercial solar power production. The Grant involves:

- **research and development of some aspects of solar electrical power using heated air,**
- **meetings between Department of Energy and other solar specialists with counterparts from the Egyptian New and Renewable Energy Authority, the U.S./Israel Science and Technology Commission, the U.S./Israel Science and Technology Foundation, the Weizmann Institute of Science, and**
- **an effort to involve a U.S. prime contractor.**

No Category in the CCL relates to the technology of the Noor al Salam project.

Based on the review of the ITAR and EAR lists, there should be no "deemed export" of the subject matter during our meetings with Egyptian and Israeli representatives

Planning and Work Shops for Egyptian Training and Noor Al Salaam Solar Power Project at The University of Alabama in Huntsville Huntsville, Alabama

DRAFT
List of Candidate Attendees

Mr. Samir Hassan – Chairman, Egyptian New and Renewable Energy Authority
Professor Mahfuz Amin Abdul El – Rahman, Zagazig University, Cairo and Technical Advisor of the Minister of Electricity and Energy
Mr. Hamed Emara Kassem–Senior Undersecretary, Egyptian Ministry of Energy and Electricity
Ms. Bothayna Amin Rashed General Manager of Planning and Follow-up
Mr. Dan Melvin - DOE – International Programs
Dr. Arnold Brenner, Executive Director, U.S./Israel Science and Technology Foundation
Professor Jacob Karni, Director, Weizmann Institute of Science Solar Facility
Dr. Ron Greenwood – Vice President, Research, UAH
Dr. Mark Bower – Chair, Department of Mechanical and Aerospace Engineering Dr. Clark Hawk – Director, Propulsion Research Center, Department of Mechanical and Aerospace Engineering
Dr. Francis Wessling – Professor and former Chair, Department of Mechanical and Aerospace Engineering
Dr. James Blackmon – Research Professor, Propulsion Research Center, Department of Mechanical and Aerospace Engineering
Dr. Marlow Moser – Research Professor, Propulsion Research Center, Department of Mechanical and Aerospace Engineering
Mr. Troy Skinner – Instructor, Department of Mechanical and Aerospace Engineering
Ms. Gloria Greene – Director, Sponsored Programs, UAH
UAH Students:
- **Mr. Sean Entrekin**
- ***Mr. David Eddleman***
- **Mr. Kevin Losser**
- **Mr. Brad Johnson**

Technical Support Personnel (Former UAH Students)
- **Mr. Frederick Gant**
- **Mr. Kevin Nichols**
- **Mr. Ben Bramblett**
- **Mr. Mike Boland**

Local Industrial Representatives

Mr. David Christensen, Lockheed Martin (former head of solar energy programs with NASA and UAH)
Mr. Steven Kusek – President, HiTek Services, LLC
Mr. Ed Wells, President, Falcon Fabrication
Mr. Jim Hughes, President, Falcon Technologies
Mr. David Best, SUMMA, Inc.
Mr. Harold Gerrish - NASA Marshall Space Flight Center (MSFC) Solar Power Technologist
Mr. Marty Runkle – Vice President, Systems - Teledyne Brown Engineering
Others, TBD

Appendix M
Request for Information (RFI) and related documentation

DRAFT

FED BIZ OPS

SOLICITATION OF QUALIFIED U.S. COMPANIES FOR EVALUATION AND SELECTION AS PRIME CONTRACTOR FOR THE SYSTEM DEFINITION OF THE "NOOR AL SALAAM" (LIGHT OF PEACE) HIGH CONCENTRATION SOLAR CENTRAL RECEIVER HYBRID ELECTRICAL POWER GENERATION PLANT

The University of Alabama in Huntsville is soliciting expressions of interest and point of contact information from qualified U.S. companies interested in considering serving as prime contractor on the current on-going U.S. Agency for International Development (USAID) and Department of Energy (DOE) Grant to the University of Alabama in Huntsville (UAH), which is to conduct a system definition study that is planned to lead to construction of the *Noor al Salaam ("Light of Peace") High Concentration Solar Central Receiver Hybrid Electrical Power Generation Plant*. The Grant involves advanced solar technologies developed in part by organizations in Israel and by The Boeing Company. Much of this technology has been developed by programs funded in Israel to develop an innovative high concentration solar central receiver system. Also, from 1995 to 2000, the U.S./Israel Science and Technology Foundation (USISTF) provided 50/50 cost-shared funding to McDonnell Douglas Corporation (now, The Boeing Company), Ormat Industries, Ltd and Rotem Industries, Ltd to advance these developments. Subsequent efforts resulted in an agreement between principles in Egypt, Israel, and the United States to develop this innovative technology as a demonstration plant in Egypt.

The Noor al Salaam plant is estimated to be approximately 10 to 20 Megawatts electrical output, with the solar plant sized to approximately 10 Megawatts (thermal) input. Natural gas would fuel a combustion turbine generator to provide the major part of the electrical power. Egyptian industrial companies would provide a substantial part of the solar field hardware, including the heliostats and tower. Israeli companies would, in accordance with the original memoranda of agreements and funding agreements with the USISTF, provide the modified turbine generator and receiver subsystems. Other arrangements may be made as required for hardware and participation, in keeping with the original agreements. Detailed information will be provided to companies responding to this solicitation on interest, in the form of a more detailed solicitation document; this information will cover background of the project, and evaluation factors to be used in the selection. Responding companies will have the opportunity to provide statements of qualifications and other information for consideration in the evaluation and selection process.

The Egyptian New and Renewable Energy Authority (NREA), under the Egyptian Ministry of Electricity and Energy, is involved in this project. NREA has agreed to provide a site for the eventual construction of the Noor al Salaam demonstration plant at Zaafarana, on the Red Sea Coast, approximately 100 miles south of Cairo, and has provided technical support for early plans.

The Grant has several objectives, among which are:

- To complete a System Definition of a hybrid solar power plant based on the USISTF technology;
- Proceed with additional tasks, as required by the new prime contractor, to move towards construction of the facility; and
- To work with partners to obtain funding and/or financing for facility construction in Egypt.

A U.S. Prime Contractor is needed during the current System Definition phase to provide expertise in the design, fabrication, installation, and operations aspects, with Israeli and Egyptian organizations serving as appropriate subcontractors. Selection of the Prime Contractor will be made by UAH, based on an evaluation performed against criteria provided in a future solicitation. Following selection, the Prime Contractor would be responsible for the project, coordinating with DOE and the Israeli and Egyptian partners as required and worked out among them. Egypt is the host country for the Noor al Salaam plant. It is anticipated that a Tri-Lateral agreement would be developed between the Prime Contractor and the principles in Israel and Egypt. Later, subsequent commercialization efforts could then be conducted by the Prime Contractor and its partners in Israel and Egypt, assuming that the market, technical, and financial aspects support such a decision. It is presumed that UAH will remain involved as a subcontractor partner.

The value of the current Grant to UAH is approximately $1M (with no required cost sharing). UAH has been performing and has or will expend approximately $300K of that total prior to the prime contractor taking over leadership of the effort. .

.

NOTE TO POTENTIAL CONSTRUCTION COMPANIES TO MANAGE NAS SYSTEM DEFINITION STUDY – SENT TO VARIOUS COMPANIES TO OBTAIN CONTACT INFORMATION

The University of Alabama in Huntsville is soliciting expressions of interest and point of contact information from qualified U.S. companies interested in considering serving as prime contractor on the currently on-going U.S. Agency for International Development (USAID) and Department of Energy (DOE) Grant to the University of Alabama in Huntsville (UAH) to conduct a system definition study that is planned to lead to construction of the *Noor al Salaam ("Light of Peace") High Concentration Solar Central Receiver Hybrid Electrical Power Generation Plant*. The Grant involves advanced solar technologies developed in part by organizations in Israel and by The Boeing Company. Much of this technology has been developed by programs funded in Israel to develop an innovative high concentration solar central receiver system. Also, from 1995 to 2000, the U.S./Israel Science and Technology Foundation (USISTF) provided 50/50 cost-shared funding to McDonnell Douglas Corporation (now, The Boeing Company), Ormat Industries, Ltd and Rotem Industries, Ltd to advance these developments. Subsequent efforts resulted in an agreement between principles in Egypt, Israel, and the United States to develop this innovative technology as a demonstration plant in Egypt.

The Egyptian New and Renewable Energy Authority (NREA), under the Egyptian Ministry of Electricity and Energy, is involved in this project. NREA has agreed to provide a site for the eventual construction of the Noor al Salaam demonstration plant at Zaafarana, on the Red Sea Coast, approximately 100 miles south of Cairo, and has provided technical support for early plans.

The Grant has two main objectives:

- To complete a System Definition of a hybrid solar power plant based on the USISTF technology, and
- To acquire the additional funds for its construction in Egypt.

A U.S. Prime Contractor is needed during the current System Definition phase to provide expertise in the design, fabrication, installation, and operations aspects, with Israeli and Egyptian organizations serving in appropriate subcontractors in their respective areas of work. If you would be interested in considering this opportunity further, please contact me or send an email and address for your point of contact.

Thank you.

James B. Blackmon, Ph.D.
Research Professor
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville

POTENTIAL INDUSTRIAL PARTICIPANTS
AND RELATED ORGANIZATIONS
DRAFT
Contact List
11/10/05

Nexant, Inc.
Mr. Bruce Kelly
101 Second Street, 11th Floor
San Francisco, CA., 94105-3672, USA
Tel: 415-369-1000 (Office)

Black & Veatch, Inc.
Mr. Larry Stoddard
Associate Vice President, Renewable Energy 11401 Lamar Avenue
Overland Park, KS 66211
Tel: 913-458-7225
Mobile 913-220-5012
Fax: 913-458-7803
stoddardle@bv.com

FPL Energy, Inc.
Mr. Joseph P. Peter
700 Universe Boulevard
Juno Beach, FL 33408-2657
Tel: (561) 691-2802
Fax: (561) 694 3647 (Fax)
Joseph_p_peter@fpl.com

Solargenix Energy
Mr. John Myles
President
1378 Charleston Drive
P.O. Drawer 10
Sanford, North Carolina 27331
Tel: Office: (919) 774 4000
Fax: (919) 774 1979
srisolar@aol.com

Ormat Industries Ltd.
Lucien Y. Bronicki
Chairman
Industrial Way
P.O.B. 68 Yavne 81100
Israel
Tel: 972 (8) 9433777
Fax: 972 (8) 9433702
Email: 100264.1177@cmopuserve.com

Rotem Industries Ltd.
Mr. Dan Peer
Temed Industrial Park
P.O. Box 9001 Beer Sheva 84190
Israel
Tel: 972-7-6567533
Fax: 972-7-6554848

Geometrica, Inc.
U.S.A. – Headquarters
Mr. Francisco Castaño
12300 Dundee Ct, Suite 200
Cypress, Texas 77429, U.S.A.
Tel: (832) 220 1200
Fax: (832) 220 1201
e-mail: sales.usa@geometrica.com

Concentrating Technologies, LLC
Mr. Stephen Kusek
President
P.O. Box 16020
Huntsville, AL 35802
Tel: (256) 539 0380
kusek@hitek-services.com

SAIC
Mr. Aaron Helfer
10260 Campus Point Drive
San Diego, CA 92121

Amonix, Inc.
Mr. Vahan Garboushian
President and CEO
3425 Fujita Street
Torrance, California 90505
Tel: (310) 325 8091
Fax: (310) 325 0771

Falcon Technologies
Mr. Ed Wells
Lacy Springs, Alabama
Tel: (256) 882 0880
Mobile: (256) 653 1723

Stirling Energy Systems
Mr. Robert Liden
6245 North 24th Parkway
Suite 209
Phoenix, AZ 85016
Tel: (602) 957 1818
Fax: (602) 957 1919
rliden@stirlingenergy.com

Parsons
Parsons Infrastructure and Technology Group
Mr. Todd Wager
Global Business Development Manager

Pratt and Whitney
Rocketdyne Division
Michael W. McDowell
6633 Canoga Ave.
P.O. Box 7922 MC LA21
Canoga Park, CA 91309
Tel: (818) 586 5256
michael.w.mcdowell@boeing.com

U.S./Israel Science and Technology Foundation
Mr. Arnie Brenner
USISTF
200 L street NW
Suite 800
Washington, DC 20036
Tel: (202) 419 0431
abrenner@usistf.org

Fluor Daniel **NO BID PER 2-6—6 EMAIL FROM STUBBS**
Ivan Stubbs
Address TBD
Ivan.stubbs@fluor.com
Office: 864 281 6224
Cell: 864 423 6128

The Shaw Group
Louisiana
TBD

Other U.S. Corporations TBD

Note: FLAGSOL is a foreign company with a U.S. office:

FLAGSOL, Germany
C/O Law offices of William Bresee,
200 North Glendora Avenue, 2nd floor,
Glendora, CA. 91741-2670.

DOE CONTACTS:

Glenn M. Doyle
Project Officer
U.S. Department of Energy
Golden Field OFfice
1617 Cole Blvd
Golden, COlorado 80401

Voice: (303) 275-4706
Fax: (303) 275-4753
email: glenn.doyle@go.doe.gov

DRAFT – FOR REVIEW PURPOSES ONLY WITH EXAMPLE ADDRESSEE

Nexant, Inc.
Mr. Bruce Kelly
101 Second Street, 11th Floor
San Francisco, CA., 94105-3672, USA
Tel: 415-369-1000 (Office)

January 23, 2006

Re: Request for Information (RFI) – Noor al Salaam Project

Dear Mr. Kelly;

This letter and appended background information is a solicitation to selected U.S. companies to consider becoming involved in a currently on-going solar power project. This project is supported by a Grant from the U.S. Agency for International Development (USAID) and Department of Energy (DOE) to the University of Alabama in Huntsville (UAH). We are conducting a system definition study that is planned to lead to construction of the *Noor al Salaam ("Light of Peace") High Concentration Solar Central Receiver Hybrid Electrical Power Generation Plant*, which would be built at Zaafarana, Egypt as an extension of the current Tri-Lateral program between UAH, Israeli companies, and the Egyptian New and Renewable Energy Authority. The Grant involves advanced solar technologies developed in part by organizations in Israel and by The Boeing Company. Much of this technology has been developed by programs funded in Israel to develop an innovative high concentration solar central receiver system. Also, from 1995 to 2000, the U.S./Israel Science and Technology Foundation (USISTF) funded McDonnell Douglas Corporation (now, a wholly owned subsidiary of The Boeing Company), Ormat Industries, Ltd, and Rotem Industries, Ltd to advance these developments. Subsequent efforts resulted in an agreement between principles in Egypt, Israel, and the United States to develop this innovative technology as a demonstration plant in Egypt.

The Egyptian New and Renewable Energy Authority (NREA), under the Egyptian Ministry of Electricity and Energy, is involved in this project. NREA has agreed to provide a site for the eventual construction of the Noor al Salaam demonstration plant at Zaafarana, on the Red Sea Coast, approximately 100 miles south of Cairo, and has provided technical support for early plans.

The Grant has two main objectives:

- To complete a System Definition of a hybrid solar power plant based on the USISTF technology, and
- To acquire funds for its construction in Egypt.

A U.S. Industrial Participant is needed during the current System Definition phase to provide expertise in the design and fabrication aspects, and to serve as the Prime Contractor, including responsibility for the Israeli and Egyptian organizations efforts in their respective areas of work. In addition, companies having expertise in specific areas of interest are invited to provide relevant capability statements; these will be provided to the selected Industrial Participant, as an aid in developing subcontractor support. Later, assuming funding has been secured for the follow-on phase, the selected Industrial Participant would be responsible as Prime Contractor for the detailed plant design, construction, and operation. Selection of the Industrial Partner will be based on an evaluation of capability and interest that will be coordinated with the Department of Energy by UAH. Further coordination of this selection will be conducted under the direction of DOE with the Israeli companies that have developed much of the technology and with Egypt's New and Renewable Energy Authority. Egypt is the host country for the Noor al Salaam plant. It is anticipated that a Tri-Lateral agreement would be developed between the Industrial Participant and the principles in Israel and Egypt. Later, subsequent commercialization efforts could then be conducted by the Industrial Participant and its partners in Israel and Egypt, assuming that the market, technical, and financial aspects support such a decision.

The scope of the current Grant to UAH is approximately $1M, of which a portion has been assigned to completion of certain technical tasks as well as oversight and support for the transition a major part of the Grant to the selected Industrial Participant.

The Noor al Salaam plant is estimated to be approximately 10 to 20 Megawatts electrical output (and possibly higher), primarily from a natural gas powered turbine, with the solar plant sized to approximately 10 Megawatts (thermal) input to augment the heating of the air into the turbine's gas generator. Egyptian industrial companies would likely provide the majority of the solar field hardware, including the heliostats and tower. Israeli companies would, in accordance with the original memoranda of agreements and funding agreements with the USISTF, provide the modified turbine generator and receiver subsystems. Other arrangements may be made as required for hardware and participation, but this summarizes the existing agreements.

Appended to this letter are the following documents:

Attachment 1: Background information on the U.S./Israel Science and Technology Foundation (USISTF) and Noor al Salaam solar central receiver projects.

Attachment 2: Non-proprietary overview of the USISTF program and the Noor al Salaam plant characteristics

Attachment 3: Description of the types of information sought as part of this Request for Information (RFI).

Attachment 4: Patents associated with the technology to be applied to the Noor al Salaam program.

As part of this RFI, UAH is seeking expressions of interest and capability statements for this activity. It is our intention to gather the necessary information over an approximately 8-week period from the date of this letter, with follow-up discussions to be held as necessary for clarification purposes. UAH would then support the evaluation of the responses in cooperation with the Department of Energy. The Department of Energy would then develop the appropriate contractual mechanism for the work to be conducted under the existing Noor al Salaam System Definition study; in short, the current Grant to UAH would likely be novated to the selected Industrial Participant to serve as Prime Contractor. Discussions would then be held between the selected Industrial Participant or Participants and the Israeli and Egyptian team-members for the purpose of developing the appropriate business relationship, including memoranda of agreements (MOAs) and Non-Disclosure Agreements (NDAs) for conduct of the Noor al Salaam program and future commercialization of the technology. The development of these agreements between the Industrial Participant and the Israeli and Egyptian partners would be made at a time and under conditions suitable to all parties.

If your company has an interest in this project, and will consider the appended information further with the intent of submitting the requested capability statement, please contact me for all business matters, and our Principal Investigator, Dr. James B. Blackmon, for technical questions, at the following address:

James B. Blackmon, Ph.D.
Research Professor
Department of Mechanical and Aerospace Engineering
S233 Technology Hall
University of Alabama in Huntsville
Huntsville, Alabama 35899
blackmoj@email.uah.edu
Telephone: (256) 824-5106

Sincerely,

Andrea Dixon
Senior Contracts Administrator
Office of Sponsored Programs
University of Alabama in Huntsville
Huntsville, Alabama 35899

Attachment 3:

Request for Information
Noor al Salaam High Concentration Solar Central Receiver Programs

The role of UAH is to facilitate the Phase 1 program and its transition to the Phase 2 plant construction. However, it is recognized that the University is not equipped to conduct the Phase 2 program, nor is it able to establish the agreements and conditions in Phase 1 between the Parties that are required for the transition into Phase 2. Therefore, a U.S. Industrial Participant is needed as part of Phase 1, and that this Industrial Participant have the breadth of capability and past experience necessary to conduct a part of Phase 1 and transition this responsibility into the Phase 2 system integration, system engineering, construction and/or construction management, and plant operation. It is also critical that this Industrial Participant serve as the prime contractor, and that there be a support team of subcontractors with the requisite capabilities to provide the various subsystems. It has also become clear that the selected Industrial Participant should take over all or part of the Phase 1 effort at an appropriate time.

UAH is responsible under the Grant for soliciting and evaluating candidate industrial partners, for both the prime contractor and support subcontractor roles. Candidate companies must be willing and able to provide assistance during the Phase 1 program in order to be fully capable of leading the transition effort to Phase 2. In particular, it will be necessary to acquire the funding necessary for Phase 2. It is also important that the selected company or companies be available to participate with Egypt's New and Renewable Energy Authority (NREA) and the Israeli industrial partners as early in Phase 1 as practical, in order to address issues regarding subsystems, potential vendors, and other policy and procedural issues leading to Phase 2.

UAH will submit a Request for Information to companies having the interest and capability to serve as the prime contractor or one of the supporting subcontractors for the Phase 1 System Definition and the Phase 2 Plant Construction and Operation. These contacts will first involve non-proprietary information that describes the overall system, the objectives of the Noor al Salaam program, the participants, and such past accomplishments, references, and other source material as may be of interest in the internal evaluations by the candidate companies. A draft NDA will be included with this initial package such that discussions between these companies and UAH can take place that will protect the interests of both parties. UAH will ensure that proprietary information related to prior programs (i.e., U.S./Israel Science and Technology Commission High Concentration Solar Central Receiver) is protected. The candidate companies will only have access to the non-proprietary information necessary to determine their role and level of interest.

However, joint and/or bi-lateral NDA(s) may be required between companies having an interest in considering this opportunity in greater detail with Ormat, Rotem, the Weizmann Institute of Science, and/or NREA. At that point, certain proprietary information may then be exchanged between these companies. UAH will, as part of this process, receive information and permission from Boeing for release of certain proprietary information developed by Boeing under the previous USISTF cost-shared program. UAH will facilitate the transfer of such information in accordance with an NDA between Boeing and one or more of these companies, as required.

The companies selected for this next step in the evaluation will be evaluated on the basis of the following factors:

17. Corporate structure, ownership (U.S. or foreign), and eligibility for receiving U.S. Government funding.
18. The capability, background, and scope that would be provided either as a prime contractor or as a supporting subcontractor, in such areas as civil engineering; architectural and engineering; plant construction; subsystem design, fabrication, and test; Egyptian In-Country manufacturing; plant integration; optical analysis; inspection and checkout; operation; etc. In the case of supporting subcontractors, selected areas from the above may be addressed. The ability of the prime to conduct and/or manage these areas will be evaluated on the basis of the information provided in the response to the RFI.
19. Experience in conducting business in the Middle East, especially in Israel and Egypt. As appropriate, a list of past contracts will be requested, with summary descriptions of the scope, duration, purpose, customers, degree of success, etc.
20. Corporate presence or representation in one or both of these countries, including a description of the in-country representatives, offices, plants, manufacturing and/or engineering facilities, relevant on-going contracts with companies and/or government organizations in one or more of these countries, names and addresses for points of contact, brief biographies of key personnel residing in, or responsible for, the in-country activities, etc.
21. Experience in the technologies involved, both at a corporate level and in the assignment of personnel with the appropriate capability and experience. Biographies of key technical personnel or equivalent experience/capabilities that would be assigned for the Phase 1 and Phase 2 effort is requested. Also, identification of relevant Intellectual Property, such as patents, technical papers, etc., is requested.
22. Ability and interest in supporting the establishment of such agreements between the Participants as would be required to conduct the Phase 1 effort and continue this into Phase 2, as well as subsequent commercialization efforts.
23. Ability and interest in participating in a planned one-week conference in Cairo and/or in Huntsville regarding solar power plants and technologies; the conference is likely to be held in 2004; there may also be a pre-meeting in 2004 at which the participation of the industrial partner(s) or candidates would be welcomed.
24. Ability and interest in providing cost-sharing of the Phase 1 effort, including management support at the appropriate level, other indirect funds, capital equipment, new business development funds, legal and financial analysis support, Independent Research and Development funds, travel funds, etc. The total level of effort that would be committed to Phase 1 to support the System Definition and the development of the System Definition Document, including level and type of cost-sharing, is an important evaluation factor.

25. Ability to conduct on its own, or to secure the Egyptian in-country companies required to conduct, such tasks as civil engineering, architectural and engineering, plant construction, subsystem manufacturing, plant integration, checkout, and operation, etc.
26. A major objective of the Phase 1 System Definition is to determine the extent to which Egyptian companies will have the interest and ability to conduct the work required for the Phase 2 plant construction. The means by which this effort would be conducted by the candidate companies is requested.
27. Certain intellectual property and hardware will be provided by U.S. and Israeli companies to the Noor al Salaam plant in Egypt. The ability to ensure the transfer of this intellectual property and hardware to Egypt in full compliance with regulations and procedures in Egypt, the U.S. and Israel will be required. Ability and experience in such transfers should be outlined in the response.
28. Providing the training necessary for Egyptian personnel to operate and maintain the plant is important to its success. The means by which this effort would be conducted is requested.
29. Ability and interest to support the pursuit of funds for Phase 2 from government and private sources is critical. The means by which this effort would be conducted is requested.
30. Ability and interest to operate the plant and/or be available for consulting during the plant startup, checkout, and modification is requested.
31. Ability and interest to support the evaluation of the plant in terms of reliability, performance, O&M costs, life-expectancy, and improvements is requested. A substantial level of sustaining engineering is expected for Phase 2, since this is a first of a kind plant with opportunities for substantial revision and testing to determine the performance parameters.
32. Ability and interest to support the commercialization efforts that would follow a successful Phase 2 is requested, assuming that the Phase 2 plant is successful and that cost and marketing studies indicate commercialization is justified.
33. Plans to ensure continuity of technology development efforts conducted by the Weizmann Institute of Science, the University of Alabama in Huntsville, the University of Houston, and very likely one or more universities in Egypt. This effort would ensure a degree of continuity from the inception of the concept at the Weizmann Institute through its development at UAH and its future advanced development and experimentation with one or more Egyptian academic institutions. One purpose of the Noor al Salaam plant is to evaluate additional advanced solar technologies, and to ensure that these technology advances are widely disseminated.
34. Consideration of legal and/or financial restrictions and conditions such as exit criteria, program duration, financial return "hurdle rates", liability limitations, etc., that would compel the company to withdraw from the program at Phase 1, Phase 2, or subsequent commercialization efforts.

A Capability Statement is requested from each company addressing the evaluation factors presented above, as appropriate.

UAH would support evaluation of the information provided in the responses, hold telecons with the responding companies to obtain clarifications as required, consolidate the information, and develop a quantitative evaluation for each criteria and the total. These data and responses would then be provided to DOE and to Ormat, Rotem, and NREA. If requested, UAH will provide DOE with a recommendation and/or ranking of the Industrial Participants.

APPENDIX N

RECEIVER SUBSYSTEM TECHNOLOGY DEVELOPMENT RELATED TECHNICAL DOCUMENTATION AND PAPERS

Proceedings of ISEC2006 ASME International Solar Energy Conference July 8-13, 2006, Denver, CO
ISEC2006-99119

CALORIMETRIC MEASUREMENTS OF THE INPUT POWER INTO A 500 KW HIGH CONCENTRATION SOLAR ENERGY VOLUMETRIC RECEIVER

Gideon Miron, Eliezer Reich, Jacob Kagan, Akiba Segal*
Rotem Industries Ltd, P.O.Box 9046, Beer-Sheva 84190, ISRAEL
*** Weizmann Institute of Science, P.O.Box 26, Rehovot, ISRAEL**

ABSTRACT

A Solar Thermal Demonstration Power Plant with a high concentration central volumetric air receiver was built at the Weizmann Institute of Science (WIS). The plant was based on the Beam Down/Tower Reflector concept with a secondary Compound Parabolic Concentrator (CPC). Initial solar tests were carried out during 2001 in order to demonstrate the feasibility of a large-scale central solar receiver. The receiver was tested initially under low and medium solar power inputs. Thermal output power of 210 kW and air outlet temperature of 580 ºC were measured. The evaluation of solar power input into the receiver was based on a ray tracing program. More tests, with a refurbished solar field, were planned for 2004. In order to validate the calculated input power it was decided to measure the solar power directly at the receiver's inlet. Water calorimetric measurement was selected as the preferred method. A 450 mm diameter cylindrical calorimeter was selected, designed and manufactured by Rotem's engineers. The calorimeter was installed during March 2004. Measurements were taken successfully during the next weeks, with various heliostats' combinations. The measured solar power values were compared to calculations with the ray tracing program. The results show that a good agreement could be achieved between the two by adjustment of the Beam Quality parameter. However, the results also showed that the actual inlet power to the receiver could not be expected to exceed 350-400 kW. Based on these results, further tests with the receiver were suspended. The calorimeter is used at the WIS as a calibration tool for further projects run on the same platform.

Keywords: solar thermal, receiver, CPC, calorimeter, solar power, beam quality

INTRODUCTION

A Solar Thermal Demonstration Power Plant with high concentration central volumetric air receiver was built at the Weizmann Institute of Science (WIS) as a joint project of Rotem Industries, Ormat industries, WIS and the Boeing Company [1]. The work was performed within the framework of the Israeli CONSOLAR Thermal Consortium and the US - Israel Science & Technology Foundation (USISTF). The plant was based on the Beam Down/Tower Reflector concept [2,3] with a secondary Compound Parabolic Concentrator(CPC) (Figs.1,2). The receiver and the secondary concentrator were designed and built by engineers at Rotem Industries in collaboration with WIS scientists [4].

The project was aiming to demonstrate the feasibility of a large-scale central solar receiver, supplying high pressure, high temperature air to a gas turbine [5]. The receiver was designed to produce 1 MW of thermal energy, however, it was limited to 500 kW input power by the existing solar field arrangement and budget constrains.

Initial solar tests with the receiver were carried out during 2001 [1,6]. Due to degradation of the heliostats' mirrors at WIS over the years, the receiver could only be tested under low and medium solar input power. Thermal output power of 210 kW and air outlet temperature of 580 ºC were achieved.

The evaluation of power input into the receiver during the tests was based on a ray tracing program used at the WIS throughout the years [7]. At early stages of the project, a special camera and shutter arrangement was envisioned for the purpose of analyzing the beam profile and input power. Due to various considerations, the 2001 tests were carried out without a direct input power measuring arrangement. The receiver's performance evaluation

1 Copyright © ASME 2006 2 Copyright © ASME 2006

was therefore based solely on ray tracing calculations. Because the position of the receiver's system center is offset to the solar tower and solar field center line, and because the heliostat's mirrors were now degraded, the input power estimate based on the non validated ray tracing calculations was regarded as insufficient.
Since WIS was planning on renewing their heliostats' mirrors, more tests were to be performed in 2004 with the refurbished field. In order to reduce the uncertainty related to power estimation, it was decided to measure the solar power at the receiver's inlet. Such direct measurements would prevent calculation errors and inaccuracies that could arise with each of the elements along the ray track: heliostats, tower reflector and secondary concentrator.

Fig. 1. Solar Power Plant Schematic

THE SOLAR RECEIVER

The Solar Receiver is a stainless steel pressure vessel (fig. 3) with high temperature ceramic lining. The center of the receiver is a hollow void, closed by a transparent conical quartz window. The window transmits the concentrated solar radiation into the receiver and onto ceramic "bed". The "bed" that absorbs the radiation is made of thousands ceramic hollow pins that are set in the ceramic lining and nicknamed "porcupine"(figure 4). The flow pattern within the receiver is similar to the pattern in the 50 kW receiver that was tested as a prototype for the 500kW receiver [8,9]: Air enters the receiver in two separate streams. One, of relatively cold temperature that cools the window and a second parallel, preheated stream. Both streams merge and are heated by the hot "Porcupine". During this pass, only very low pressure drop is induced. The air at high temperature and high pressure flows to a gas turbine to produce electricity.

Fig. 2. The solar plant (bottom right), the Tower Reflector (center) and the heliostats' field as seen from the top of the Solar Tower(right).

Fig. 3. The solar receiver installed on site under the secondary concentrator. 3 Copyright © ASME 2006

Fig. 4. A top view of the receiver showing the ceramic pins ("porcupine") through the transparent window.

CALORIMETRY

The initial plan to measure the input solar power was based on thermal photography of the solar focal spot on an insulated shutter at the CPC entrance plane. In addition to required data processing and elaborated validation technique, it required a complex mechanical shutter system. Since the measurement is at the CPC plane, further calculations are required to evaluate the power at the receiver's inlet, thus depending on the CPC performance.

These considerations led to a decision to design and install a device that will measure the power directly at the receiver's inlet and will be based on simple calorimetric principles (fig.5). The measurements would allow for validation and calibration of the ray tracing model with various heliostats and at different solar conditions combinations. The calorimeter will absorb the solar radiation and heats circulating water at specified and controlled flow rate. The water temperature will be measured at inlet and outlet points and with the measured flow rate used to calculate the absorbed solar power.

Fig. 5. Calorimetric measurement arrangement.

Previous experience of other researchers was studied in order to asses the feasibility of the proposed calorimeter. The WIS group has previously used flat type calorimetry for several of their solar tower projects, including the 50 kW receiver. Dr. Reiner Buck of the Deutsches Zentrum fur Luft und Raumfahrt (DLR) and his group used a bucket type calorimeter and was kind enough to share his knowledge. The calorimeters were based on absorbing the radiation on a high emissivity blackened surface cooled by water tubes. In most cases the calorimeters were made to suit the specific solar arrangement. The geometry and arrangement of the 500 kW solar receiver system (Fig.6) dictated a tailor-made calorimeter to fit the receiver.

The main goals for the calorimeter were defined as follows: 1. Measurement of the solar radiation power entering the receiver at various conditions (time of day, radiation flux, heliostat position and combination of heliostats), 2.Validation of the WIS ray tracing code for further solar receiver tests, 3. Defining the maximum actual possible solar power in order to decide on further solar receiver tests, and 4. Development of a reliable power measuring tool for future solar projects on the same platform.

Fig. 6. A section view through the Solar Receiver (bottom) and the CPC (top).

More requirements were set in order to achieve the abovementioned goals: 1. Minimal heat loss from the receiver inlet is desired. 2. The calorimeter is to be based on proven basic heat transfer principles. 3. The calorimeter should fit into the existing Receiver-CPC system. 4. Water tubing should fit into existing passages. 5. Available parts and materials and low cost. 5. Simple and quick assembly. 6. Simple connection to the existing control system. A preliminary calculation showed that while the 4 Copyright © ASME 2006

maximum solar input power into the receiver was estimated at 500 kW, the Calorimeter could be able to absorb only up to 75 kW in order to keep reasonable calorimeter temperature and structure stability. Therefore, although 40-47 heliostats of the WIS heliostats' field were allocated to the solar tests, calorimetric measurements could be done with single heliostats and groups of up to 8 heliostats only.

CALORIMETER DESIGN ALTERNATIVES

Three major design alternatives were considered: 1) A flat calorimeter that does not require disassembly of the receiver's quartz window (Fig.6). It could be a fairly simple structure to build and assemble; however, its energy absorbing area is limited and could prohibit large radiation flux. Re-radiation from such calorimeter could be relatively large and limit the accuracy of the measured power. In order to prevent heat loss by reflection, the use of high emissivity paint was considered for all alternatives. 2 and 3) A "bucket" type calorimeter that provides a "black hole" for the radiation. Its surface area is large, thereby leading to smaller heat flux, lower temperature and less surface heat loss due to radiation and convection/conduction. Its main disadvantage is the required window's disassembly. This type could be manufactured from machined aluminum sections with internal water passages (Fig.7), or from a copper cylinder and flat bottom with internal coiled black painted copper tubes (Fig.8).

Fig. 6. Flat Calorimeter.

Fig. 7. Machined Bucket type Calorimeter.

Fig. 8. Selected calorimeter type

DESIGN CALCULATIONS

Calculations were carried out in order to estimate the calorimeter expected performance. Water flow rates and pressure head loss were required in order to asses the feasibility of connection to the existing water supply system. Reduction of heat loss from the calorimeter dictates work at low calorimeter wall temperature. This requires a relative high water flow rate for high solar power but is limited by available water supply. Maximum water flow rate was set at 20 l/s obtained from the existing cooling water piping.

Thermal analysis was performed to check the temperature profile in the water tube wall (Fig.9). Evenly distributed temperature improves the heat transfer to the water. More calculations were done to check the maximum temperature on the calorimeter in order to avoid structural failure at the expected high heat flux of up to 100 kW/m^2.

Fig. 9. Temperature distribution in the tube wall for thin (left) and thick wall.

Error estimation was carried out in order to asses the calorimetric results. The estimation is based on 5

Copyright © ASME 2006

the calorimetric relation $_{lossabs}qTmQ-\Delta$□□$^{\cdot}$ where Q_{abs} is the absorbed power, is the water flow rate, ΔT is the water temperature difference and q$m^{\cdot}_{loss}$ is the heat loss due to conduction, convection and radiation. Assuming conductivity of 0.045 W/m-K, convection factor of 6 W/m^2, surface area of 0.65 m^2, emissivity 1 and shape factor of 0.22 for the top-less calorimeter, calculation of the heat loss yields a figure of around 300 watts for 100 kW of solar input power. This is only 0.4% of the total power and therefore neglected within the accuracy estimate. The estimate is then based on the multiplication of the two quantities and ΔT and is expressed by the formula: $m^{\cdot}$

$$_{22}\square\square\square\square\square\square\Delta\Delta\Delta+\square\square\square\square\square\square\Delta=\Delta TTmmQQ_{absabs}{}^{\cdot\cdot}$$

Where and are the water flow rate and the differential temperature measurement errors respectively. With ±2.5% error for the water flow rate and ±0.5°/30° for the differential temperature (see next chapter), an overall accuracy of better than 3% is received. It is worth mentioning that at this stage of validating the solar input power estimates, such accuracy exceeds the requirements by far. $m^{\cdot}\square T\Delta\Delta$

MECHANICAL DESIGN AND CONSTRUCTION

The mechanical design model and intermediate construction stages are depicted in Figs.10 and 11. The calorimeter is made of a copper cylinder internally wound with coiled copper tube. The bottom is similar in concept except that the central section is made of a machined hollow disk through which the inlet and outlet pipes are connected. The calorimeter is located in the solar receiver, replacing the quartz window and attached to the bottom part of the CPC (Fig.12). The inlet and outlet water pipes are channeled through the bottom part of the receiver that was previously used for the receiver's back reflector passage. Five thermocouples Type K (±0.5 °C) are used to measure the temperature (Fig.13): Inlet water temperature (A), outlet water temperature (B), water temperature in the inlet manifold (C), inlet manifold wall temperature (D) and the upper rim of the calorimeter (E). While A and B are used to calculate the power, C,D and E are used to monitor the structure temperature to ensure structural stability and indicate possible overheating.

The calorimeter was checked for leaks and pressure tested and sent for painting with special high emmisivity paint (NEXTEL Velvet-Coating 811-21, 98% absorbance). It was then externally insulated with 1" tk. rock wool thermal blankets (0.045 W/m-K) to ensure minimal heat loss into the receiver's void.

Fig. 10. The calorimeter design model

Fig. 11. The calorimeter in the workshop 6 Copyright © ASME 2006

Fig. 12. The calorimeter assembly inside the solar receiver.

Fig. 13. Location of the thermocouples in the calorimeter.

INSTALLATION

The completed calorimeter was moved to the WIS site. The receiver's quartz window and back reflector were removed to make room for the calorimeter (Fig.14). The calorimeter was lowered into its place with the two water pipes passing through the bottom (Figs.15,16). The water inlet pipe was connected to the water supply through an "ARAD" flow meter (Fig.17). The flow rate was checked and calibrated and found to have a ±2.5% error. The thermocouples and the flow meter were connected to the control system. The control program was revised to include and record the new parameters and readings, and show the calculated input power results.

Fig. 14. Removal of the quartz window.

Fig. 15. Lowering the calorimeter into the CPC. 7 Copyright © ASME 2006

Fig. 16. The (black) calorimeter in position.

Fig. 17. The calorimeter water pipes under the receiver and the (blue) flow meter.

EXPERIMENTS

The calorimetric tests were run remotely from stations in the WIS Solar Tower control room. The heliostats were controlled by the Solar Tower controllers and coordinated with the Solar Receiver control station. Pre checks started on March 3, 2004. Initially 650 w/m^2 solar radiation flux was measured at the solar field by an Eppley Radiometer model N.I.P. The radiometer has been previously checked with Eppley Group of reference standards. The derived value of the constant for this radiometer is 8.39*10^{-6} V/W-m^2. It was temperature compensated from -20 to +40 °C. A total of four heliostats were activated but the solar radiation dropped to 300 W/m^2 due to clouds cover. The test confirmed the operability of the system components.

More tests started on March 24 and 25, with a total of 6 heliostats averaging 6 kW each. The following days were cloudy, as could be expected during this season. The tests resumed on April 1st. During close to 3 hours, starting 11 AM, 34 heliostats were separately moved to position and the inlet power was measured by the calorimeter. Changes between the heliostats, in relation to their position in the solar field, were clearly observed. Towards the end of the test 5 heliostats were grouped to achieve a combined 50 kW power.

RESULTS

Temperature output was recorded for the five thermocouples (A-E) positioned as indicated in Fig.13. Tests started on March 24th and were used to check and validate the readings from the various sensors.

Figure 18 shows the temperature and input power results of March 25th, ending with 6 heliostats. Initially, each heliostat was entered until temperature was clearly rising and stabilized. Then, the heliostat was removed and the temperature dropped until reaching initial value. Later, all 6 heliostats were entered one at a time and additive response is seen until maximum power of 35 kW is reached.

The results of April 1st are shown in Fig.19 and Table 1 that summarizes the maximum power data for each heliostat, including time, heliostat number, solar radiation flux and theoretical power assuming 880 w/m^2 radiation. Past tests have shown radiation fluxes of up to1000 w/m^2 only on few days. Therefore, 880 w/m^2 is a reasonable upper boundary for maximum potential power. Figure 20 shows the maximum measured power and the related solar radiation flux at the time, and the potential maximum power that could be expected for each of the heliostats. The heliostats' numbers relate to their location in the field, where the closest row is 100's and the furthest 600's. It is clear that power varies considerably for each heliostat.

The combined maximum potential input power of the 34 heliostats at test conditions and 880 w/m^2 is 295 kW. Assuming nominal average of 8600 watts per heliostat with 40 potentially available heliostats at similar conditions results a total of 350 kW.

The calorimetry results were compared against the WIS model (Fig.21). The comparative results between the measurements of April 1st, 2004 and calculations, suppose that the reflectivity of the heliostats (0.85), the Tower mirror (0.87) and the CPC (0.90), are fixed. The variable parameter is the Beam Quality (BQ in mrad.). The Beam Quality compensates both for estimated optical and mechanical errors. The BQ is artificially established at the value around 2.2 for "best fit" of model results with the experiment result. Because it is almost impossible to measure the surface errors of the tower mirror and/or the CPC mirrors, all these effects are set on account of the heliostats facets surface error – BQ. BQ of more than 2.2 was regarded and marked as questionable and further validation could be required. Error bars are applied to the measured power at ±3% and overall agreement between the results and the model is generally observed. Calculation for four heliostats exceeds 20%, 3 are between 5% to 15% and the rest are below 3%. While low power level heliostats' calculation 8 Copyright © ASME 2006

agreement is poorer, combination of several heliostats yields an even better agreement of 0.5% to 1.7%.

SUMMARY AND CONCLUSIONS

It was successfully demonstrated that a direct off-line calorimetry could be achieved with the Beam Down solar platform. A tailor-made calorimeter was designed and installed directly at the Volumetric Solar Receiver's inlet. The tests have shown that the solar power was measured successfully by the calorimeter. The solar power obtained from the different heliostats depends greatly on their location in the solar field relative to the solar receiver. It results from the difference in optical ray track and the reflection properties from the tower mirrors. In general, the closer the heliostat is to the tower the higher the power. Heliostats' power measured at test conditions was between 1 Kw to 15Kw per heliostat.

Assuming good solar conditions for all the heliostats, the potential maximum power from 40 heliostats at the receiver's inlet could be as much as 350 Kw. This figure is much lower than the expected power at the beginning of the project, although with 47 heliostats at that time. Previous supporting calculations, based solely on the WIS model for one of the solar tests conducted in 2001 with 47 heliostats, estimated CPC inlet power of 379 Kw and Receiver's inlet power of 282 Kw. The calculation assumed correction factor (BQ) for the degraded heliostats' mirrors, however, with no further validation. Previous solar field calculations in 1998 for the then future project have estimated more that 1200 Kw at the CPC entrance and 850 Kw into the receiver. The actual receiver thermal output in one of the 2002 tests was 210 Kw with calculated inlet power of 300 Kw, indicating estimated 70% receiver's efficiency. This figure, however, could not be validated without a direct measurement of the solar power and may have been higher should calorimetric measurements were done at that time. The discrepancy between the original inlet power estimates and the calorimetric measurements is noticeable. Although it deserves its own investigation it is outside the scope of this paper. It will only be pointed out that the value of the input power is sensitive to the three following major optical elements: heliostats, tower reflector and CPC. Degradation of the reflective surfaces, inaccurate canting and other optical parameters could contribute to major discrepancies between calculations and actual measurements. It is common engineering practice to accompany analysis and calculations with measurements followed by model calibration.

It is therefore clear that the direct measurement of the solar power, at a point as close as possible to the Solar Receiver's inlet, is essential to estimate the true performance of the receiver and the system. Since the proposed measurement is an off line operation, the results should be used to calibrate the model that is used on-line, with suitable correction factors. More calorimetric tests could be necessary to establish better correction factors for various field conditions and heliostats' combinations as well as establishing the uncertainty of the calorimetry measurement.

Since the expectations for high solar power were not realized, the continuation of the project was suspended. The solar receiver was later removed but the Beam Down platform, including the CPC, was rearranged to accommodate other solar projects. The calorimeter remains at WIS for further power measurements and calibration of the ray tracing program for future experiments.

REFERENCES

[1] Miron G., Assis E., Erez A., Taragan E., Reich E., Weiss S., Ostreich B., Gruntman S., Duchan S., Arad M., Kravitz M. and Halpern D., 2002, "Solar Thermal Demonstration Power Plant – Results of First Testing Period", IAEC 2002 Annual Report, http://www.iaec.gov.il/pages/card_report.asp.

[2] Rabl A., 1976, "Tower Reflector for Solar Power Plant", Solar Energy **18**, p269.

[3] Kribus A, 1996, "High Concentration Solar Energy Optics", Sun Day Symposium at WIS, May 1996.

[4] Miron G., Weis S., Anteby I., Taragan E., Sagie D., 1998, "Secondary Concentrator for a Commercial Solar Receiver System – Design and Evaluation", The 27th Israel Conference on Mechanical Engineering, Technion, Haifa, Israel, May 19-20, 1998, p586 .

[5] Kribus A., Zaibel Z., Segal A., Carey D. and Karni J., 1998, "A Solar Driven Combined Cycle Plant", Solar Energy **62**, p121 .

[6] Miron G., Assis E., 2002, "Semi- Foundation & CONSOLAR Tests Summary Report", ROTEM Ind. Internal Report no. 6044-d210, March 2002.

[7] Segal A., 1996, "WISDOM - Weizmann Institute Solar Dedicated cOmprehensive Mastercode", at Proc. of the 1996 Annual Conf. ASES, pp 308-312.

[8] Kribus A., Doron P.,Rubin R., Karni J., Reuven R., Duchan S. and Taragan E, 1999, “A Multistage Solar Receiver: The Route to High Temperature”, Solar Energy **67**, 3.

[9] Sagie D., 1994, “The Development of a Volumetric Solar Thermal Receiver – An Overview”, IAEC Annual Report 1994, p25.
9 Copyright © ASME 2006

Calorimetry 25/3/04010203040506025/3/0411:4525/3/0412:0025/3/0412:1425/3/0412:2825/3/0412:4325/3/0412:5725/3/0413:1225/3/0413:2625/3/0413:40Date-TIMETemperature (C)-50000500010000150002000025000300003500040000Calculated Power (Watt)A water inletB water outletC water manifoldD body manifoldE body top rimCalculated Power

Fig. 18. Temperature measurements and power results of 25.3.04

Calorimetry 01/04/04152025303540455055601/4/04 10:331/4/04 11:021/4/04 11:311/4/04 12:001/4/04 12:281/4/04 12:571/4/04 13:261/4/04 13:55Date-TIME Temperature(C)-60000-40000-200000200004000060000**Calculateded Power (Watt)A water inB water outC water manifoldD body manifoldE body top rimCalculated Power**

Fig. 19. Temperature measurement and power results of 1.4.04 10 Copyright © ASME 2006

020004000600080001000012000140001600018000200001001012012022032052073013023033053073094004014024034044054074095005015025035045050650850951160160360 5Heliostat No.Receiver Inlet Power (W)0100200300400500600700800900Solar Radiation Flux (W/m2)Measured Power (Watt)Max Power (Watt)Solar Radiation (W/m2)

Fig. 20. Receiver's inlet measured power related to Heliostat's No. at solar radiation flux & maximum power at 880 W/m^2.

05101520253035404510010120120220320730130230330530740040140240340440540750050150250350450550951160360510 0+101100+101+201100+101+201+202Heliostat No.Receiver Inlet Power (kW)/Beam Quality (mrad)0100200300400500600700800900Solar Radiation Flux (W/m2)Measured Power (kW)Calculated Power (kW)Solar Radiation (W/m2)BEAM QUALITY (mrad)

Fig. 21. Receiver's inlet Measured power vs Calculated power at Beam Quality. 11 Copyright © ASME 2006

TIME	Heliostat No.	Measured Power kW	Solar Radiation W/m2	Fraction of Maximum Power	Maximum Power kW@880W/m 2	Efficiency %
12:07	100	14.47	721	0.819	17.66	41.8
12:03	101	12.47	719	0.817	15.26	36.1
11:13	201	14.47	789	0.896	16.14	38.2
13:00	202	11.55	635	0.721	16.00	37.9
12:50	203	9.85	655	0.744	13.24	31.3
11:58	205	8.62	735	0.835	10.32	24.4
13:22	207	3.54	612	0.695	5.09	12.1
11:23	301	11.39	773	0.878	12.97	30.7
12:57	302	8.82	637	0.723	12.18	28.8
12:46	303	6.93	654	0.743	9.32	22.1
11:53	305	9.39	725	0.823	11.40	27.0
13:09	307	5.39	629	0.714	7.54	17.9
13:16	309	1.38	614	0.697	1.98	4.7
11:27	400	10.16	771	0.876	11.60	27.5
12:35	401	8.47	680	0.772	10.96	25.9
12:54	402	8.00	643	0.730	10.96	25.9
12:41	403	7.39	666	0.756	9.76	23.1
11:47	404	7.08	744	0.845	8.37	19.8
11:44	405	8.31	758	0.861	9.65	22.9
12:21	407	5.23	702	0.797	6.56	15.5
13:11	409	1.84	627	0.7125	2.59	6.1
12:26	500	4.46	695	0.789	5.65	13.4
11:30	501	7.08	760	0.863	8.20	19.4
12:15	502	5.69	706	0.802	7.10	16.8
12:44	503	5.39	661	0.751	7.17	17.0
12:31	504	5.08	693	0.787	6.45	15.3
11:40	505	8.00	758	0.861	9.29	22.0
13:19	506	2.92	616	0.700	4.18	9.9
13:24	508	0.73	605	0.687	1.06	2.5
13:05	509	2.05	632	0.718	2.86	6.8
13:27	511	0.29	606	0.688	0.42	1.0
11:05	601	7.23	780	0.886	8.16	19.3
12:37	603	5.69	665	0.755	7.54	17.9
11:34	605	6.46	763	0.867	7.46	17.7
13:33	100+101	20.48	606	0.688		
13:36	100+101+201	30.64	602	0.684		
13:42	100+101+201+201+301	50.71	593	0.673		
13:38	100+101+201+202	41.27	600	0.681		

Maximum Power @ 34 Heliostats 295.23 kW

Average Power Per Heliostat 8.68 kW

Maximum Power @ 40 Heliostats	**347.33**	kW

Solar Thermal Demonstration Power Plant – Results of First Testing Period

G. Miron, E. Assis, A. Erez, E. Taragan, E. Reich, S. Weiss, B. Ostreich, S. Gruntman, S. Duchan, M. Arad, M. Kravitz and D. Halpern

Summary

A Solar Thermal Demonstration Power Plant with a High Temperature central Volumetric Solar Receiver was built in Rehovot as a joint project of Rotem Industries, Ormat industries, the Weizmann Institute of Science (WIS) and the Boeing Company. The plant was based on the Tower Reflector concept with a secondary concentrator. Solar tests were carried out throughout 2001 in order to demonstrate the feasibility of a large-scale central solar receiver. Receiver power of 210 kW and air outlet temperature of 580 ºC were achieved. Simulations of the receiver were performed using a Computational Fluid Dynamics model that was developed for this purpose. Due to degradation of the heliostats' mirrors at WIS over the years, the receiver was tested under low and medium solar power input. More tests will be performed in 2002 and full power tests are planned for 2003 when renewal of the heliostats' mirrors is expected to be completed.

Introduction

Solar Thermal Electricity Power Plant with a central receiver has been regarded long ago as potentially the most promising option for Concentrated Solar (CS) energy [1]. The basic typical plant comprises of mirror reflectors (heliostats) that direct and concentrate the solar radiation at a solar receiver on a high tower. Suitable thermal fluid flows through the receiver and is heated to high temperatures. The concept of a central solar receiver with high solar radiation concentration, heating air to temperatures as high as 1300 ºC is more thermodynamically efficient than any other solar plant arrangement. The positioning of the receiver on a tower in the midst of a properly sized heliostats' field can result power plants of between a few Megawatts of electricity (MWe) to more than a hundred MWe. During the 1980th, a demonstration solar power plant that was called Solar One was built and tested in Barstow [2]. It operated with water to generate steam at about 500 ºC. A more advanced 10 MW demonstration plant named Solar Two was built in the same place using some of the Solar One hardware and was run during the 1990th [3]. Its main achievement was to prove the

2 1

ability to work with molten salt fluid that acted also as a thermal storage capacitor. In the late 1990th the REFOS project, Led by the DLR, Germany, have demonstrated in Spain the operation of air solar receiver at high power and temperature [4]. Scientists of the Weizmann Institute of Science, Rehovot, Israel, adopted a derivation to the basic tower concept. This was called the Tower Reflector or the Beam Down concept [5,6]. It takes the receiver off the tower and replaces it by a reflector mirror, thus locating the receiver, the secondary concentrator, and the heavy power generating block and its accessories on ground level. The tower for the reflector is of a lighter construction although some additional solar power losses are expected at the reflector.

In utilizing air as the thermal fluid, the heated air can be directly injected into a gas turbine. The coupling of such a turbine allows for a hybrid system. Fuel or gas can be injected into the turbine combustion chamber and compensate for poor solar irradiation or replace it totally when not available. In order to couple the receiver to a gas turbine, the solar receiver should induce a very low pressure drop on the air flow. Such volumetric solar receiver was developed as part of a joint project between WIS and Rotem Industries Ltd. Its 50 Kilowatts (kW) prototype was operated successfully at the solar tower facility in WIS during the 1990th proving the feasibility of a high temperature, high-pressure solar receiver [7,8]. It operated achieving air temperature as high as 1200 ºC at 20 Barg pressure. Tests were also run with peripheral pre-heaters that increase the overall system efficiency. The 50 kW receiver and the results of its tests opened the road for a full-scale, 500 kW to 1 MW prototype and its demonstration plant.

The High Concentration Solar Receiver Demonstration Plant project was started within the framework of the Israeli CONSOLAR Thermal consortium and the US - Israel Science & Technology Foundation (USISTF). The facility was built next to the Weizmann Institute of Science solar tower facility. Except for the existing WIS heliostats' field it includes a tower reflector, a secondary concentrator, high temperature volumetric receiver, piping and peripheral systems.

The solar tests of the 500 kW high temperature receiver were aimed to demonstrate the performance and prove the feasibility of the full-scale receiver together with the Beam Down concept and the integration with the peripheral systems for use in a future commercial solar plant. The receiver was actually designed for 1 MW output power but was limited to 500 kW by the existing WIS solar field. The following paragraphs describe the plant and present some current testing results.

System Description

The basic layout of the solar electric power plant is shown in figure 1. Air at atmospheric pressure is compressed by the turbine's compressor to a typical pressure of 15 Barg. The air enters the volumetric solar receiver where it flows over a ceramic bed. Heliostats reflect and concentrate the solar radiation onto a tower reflector that directs it down to a ground level secondary Compound Parabolic Concentrator (CPC). Solar radiation concentration could by then reach an equivalent of a few thousand suns ("1 sun" equals the natural solar flux on ground level). The concentrated energy enters the solar receiver through a transparent quartz window and is absorbed by the ceramic bed. The compressed air heats up, exits the receiver and enters the turbine where it expands. The turbine rotates the generator that in turn generates electricity. Lack of solar radiation is compensated by burning fuel in the turbine's combustor, thus making the system a hybrid system. Variation to this basic layout includes a recuperator, heat exchanger that preheats the inlet air by using the remaining heat of the outlet air. In the demonstration plant, additional heat exchangers serve to control the inlet and outlet air temperature as part of the various test run modes and experiments.

Figure 1: The solar power plant basic concept

The receiver and the secondary concentrator were designed and built by engineers at Rotem in collaboration with WIS scientists. The receiver is a stainless steel pressure vessel (figure 2 and 3) with high temperature ceramic lining. The center of the receiver is a hollow void, surrounded by a transparent conical quartz window. The window is designed to take high air pressure that is needed for turbine power cycles. The part that absorbs the radiation is actually made of thousands ceramic hollow pins that are set in the ceramic lining and nicknamed "porcupine"(figure 3). The flow pattern within the receiver is similar to the pattern in the 50 kW receiver [7] (figure 11): Air enters the receiver in two separate streams. One, of relatively cold temperature, that cools the window and a parallel, preheated stream. Both streams unite and are heated by the hot "Porcupine". During this pass, only very low pressure drop is induced. A third small air stream, nicknamed "FuFu", is flowing externally along the window and assists in its cooling.

Figure 2: The solar receiver installed on site under the secondary concentrator.

Figure 3: A top view of the receiver showing the ceramic pins through the transparent window

The secondary concentrator is located directly above the receiver and is made of 120 mirrors in different sizes that are attached to aluminum water-cooled plates. A description of this modular design is given in [9]. A view from the top of the concentrator down to the receiver is shown in figure 4. The tower reflector was designed and built in cooperation between WIS and Ormat Industries that are partners to this project.

Figure 4: A top view of the secondary concentrator.

Tests were planned in two different modes:

CONSOLAR tests: These tests are aimed at operating the receiver at its highest design conditions. In order to demonstrate the operation of the receiver at close to turbine conditions the system was initially set as an “open system”. Nominal conditions for these test runs were set at: Airflow rate - 0.7 kg/sec (limited by utilized compressor output), Pressure 7 Barg, outlet air temperature 700 ºC. In order to achieve the desired high pressure test parameters the system was closed with parameters set to: Air flow rate – up to 0.8 kg/sec, Pressure 15 Barg, 600 kW solar power at receiver’s aperture, with 470 kW output and maximum outlet air temperature that will not exceed the set safety limits.

Foundation tests: Are aimed to demonstrate the full power cycle with the turbine and electricity production. It will test the hybrid mode of the system and integration of sub systems. Nominal conditions are: Airflow rate - 1.5 kg/sec, Pressure – 7 Barg, outlet air temperature ~700 ºC. Tests at this mode were not performed yet and are not discussed hereunder.

A series of preliminary “cold” tests, started in November 2000. They were aimed at checking up the integration between the various sub-systems, the control program, the operating procedures and the safety and emergency procedures. These tests ended by the beginning of January 2001 after incorporating and verifying changes and modifications. “Hot” solar tests followed.

The original design parameters were based on the expected performance of the existing heliostats' field in WIS. Modified calculations that took into account the degradation of the heliostats’ mirrors over the years, have shown that only about 350 kW of the planned 640 kW at the entrance to the receiver could now be expected. It was therefore clear that the testing of the system at full power could only be concluded after renewal of the heliostats. This operation is headed by WIS and is expected to be completed by 2003. The following tests were carried out with the present heliostats’ field.

The following chapters include a review of the tests and the results together with conclusions and interpretation of the results. The results cover the period from November 2000 to November 1, 2001, when the latest CONSOLAR “Hot” test was carried out.

Test Runs and Results

The “cold” tests were the preliminary stage before entering the “hot” solar tests, and they concluded with “Warm” test runs that involve a small number of heliostats. 15 Cold tests in a “open system” mode started in November, 2000 and ended in January 2001. Three of the tests were "Warm" with some operating heliostats. During the cold tests, the System Operation Procedure was checked and revised and technical hardware problems were attended to and fixed.

By the end of the cold tests, the following goals were achieved:

- The system operated successfully at the SF flow regime conditions.
- The operation and control systems operated successfully.
- System integration with the heliostats field control was tested successfully.
- Pressure drop values were measured and found to be as low as predicted.
- The system reaction to faults was tested successfully.
- The system reaction to emergency conditions was tested successfully.
- Operation and safety procedures were tested and approved.

Figure 5 shows a general flow diagram of the open system. This system simulates the Foundation mode by replacing the turbine with a throttle valve that controls the system pressure.

Figure 5: Open System Flow Diagram

The “Hot” tests started in January 2001. Three test runs were performed. Receiver power of more than 200 kW and outlet temperature of 310 ºC (no preheat) were achieved. 13 to 42 out of 47 heliostats that were planned for the tests were engaged in the tests. Figure 6 shows the tower reflector as seen from the heliostats’ field with one solar spot advancing on the tower wall towards its position on the reflector. Figure 7 is a view from the tower down to the CPC aperture during the test.

Figure 6: The tower reflector during the tests.

Figure 7: A top view: The CPC (in the center) during a solar test as seen from the tower
Changes of piping were required in order to close the “open system” and were accompanied by some modifications. In May 2001 the “closed system” was ready for operation.

Figure 8 shows the general flow diagram of the CONSOLAR closed system. This system circulates the air from the compressor to the receiver and back through a series of heat exchangers allowing operation at high pressure.

Figure 8: CONSOLAR Closed System Flow Diagram

The CONSOLAR “closed system” test runs started with some cold tests that were aimed at checking the new modifications. Several Hot solar tests were performed. Outlet air temperature of 580ºc with preheating was achieved. Figure 9 is a typical test graph showing the course of SF-HOT-03 test. The test run started at 10:35. The first few stages of the test are preparatory stages that check the auxiliary systems and the emergency procedures, establish air flow and reach stabilization of the system, all according to preset test parameters. After 2 previous runs (HOT 1 and 2), this run was aimed at achieving maximum performance at given heliostats and solar conditions. The solar insolation was above 900 Watts/m^2. Heliostats were engaged gradually starting at 11:23. Outlet air temperature started to rise steadily and so was the receiver’s power. The outlet air goes through a recuperator before it is discharged outside, leading to temperature rise of the Hot inlet air. At 12:36, the receiver’s power reached 190 kW with outlet temperature of 277 ºC and 34 heliostats engaged. At this moment, an error in adjustment action of the control operator caused all the heliostats to shift from their position. This in turn moved the solar spot off the CPC center, causing an immediate fall in power and temperature. A quick response of the operator corrected the error and power/temperature recovered in 4 minutes with only a few kW of power loss.

More heliostats were engaged up to a maximum of 42 (of possible 47). Outlet air reached 322 ºC and receiver’s output power was measured at 216 kW without any preheating. Pressure along the test run was steady at 7 Barg.

Figure 9: Power and Temperature results of SF-HOT-03 test.

The quartz window's surface temperature is constantly monitored by an IR camera. A sample Thermogram and a close up visible light view of the window during one of the tests is shown in Figure 10.

Figure 10: A visible picture and a Thermogram of the quartz window during tests.

Receiver's Simulation

In parallel to the experiments, Computerized Fluid Dynamics (CFD) model simulations of the receiver were run. The simulations were designed to check the receiver's performances in various operational conditions that correspond to the CONSOLAR modes. The model was initiated during the 50 kW project period and developed further in preparation for the 500 kW receiver.
The main objectives of this simulation are:

1. Prediction of receiver's performances for various operational conditions.

2. Analysis and interpretation of experimental data, and

3. Checking the flow patterns in the Receiver, the window's temperature, the outlet temperature, and the pressure drop.

A schematic design of the simulated receiver is given in Figure 11. The chamber's geometry is described by a characteristic cross-section and represented in the simulation by an axi-symetric assumption. The chamber's inner edge describes the quartz window, and the outer edge consists of the receiving and the ceramic bed layouts. The working gas (air) enters the receiver through two parallel inlets. The first inlet – the cold stream – is located very near the quartz window and lets a relatively cold gas to enter. The cold gas prevents the window from reaching temperatures of over 800°C (1073K). The main inlet serves as an opening for relatively (preheated) hot gas.

The solar radiation that reaches the receiver's aperture is absorbed by the various receiving surfaces, the ceramic bed, the receiver's sidewalls, and the window. The working gas is heated as a consequence of heat exchange with these surfaces until it reaches the receiver's outlet.

Figure 11: Schematic of CFD and REXAN domain

For the definition of the flow field and the temperatures in the simulation we have defined a simulation using the following conservation equations: the mass, momentum, energy equation, the state equations, and the turbulence equation. The simulation is axisymetric and includes several physical aspects:

1. A hydrodynamic model for the resistance to the flow within the ceramic bed.
2. Gravitation.

3. Heat transfer through convection and conduction from the receiver's external shell.

4. Cooling the window's outer part with the “FUFU” air stream.

5. Turbulence is treated using a standard *High* $\varepsilon - k$Model.

6. The heat sources in the ceramic bed and the window are divided into three areas – Front, Middle, Back – each having a homogenous heat source.

7. The working gas behaves according to the prefect gas law when the temperature range is between 300ºK and 200ºK.

The radiation reaching the receiver's aperture from the heliostats field is given by a radiation simulation that was developed by Akiva Segal from the Weizmann Institute of Science. The radiation was calculated based on the actual recorded solar insolation, the time of the experiment (date and time), and the specific heliostats that took part in the experiment at that time.

The radiation reaching the ceramic bed and the radiation between the various surfaces within the receiver are calculated using the REXAN (Radiation EXchange in Axisymmetric eNclosure) code version 2.2 that is based on the Ray Tracing Technique. The code input receives radiation on the surfaces and provides thermal fluxes onto the same surfaces.

The receiver was simulated on the commercial CFD Simulation Package PHOENICS Version 3.2, with additional user supplied modeled – *diapr-ground* version 1.9.

An EXCEL spreadsheet is used for the interaction between the INPUT and OUTPUT of the PHOENICS Software until the solution converges.

The radiation reaching the receiver's aperture was individually calculated for each experiment according to the date, hour, and the heliostats. The nominal solar input for the major test runs was calculated between 112÷298 kW .

An identical qualitative behavior of flow and temperature patterns was observed in all cases tested in the simulation, Figure 12. This indicates that the receiver's temperature distribution is largely determined by the radiation that is reaching and reradiated by the surfaces and not by the stream convection. At those flow conditions the cold flow manages to move along the window without separation. The high temperature is reached on the ceramic bed near the outlet section.

Figure 12: Flow field for Case CO-HOT-09, velocity vector (in m/s) and fluid temperature (in ºK).

A comparison between the results obtained in the experiment and the simulation was made using three parameters: the window's temperature, the ceramic bed temperature, and the gas temperature at the receiver's outlet. The results show that the temperatures are lower in the experiment in all three parameters. This is particularly evident with the temperatures measured at the window and the gas outlet with a deviation of 30 ÷ 40 percents. A smaller deviation of 15 percents, i.e. between the simulation and the experiment is seen at the ceramic bed temperature. These phenomena were observed in all other experiments with similar rates of deviation.

For the working ranges that were checked in this simulation one can point out that:

1. The receiver is not very sensitive to changes in the flow rates or to changes in the temperatures of the flows entering it.

2. Working pressure has only a slight impact on flow and the receiver's temperature patterns.

3. The FUFU System has great significance in cooling the window.

4. Since the radiation entering the receiver was relatively low, the window did not reach temperatures exceeding 660°C in the experiments and the simulation.

Summary and Discussion

The main purpose of the solar tests was to demonstrate the performance of the solar receiver. Tests were conducted accordingly with pre-set operation parameters. The receiver system and its peripheral subsystems were operated successfully at low and medium solar inputs.

From the initial test results it appeared that the heliostats' field at WIS is not supplying the required power to the receiver. Revised calculations by WIS have shown that only about half of the planned 640 kW were available as input into the receiver on an optimal sun day conditions.

Output power of more than 210 kW and outlet temperature of 300 ºC (no preheating) were achieved in the "open system" mode at 7 Barg. Higher air temperature was achieved during the "closed system" set of test runs. Output power of 150 kW and outlet air temperature of 580 ºC were measured at 13 Barg. Maximum air pressure of more than 14 Barg was maintained throughout another test run.

CFD analysis was performed for all the major solar test runs. In general, all the analyses have shown higher values than the actual test measurements. This can be attributed to the following reasons:

1. The actual input energy into the receiver was significantly lower than the figure calculated by WIS. This assumption is supported by lack of well-established verification on the optical parameters inserted in the ray-tracing model. In addition, the accuracy of centering the solar spots on the CPC opening is not perfect and might need better alignment through the heliostats' control system.

2. Optical parameters of the receiver's components in the model were taken based on previous experience with the 50 kW receiver. Although they should generally be close to the 500kW receiver, some deviation could exist, leading to errors in the model results. Additionally, these parameters have possibly changed throughout the course of the test due to dust and loss of reflectivity. Final estimation of these deviations will be established when actual power measurements are carried out.

3. The CFD model is calculating the receiver at steady state conditions. In many of the test runs, the runs were aborted prematurely, due to control problems or precautionary shut down. It can be seen in the graphs of the results that hot air temperature and preheated inlet stream temperature have not completely stabilized. If steady state conditions were established, higher receiver temperature could have been reached and test to model deviation could have been smaller.

Generally, the simulation results show qualitative agreement with the test results. More studies of the correlation shall be done after another set of test runs, planned for this year, will be performed. A high power calorimeter was designed and is being manufactured in Rotem. The calorimeter will be installed in the receiver to allow actual power measurements of the radiation entering the receiver. These measurements will enable calibration of the ray tracing model in the existing heliostats' field and repeating the calculations for the CONSOLAR test runs. Moreover, WIS are now ordering new heliostats' mirrors that will be installed and ready by 2003. After completing the installation, CONSOLAR tests will be repeated at the higher power levels in order to demonstrate the receiver's operation in its original design envelope.

References

1. Kribus A., Zaibel Z., Segal A., Carey D. and Karni J., *A Solar Driven Combined Cycle Plant*, Solar Energy **62**, 121 (1998).

2. Radosevich L.G. and Skinrood A.C., *The Power Production Operation of Solar One: The 10 MWe Solar Thermal Central Receiver Pilot Plant*, ASME J. Sol. Energy Eng., **111,** 144 (1989).

3. Kelly B. and Singh M., *Summary of the Final Design for the 10 MWe Solar Two Central Receiver Project*, Solar Engineering 1995 ASME **1**, 575 (1999).

4. Buck R., Brauning T., Denk T., Pfander M., Schwarzbozl P., Tellez F., *Solar-Hybrid Gas Turbine-based Power Tower Systems (REFOS)*, J of Solar Energy Eng, **124**, no.1, 2 (2002).

5. Rabl A., *Tower Reflector for Solar Power Plant*, Solar Energy **18**, 269 (1976).

6. Kribus A, *High Concentration Solar Energy Optics*, Sun Day Symposium at WIS, May 1996 (1996).

7. Kribus A., Doron P.,Rubin R., Karni J., Reuven R., Duchan S. and Taragan E, *A Multistage Solar Receiver: The Route to High Temperature*, Solar Energy **67**, 3, (1999).

8. Sagie D., *The Development of a Volumetric Solar Thermal Receiver – An Overview*, IAEC Annual Report 1994, 25 (1994).

9. Miron G., Weis S., Anteby I., Taragan E., Sagie D., *Secondary Concentrator for a Commercial Solar Receiver System – Design and Evaluation*, The 27th Israel Conference on Mechanical Engineering, Technion, Haifa, Israel, May 19-20, 1998, 586 (1998).

APPENDIX O

ITAR

Review of ITAR/EAR Export Control Issues Related to Noor al Salam Project

James B. Blackmon
Research Professor
Department of Mechanical and Aerospace Engineering
University of Alabama in Huntsville
Huntsville, Alabama
February 13, 2004

Both ITAR and EAR Export Control regulations and documents were reviewed to ensure compliance with the Noor al Salam project.
The United States Munitions List (USML) – 22 DFR 121 was reviewed to ensure compliance with all ITAR-related Export Control laws and regulations. Only one category (Category XIII) relates in any way to the Noor al Salam project under the DOE Grant(Pre-Award Planning and Egyptian Engineer Training_DOE fg36-02g)12030). The category description for subheading (f) is given below in its entirety.

Category XIII -- Auxiliary Military Equipment

(f) Energy conversion devices for producing electrical energy from nuclear, thermal, or solar energy, or from chemical reaction which are specifically designed or modified for military application.

The EAR Commerce Control List (CCL –15 CFR 774) was reviewed. There is no category that relates to the solar power aspects of the Noor al Salam project . However, Category 1 – Materials, Chemicals, Micro-organisms and Toxins, was reviewed and no area was found that related to the subject technologies.

Conclusion

The production of electrical energy from solar energy that is the subject of the Grant (Pre-Award Planning and Egyptian Engineer Training_DOE fg36-02g)12030) is not specifically designed or modified for military application. The purpose of this Grant is to conduct a System Definition for a 10 to 20 Megawatt solar central receiver plant in Egypt, as a forerunner to commercial solar power production. The Grant involves:

- research and development of some aspects of solar electrical power using heated air,
- meetings between Department of Energy and other solar specialists with counterparts from the Egyptian New and Renewable Energy Authority, the U.S./Israel Science and Technology Commission, the U.S./Israel Science and Technology Foundation, the Weizmann Institute of Science, and
- an effort to involve a U.S. prime contractor.

No Category in the CCL relates to the technology of the Noor al Salam project.

Based on the review of the ITAR and EAR lists, there should be no “deemed export” of the subject matter during our meetings with Egyptian and Israeli representatives.

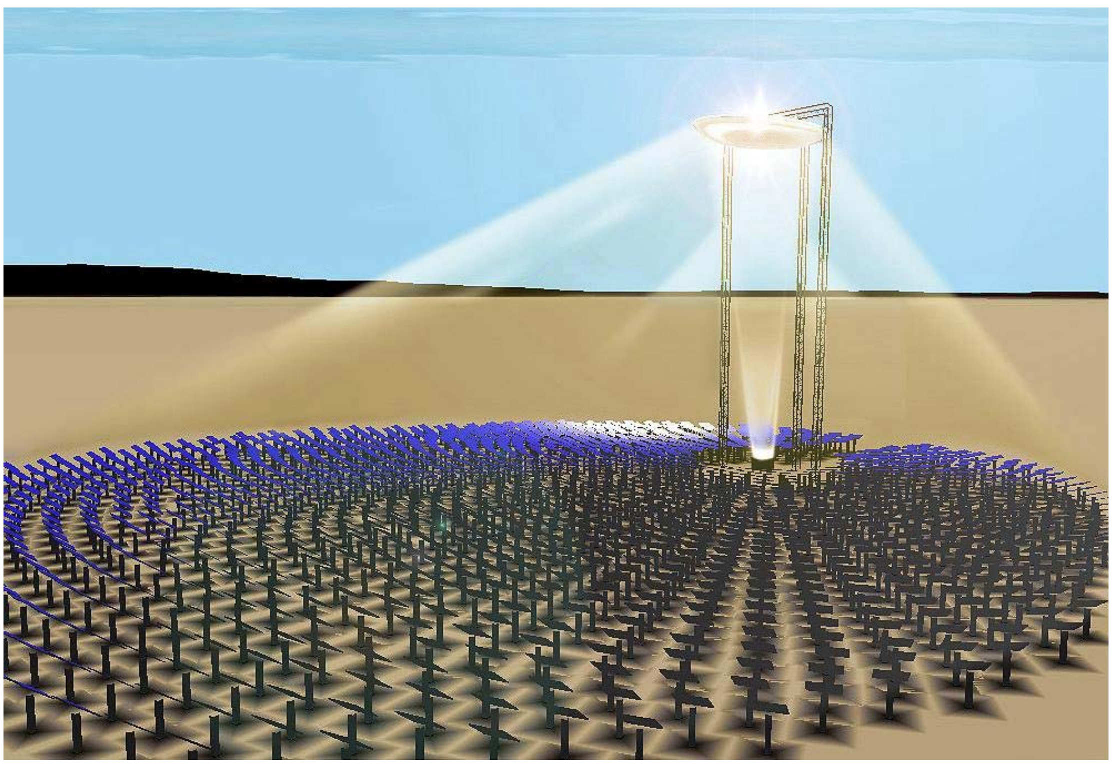
APPENDIX P

DRAFT SUMMARY OF SYSTEM DEFINITION AND ASSOCIATED REQUIREMENTS

DRAFT

NOOR AL SALAAM SYSTEM DEFINITION SUMMARY

General Requirements and System Architecture



DRAFT

NOOR AL SALAAM SYSTEM DEFINITION SUMMARY

General Requirements and System Architecture

Draft High Level Requirements:

1. **Provide substantial power from natural gas, with solar supplement, to better meet Egyptian needs**
2. **Provide hybrid solar and gas power under normal operational conditions**
3. **Provide option of producing power during night-time and inclement weather conditions, using natural gas (or alternatives) and possibly thermal storage (advanced technology);**
4. **Serve as both a power plant and as a research and development facility to evaluate system performance;**
5. **Offer versatility to allow for advanced technology evaluation.**

Basic characteristics:

Per the SOW, plant architecture is based on USISTF program:

- **o. Beam down optics (tower mounted reflector)**
- **p. Volumetric air receiver with secondary optics at the base of the tower**
- **q. Field of heliostats sized to provide high optical quality and low off-axis aberration**

Reflected energy from the heliostat field of 10 Megawatts thermal (or greater) at solar noon on the Summer Solstice for the solar conditions at Zaafarana.

Optical system will have the concentration ratio, efficiency, configuration, and size appropriate for commercial solar hybrid systems in this size range.

General Requirements and System Architecture

Basic requirements (Continued):

A 10 to 20 Mwe simple gas turbine will be used, with the ability to be interfaced to a Rankine bottoming cycle (steam and/or organic) at some later time to operate as a Combined Cycle Gas Turbine.

System will incorporate design flexibility to later add promising options such as:

- **r. high temperature phase change thermal storage;**
- **s. spillage thermal energy collection (for other ancillary uses);**
- **t. larger tower reflector area (of the order of 10% to 15%);**
- **u. additional heliostats (of the order of 10% to 15% additional area);**
- **v. steam injection to the turbine;**
- **w. absorption cooling for turbine inlet air temperature control; and**
- **x. such other subsystems as shall provide for potential improvements by use of additional hardware or revisions to the operation.**

General Requirements and System Architecture

Basic requirements (Continued):

System versatility accommodates other advanced technologies such as:

- **y. concentrating photovoltaics or solar thermal collectors for spillage collection;**
- **z. biogas use with the turbine;**
- **aa. synthetic fuel formation using solar energy;**
- **bb. expert system control of the plant with minimal human operator requirements;**
- **cc. expert system communication to remote operators**
- **dd. internet access for access by researchers throughout the world;**
- **ee. advanced heat exchangers;**
- **ff. advanced technology receivers;**
- **gg. Organic Rankine systems for waste hear recovery and power production: and**
- **hh. ancillary applications such as desalination and water purification using waste heat.**

General Note

- **ii. The Noor al Salam plant would be the world's largest solar research and power plant facility for high concentration technologies in the world**
- **jj. Much of the USISTF design and related technology is patented, thus affording competitive advantage to participants**

General Requirements and System Architecture (Continued)

Purpose of NAS system versatility is to:

i. **Provide Egypt, the commercial partners, and solar researchers throughout the world with a first class facility for advancing the state of the art, while helping to meet Egypt's goals for renewable power production.**

ii. **Plant will be designed such that it does not preclude eventual use of additional technologies, such as:**
   a. **building housing the turbine would be located, sized, and designed to accommodate the bottoming cycle;**
   b. **sufficient space and access would be provided for a phase change thermal storage system;**
   c. **office building over-sized and configured to allow for growth in number of personnel;**
   d. **options for ducting the compressor outlet through the receivers will be provided, such that partial or full parallel flow can be used;**
   e. **tower design allows for positioning the tower reflector at various heights, with additional reflector facets, ability to cant reflector to reflect concentrated sunlight onto test areas adjacent to the CPC aperture;**
   f. **tower design allows for additional hardware to be mounted at varying positions (reflectors, receivers, etc.);**
   g. **ability to vary the flux distribution at the CPC aperture;**
   h. **heliostat field configured such that additional heliostats can be added;**
   i. **CPC aperture area configured so that the cover could be used to not only protect the CPC/receivers, but also serve as a target for one or more beams, for optical beam characterization purposes;**
   j. **area beneath the tower sized to accommodate additional subsystems and components.**

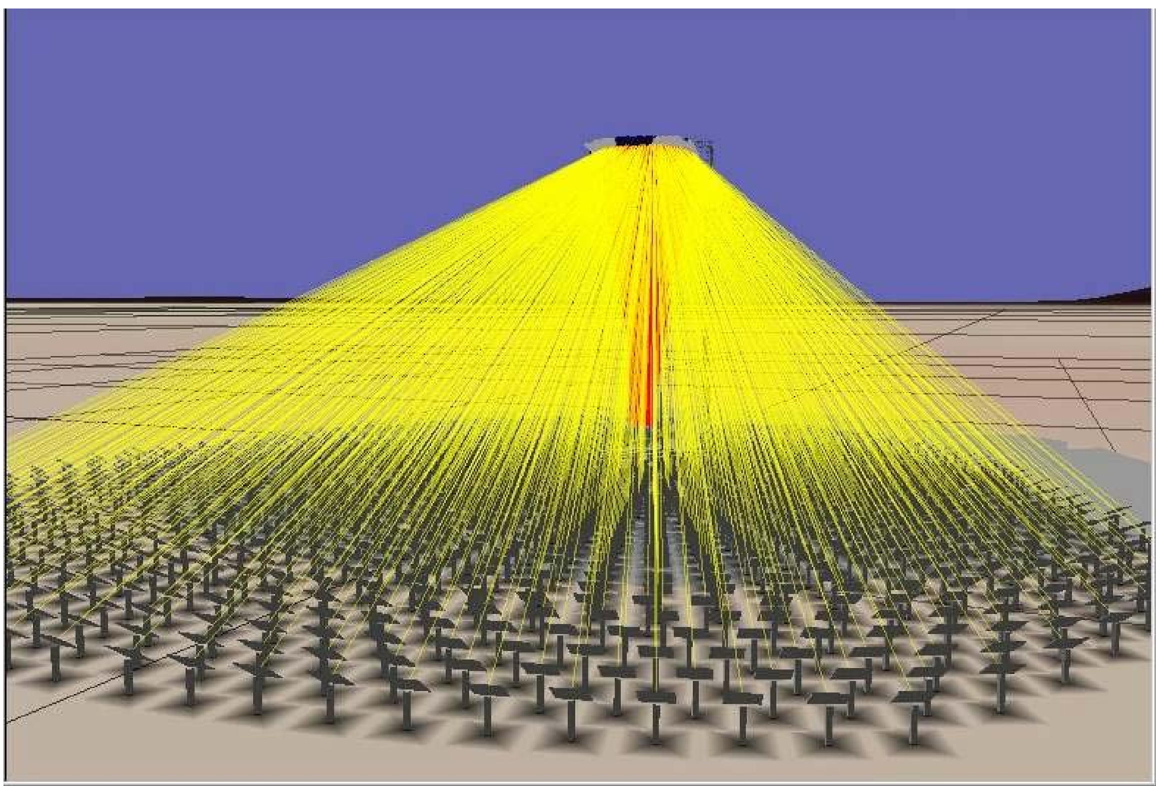
SYSTEM OPTIMIZATION

RCELL

The overall full system optimization code developed in the late 1970s and early 1980s at the University of Houston would be used to develop an optimized field layout relative to the beam down optics of the tower mounted reflector. Input data would be provided for cost estimating relationships, output power, etc.

SOLARSIM

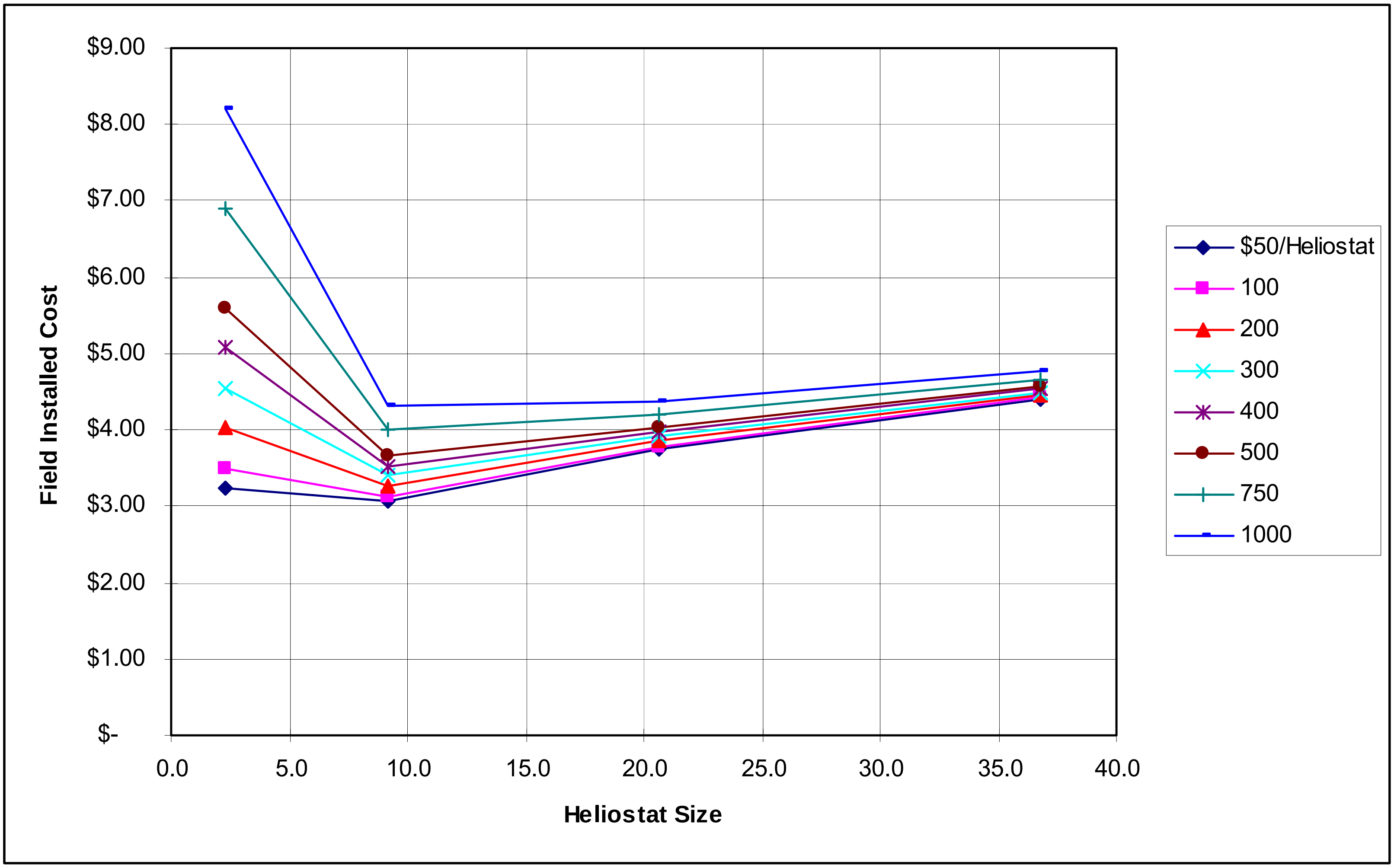
An animated graphics CAD based computer program would be used to layout the field and determination of the optics of the systm One such code used for USISTF is SOLARSIM. A screen shot of SOLARSIM is given below, showing selected rays from each heliostat. Ray traces are based on the McDonnell Douglas CONCEN code. SOLARSIM uses location data for the heliostats and tower/tower reflector, together with error data for the reflectors, and CAD drawings of the heliostats and reflector, etc., to determine actual flux distributions at any location and time.



Heliostat Design
<u>General</u>

Design Requirements:
(Based on over 30 years of similar requirements for various DOE programs)

- **Operate (Track) during wind speeds of 35 mph**
- **Operate (slew) during wind speeds of up to 50 mph**
- **Position heliostat into stow during wind speeds above 50 mph**
- **Support wind loads generated at 90 mph**
- **Obtain and maintain positional accuracy of 1.5 mRad in winds up to 10mph and 2.0 mRad in winds up to 35 mph**
- **Be self-locking under back-driving conditions**
- **Sustain a 30 year life under outdoor conditions**
- **Sized to provide high optical efficiency and minimum overall cost of the heliostat field**



The optimum heliostat size is determined by factors such as the optical requirements, especially the concentration ratio required, size of the plant, capital costs on a per area basis, installation costs per heliostat, and to a lesser extent by the field layout. In the above, the cost per heliostat is provided as a set of curves for a range of installation costs indicating that a smaller heliostat offered some potential cost advantages for the High Concentration Solar Central Receiver System. The resulting USISTF 9.2 m^2 heliostat developed by McDonnell Douglas is shown below.

Heliostat Design

<u>Drive Unit</u>

Manufacturability Requirements:
(Based on low cost manufacturing in Egypt with minimum investment in special tools, facilities, etc.)

- **Majority of components available off the shelf**
- **Minimum or no custom components required**
- **Housing formed from welded plate stock**
- **Easily assembled with low-cost manual labor**
- **Minimal special tooling investment required**
- **Fabricated with standard machine shop tools**
    - **(Shears, breaks, mills, lathes, etc.)**
- **Production in Egypt of essentially entire azimuth drive unit**
- **Off the shelf procurement of elevation drive unit (e.g., tracking TV Dish actuator)**

Design Features:

- **Compact dual shaft multistage gear reduction**
- **High efficiency chain/sprocket drive**
- **Easily assembled and repaired**
- **Fail operational mode with dual output drive chain**
- **Low cost, off the shelf, commercially available chains, sprockets, bearings, gear motor**
- **Proven hermetic seal under long term exposure (Alabama, five years, rain, temperature extremes, etc.)**
- **Patented design protects commercial partners and enhances competitive position.**

Heliostat Design

<u>Reflector</u>

Design Requirements:

- **Similar to Drive Unit Requirements and Typical DOE Requirements**

Manufacturability Requirements:

- **Minimum Investment in Tooling Required**
- **Hand lay-up of fiberglass with semi-skilled labor**
- **Five curved reflector tools with one reflector per day produce the needed number of heliostats in approximately one year**
- **Fabrication proven with first reflector; additional work in progress on second, improved reflector**

Design Features:

- **Very high compressive loads "built-in" to the glass to resist breakage**
- **Sealed edges using combination of low cost resins***
- **High optical efficiency with very low off-axis aberration achieved by:**
  - **use of five radii of curvature and**
  - **approximately 10 m^2 area heliostat**

*** One of the polyester fiberglass coupons exposed for approximately 10 years showed no visible edge intrusion or corrosion; a second showed no edge intrusion or corrosion over approximately 8 years. However, the full-size heliostat had edge intrusion after approximately 1 year of field exposure. The reason for this is conjectured to be due to a combination of inadequate cleaning and a lower pressure achieved by the vacuum pump during cure. Additional efforts to ensure integrity are recommended.**

Heliostat Design
Foundation/Pedestal

Design Requirements:

- **Similar to Drive Unit Requirements and Typical DOE Requirements**

Manufacturability Requirements:

- **Minimum Investment in Tooling Required**
- **Pedestal Fabrication from Commercially Available Steel Pipe, Welded Flange**
- **Foundation Formed from Rebar Cage, J-Bolts, Concrete**
- **Augered Hole Assumed Appropriate for Zaafarana (to be verified, depends on type of soil, bearing strength, etc.)**

Design Features:

- **Rebar cage easily formed with low-cost labor (cut pieces of rebar hand assembled and arc welded)**
- **Tractor Mounted Auger easily forms hole**
- **Four foundations formed and installed (Three in Alabama, one at Weizmann Institute)**
- **Pedestal with Drive Unit Quickly Erectable by Two – Three Men without Special Assembly Equipment**


N114A

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

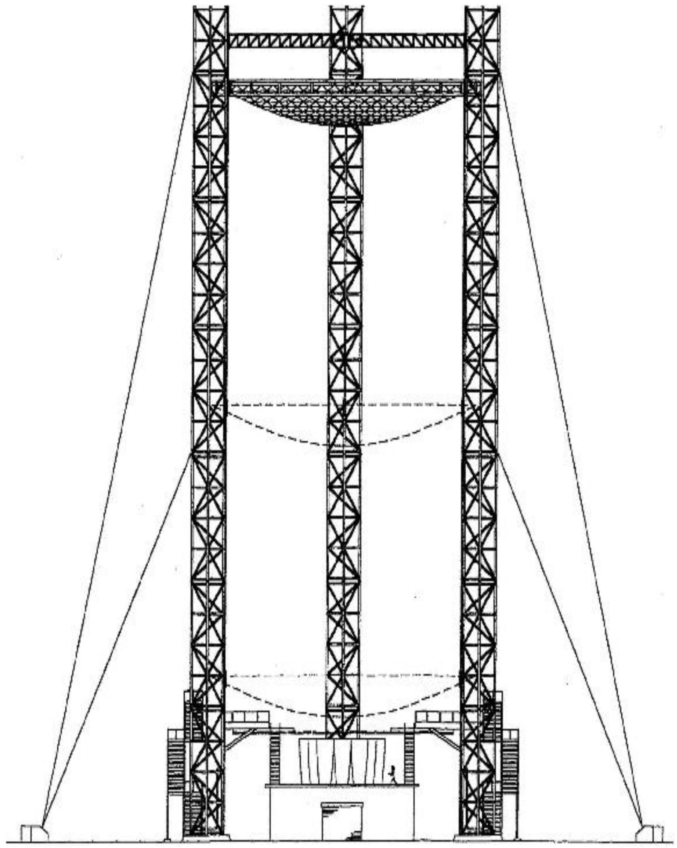
Basic Design Requirements:

•Environmental conditions include winds and gusts, temperature extremes, rain, snow, hail, airpollutants, animal and insect exposure, and earthquake conditions

• Wind velocities: $V_h = V(10m) \times [H(h)/H(10m)]^{0.15}$•Operational: 0 - 50 mph (at 68 m height) - 35 mph at 10m
• Survival: 120 mph (at 68m height) - 90mph at 10m
• Sandstorm environment
• Air temperature range: -30C to 55C
• Rain: Max for 24 hours: 75mm
• Ice: Freezing rain may deposit ice in a layer up to 50mm thick
• Hail: 25mm diameter, e.g.=0.9, 20m/s any direction
• Snow: Max 24 rate: 0.3m (1 ft); max loading 250Pa (5 lbs/ft^2)
• Earthquake: seismic zone: TBD
• Corrosive environments: TBD•Solar Irradiance:
•Peak incident flux from heliostats: TBD (30-50 kW/m^2 , steady state)
• Backside of reflector exposed to 1 sun

A basic design developed after consideration of over ten different options is provided below.

Tower/Tower Reflector



The preferred tower reflector support structure was an easily assembled Geodesic dome, shown below. Such structures have spanned several hundred yards and can withstand high winds.

Geometrica Geodesic Dome Support Structure Test Article, with Tower Reflector Facet

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements (Continued):

- **Reflectivity**
  - **Under normal operational usage with periodic cleaning, the average reflectivity shall be at least TBD. Clean new facet reflectivity should exceed TBD within a 1-mrad cone integrated over the incident spectrum. Surface degradation rate shall be minimized consistent with a 30 year mirror life**
  - **Surface waviness shall be < TBD mrad (expect less than 1 mr, based on prototype performance)**
  - **Reflective Surface Deflections under operational wind load: Facets and their supports shall be designed to prevent reflective surface deflections from exceeding TBD mrad**

- **Alignment:**
  - **Digital Image Radiometer Video System, Mounted on Tower, with Backside Flat Glass Reflectors on Facets**

- **Thermal Management**
  - **Cooling of Tower Reflector Facets with Option for Waste Heat Recovery and Sale**

- **Assembly**
  - **Easily assembled in remote areas without special equipment**

Note: The TBD Reflectivity is likely to be of the order of 92%.

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements (Continued):

Manufacturability Requirements:

- **Fabrication with Low Cost Tooling**
- **Fabrication from Commercially Available Stock**

- **High Optical Performance Achievable Without High Cost Tooling or Processing**

Design Characteristics:
<u>TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)</u>

<u>Basic Design Requirements (Continued):</u>

- **Welded Stainless Steel Facets**
- **Glass Bonded to Stainless Steel**
- **Heat Exchanger Heat Recovery Offers Option for Offsetting Tower Cost with Sale of Power (Process Heat, Organic Rankine Cycle, etc.)**
- **Successfully Tested at High Heat Flux and Exposed in the Field for Four Years**
- **Easily Aligned to Meet Required Flux Distribution at the Aperture of the CPCs (Similar to Proven 25 Kwe Dish Stirling Concentrator with Patented Digital Image Radiometer Alignment System)**

TOWER SUBSYSTEM (TOWER, TOWER REFLECTOR SUPPORT STRUCTURE AND FACET)

Basic Design Requirements (Continued):

- **Ancillary Hardware**
  - **Spillage Collector/Waste Heat Recovery/Target/Enclosure:**

    - **A movable pair of panels can be moved across the CPC aperture to protect the CPCs and Receivers from rain, dust, debris, etc.**

      - **This enclosure also serves as a Beam Characterization System (BCS) target.**

    - **Waste Heat Recovery System**
      The tower reflector facets, CPCs, and the Spillage Collector/Target Enclosure are cooled with a water/ethylene glycol mixture. The heat recovered can be used

in an Organic Rankine Cycle to produce additional power, or used with heat exchangers to provide process heat, at approximately 80 to 120C or higher, depending on detailed
design conditions.

DIGITAL IMAGE RADIOMETER (DIR) BEAM CHARACTERIZATION AND ALIGNMENT SYSTEM

- **DIR is a patented method for aligning mirrors and determining the flux distribution of solar radiation incident on a target**

- **DIR hardware includes a modified video camera, lens, digitizer, computer, and pinpoint light source panel.**

- **Camera and light source panel is mounted above the tower reflector. Reflected light from the mirrors on the back of each panel is analyzed to determine the angular error of each facet, and the corrections required.**

- **DIR is a proven system used to rapidly align the McDonnell Douglas/SES Dish Concentrator to within +- 0.1 milliradians.**