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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Transportation

*Solar Dish Concentrator with Stirling Engine* is the final report for the SMUD ReGen project (Contract Number 500-00-034), conducted by Science Applications International Corp. The information from this project contributes to Energy Research and Development Division’s Renewable Energy Technologies Program.

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ABSTRACT

Science Applications International Corporation produced a 22 kilowatt hybrid solar dish/Stirling power system by upgrading an existing solar dish concentrator system with advanced, fixed-focal length mirror facets and an STM Power Beta Stirling engine (a precursor to commercial production units). This hybrid system operates on a combination of natural gas and solar energy to produce full power under all solar conditions. The system was operated for ten months to characterize its performance and to measure and demonstrate its reliability. The system operated over 780 hours in solar hybrid mode and delivered 14.3 megawatt hours of energy during that period. It also operated 315 hours in gas-only mode, delivering 5.5 megawatt hours of energy.

Science Applications International Corporation also designed and fabricated advanced fixed-focal length mirror facets for integrating with an advanced concentrator photovoltaic receiver that was developed and tested under a separately-funded program.

The demonstration of a hybrid solar dish/Stirling system provided a dispatchable, efficient system that can be employed in various markets as a viable alternative for solar power production in California. The demonstration of the advanced photovoltaic mirror facets supported the development of dish/photovoltaic systems that can be efficient and low-cost alternatives to flat-plate and other concentrating photovoltaic power systems.

**Keywords:** Solar dish concentrator system, Stirling engine, solar hybrid, mirror facets, PV, photovoltaic

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EXECUTIVE SUMMARY

Introduction

Science Applications International Corporation (SAIC) has been developing solar concentrating dish technology as a contractor to the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories since 1984. SAIC developed and operated four prototype 22 kilowatt (kW) solar dish / Stirling systems. The SAIC dish concentrator is a large steel structure about 50 feet (15 meters) in diameter mounted with mirror facets. The structure is supported atop a pedestal on a gear drive that provides azimuth and elevation rotation for tracking the sun.

The primary barriers to more widespread use of dish / Stirling systems have been low system reliability and high cost. The stretched-membrane mirror facets were difficult and expensive to produce and were optically less effective than desired in prior SAIC dish concentrator systems. The Stirling engines used to date have not displayed high reliability, due in part to their complexity and to the variation in operating conditions dictated by solar operation. Developing and demonstrating improvements to both the dish and engine are needed if these systems are to be a viable commercial product.

A related technology is concentrating dish / photovoltaic (PV) systems. No United States company currently manufactures a large concentrating dish / PV system. Although flat-plate photovoltaic systems are technically proven in non-concentration applications, they are not currently cost-effective in large-scale utility grid applications because of the cost of large areas of PV panels. NREL believed that a PV concentrating system could achieve 18 percent solar-to-alternating current (AC) power efficiency and in the next few years could achieve 30 percent efficiency or higher. A concentrating dish / PV system achieves cost reductions using a small array of efficient PV cells and a low-cost concentrator. The potential of these systems needed to be demonstrated.

Project Purpose

The overall goal of this project was to integrate the proven SAIC solar concentrating dish with a STM Power Beta Stirling engine to create a solar hybrid dish / Stirling system suitable for commercial use in California. The SAIC dish concentrator is a large steel structure about 50 feet (15 meters) in diameter mounted with mirror facets. The mirrors on the concentrator needed to be upgraded to an advanced, fixed-focal length mirror facet design. Prototype facets were produced for the dish / Stirling system and for a solar dish / PV system designed to integrate with a 20 kW PV receiver.

The specific technical and economic objectives of this project were:

- Demonstrating the design and fabrication of SAIC advanced fixed-focus facets by producing prototype facets for the hybrid dish / Stirling system and for a dish / PV system.
• Upgrading the controls of the SAIC concentrator to accommodate fixed-focus facets, incorporating a fast, off-track system, and modifying the tracking algorithms.

• Integrating the STM Power Beta Stirling engine with the dish system to create a hybrid solar power system, and upgrading the controls of the STM Power engine to improve performance and operability.

• Operating the hybrid dish/Stirling system for several months and gathering operational, efficiency, and reliability data.

• Installing and operating a demonstration solar dish/Stirling system in Sacramento to characterize performance and demonstrate reliability.

**Project Results**
The requirements of a dish/Stirling and a dish/PV system with advanced fixed-focus mirror facets were identified, and specific design changes to the existing SAIC dish concentrator were developed. An existing SAIC dish system was upgraded and integrated with an improved Stirling engine to form a hybrid solar dish/Stirling system. The system was operated over several months and operational and reliability data were collected. Figure 1 shows the solar hybrid dish/Stirling system in operation.
The project had the following primary outcomes:

- Demonstrated the SAIC advanced fixed-focus mirror facet concept by successfully producing and testing facets for both a dish / Stirling and a dish / PV system.
- Demonstrated the integration and operation of a hybrid solar dish / Stirling power system for electric power generation, and demonstrated improved reliability of this system compared to prior systems.
Operated the system in solar hybrid mode more than 780 hours over ten months of testing, delivering over 14.3 megawatt hours (MWh) of electrical energy. Operated in gas-only mode for 315 hours, delivering 5.5 MWh of energy. The overall system efficiency reached 18 percent in hybrid solar mode and 21 percent in gas-only operation.

The objective of installing a system in Sacramento was not met because insufficient operational hours to demonstrate reliable operation were achieved. The project team decided to make additional system improvements and operate the system several more months at its initial location in Tempe, Arizona to demonstrate reliability and achieve operational success.

Some key features of the final prototype hybrid solar dish / Stirling system included:

- Optimized, advanced mirror facets, which provided design flexibility, high optical quality, and low production cost.
- Multiple-speed direct current tracking control with high-speed off-track. High-speed slew decreased the time needed to come on-sun or go off-sun, and the low-speed tracking mode increased the accuracy of the tracking system.
- Autonomous operation controls that operated without operator intervention or input, except to enable and disable operation.
- The output of this system was fully dispatchable 24-hours-a-day. The uniform operating environment enhanced the reliability of the Stirling engine.
- A low-cost borosilicate window with sweep air blower. The window sealing the receiver cavity was a relatively low-cost item. A small blower provided sweep air across the window that kept it cooler and cleaner and provided backpressure to reduce exhaust gas leakage.
- The STM Power Beta engine incorporated many improvements designed to increase reliability and reduce production costs, including a fixed swashplate, mechanically-driven oil and water pumps, and a simplified fuel train for the natural gas burner system.

The conclusion from the main portion of this project was that a hybrid solar dish / Stirling system could be integrated and operated to produce power for a utility grid. The system developed in this project operated mainly in an unattended, autonomous manner.

This project also demonstrated the promise of SAIC’s advanced fixed-focus mirror facet and fast off-track system protection for solar concentrators. The advanced mirror concept allowed a designer maximum flexibility to produce any desired configuration of solar flux on a receiver by adjusting the aimpoint of each mirror tile on the concentrator individually. The mirror facets are produced by an automated robotic system controlled by a computer, so the desired design is implemented without human error and at low cost. The advanced
mirror concept is especially useful for systems in which the solar flux must be carefully tailored to the receiver, as in dish / PV systems.

This project has significantly enhanced the potential for commercializing utility-scale and distributed power solar power systems. SAIC has demonstrated a new solar thermal power system previously unavailable to utilities and power generators, and has improved the cost-effectiveness of that system by reducing its production and operating costs and improving its performance. In addition, the commercialization of dish / Stirling and dish / PV systems has been advanced by the successful demonstration of the SAIC advanced mirror facet system.

This project proved that the solar concentrating dish, tracking system, and controls were technically successful and reliable. They also have the potential of being cost competitive in commercial production. The Stirling engine receiver did not accomplish the same results. Development is continuing on Stirling engines as well as high concentration photovoltaic receivers and Brayton engines. The authors recommend that a project integrating these technologies with the proven solar dish concentrator be supported as soon as one of these receiver options shows success in the research and development phase.

The commercialization path for solar hybrid dish / Stirling systems is from demonstration to pre-commercial application to full commercial system sales. The next step would be to implement a pre-commercial project to allow economies of scale and to demonstrate long-term operation. A 1 to 2 MW project consisting of 50 to 100 systems would be an appropriate size. Such a project could be implemented by providing economic incentives to a utility or commercial entity to allow them to justify the risk of the new technology.

**Project Benefits**
California will benefit if the results of this project become widely used. Further development and implementation of these systems would result in job growth and economic activity in the state since SAIC production and engineering facilities are based in California. Widespread use of these systems in California would reduce pollution and increase the sustainability and stability of the state’s electric generation system. Increased energy security would be achieved by increasing the use of distributed energy from solar power, reducing the need to import energy.
Chapter 1: Introduction

1.1 Background and Overview

Since 1984, Science Applications International Corporation (SAIC) has been developing solar concentrating dish technology as a contractor to the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories. SAIC developed and has operated four prototype 22 kilowatt (kW) solar dish / Stirling systems. Two are located in Tempe, Arizona, in partnership with Arizona Public Service and Salt River Project, another is located in Las Vegas in connection with the University of Nevada, Las Vegas, and the fourth was located at NREL in Golden, Colorado. The SAIC dish concentrator is a large steel structure about 50 feet (15 m) in diameter on which mirror facets are mounted. The structure is supported atop a pedestal on a gear drive that provides azimuth and elevation rotation for tracking the sun. Figure 1 shows the SAIC dish / Stirling system that was developed in this project in solar hybrid operation.

The primary barriers to more widespread use of dish / Stirling systems have been low system reliability and high cost. In the prior SAIC dish concentrator systems, the stretched-membrane mirror facets proved to be difficult and expensive to produce, and are optically less effective than desired. The Stirling engines that have been used to date have not displayed high reliability, due in part to their complexity and to the variation in operating conditions dictated by solar operation. Development and demonstration of improvements to both the dish and engine are therefore needed if these systems are to be a viable commercial product.

A related technology is concentrating dish / PV systems. No United States company currently manufactures a large concentrating dish / PV system. Although flat-plate photovoltaic systems are technically proven in non-concentration applications, they are not currently cost effective in large-scale utility grid applications because of the cost of large areas of PV panels. The National Renewable Energy Laboratory believes that a PV concentrating system currently can achieve 18 percent solar-to-alternating current (AC) power efficiency and in the next few years can achieve 30 percent efficiency or higher. A concentrating dish / PV system achieves cost reductions using a small array of efficient PV cells and a low-cost concentrator. However, the potential of these systems needs to be demonstrated practically.

1.2 Project Objectives

The primary objective of this project was to address the barriers to widespread use of dish / Stirling systems by making improvements to both the present SAIC dish concentrator and the engine system and demonstrating the operation of the resulting system. The integrated system operates in a solar-gas hybrid mode where natural gas energy is used to supplement solar input. Hybrid operation provides a uniform operating environment for
the engine, enhancing its reliability, and provides the ability to produce rated power at all times.

A secondary objective was to demonstrate the production of mirror facets suitable for a dish / PV system. SAIC is integrating a PV receiver with their proven solar dish concentrator under a separately-funded project at the University of Nevada, Las Vegas (UNLV) to produce a cost-effective and reliable concentrating PV system for future implementation.

Specific objectives of this project were as follows, based on the task structure of the project:

**Task 3.8.1 Dish / Stirling System Design and Integration**

The objective of this task was to develop complete integration requirements for the hybrid dish / Stirling system.

**Task 3.8.2 Dish / Stirling System Installation and Operation**

The objective of this task was to integrate and install the Stirling engine with the dish system and operate the resulting system for six months.

**Task 3.8.3 Dish / PV System Design and Integration**

The objective of this task was to develop complete integration requirements for a dish / PV system.

**Task 3.8.4 Dish / PV Mirror Facet Fabrication**

The objective of this task was to fabricate fixed focal length mirror facets for a solar dish / PV system to be tested with a dish / PV system under a separate program.

**Task 3.8.5 Demonstration System Selection and Site Design**

The initial objective of this task was to evaluate and identify a site in Sacramento for installation of the dish / Stirling system after Phase 1 testing. This was changed to be a report detailing recommendations for continuation of activities into the Phase 2 of the project.

**Task 3.8.6 Site Installation and Operation**

Originally, this task was to have included the installation of a system at a site in Sacramento and operation of that system for nine additional months. After the re-scoping of the Phase 2 efforts, this task was changed to include limited improvements to the system and six more months of operation of the system at Tempe, Arizona.

### 1.3 Report Organization

This report is organized as follows:

Section 1.0 Introduction.
Section 2.0 Project Approach presents the approach and methodology that SAIC has used to perform the development work in this project. This includes the design and implementation of fixed-focus mirror facets and improved controls on the dish concentrator and the integration of the STM Power Beta engine system with the dish to create a hybrid dish/Stirling system. The approach is presented in terms of the task structure that was used in the project.

Section 3.0 Project Outcomes explains the outcomes and results of the project activities. The implementation of the fixed-focus mirrors and control improvements on the dish concentrator, the integration of the STM Power Beta engine, and the operation of the hybrid dish/Stirling system are detailed. The design and production of PV mirror facets are also described.

Section 4.0 Conclusions and Recommendations outlines the conclusions drawn, benefits to California, recommendations for future steps and the commercialization potential for the hybrid solar SAIC dish/Stirling system.
Chapter 2: Project Approach

System design and integration were performed for the hybrid solar dish / Stirling system. The identified improvements were implemented on an existing SAIC solar dish concentrator in Tempe, Arizona, and a STM Power Beta engine was installed on the system. The system was operated for four months in Phase 1, followed by six months of operation in Phase 2, during which time its performance was characterized and measured.

The system requirements for integration of a PV receiver were evaluated and PV facets were produced and shipped to UNLV for testing with a dish / PV system being developed there under another program.

The following sections detail the approach that was used in each task of the project.

2.1 Task 3.8.1 Dish / Stirling System Design and Integration

The objective of this task was to develop complete integration requirements for the hybrid dish / Stirling system. First, the changes to the dish system required for the new Stirling engine were evaluated. Designs were prepared to modify the existing SAIC controls and mechanical structure to accommodate the new Stirling engine. A design for fail-safe off-tracking was also developed, based on multi-speed direct current (DC) motors driven by uninterruptible power supplies. Complete specifications and design drawings for the proposed modifications were produced.

2.2 Task 3.8.2 Dish / Stirling System Installation and Operation

The objective of this task was to integrate and install the Stirling engine with the dish system and operate the resulting system for six months. This involved fabrication of the advanced fixed-focal-length mirror facets; purchase of DC motors and drive components for upgrading of the dish tracking system to accommodate the fixed-focus mirrors; purchase of the hybrid Stirling engine; installation and checkout of all components on an existing SAIC dish at the APS test facility in Tempe, Arizona; and initial operation of the completed system. Figure 2 shows the fabrication of the mirror facets at the SAIC production facility and Figure 3 shows the installation of the DC drive components in the control cabinet at APS.
Figure 2. Mirror facet production equipment

Photo Credit: SAIC

Figure 3. DC drive components installed in dish control cabinet

Photo Credit: SAIC
2.3 Task 3.8.3 Dish / PV System Design and Integration

The objective of this task was to develop complete integration requirements for a dish / PV system. This included evaluation of the changes to the dish system required for a PV receiver and for fixed-focus mirror facets, preparing designs to modify the existing SAIC controls and mechanical structure to accommodate the PV receiver, and investigation and development of secondary optics and receiver protection techniques. After that, complete specifications and design drawings for the proposed modifications were made.

2.4 Task 3.8.4 Dish / PV Mirror Facet Fabrication

The objective of this task was to fabricate fixed-focal length mirror facets for a solar dish / PV system to be tested under a separate contract with NREL. This included purchase of the materials and fabrication and assembly of the materials into the desired facet configuration. Figure 4 shows the completed facets on the dish / PV system at the University of Nevada, Las Vegas test site.

Figure 4. Advanced PV mirror facets on UNLV dish system

Photo Credit: SAIC; Photo Credit: NREL
2.5 Task 3.8.5 Demonstration System Selection and Site Design

The initial objective of this task was to evaluate and identify a site in Sacramento for installation of the dish/Stirling system after Phase 1 testing. Due to integration delays, the system was not operated for as long as desired in Phase 1 to demonstrate reliability and measure system performance. At the critical project review, it was decided that the tests had not yet demonstrated high enough reliability to allow for installation of the Sacramento system. Therefore, the deliverable was changed to be only the first subtask of this task—a report detailing recommendations for Phase 2 of the project.

2.6 Task 3.8.6 Site Installation and Operation

Originally, the objective of this task was to have been the installation of a system at a site in Sacramento and operation of the system for nine additional months. After the re-scoping of the Phase 2 efforts, this task was changed to include specific improvements to the dish and engine system to improve performance and reliability, and then up to six more months of operation of the system at Tempe, Arizona. A test plan was created to direct the operations, and several incremental enhancements were undertaken to improve system efficiency and reliability.
Chapter 3: Project Outcomes

The overall outcome of this project was the successful system integration and operation of a hybrid solar dish/Stirling system and the design and fabrication of facets for a dish/PV system. SAIC made significant improvements to their solar dish concentrator which has shown very good reliability and potential low cost in mass production, by implementing lower-cost fixed-focus mirrors and the tracking and control changes needed to accommodate those mirror facets. SAIC then integrated the improved dish with the new STM Beta Stirling engine that has the potential to be the most reliable Stirling engine in the 22-kW size range. The result was the demonstration of a hybrid solar dish/Stirling system that operates with improved reliability, meets performance goals, and is ready to be commercially deployed in megawatt-scale solar farms and distributed applications in California and the desert Southwest. When mass-produced, costs can be reduced to be competitive for the California grid market when considering the environmental and renewable nature of the technology. Hybridization of the solar package means that the system is fully dispatchable to utility owners, giving full power day or night when called upon to produce. The uniform operating environment maximizes the reliability of the Stirling engine by reducing transient and off-optimum operating points.

The following subsections detail the results of the project, based on the task structure of the project. A summary of the accomplishments in the project is presented below:

- Produced advanced fixed-focus mirror facets for both a solar thermal (dish/Stirling) and a solar dish/PV system for testing. This demonstrated the potential for designing custom mirrors for different applications and fabricating them using the SAIC robotic system in a cost-effective and efficient manner. The mirror facets produced in this program were demonstrated to be better optically than the stretched-membrane mirrors they replaced and to have more flexibility in design due to the computerized, robotic assembly system.

- Upgraded the control hardware and software of the SAIC concentrator to accommodate fixed-focus facets, incorporating a fast off-track system and changes to tracking algorithms. With a fixed-focus dish, the fast off-track system is necessary to provide safety to the Stirling engine receiver when a fault occurs. It provides additional benefits in speeding up the slewing process to and from stow position during normal operation and in case of high winds. Testing indicated that a DC motor, rather than an AC motor, provided the slewing speed desired. These changes made the dish concentrator faster in tracking on- and off-sun and faster to produce power or cease producing power when called upon.

- Integrated the STM Power Beta Stirling engine with the dish system. Upgraded the control software of the STM Power engine to improve performance and operability.
Operated the hybrid dish / Stirling system in a routine, normally-unattended manner for ten months and gathered operational and efficiency data. During the operational period, SAIC made other improvements to the system including replacement of the quartz window with a far less expensive borosilicate glass window.

Specific outcomes from each task are presented in the following paragraphs. Reports giving detailed results from tasks and subtasks were delivered to the project manager.

3.1 Task 3.8.1 Dish / Stirling System Design and Integration

The objective of this task was to develop complete integration requirements for the hybrid dish / Stirling system. The following reports were generated.

- Del 3.8.1.1 Report on design and structural modifications needed to accommodate the new Stirling engine
- Del 3.8.1.2 Report on fail-safe off-tracking methodology
- Del 3.8.1.3 Specifications and drawings for modifications

The following subsections summarize the results from the design and integration tasks.

3.1.1 Dish Concentrator

The SAIC dish concentrator is a large steel structure on which 16 mirror facets are mounted. The structure is mounted atop a pedestal on a gear drive that provides azimuth and elevation rotation for tracking the sun. The existing dish had stretched-membrane mirror facets that were actively focused using a vacuum system. Although the stretched-membrane concept provides some advantages such as infinitely adjustable focal length and fail-safe defocus, stretched-membrane facets have demonstrated marginal optical quality and have not proven to be amenable to low-cost manufacture. Therefore, SAIC identified an advanced fixed-focus mirror approach to improve the optical quality of the dish concentrator and to improve its manufacturability. The modified dish concentrator design incorporates the following improvements:

- Hexagonal facets—changing from round to hexagonal facets increases the potential reflective area of the concentrator, and hence its potential power rating, by seven percent without other changes to the structure.

- Flat mirror tiles—the unique design of the SAIC advanced mirror facets uses small, flat mirror tiles that are easily procured and low in cost. The mirror tiles are supported on a plastic puck that allows the angle of the mirror relative to the flat facet substrate to be set at any desired value. Figure 5 shows a schematic of the mirror tiles and their supports on the honeycomb substrate.
• Computer-generated aiming strategy—the fabrication of the mirror facets uses a computer-controlled robotic mechanism (pictured previously in Figure 2) to place individual mirror tiles at specified angles. Therefore, the aimpoint of each individual tile can be optimized to produce a uniform flux profile on the receiver. This approach eliminates the expensive tooling associated with formed mirrors, allowing one set of tooling to produce any desired variety of mirror facet configurations.

• Fixed-focus—by eliminating the delay associated with focusing and defocusing the dish, the system will produce energy faster when brought on-sun, and will not draw as much power to cool itself down after being removed from the sun. This will increase the overall energy efficiency of the system.

• Fast off-track—in order to provide safety to the Stirling engine receiver with a fixed-focus dish, it is necessary to off-track quickly when a fault occurs. This provides additional benefits in speeding up the slewing process to and from stow position during normal operation and in case of high winds.

Dish Control System Modifications

The modifications to the dish control system may be separated into those needed because of the fixed focal-length facets, and those needed for implementation of augmented solar operation. These are discussed in the following paragraphs.

Fixed Focal-Length Facet Modifications

The primary difference due to fixed focal-length facets is the potential for high-concentration solar flux to be present around the dish any time the dish is moved from its
stow position (either face-up or face-down). This requires that more care be taken in moving the dish at all times, especially when coming on- and off-sun. To address this requirement, the following changes were implemented:

- The downward stow position was moved to north-facing so that the mirrors would not be exposed to sunlight when going to or from downward stow.
- The dish was moved only straight up or down and at the highest slew speed when going between downward and upward stow.
- The dish was allowed to rotate in azimuth to track the azimuth of the sun only when it is face-up.
- Once the dish reached the sun’s azimuth position, it was slewed downward from face-up to an on-sun position. Gas operation was initiated before the system was allowed to go on-sun and continued until after the sun went down. The system was aimed at the sun any time the sun was above the horizon so that any available solar energy could be collected. The system was operated at full power throughout the day. When solar power was available, the gas supply was throttled back automatically to maintain an even power level.
- If a fault occurred or the system was disabled, it would slew upwards to face-up. When the sun went down, the dish rotated around in azimuth to it’s stow position and proceeded to face-down stow.
- The focus control blower relay and associated logic and hardware were eliminated.

Augmented Solar Operation Modifications

The implementation of augmented solar operation is relatively straightforward from the perspective of the dish controller. The only change to the present control software necessary to allow augmented operation is to eliminate the command to close the engine flux shield/shutter when the engine is running on gas. The shutter will be commanded to close whenever the system is off-sun in order to reduce heat losses from the front of the receiver cavity. The current dish controls have provision for a “calibration tracking” mode, in which the dish automatically dithers its aimpoint around the sun’s calculated position in order to maximize power output or minimize the temperature spread in the engine receiver. The location of the “sweet spot” (where maximum power or minimum temperature spread is achieved) is stored in an array and used to optimize the tracking of the system. Implementation of “calibration tracking” control with the Beta engine was more difficult since the engine output and temperatures were nearly constant and therefore could not be used as control variables. Instead, the dish controller needed information on the amount of gas energy being supplied to the engine and it performed a calculation of the solar efficiency of the system at each point. Therefore, a gas flow was being provided to the dish controller. Also, the “augmented calibration mode” algorithm was changed so that mode is entered automatically whenever the solar intensity is above a minimum value, eliminating the need for operator action to enter “calibration tracking.”
Fast Off-Track System

One of the requirements with a fixed focal-length mirror system is a fail-safe off-tracking system for the system. This system is necessary to protect the engine from damage in case of a system fault while on-sun with the new mirror system.

The requirement for a fast off-track system stems from the fixed-focus facets in the new dish design. With fixed-focus facets, a focal spot will always exist somewhere in space. If that focal spot can exist where flammable materials or materials subject to damage by high temperatures may be present, there is the possibility of damage to the dish or other surrounding equipment. The highest danger exists at approximately the dish focal length—at locations closer or farther from the dish, the images diverge and the maximum flux drops quickly. At a distance of two focal lengths from the dish, the reflected flux never exceeds one sun anywhere, and points at any distance beyond two focal lengths will never have dangerous solar flux levels.

The most stringent requirement is to keep the system safe in the case of a power failure. If such a failure occurs and leaves the dish immobile, the focal spot can move in any direction as the sun continues to move in the sky, depending on the time of day and time of year. So, a simple shield will not provide security in all orientations unless it is made quite large and actuates to protect the receiver as well as all surrounding materials. Off-tracking upwards to a face-up position places the focal spot in a safe location no matter the time of day or year. The process can be made fail-safe by providing an uninterruptible power supply for the elevation drive motor.

The other major requirement is to remove the flux from the receiver quickly in case of an engine fault. If a fault leads to the engine stopping, the flux on the receiver can lead to failure of the absorber tubes within a few seconds. Therefore, a separate flux shield has been included in the design. The flux shield will deploy within two seconds and be capable of withstanding the solar flux for several seconds, allowing more time for the system to move off-sun. If testing shows that the off-tracking system is sufficient for protection of the receiver, the flux shield may later be removed.

The procedure used was to develop a set of requirements for the solar flux protection system and then to use them to evaluate proposed concepts for flux protection when testing was performed on one of SAIC’s existing dish systems. Finally, based on the testing, a “best” system was selected and final design was completed.

Flux Protection Requirements

The requirements of the flux protection system are as follows:

- Remove all concentrated solar flux from the receiver within three seconds after a fault is declared.

- Continue to protect the receiver and other system components and surrounding equipment and personnel from reflected solar flux indefinitely.
• Perform in a fail-safe manner upon loss of grid power to the system.
• Provide for normal on-sun and off-sun tracking without damage to system components or danger to surrounding equipment or personnel.

Off-Track System Configurations

The original elevation tracking system consisted of a 1 horsepower (hp), 1,725 rpm single-phase 120 V<sub>AC</sub> motor connected through a 5.5:1 gear reducer to the input stage of the Flinders gear drive. The 5.5:1 gear reduction was needed to provide sufficient torque to the drive. This system was capable of driving the dish system at a rotational speed of about 6.3°/minute, or about 14 minutes from the horizon to face-up. This speed was more than adequate for tracking the sun, but is too slow for moving the sun off the receiver in an emergency situation. For example, with a receiver aperture diameter of 0.4 m, the dish needs to move about 0.9° to move a focused image completely off the receiver. At 6.3°/minute, this motion would take about 8.5 seconds. In that time, the focused solar flux could melt receiver tubes or surrounding insulation.

The dish structure is well balanced so above the horizon the power requirements for motion are modest, but there is a large spike in power when moving below the horizon to face-down stow (>-90° elevation). This is due to the articulation of the arm supporting the engine. When the dish moves downward, a wheel attached to the arm rolls down the pedestal, causing the arm to articulate and rotate outward away from the pedestal. When that wheel contacts the pedestal, a large moment is transferred to the drive system. As the system continues to rotate to the face-down position, the moment decreases.

Two configurations were considered to improve the off-tracking speed of the system. One system consisted of an AC variable-speed drive with a three-phase AC motor. The drive specifications stated that the speed could be controlled up to 120 Hertz (Hz), which would be twice the nominal speed of the motor. The other consisted of a DC motor drive and 1½-HP motor. The systems were sized to replace the existing drive motor and the 5.5:1 gear reducer and to drive the Flinders drive directly.

The two variable-speed drive systems were tested in December 2002 on the SAIC dish system installed at the APS test site in Tempe, Arizona. The variable-speed AC drive was tested with a ½-hp, three-phase motor. This was found to drive the dish adequately through the 5.5:1 gear reducer, but was unable to drive the system from stow when driving the Flinders drive directly. Through the gear reducer, the maximum speed was only about 5.1°/minute (i.e., slightly less than the single-phase motor). The power measurements on the drive were very noisy and indicated that the drive operated at low efficiency.

The DC motor was connected directly to the Flanders drive, and was operated with both 120 V<sub>AC</sub> and 240 V<sub>AC</sub> input (i.e., 90 V<sub>DC</sub> and 180 V<sub>DC</sub> outputs). At the lower voltage level, the drive motor functioned adequately throughout the tracking region, but clearly slowed when the dish was driven to face-down stow (at the point when the wheel on the arm hit the pedestal). The speed of movement was 17 to 19°/minute.
With 240 V\textsubscript{AC} input to the DC motor, the dish moved effortlessly and rapidly in all orientations. The average speed of rotation was increased to over 42°/minute. The specification of the DC controller allows a maximum continuous current of 6 A, with a two-minute (0.03 hour) 100 percent overload current. The tests indicated the overload current is well within this specification. It may be noted that the dish was only tracked from face-down to the horizon and back down. This was done to avoid glinting surrounding areas and because it was known from earlier tests that the power for moving above the horizon was always less than that required to move up to the horizon.

The requirement for removing all flux from the receiver within three seconds translates to a rotational speed of 18°/min (based on a 0.4 m diameter aperture). The AC variable-speed drive was not able to achieve this, but both the DC tests achieved acceptable results. The DC tests with 120 V\textsubscript{AC} input provided only a small margin of safety over the required speed. The results at 240 V\textsubscript{AC} input showed a speed of nearly 2.5 times the requirement, and because of the higher voltage, the current draw was also well within specs for the driver. Therefore, the 240 V\textsubscript{AC} DC drive system was selected as the preferred fast off-track system. To limit wear and tear on the motor and drive components, the speed in operation will be limited to about 25 to 30°/min. A description of the final system, including the fail-safe power system, is given in the following paragraphs.

Implementation of Fast Off-track System

The present dish control power system is designed around a single-phase, 120 V\textsubscript{AC} power supply. An uninterruptible power supply (UPS) is included to provide fail-safe power to the controls and the engine in case of a grid power loss during operation. This allows the controls and engine to perform an orderly shutdown and report the loss of grid power. In order to provide fail-safe operation of the selected fast off-track system, the uninterruptible power supply system must be upgraded to a 120 V\textsubscript{AC}/240 V\textsubscript{AC} system. This involves rewiring of the existing control power transformer to give 240 V\textsubscript{AC} instead of 120 V\textsubscript{AC}, and replacement of the 120 V\textsubscript{AC} UPS with one that provides 120 V\textsubscript{AC}/240 V\textsubscript{AC} power. The 120 V\textsubscript{AC} uninterruptible power for the dish controls and engine can be pulled off one leg of the 240 V\textsubscript{AC} supply, so they will remain unchanged in configuration. The elevation drive motor will be powered from the full 240 VAC uninterruptible supply. For simplicity in the retrofit of the existing systems, the azimuth drive motor will remain a 120 V\textsubscript{AC}, ½-hp single-phase AC motor, and will be powered off the other leg of the 240 V\textsubscript{AC} power from the dish controls and engine. This will tend to balance the power draw and since there is no requirement for fast movement in the azimuth direction, no changes to that drive are necessary.

In an emergency, the elevation motion will occur first, followed by azimuth motion. Thus, even if the batteries are exhausted by the elevation motion, the dish will be in a safe position. Other wiring changes necessary to implement the upgrade will be minor in nature.

Dish Structural Modifications
The original structure of the dish concentrator was found to lack sufficient out-of-plane stiffness in testing that was done with stretched-membrane mirror facets. Joints within the system were also found to have movement that was compromising the rigidity of the structure. Therefore, modifications have been made to the structure to stiffen it and to reduce joint movement. Modifications included welded splints at many of the joints to eliminate movement, and stiffening of the umbrella struts between the dish structure and the hub to provide additional out-of-plane stiffening to the dish structure. The umbrella struts are visible in Figure 1.

Mirror Facet Structure

The structure of the SAIC dish concentrator was designed around stretched-membrane mirror facets. The stretched-membrane facets are round, with three equally-spaced mounting bolts around their perimeters. The advanced facets are designed to mount to the same locations as the stretched-membrane facets.

In the original dish design, it was found that the stretched-membrane mirror facets were being loaded by in-plane movement of the structure in the course of tracking motions. To eliminate this, triangular supports have been incorporated into the structure of the advanced facets. These supports triangulate between the facet mounts of the original system and provide a strong, stiff base on which the advanced fixed-focus facet components are mounted. Because the triangular supports are bonded to the back of the facet substrates they are considered part of the facets, not part of the dish structure. However, besides their function of supporting the facet components, they have the system-level function of keeping in-plane dish loads from being transmitted to the facet substrates. As a result of incorporating these supports into the facet design, no physical changes to the present dish structure will be required to accommodate the new facets.
Mirrors Facet Design for the STM Power Beta Engine System

The STM Beta engine receiver consists of an annular, conical-shaped bank of tubes. Each of the four cylinders of the engine has a quadrant of tubes feeding it, so the system requires facets that direct the sunlight onto the engine receiver to provide uniform heating to each quadrant of the engine. The receiver is contained in a cavity to minimize heat losses, so an additional requirement is to minimize the size of the cavity opening. These two constraints were incorporated into the design of the mirrors for the engine system.

The resulting design has mirror facets with 15 centimeters (cm) (6 inch) square mirror tiles. These tiles form an image from each facet that is comparable to the size of the receiver tube banks. The aperture of the cavity was chosen to be a rectangle 22 cm wide and 24 cm high. This shape reduces spillage while keeping the area of the aperture to a minimum.

The focus and aiming strategy developed for the engine system has all the mirror tiles from each facet aimed at a single point on the aperture plane. Placing the aimpoints at or near the center of the aperture minimizes the size of the flux profile at that location. The images from the 16 mirror facets are distributed near the center of the aperture plane in order to form a uniform annular flux profile at the location of the engine receiver. The uniformity of the flux profile is enhanced by the use of a flux-scrambling quartz window just inside the aperture of the receiver. The window seals the receiver cavity to allow recuperation of the exhaust gases from the fuel gas operation and the surface is slightly diffusing to eliminate hot spots and scatter the solar flux entering the receiver.
Because the dish structure is not rotationally symmetric (there are two mirror facets missing where the mounting pedestal of the dish passes through the structure), the upper portion of the receiver would normally be an area of reduced flux. To combat this, the aimpoints of some of the inner ring of facets are adjusted somewhat towards that area. Also, a diffuse ceramic reflector has been placed at the center of the receiver to re-direct flux from the center of the receiver to the upper portion of the receiver tubes.

Figure 7 shows a schematic representation of the main elements of the receiver cavity, derived from the ray-tracing program. The receiver aperture is shown as the rectangular object formed from “+” signs to the right in the figure. Solar flux would be traveling from right to left into the receiver cavity. The oval solid object in the center of the receiver is the diffuse ceramic reflector, which is angled upward to reflect light preferentially to the upper part of the receiver. Finally, the small circles indicate where individual rays in the ray-trace intersected with the conical surface of the receiver.

![Figure 7. Schematic representation of receiver cavity geometry with aperture, internal reflector and receiver](image)

Photo Credit: SAIC

Structural Modifications

The existing focus blower system was removed, along with the manifold and the hoses to each of the original facet focus control systems. Counterweight plates were adjusted as needed on the dish to accommodate the change in center-of-gravity due to the substitution of the advanced hexagonal facets for the original stretched-membrane mirror facets and the new Beta engine. The azimuth stow limits and stow limit switch were modified to allow the dish to rotate further to the east to a north-facing position for the new downward facing stow position. Cable runs were adjusted to allow the extended motion. A roller pad on the pedestal was installed at the new stow position. Other wiring was moved as needed to avoid conflicts.
3.1.2 STM Power, Inc. Beta Stirling Engine

The STM Beta engine system is shown during assembly in Figure 8. The photo shows the tubes of the receiver cavity at the near end, with the generator and other ancillary equipment at the far end. The Beta engine incorporates many advances over the Gen. 2 engines used in previous tests. Most of the improvements have been made due to design-for-manufacturability studies performed by STM, and are aimed at simplifying the engine, increasing reliability, and reducing manufacturing and maintenance costs.

![Figure 8. STM Power Beta engine system during assembly](image)

Photo Credit: STM Power Inc.

The primary changes between the Gen. 2 engine and the Beta engine system are as follows:

- **Fixed swashplate**—the Gen. 2 engine had a variable-angle swashplate, and many problems were encountered with the mechanisms involved. The swashplate is used to convert the up-and-down motion of the four axial pistons into rotary motion of the crankshaft. The angle between the swashplate and the crankshaft determines the stroke of the pistons and therefore the power output of the engine. In the Gen. 2 engine, an electrically-driven mechanism was used to adjust the swashplate angle in real-time to respond to changes in input power. In the Beta engine, the swashplate angle is fixed at full stroke and the power output is therefore fixed at full output.

- **Belt-driven oil pump**—this reduces the parasitic electrical loads on the system and provides an oil supply system that is fail-safe on loss of grid power. In the Gen. 2 engine, the oil pump was driven electrically. The power to drive the oil pump had to be generated mechanically by the engine, be converted through the generator to
electrical energy, be processed through a UPS, and finally be converted back to mechanical power by the electric motor of the pump. Each step involved inefficiencies, leading to power losses. The electrically-driven oil pump system also required an uninterruptible power supply to keep the oil pump operating if the electrical grid failed. The Beta engine uses a belt drive directly from the engine output shaft to power the oil pump. This is an efficient mechanical linkage and guarantees that the oil pump will be powered whenever the engine is operating.

- Belt-driven combustion air blower—like the oil pump, this provides a more efficient linkage from the engine to the air blower, and provides fail-safe operation in case the grid fails.
- Induction generator—this is a simple and robust generator configuration. With power factor capacitors installed, it also provides good power quality and power factor. A beneficial upgrade to the system that is being evaluated would include power electronics to allow the engine to operate at variable speed and hence variable output power.
- Aperture window and augmented operation—the system incorporates a quartz window at the aperture. This serves two purposes: (1) acts as a “flux scrambler” to disperse the solar flux and reduce hot-spots on the receiver and (2) seals the aperture to allow “augmented” gas operation. Augmented operation is the addition of natural gas power along with solar power to the receiver. It allows the engine to run at constant power as the solar power input varies during the day.

The principal change in the engine is the fixed-swashplate system. This means that the engine can only be operated at full power. The augmented mode makes operation possible with variable solar input, since the natural gas supply will make up the difference between the available solar energy input and full power.

3.1.3 STM Beta Stirling Engine Package Requirements

The following are the requirements that were determined for the STM Beta engine package (Beta PCS) delivered to SAIC under the SMUD program, Task 3.8.2.1. The following requirements reference the existing Phase 2 JVP hybrid solar PCS units (Phase 2 PCS). Where nothing is mentioned explicitly, the Beta PCS was configured the same as the Phase 2 PCS configuration.

Generally, the Beta PCS is a “form, fit, and function” replacement for the Phase 2 PCS. The only visible changes are that the Beta engine system has a quartz window allowing augmented solar/gas operation, and it has a hydrogen replenishment unit that will produce hydrogen from de-ionized water. Internally, many changes were made to improve reliability and performance, such as the elimination of the swashplate adjustment mechanism and implementation of belt-drives for the oil pump and combustion blower. These do not affect the PCS interface to the dish and therefore do not affect the form, fit and function of the PCS system.
Physical Requirements

**PCS Mounting and Lifting Provisions**

The Beta PCS shall have the same physical mount as the Phase 2 PCS, including the number of PCS mounting bolts (6), their size, and their locations.

Lifting provisions shall be the same as the Phase 2 PCS. STM may incorporate improvements to the mounting or lifting provisions with approval by SAIC.

**Access Panels and Lids**

The PCS lid shall have latches or restraints to prevent its unintended separation from the PCS.

Access and side panels shall be fitted where possible with quick-release fasteners (e.g., Dzus 1/4-turn fasteners) having no free parts. Where possible, panels shall slide into position mechanically and have fasteners only along their most accessible side. Cutouts in removable panels for cables and connectors shall be, where possible, in the form of open slots rather than closed holes.

**480 VAC Physical Interface**

The 480 VAC plug configuration and location shall be the same as the Phase 2 PCS (Twist-lock Hubbell connector below PCS).

No. 4 AWG 4-conductor SOW cord or THHN conductors or equivalent shall be used between the PCS and the connector.

**120 VAC Physical Interface**

The 120 VAC plug configuration and location shall be the same as the Phase 2 PCS (Twist-lock Hubbell connector below PCS).

**Control Cable Physical Interface**

Control cable plug configurations and locations shall be the same as the Phase 2 PCS.

**Gas Physical Connections**

Hydrogen: A 1/4” nominal, stainless steel O-ring fitting solidly attached at the bottom or side of the PCS shall be provided.

Natural gas: A 1” nominal, female threaded pipe fitting solidly attached at the bottom of the PCS shall be provided.

**Outside Dimensions**

The Beta PCS shall have outside dimensions that do not exceed those of the Phase 2 PCS. The location of the receiver and the aperture relative to the PCS mount shall be the same as the Phase 2 PCS.
Electrical Requirements

480 VAC nominal, 60 Hz, three-Phase, four-wire (three phases and ground), Delta-connected.

120 VAC nominal, 60 Hz single-phase uninterruptible power supply with 5A capacity.

The PCS shall feed power into a 60 A circuit, protected by time-delay fuses at the pedestal base (supplied by SAIC).

The PCS shall generate power at a power factor of greater than 90 percent at full power.

The PCS shall generate power with less than 5 percent THD at full power.

Control Interfaces

Dish Control Interface

The RS-485 communications protocol and the connection to the dish controller shall be the same as the Phase 2 PCS (1200 baud, single twisted pair; ASCII data strings with checksums). The PCS status response to the dish controller shall include ASCII character flags for “PCS Ready,” “running on gas,” and “shield open.” It will also include an ASCII digital value for receiver delta T. Dish commands shall include those to open or close the flux shield, start/stop operation on gas, and inquire as to PCS status.

A dry contact shall be provided that opens to indicate a “PCS Fault” or loss of 480 VAC power.

Engine Control/Monitoring Interface

The engine controls shall be capable of remote diagnostics via a phone line or the Internet.

The engine controls shall be adaptable for multiple-dish, large installations (e.g., 20-plus systems to be monitored, 1+ km from system to monitoring system).

Gas Supplies

Hydrogen Supply

STM shall deliver a system to produce hydrogen from de-ionized water. This system may be installed at the bottom of the pedestal.

Natural Gas Supply

The PCS shall operate with a natural gas supply pressure of 2 psig and a flow of up to 10 scfm.

Optical Interface

Receiver

The solar receiver geometry shall be the same as the Phase 2 PCS.
The PCS shall be capable of accepting and processing up to 100 kW of solar heat without overheating or sustaining damage.

**Aperture**

The optical aperture shall be 10 inches (25.4 cm) in diameter unless changed by mutual agreement. The exact location will be determined by STM.

**Provision for Quartz Window**

A mount for a quartz window shall be provided inside the receiver cavity, at least 2 inches (5.08 cm) from the front aperture. Sheet metal contact on the front and back sides and around the edge of the quartz window shall be sufficient to avoid direct contact of the window with insulation material and provide sealing of the cavity. Access for installation and removal of the quartz window shall be provided.

**Exposure of Components to Solar Flux**

All wiring, all electrical components, and all mechanical components with moving parts shall be protected from exposure to concentrated solar radiation. Concentrated solar radiation may be present on the entire front face and on the top of the PCS package.

**Flux Shield**

The Beta PCS shall be equipped with an external flux shield to protect the receiver from solar flux. The shield shall be controlled by the engine controller under command from the dish controller and the engine shall be able to operate with the flux shield open or closed. In the event of a PCS fault or loss of 480 VAC power, the flux shield shall close automatically.

**Aperture Insulation**

STM may propose the addition of an aperture plug to provide additional insulation during gas-only operation.

**Acceptance Requirements**

**Full Power Test**

The PCS shall generate at least 22 kW net power under ISO conditions at full load when powered by natural gas.

**Power Quality Test**

The PCS shall demonstrate compliance with electrical requirements (e.g., power factor, THD).

**Gas Operation Test**

The PCS shall demonstrate uninterrupted operation at full load on natural gas without operator intervention for a period of at least 48 hours.
Solar Operation Test
The PCS shall demonstrate 100 hours of augmented solar operation with positive net power and without operator intervention or forced outage during times the direct insolation is above 400 W/m² and the system is not shaded. It is understood that this will require several days of operation, including normal startup and shutdown operations each day.

Other Requirements

Augmented Solar Capability
The engine shall be configured to operate on natural gas with the flux shield open or closed to allow for augmented solar operation.

Fail-Safe Operation
The engine shall demonstrate fail-safe operation to protect itself from damage in case of a loss of 480 VAC grid power. This may include a brake or vent valve to prevent overspeed conditions and a flux shield to block solar flux from the aperture of the receiver. In case of loss of 120 VAC control power, the system shall also shut itself down in a fail-safe manner.

3.2 Task 3.8.2 Dish / Stirling System Installation and Operation
The goal of this task was to integrate and install the Stirling engine with the dish system and operate the resulting system for six months. This involved design and fabrication of the advanced fixed-focal-length mirror facets for the dish / Stirling system; purchase of DC motors and control and drive components; implementation of modifications to the tracking algorithms and controls to accommodate the fixed-focus facets; purchase of the Stirling engine; installation and checkout of all components on an existing SAIC dish at the APS test facility in Tempe, Arizona; and operation of the completed system. Unfortunately, due to delays in integrating the engine system on the dish, only about two months of operation were obtained in Phase 1. This led to the modification of the Phase 2 activities to include only limited improvements to the system and continued operation at the Tempe, Arizona, test site, rather than installation of a system at SMUD in Sacramento. The following reports were generated as deliverables in this task:

- Del 3.8.2.1 Letter of notification that the Stirling engine had been ordered.
- Del 3.8.2.2 Letter of notification stating that all facet materials had been purchased and received. The letter included a bill of materials.
- Del 3.8.2.3 Report covering the fabrication of the facets.
- Del 3.8.2.4 Notification Letter stating that the Stirling engine was delivered and including a bill of materials.
- Del 3.8.2.5 Notification Letter stating that the dish Stirling system was operational and including initial operating data on the startup of the Stirling engine.
- Del 3.8.2.6  Interim report showing results of testing at the Arizona facility for the first 3 months (October 2003 to December 2003).
- Del 3.8.2.7  Task report summarizing the results of testing at the Arizona facility and describing all work performed in Task 3.8.2.

The following subsections summarize the results of the task.

### 3.2.1 System Modifications and Stirling Engine Integration

The engine was manufactured by STM and assembled into a solar “package” with significant input from SAIC. It was then delivered to the APS site (subtask 3.8.2.4). In parallel with the manufacture of the engine system by STM, SAIC completed the design, ordered, and received all materials and components to manufacture the advanced fixed focal length mirror facets for the Stirling engine system (subtask 3.8.2.2). The mirror facets were then manufactured in San Diego by SAIC and shipped to the APS site for installation on the existing dish structure (subtask 3.8.2.3). Modifications to the dish to accommodate the new facets and engine were completed, including installation of new DC tracking motors and an uninterruptible power supply system to drive the dish off-sun during a power outage or other emergency. Following the complete integration of the new components into the system, startup was commenced followed by full operation.

The integration of the advanced hybrid solar dish / Stirling system proceeded smoothly, and system operational characteristics were generally as expected. The goals of integrating and demonstrating a hybrid solar dish / Stirling system were therefore completely fulfilled. Initial system operation was delayed due to a laborious process of engine subsystem checkout, so the system was operated on-sun only for about two months before the end of the task period of performance and budget were reached. However, the system as a whole operated with high reliability during the several hundred hours of operation that were achieved in Phase 1.

#### Mirror Facet Production

The goal of this subtask was to produce a set of facets with the required optical performance for the dish / Stirling system. These facets were replacements designed to fit on existing structures. This determined the size and shape of the facets and influenced the fabrication procedure. PV and PCS systems require different optical alignments, focal lengths, and image configurations. SAIC has developed a process whereby these variations can be readily made simply by changing the programming of the equipment and perhaps the mirror tile size. The main innovation is that the substrates are flat and the mirrors are flat rather than having to be pre-shaped for a specific application. Focusing is achieved by angling the mirror tiles on the flat substrate. One major obvious goal for success is that each tile can be placed on the substrate with sufficient accuracy to meet the optical requirements of the system. An error of less than +/- 0.005° for each tile on the substrate was considered permissible.
SAIC converted a CNC router system to place and bond mirrors to a flat “optical bench” with optical accuracy (Figure 2). Aluminum honeycomb panels were chosen as substrates for the mirror facets because of their high stiffness to weight ratio. The size of the router bed did not allow a facet to be populated with an array of mirror tiles in one piece so the honeycomb substrate had to be built in two pieces that could be assembled after being tiled and joined while maintaining flatness. Modifications to the system had to be made for this program after an analysis showed that 12-inch square mirror tiles were optimum for the PV configuration. The original design would only accommodate 6-inch and 9-inch tiles.

**Preparation of Mirrors**

The mirror tiles needed to have a pre-attached PVC component on the center of the back of the mirror for the router to be able to lay down tiles at an acceptable rate. The PVC part was the convex side of a ‘ball and socket’ connector that allowed an infinitely variable range of angles to be set between the mirrors and substrate. The PVC part was attached to the mirror, with a 3” square glass plate sandwiched between, using silicone adhesive on both sides of the glass plate. Silicone adhesive was not the initial choice (as discussed in the Significant Issues section) and a cure time of one to two days necessitated that this sub-assembly be made ahead of time. A custom fixture was used to align and press the PVC and glass onto the center of the tiles. The adhesive was dispensed through a pneumatic caulking gun. The mirrors were stacked flat using cardboard spacers to allow the silicone to cure undisturbed. The stacked mirrors were then carted over to the router for installation.

**Preparation of Substrates**

Custom shaped flat honeycomb substrates were procured for this project. The substrates were delivered from the manufacturer stacked in crates. Prior to use, the surfaces were inspected and any excess glue and tape from manufacture were removed. Either side of the substrate can be used but the orientation of the centerline extrusion had to be observed to ensure two halves of the same facet would fit together correctly. The substrate was aligned to stops on the router surface then clamped in place. Shimming was applied if the substrate was not quite flat. Two sets of stops were used, one for the top half of the facet and one for the bottom half, that allowed the same coordinates for mirror placement to be used in the software program.

The top surface was prepared to improve adhesion by abrading the aluminum skin surface with Scotch-Brite fine abrasive pads and following up with an alcohol rinse and MEK wipe.

**Assembly of Mirrors onto Substrates**

A supply of concave PVC connector parts, stacks of mirrors, PVC glue in a syringe (attached to a time air pressure system) and acrylic adhesive in a caulking gun were located near the home station. Air pressure for the syringe and acrylic activator spray nozzle and a vacuum pump for picking up and transporting mirrors on the tilt head had to be on in addition to the router electronics and software. Both manual and computer controlled actions were coordinated to populate the substrate with mirror tiles. A mirror was
manually picked up and wiped clean of particulate matter on the PVC connector and on the mirror face where the vacuum head contacted (a particle here could cause a vacuum leak and perhaps tilt the mirror from its intended angle). It was placed face-up in the home station firmly against the corner stop to ensure good alignment. The other manual operations were to apply acrylic adhesive to the flat bottom of the concave PVC connector, drop the part into the home station holder then dispense PVC solvent glue to the concave top of the connector. These manual operations were coordinated with the computer by using a ‘wait for input’ push button to indicate that each step had been accomplished. The sequence of operations is listed in Table 1.

Completed facet halves were labeled with the date and facet number then were removed from the router and stacked vertically, using temporary wooden blocks as spacers to protect the mirrors, until they could be transferred into the shipping carts. As the parts were being prepared for shipping, mirror-protection angles on the outer edges were glued and screwed to the channel extrusions. Holes for pins were also drilled into the edges so that nylon straps attached to a hoist could be used to lift and move the pieces safely.

Figure 9 shows a completed mirror facet half and the resultant image when the facet was taken outside in sunlight and the mirrors were aimed towards the ground. The focal plane of the facet is clear in the reflected image.

Table 1. Operating sequence for robotic mirror fabrication system

<table>
<thead>
<tr>
<th>Step</th>
<th>Action</th>
<th>Operation</th>
<th>Axis(es)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Move head tilt head to flat orientation</td>
<td>Tx, Ty</td>
<td>1,2</td>
<td>‘Home’ orientation</td>
</tr>
<tr>
<td>2</td>
<td>Place mirror in (mirror) pickup station 1</td>
<td>Manual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Wait for remote input</td>
<td>Remote</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Move head to mirror pick up station 1</td>
<td>XA,XB,Y</td>
<td>6,5,4</td>
<td>Home position</td>
</tr>
<tr>
<td>5</td>
<td>Lower tilt head</td>
<td>Z</td>
<td>3</td>
<td>Fixed distance</td>
</tr>
<tr>
<td>6</td>
<td>Turn on vacuum</td>
<td>Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Raise tilt head</td>
<td>Z</td>
<td>3</td>
<td>To or near limit switch</td>
</tr>
<tr>
<td>8</td>
<td>Tilt mirrors per program</td>
<td>Tx, Ty</td>
<td>1,2</td>
<td>From Excel Data File</td>
</tr>
<tr>
<td>9</td>
<td>Add glue to bottom of PVC base</td>
<td>Manual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Place PVC base in pickup station 2</td>
<td>Manual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Wait for input</td>
<td>Remote</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Move above PVC pickup station 2</td>
<td>XA,XB,Y</td>
<td>6,5,4</td>
<td>From Excel Data File</td>
</tr>
<tr>
<td>13</td>
<td>Dispense glue to PVC, timed shot</td>
<td>Manual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Wait for input</td>
<td>Remote</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Lower head</td>
<td>Z</td>
<td>3</td>
<td>Fixed distance</td>
</tr>
<tr>
<td>Step</td>
<td>Action</td>
<td>Operation</td>
<td>Axis(es)</td>
<td>Comments</td>
</tr>
<tr>
<td>------</td>
<td>-------------------------------------</td>
<td>-----------</td>
<td>----------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>16</td>
<td>Read inclinometers on head</td>
<td>T1,T2</td>
<td></td>
<td>To Excel File for record</td>
</tr>
<tr>
<td>17</td>
<td>Raise tilt head to travel position</td>
<td>Z</td>
<td>3</td>
<td>To or near limit switch</td>
</tr>
<tr>
<td>18</td>
<td>Move head to near mirror destination</td>
<td>XA, XB,Y</td>
<td>6,5,4</td>
<td>From Excel Data File</td>
</tr>
<tr>
<td>19</td>
<td>Spray initiator facet</td>
<td>Output</td>
<td></td>
<td>Timed by spray controller</td>
</tr>
<tr>
<td>20</td>
<td>Move head to mirror destination</td>
<td>XA, XB,Y</td>
<td>6,5,4</td>
<td>From Excel Data File</td>
</tr>
<tr>
<td>21</td>
<td>Lower head</td>
<td>Z</td>
<td>3</td>
<td>Fixed distance</td>
</tr>
<tr>
<td>22</td>
<td>Hold for 20-30 seconds</td>
<td>Timer</td>
<td></td>
<td>Set by keyboard, temperature dependent</td>
</tr>
<tr>
<td>23</td>
<td>Release vacuum on head</td>
<td>Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Raise head to travel position</td>
<td>Z</td>
<td>3</td>
<td>To or near limit switch</td>
</tr>
</tbody>
</table>

RETURN

Figure 9. Completed mirror facet half and resulting reflected sun image

Photo Credit: SAIC

33
Shipping

Reusable custom steel carts were fabricated to support and separate each facet half in a vertical position. Wooden supports (attached to the steel frame) that fit in the extrusion channels prevented movement and mirror damage. The cross bars on the carts were removable so that the facets could be easily moved in and out. An outer facet was reversed so that none of the mirror tiles was exposed on the outside of the cart. Each cart could hold 11 sections so that a full set of 32 facet halves could be transported in three carts on a flatbed truck. Each cart weighed approximately 2,000 pounds when fully loaded. Figure 10 shows a cart loaded with facet halves ready for shipping to the site.

![Shipping cart with facet halves](image)

**Figure 10. Shipping cart with facet halves**

Photo Credit: SAIC

Alignment of Facet Halves and Mirror Facet Assembly

To simplify shipping, the halves of each mirror facet were assembled at their destination. The procedure had been previously worked out and a fixture was assembled on site to use with available lifting equipment (Figure 11). The joint is horizontal on all the facets and the centerline extrusion allowed some movement out of plane so that the halves could hinge
slightly. The bottom half was clamped in place vertically and the two halves were visually aligned without any adhesive so that the top half position could be set with threaded bolts and locknuts contacting the back of the panel. The halves could then be separated for a final clean with abrasives and solvents and to apply two-part acrylic glue to the fingers of the extrusion then set down into the same position to fully cure within a few hours.

The visual alignment was simple when using a card with three horizontal bands of colors with a viewing hole in the center of the card. The width of each band was about twice the size of a mirror tile. By standing at a distance of twice the focal length of the mirror and looking through the hole, the reflections of the bands can be seen in each tile. By moving the card vertically, each color can be seen in turn. When the same color is seen in both halves of the facets, perfect alignment has been achieved. Misaligned mirrors are easy to detect because they do not reflect the same color as surrounding mirrors. Figure 12 shows the resulting reflected image from one of the mirror facets during the assembly process.

![Figure 11. Mirror facet assembly on-site at APS](image)

Photo Credit: SAIC
Attachment of Mounting Triangles

Triangular structures were used to adapt the mirror facets to the existing mounting points on the dish. These structures were adhesively attached to the rear of each mirror facet. Figure 13 shows a mockup of one of the triangles on the back of a facet substrate.

Figure 12. Alignment image of mirror facet

Photo Credit: SAIC

Figure 13. Mock-up of mounting triangle on hexagonal honeycomb substrate

Photo Credit: SAIC
A fixture was needed to assemble each facet onto its mounting triangle in the field. The fixture was sloped so that the facet would rest against the mounting triangle and provide pressure to spread out the glue at the interface. The facet was pre-aligned “dry” and the outline of the triangle marked on the back skin of the substrate. The facet was then “hinged” by lifting up on the top of the facet so that the top of the triangle and the back of the facet (in the marked area) could be cleaned and glued. Abrasive cleaning of the surfaces was done by an orbital sander followed by a rinse with alcohol and MEK. First, a bead of two-part epoxy was run near the outer edge of the triangle, and then a parallel bead of two-part acrylic was run near the inner edge. The facet was then lowered down onto the glue and the alignment was rechecked with the markings. The acrylic was fast cured to allow the facet to be moved off the fixture sooner. The slower curing epoxy would later provide better peel strength than the acrylic and also has a higher overall strength. Mechanical fasteners are not an option on some facets so a reliable adhesive bond is necessary. Different orientations are used for each facet to match the attachment points on the dish structure.

Facet Fabrication Results

The overall quality of the mirror facets produced in this program was very good based on focusing tests. This was quantified by NREL data performed on two of the first panels made. The overwhelming majority of the mirrors were accurately tilted. Mirrors near one end of the panels tended to drift from the desired value. This was attributed to an apparent “sag” at that end of the router that may not have been fully corrected with SAIC’s survey of the systematic errors in the X and Y axes. The “sag” and other deviations in the router tracks were of course very minor and quite insignificant for the normal machining operations for which the router is normally used. In optical terms, these deviations were large and had to be accounted for when producing facets.

There were also random mirrors that were obviously misaligned even though the data show the correct angles were originally applied. The cause has not been determined – there may be more than one – and is discussed further in the Significant Issues section. These errant mirrors reduce the overall accuracy of the facets. We are confident that these errors can be eliminated after further evaluation and improvement of the system to produce a complete system with errors less than 0.5 mill radians. The current facets, with average errors of 1 to 2 mill radians, are as good as or better than other competitive solar mirrors and have a distinct price advantage as well.

The equipment and procedures met SAIC’s original goals of applying one mirror per minute although we conservatively extended “curing” time of the adhesives by 5 to 10 seconds depending on the room temperature. Automating some of the repetitive manual tasks could increase speed further and eliminate any human errors that might contribute to delays or inaccuracies.
Significant Issues

The random mirror tile slope errors that were observed in the facets are of concern because they are not immediately noticeable during production and so the causes are hard to pin down. Movement of the tile before curing is a likely cause—if it sticks to the head during retraction or if the PVC “ball and socket” is not properly seated to each other or to the facet skin. These require further study for a suitable solution.

Springiness in the substrate can cause larger area deviations but this also has to be proven and corrected. The unregulated room temperature caused problems with the adhesives. Cure speeds are dependent on temperature and working in winter in an unheated space slowed the production rate dramatically. Fast curing adhesives were chosen specifically to increase the throughput. If the mirror is released before “fixture strength” has been reached, it could move and later cure permanently out of alignment.

Molding problems with the PVC connectors caused a change in the way that the larger convex disc connector was pre-bonded to the back of each mirror tile. Ideally, the connector would be convex on one side and quite flat on the other. The flat side would be bonded to the flat mirror back by a 2 millimeter (mm) thick transfer tape adhesive (3M 966 tape). This material has been qualified through long exposure tests to be compatible and satisfactory as a solar mirror adhesive. The flat side of the connector bowed sufficiently after molding so that the tape would be unable to adequately bond over the whole area. A raised ridge was molded around the “flat” side to prevent it from rocking. On some lots, the bulge on the flat side even exceeded the height of the ridge and still rocked slightly. Gap filling adhesives were tried to bond the disc to the mirror back. Silicones, mirror mastics, epoxies, and acrylics were tried. Occasionally the acrylics caused a tear or discoloration in the silver coating. There was a concern that even the apparently successful adhesives may cause a problem over time and there was no time to research this.

An approach was devised to allow the 3M 966 tape to be used even with these slightly distorted discs. A 2 mm thick glass square (3 inches/side) was used as an interface between the mirror and the disc (see Figure 14). The flat square could be adequately bonded to the flat mirror with the approved 3M 966 tape and the other side of the glass could be bonded to the disc with a gap filling adhesive without concern for any latent reaction with the silver or paint backing on the mirror.
The glass square also acted as a spacer so fewer PVC spacers on the outer mirrors were needed to achieve the larger slopes of those mirrors. The downside of course is the extra cost of materials and labor and the additional weight. Changes in molding procedures and compounds can provide the necessary flat surface on the PVC disc to allow direct bonding of the disc to the mirror, but this option was not available in this instance.

Silicone was eventually used as the adhesive for the glass and PVC to give a much more reliable bond. One problem with the long curing time was the potential for the disk to slide out of place before curing – if moved or mishandled. Several tiles were found in this condition and missed ones could perhaps account for random misalignments of the tiles.

The CNC router is quite adequate for the accuracies required in woodworking, sign making etc. The spatial accuracies of the router in the X-Y plane (within 0.001 inch) are also adequate for laying down the array of mirrors. The necessary precision with which the angles of the mirrors are tilted and held in position on the substrate is quite high and much higher than the normal machining tolerances required for router manufacture. It was originally intended to use precision inclinometers to measure the tilt head angles in real time and orient the mirrors (via feedback) with respect to gravity and therefore be unaffected by imperfections in the flatness and uniformity of the facet substrate and the router’s tracking and alignment. The inclinometers proved to be affected by temperature and the router was in an unregulated open area. Applying temperature corrections or control and adding feedback were also additional complications to put in the first design.

Since the router moves in X-Y planes and the tilt head uses X-Y tilt coordinates rather than R-theta, it was relatively easy to correct for X-Y tilt errors from motion irregularities of the router and compensate for them in the tilt angle at the tilt head holding the mirror. Fixing the substrates in the same position each time means that the mirrors are “dropped” at the same router X-Y locations each time (for the upper and lower halves of each facet, most of the mirror locations are also coincident). There were 200 different mirror locations for the PCS facets. The inclinometers attached to the tilt head were set to zero and the head was left in the flat “home” position, the head was then moved laterally to each mirror location.
Any non-zero readings were found to be repeatable and were due only to irregularities in the tracks of the router. These angular displacements were recorded and used to correct the tilt angle input in the Excel program for each mirror on each facet. The inclinometers were used during production to record the angle of the tilt head at each tile “drop” and recorded for later evaluation as needed. The readout could also be observed in real time to monitor the performance of the system. Used in this manner, a slight drift due to temperature changes was not critical.

National Renewable Energy Laboratory Mirror Evaluation

Optical characterization of SAIC’s new mirror facet design was completed at NREL using the Video Scanning Hartmann Optical Test (VSHOT). The new mirror panel designs are intended to replace the stretched membrane facets currently used on both their 25 kW dish / Stirling system and their dish/concentrating photovoltaic (CPV) system. The design utilizes fixed flat mirror tiles arranged, oriented, and fixed to a structurally stiff aluminum honeycomb panel. The accuracy goal for the mirror tile attachment angles is on the order of 0.5 milliradians.

The lower halves of two hexagonal panels were shipped to NREL for testing. These panels were part of the production run for a dish/engine project funded by SMUD. The half panels consisted of 162 6”x6” mirror tiles aligned for a single aim point (minimum aperture). Panels for the CPV application will use larger tiles (12”x12”) and will have multiple aim points to generate a more uniform flux profile.

VSHOT results indicate that the RMS statistical error for all the tiles is somewhere in the 1.0 to 1.5 milliradian range, but with a few tiles with significantly larger errors. Figure 15 shows the results for the mirrors of one of the half-facets. While the 0.5 milliradian goal was not achieved in these first prototypes, this level of accuracy may still be acceptable for concentrating solar power applications. Additional modeling is underway to determine the impact of these errors. SAIC believes the 0.5 milliradian goal is worth pursuing, however, and, as a result of this testing; they have identified several possibilities to improve the mirror tile slope accuracy. They have already made several changes and continue to modify their fabrication process. They will be producing new panels for further VSHOT testing to verify process improvements.
Conclusions

The fabrication of the SAIC advanced mirror facets was the first such production ever done. Although some minor discrepancies in the mirror tile placement remain to be eliminated, the automated production system and the mirror facet concept were demonstrated successfully. The facets that were produced, even with their flaws, are significantly better in quality than the stretched membrane mirrors they replaced. The SAIC advanced mirror facet approach that has been demonstrated here has the potential to provide high-quality, low-cost concentrator mirror systems for solar thermal and concentrating PV systems. This can only help in developing and marketing more cost-effective solar power systems.

3.2.2 Dish Upgrade and Stirling Engine System Startup

The mirror facets were received at the site in Arizona, assembled, and aligned on the structure in May and June 2003. Figure 16 shows the first facet installed on the system, and the resulting reflected image on the Beam Characterization System (BCS) target.
SAIC received the STM Beta Stirling engine at the test site on May 27, 2003. Due to delays in assembly and alignment of the mirror facets, the engine was not installed until July 22, 2003. SAIC completed startup and initiated operation of the dish/Stirling system at the test site in Phoenix, Arizona, on October 21, 2003.

Although the engine was delivered in a timely manner, several components were not pre-installed and tested. This led to significant delays in checkout and startup of the system. For example, the shutter mechanism was delivered with incorrect wiring and faulty components. To address these problems, it was necessary to verify and check out components and wiring in the field using manuals and wiring diagrams supplied by STM and sub-component vendors. At least one problem may have resulted in damage to the engine—as received, the hydrogen supply system was connected backwards, causing a high-pressure condition in the engine. This over-pressure situation may have contributed to seal failures that required an engine exchange before the system was placed in on-sun operation.

The approach used was to assemble and checkout the sub-systems and then perform startup testing and begin routine operation in a solar hybrid mode. Testing included operational results from a 48-hour gas operation test and a 100-hour solar operation acceptance test.

The major activities and milestones in the upgrade and operation of the system are summarized in the following table (Table 2). Dish upgrade activities started in May 2003, the engine was first operated on gas in July 2003, and the system first operated as a solar hybrid system in October 2003.
Table 2. Timeline of activities

<table>
<thead>
<tr>
<th>Date</th>
<th>Activity or Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 4, 2003</td>
<td>Advanced mirror facets delivered to the APS STAR site</td>
</tr>
<tr>
<td>May 22, 2003</td>
<td>STM Power “Beta” engine package arrived at APS STAR site</td>
</tr>
<tr>
<td>June 26, 2003</td>
<td>Completed installation of advanced mirror facets and dish alignment</td>
</tr>
<tr>
<td>July 2, 2003</td>
<td>Installed STM “Alpha” engine for testing</td>
</tr>
<tr>
<td>July 22, 2003</td>
<td>Installed STM Power “Beta” engine</td>
</tr>
<tr>
<td>July 25, 2003</td>
<td>First operation on fuel gas</td>
</tr>
<tr>
<td>July 30, 2003</td>
<td>Achieved 21.9kW power on fuel gas</td>
</tr>
<tr>
<td>Sept 12, 2003</td>
<td>Completed 48-hour gas acceptance test</td>
</tr>
<tr>
<td>Sept 25, 2003</td>
<td>Re-built engine with new block, heads, and pistons</td>
</tr>
<tr>
<td>Oct 5, 2003</td>
<td>First solar hybrid operation</td>
</tr>
<tr>
<td>Oct 21, 2003</td>
<td>Began routine daily operation</td>
</tr>
<tr>
<td>Nov 1, 2003</td>
<td>Completed 100-hr solar hybrid acceptance test</td>
</tr>
<tr>
<td>Dec 1, 2003</td>
<td>Began continuous (24-hr/day) operation on gas and hybrid solar</td>
</tr>
</tbody>
</table>

Significant delays and problems were encountered in the assembly of the advanced facets and in the startup of the Stirling engine system. A summary of the problems encountered up to the time that the system first operated in hybrid mode is found in Table 3.

Table 3. Problems encountered in system startup

<table>
<thead>
<tr>
<th>Problem</th>
<th>Description/Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facet Assembly</td>
<td>Handling of facet halves, facet half alignment, and attachment of the mounting triangles were much more difficult than anticipated and made worse by extremely hot weather. High ambient temperatures led to short working times for the adhesives, so workers were rushed. Eventually, an indoor facility was located and used to improve working conditions.</td>
</tr>
<tr>
<td>Beta Engine Comm to Console</td>
<td>The RS-485 communication cable between the engine controller and the engine console computer was not connected when the engine was received, and did not function properly when first connected. A bypass cable was used initially, but later the original cabling was made to work by eliminating an unnecessary ground connection in the circuit.</td>
</tr>
<tr>
<td>Beta Engine Hydrogen</td>
<td>An Ergenics hydride hydrogen compressor was installed in the engine package to supply hydrogen to the engine. The controls were programmed in reverse, so that it was operating when not needed, causing at least one overpressure condition</td>
</tr>
</tbody>
</table>
and several faults due to lack of hydrogen supply during operation. The overpressure may have contributed to the seal failure in the first engine block installed on the system. Other problems were bad parameter values and faulty components that caused nuisance faults. Once functional, the system was found to be unable to supply sufficient hydrogen flow at the supply pressure for which it was specified so a higher supply pressure was provided from a hydrogen bottle at the base of the pedestal.

| Fill System | and several faults due to lack of hydrogen supply during operation. The overpressure may have contributed to the seal failure in the first engine block installed on the system. Other problems were bad parameter values and faulty components that caused nuisance faults. Once functional, the system was found to be unable to supply sufficient hydrogen flow at the supply pressure for which it was specified so a higher supply pressure was provided from a hydrogen bottle at the base of the pedestal. |
| Beta Engine Gas Burner Leaks | The sheet-metal burner assembly was found to be cracked, leading to leaks of natural gas and exhaust gases. The burner delivered with the engine was not a new unit, and several replacements (also not new) were found to have leaks as well. The leaks caused bad fuel-air mixtures and imbalances in temperatures in the engine. Eventually, a burner assembly was patched effectively and it has functioned well. |
| Engine Hydrogen Leak | Immediately following the 48-hr gas acceptance test, the engine developed a significant hydrogen leak into the cooling water system. It is supposed that the over-pressure event due to the hydrogen fill system caused premature failure of an o-ring seal. The engine “short block” was replaced. |
| Engine Front Insulation | The insulation for the front of the engine package was not pre-fitted and required substantial re-work to fit it to the system. No center reflector piece for the center of the receiver was supplied with the engine, so one had to be fabricated in the field. The center piece later experienced a failure during operation that caused damage to the first quartz window. |
| Quartz Window Mount | The quartz window mount was not fitted to the engine, and required substantial adjustment to align the seals. Also, the front insulation required field adjustment to accommodate the quartz window. The sealing of the window system was not satisfactory, and significant exhaust gas losses have been observed in operation. |
| Shutter Faults | The shutter system as delivered from STM Power was wired incorrectly and contained faulty components. |

The problems in facet assembly were primarily due to optimistic estimation of the difficulty of handling the mirror facets. The awkwardness of handling the large facet halves in an extreme environment led to delays and frustration. Most of the engine startup problems can be traced to inadequate engine checkout at the factory. STM Power delivered the engine package without fully testing it in the configuration in which it would be used. For example, during test operation at the factory the system was connected to a high-pressure hydrogen header so the on-board hydrogen compressor unit was not operated. Also, the front insulation, quartz window, and shutter system were not installed and tested at the factory. Since these subsystems were not tested at STM Power, it was necessary to debug them in the field under difficult conditions.

After the system was placed in hybrid operation in early October 2003, a number of nuisance-level faults and problems occurred as is natural when a new system is brought
on-line. The only significant change to the system design occurred after a short period of solar hybrid operation when the DC drive for the elevation motor failed. In the course of dealing with that failure, the motor drive systems for both the elevation and azimuth axes were re-worked and improved. Originally, the motors were started and stopped “hard” using an inhibit switch on the controllers. This approach was changed to a “soft-start” approach, making the movement of the dish smoother and reducing stress and wear-and-tear on the drives, motors, and structure.

48-Hour Gas StartUp Test

As part of the SAIC acceptance criteria, the STM Beta engine system was required to demonstrate 48 hour of continuous operation at full power on fuel gas. This test was intended to demonstrate proper long-term operation of the STM Beta engine and related subsystems before the engine would be approved for solar operation. The test was completed September 10 through September 12, 2003, with the engine logging a total of 49.8 continuous hours of operation and delivering 1,019.6 kWh of energy. This translates to an average power level of 20.5 kW during the test, well within 10 percent of the rated output of 22 kW.

Solar Hybrid 100-Hour Startup Test

The second part of the SAIC engine acceptance test was a 100-hour solar operation test. Because of the intermittent nature of solar input, the test was conducted over several days and the cumulative hybrid operating hours were totaled. Figure 17 shows the results from the testing.

The reduced energy outputs on October 21 and 28 were due to partial-day operation. On October 21, the initial operation did not commence until afternoon, and on October 28, repairs were made to the insulation on the front of the engine in the morning before bringing the system on-sun. November 1 was a very cloudy day, so little solar input was available although the system tracked and was available for solar input. In the course of the test, the system delivered 1761.5 kWh of energy over 101.3 hr of hybrid operation, at an average net power output of 17.4 kW.

System power output during this initial test was restricted by limiting the operating temperature of the engine. This was done to avoid possible damage to the engine during initial solar testing, since this was the first time that the system had been operated for an extended period with solar input. After the successful completion of this test, the temperature setpoint was slowly increased as experience and confidence were gained in solar operation of the system.
3.2.3 System Operation in Phase 1

Starting on October 21, 2003, the system was operated in hybrid solar mode during daylight hours on a daily basis. By the end of October, the system had achieved about 100 hours of hybrid operation and was operating in a routine manner. Operation continued through December 2003 on a regular basis with few significant problems. As of the end of November 2003, over 250 hours of hybrid operation and almost 100 hr of gas-only operation had been logged. At the beginning of December, 24-hr/day operation (i.e., solar hybrid operation during the day, and gas-only operation at night) was instituted to demonstrate that mode of operation, test control algorithms, and measure system performance under those conditions. As of December 4 when Phase 1 operation was stopped, the system had completed a total of over 280 hr of hybrid operation and over 135 hr of gas-only operation.

Quartz Window Failures

The most significant problem during routine operation in Phase 1 was degradation and breakage of the quartz window at the front of the receiver cavity. The window is used to contain the exhaust gases in the cavity while allowing solar input during solar hybrid operation. It should be noted that the present system is the first solar dish / Stirling system ever to incorporate solar hybrid operation with fuel gas input. The quartz window is also a new addition to the design. Therefore, problems were not unexpected.
It is believed that the first quartz window was damaged during the initial 100-hr solar operation test when a bolt holding the center reflector inside the receiver melted, dripping molten metal onto the quartz window. The contamination of the window initiated devitrification at the center of the window, and this was observed to grow with time (Figure 18). As seen in the figure, there was a large area of discoloration, with a central area 3 to 5 cm in size that had more severe damage. The right-hand portion of the figure shows a close-up of the center area; the dark spots are contamination from the failed bolt. Note that the quartz window was not originally clear, but was somewhat frosted on the inside surface. This was done intentionally to disperse the light passing through the window into the receiver. Finally, on November 12, after about 100 hr of hybrid operation, the window was found to be broken, as shown in Figure 19.

Figure 18. Degradation and devitrification of quartz window

Photo Credit: SAIC
After the failure of the first quartz window, a second window was installed on the system. The receiver cavity was thoroughly cleaned before installation of the new window to avoid any possibility of contamination. It was thought that the frosted surface of the first window might have contributed to its degradation by providing anchor points for contamination; therefore, the second window was polished on both sides to be optically clear. Unfortunately, the new window lasted only about 50 hr of hybrid operation before it, too, failed. The window had become only slightly discolored and had not exhibited any devitrification in the center like the first window. However, the crack pattern suggests that the failure occurred at the center of the window, just like the first window.

A third window was installed on the system. The third window is frosted on the inside surface like the first window but with a coarser texture than the first window. One feature of this more dispersive surface is that the operating temperatures within the receiver were observed to be more uniform than for either of the other windows. Temperature spreads between cylinders in the engine were observed to be as low as a few degrees, and operation with temperature spreads of less than 40°K has been observed extending over several hours. Unfortunately, after approximately 100 hr of hybrid solar operation, the third window began showing devitrification at its center that appeared to be growing. At the end of the Phase 1 testing, that window had not yet failed, but was degrading.

In an effort to understand the cause of the window failures, samples of the first two windows were delivered to materials scientists at NREL for analysis. The samples were examined to determine the type of contamination causing the slight discoloration and the...
devitrification. NREL found iron and trace amounts of other contaminants, proving the hypothesis that molten metal from the center reflector bolt was involved. However, after repair of that bolt, the second and third windows also showed degradation so it appears that the exhaust gases themselves are the primary cause of the degradation.

Phase 1 Operational Results

Except problems with the quartz window, initial operation of the system was very successful. The dish/Stirling system operated through nearly three months in daily hybrid operation and behaved very much as expected. Continued operation to prove long-term reliability and robustness of the improved system was conducted in Phase 2, but the system had already eclipsed the operational reliability of previous SAIC/STM dish/Stirling systems. Table 4 summarizes Phase 1 operation.

**Table 4. Summary of Phase 1 performance results**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hybrid Solar Mode</th>
<th>Gas-Only Mode</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Hours of Operation</td>
<td>282.9 hours</td>
<td>125.4 hours</td>
<td>408.3 hours</td>
</tr>
<tr>
<td>Total Energy Delivered</td>
<td>5140 kWh</td>
<td>2639 kWh</td>
<td>7779 kWh</td>
</tr>
<tr>
<td>Overall Efficiency</td>
<td>~16%</td>
<td>~18%</td>
<td></td>
</tr>
<tr>
<td>System Availability</td>
<td>96%</td>
<td>87%</td>
<td></td>
</tr>
<tr>
<td>Peak Power Achieved</td>
<td>21.8 kW</td>
<td>22.6 kW</td>
<td></td>
</tr>
</tbody>
</table>

Data collected by Robin Taylor and Roger Davenport September 2003 to December 2003

In Table 4, availability is defined as the fraction of time the system is able to be operated divided by the total time. Hybrid availability is based on daylight hours, and gas-only availability is based on 24-hr/day. The overall efficiency of the system is the net electrical output divided by the total of the solar insolation on the aperture area of the dish plus the energy of the natural gas supplied to the system. Efficiency is slightly higher for gas-only operation because the shutter is closed during that operation, providing additional insulation and sealing to the front of the receiver cavity.

Phase 1 Operation Evaluation and Implications

This Phase 1 program was successful in assembling and demonstrating a hybrid gas/solar dish/Stirling system. This is a first-ever system of this type, and its demonstration has involved integration of many improvements to the SAIC dish/Stirling system. As pointed out in the previous sections, the system was able to operate in a routine manner in gas-only and solar hybrid modes, and exhibited excellent reliability (more than 90 percent) over several months and several hundred hours of operation. A few nuisance issues need to be dealt with to eliminate false off-tracks and other occurrences, but these are minor in nature.

The two pressing issues for continued operation of the system identified at the end of the first phase were as follows:
• Window Failures—the causes of the quartz window degradation and failure needed to be identified and eliminated. This led to testing of air curtains and eventual replacement of the quartz window with a borosilicate window and a sweep blower system in Phase 2.

• Improvement of Overall System Efficiency—the system efficiencies measured in the initial period of operation (17 to 19 percent) were lower than expected. In earlier dish / Stirling systems, overall efficiencies of 24 percent or more were achieved. Several sources of inefficiency were identified, including lack of thermal insulation on the receiver assembly, issues in the fuel gas control algorithm that cause intermittent “purging” of the receiver with high flows of gas (leading to excessive gas usage and cooling of the receiver), larger than ideal aperture size on the receiver, and air leakage around the quartz window and front receiver insulation. Efforts to reduce thermal losses and improve system efficiency were undertaken in the second phase of operation.

3.3 Task 3.8.3 Dish / PV System Design and Integration

Similar in scope to Task 3.8.1 for the dish / Stirling system, the objective of this task was to develop complete integration requirements for a dish / PV system. This included evaluation of the changes to the dish system required for the PV receiver, preparing designs to modify the existing SAIC controls and mechanical structure to accommodate the PV receiver, and investigation and development of secondary optics and receiver protection techniques. After that, complete specifications and design drawings for modifications were made.

The deliverables in the task were as follows:

• Del 3.8.3.1 Report on changes to the dish system required for the PV receiver.
• Del 3.8.3.2 Notification letter stating that the design for the control and structural modifications had been completed, including a set of plans and specification.
• Del 3.8.3.3 Report on the design of secondary optics and a receiver protection system, including plans and specifications.
• Del 3.8.3.4 Task report summarizing the results of all work including a complete bill of materials.

3.3.1 Dish / PV System Modifications

Because of the similarities of the dish/PV and dish / Stirling system requirements, the changes needed for implementation of the advanced mirror facets on the dish/PV were very similar to those described earlier for the dish/Dish / Stirling system. The main differences were due to the larger size of the PV receiver and the lower overall flux level. Because of the large size of the receiver, off-tracking would take several seconds, and it was initially thought that a flux shield would be needed to protect the receiver. However, the lower flux levels at the receiver (about 250 to 300 suns) meant that the flux shield was
found not to be necessary. Therefore, it was not implemented in the dish / PV system that was built at UNLV. Other modifications such as the motor controls and UPS system were identical to those for the dish / Stirling system.

3.3.2 Dish / PV Mirror Facet Design

The mirror facets for the PV receiver were different in that the mirror tiles were 30 cm (12”) squares, and they were aimed in groups of four tiles at a 60x60 cm receiver target. This was easily accomplished using the SAIC robotic mirror tile system. Figure 6 shows the layout of the mirror tiles on the substrate of a typical mirror facet. The mirror tiles on each mirror facet were aligned in square groups of four mirror tiles, each group aimed in parallel at four aimpoint quadrants at the receiver plane. Figure 4 shows the full dish / PV system with all the mirror facets in place.

Secondary Optical Element Design

Because of inevitable optical errors in the mirror facets and the blurring due to the finite size of the sun, the image at the receiver plane is not a perfectly uniform square. The flux profile from even a perfectly flat mirror appears fuzzy at the receiver plane more than 12 m away from the mirror facets. Ray-tracing analysis using the NREL computer code SolTrace was used to determine the flux profile on the receiver, and to design appropriate secondary reflectors to improve the uniformity of the flux over the receiver area. Figure 20 shows the results of the SolTrace analysis for the flux at the receiver plane. As shown in the figure, the flux profile is essentially flat over the area of the receiver, with an average flux level of about 260 suns. Outside the edges of the receiver, the flux decreases sharply.

Figure 20. Predicted solar flux on PV receiver plane (Photo Credit: SAIC)
3.4 Task 3.8.4 Dish / PV Mirror Facet Fabrication

The objective of this task was to fabricate fixed focal length mirror facets for a solar dish / PV system to be tested with a dish / PV system being developed under a separate program. This objective was completed and the facets were installed on a dish at UNLV for testing. Deliverables under this task were as follows:

- Del 3.8.4.1 Letter of notification stating that all facet materials had been purchased and received, including a bill of materials.
- Del 3.8.4.2 Final task report covering all aspects of the purchase and fabrication of the facets.

3.5 Task 3.8.5 Demonstration System Selection and Site Design

The deliverable for this task was changed to be only the first subtask of this task: a report detailing recommendations for the second phase of the project. In Phase 1 testing, the quartz window at the aperture of the receiver cavity was identified as a problem area. The windows were observed to be affected by the high-temperature exhaust gases and high solar flux at the aperture in such a way that the optical transmission was reduced and the windows eventually failed. In the second phase, testing and evaluation of alternatives including air curtains and lower-cost borosilicate glass windows was proposed. Another identified area of improvement for the second phase of operation was the control software of the engine, where nuisance faults had led to numerous system shutdowns in Phase 1 testing.

3.6 Task 3.8.6 Site Installation and Operation

This task was changed to include six more months of operation of the system at Tempe, Arizona. A test plan was created to direct the operations, and several incremental enhancements were undertaken to improve system efficiency and reliability. For example, modifications to the engine control software eliminated nuisance faults due to the hydrogen supply system and upon system shutdown. A major improvement was the replacement of the quartz window at the receiver aperture with a much less expensive borosilicate glass window. This not only improves the cost-effectiveness of the system but also improves system performance since the borosilicate window does not degrade optically over time.

3.6.1 System Operation and Performance

The deliverables for this task were subtask reports summarizing the operation, maintenance, and enhancement tests performed each month of the extended operation period. The deliverable reports were as follows:

- Del 3.8.6.1 Dish / Stirling System Operational Report: June 2004
- Del 3.8.6.2 Dish / Stirling System Operational Report: July 2004
- Del 3.8.6.3 Dish / Stirling System Operational Report: August 2004
Because costs during system operation were less than predicted, permission was sought and granted to continue operation beyond six months. Therefore, operation of the system was continued to December 2004; results from the additional operational period were documented.

In the course of this project, the hybrid solar dish / Stirling system was operated for a total of ten months—four months in Phase 1 (September 2003 to December 2003) and six months in Phase 2 (July 2004 to December 2004). During these periods of operation, the system delivered 14,320 kWh in 781.7 hr of hybrid solar operation. Overall, 56 percent of the input energy came from the sun during hybrid solar operation, with the remainder coming from natural gas. In addition, the system delivered 5,552 kWh in 315 hr of gas-only operation. Figure 21 summarizes the month-by-month and cumulative hours of operation in each operating mode for the system.

![Figure 21. Monthly and cumulative hours of operation for hybrid solar dish / Stirling system](image)

The reliability of the system as measured by the mean time between failures (MTBF) increased in this project as shown in the following table:

<table>
<thead>
<tr>
<th>Month</th>
<th>Hybrid</th>
<th>Gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sep-03</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Oct-03</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td>Nov-03</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Dec-03</td>
<td>30</td>
<td>40</td>
</tr>
<tr>
<td>Jan-04</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Feb-04</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Mar-04</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>Apr-04</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>May-04</td>
<td>80</td>
<td>90</td>
</tr>
<tr>
<td>Jun-04</td>
<td>90</td>
<td>100</td>
</tr>
<tr>
<td>Jul-04</td>
<td>100</td>
<td>110</td>
</tr>
<tr>
<td>Aug-04</td>
<td>110</td>
<td>120</td>
</tr>
<tr>
<td>Sep-04</td>
<td>120</td>
<td>130</td>
</tr>
<tr>
<td>Oct-04</td>
<td>130</td>
<td>140</td>
</tr>
<tr>
<td>Nov-04</td>
<td>140</td>
<td>150</td>
</tr>
<tr>
<td>Dec-04</td>
<td>150</td>
<td>160</td>
</tr>
</tbody>
</table>
Table 5: Mean Time Between Failures (MTBF)

<table>
<thead>
<tr>
<th>Operational Period</th>
<th>System MTBF (operating hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NREL Dish / Stirling Test Program (2001-2003)</td>
<td>~50-60</td>
</tr>
<tr>
<td>Phase I SMUD Operation (September 2003 – December 2003)</td>
<td>141</td>
</tr>
<tr>
<td>Phase II SMUD Operation (July 2004 – December 2004)</td>
<td>166</td>
</tr>
</tbody>
</table>

As indicated in the table, the MTBF for the system was approximately three times better than in earlier testing, and showed growth between the two phases of this program. The components and systems that limited MTBF during this project have been identified (e.g., the quartz window in the Phase I testing period) and would be addressed in a future, improved system design to cause the MTBF to increase further.

The efficiency of the system was improved over the period of operation by improvements to the insulation and control logic. The monthly average efficiency in solar hybrid mode increased from 13 percent to 18 percent over the course of operation. Likewise, the monthly average gas-only operating efficiency was raised from 18 percent to 21 percent. The increase in gas-only efficiency was observed despite the fact that during operation with the borosilicate window in place the shutter could not be closed to help insulate the receiver cavity. A possible explanation is that better sealing of the plenum was achieved with the borosilicate window, so less exhaust gas was lost before passing through the regenerator.

The solar hybrid efficiency is lower than the gas-only efficiency for several reasons. The main reason is the solar hybrid efficiency is calculated using the solar energy that falls on the projected mirror area of the dish, whereas the energy that actually gets to the receiver is reduced from that value by reflection and scattering losses in the mirrors and transmission losses in the window. These factors represent a 15 to 25 percent loss in energy depending on mirror and window conditions. Also, during gas-only operation, the symmetrical arrangement of the burners leads to more uniform temperatures on the receiver, thereby maximizing efficiency. The solar input is not as uniform which leads to receiver temperature imbalances and reduced efficiency.

Overall, the efficiency numbers are somewhat lower than the 24 percent efficiency achieved in prior testing of solar and gas-fired operation of dish systems with STM Power Alpha engines. Part of the decrease is due to higher heat losses from the receiver of the hybrid system when operating on gas since the shutter cannot close with the borosilicate window in place. Another factor was intermittent cycling that took place between solar-only and hybrid operation at times when the solar insolation level was marginal for solar-only operation. When re-starting on gas at each cycle, the system vented for several seconds at high flow, cooling down the receiver area and regenerator. Optical degradation of the quartz windows over time also contributed to a decrease in efficiency before the borosilicate window was installed. Finally, due to poor operation of the hydrogen make-up
subsystem, the engine often operated at less than its optimum internal pressure and temperature, reducing efficiency. Although the scope of SAIC’s present operational phase did not allow it, these issues can be resolved or their effects mitigated with further improvements to the engine package and its control logic that would be possible in a second-generation system.

3.6.1 System Availability and Utilization

The reliability of the dish / Stirling system can also be measured by its availability, defined as the fraction of time the system was available to operate over a given period of time. The cumulative availability of the hybrid solar dish / Stirling system was 87 percent over the period of operation in this program. This is good for a prototype system, and reflects the relatively high degree of development of the SAIC dish system and the pre-commercial Beta engine. The availability was reduced primarily by a small number of maintenance events that required some time to repair, notably an o-ring failure in August and at the end of November. Maintenance scheduling contributed to some of these delays, particularly in August. Monthly values of availability were well over 90 percent for 6 of the 10 months of testing.

During the times the system was available to be operated, the fraction of time that the system actually was operated is a measure called the “utilization” of the system. For a solar power system, the availability of sunlight is taken into account by limiting the period of interest to daylight hours only. Using this definition, the cumulative solar utilization of the hybrid solar dish / Stirling system during the operational period was 36 percent. This low value is the result of several factors. First, the system was normally only operated five days per week, and not operated during holidays. Also, operation was normally not started very early in the morning (because of the placement of the unit at the test facility, it was necessary that the sun be 20 to 25° above the horizon before shadows from adjacent collectors were clear of the dish). Finally, planned implementation and testing of system improvements (such as the borosilicate window tests) took the system off-line for several days at a time, especially during the Phase 2 operational/test period. Elimination of these effects yields a net system utilization of just over 80 percent which is more reasonable.
Chapter 4:  
Conclusions and Recommendations

4.1 Conclusions

The main conclusion from this project is that a hybrid solar dish/Stirling system has been successfully integrated and operated to produce power for a utility grid. The system that was developed in this project operated mainly in an unattended, autonomous manner and produced 19,871 kWh of dispatchable electric power during 1,097 hours of operation over a 10-month period.

This project also demonstrated the promise of the SAIC advanced fixed-focus mirror facet for solar concentrators. This concept allows a designer maximum flexibility to produce any desired configuration of solar flux on a receiver by adjusting the aimpoint of each mirror tile on the concentrator individually. Then, the mirror facets are fabricated by an automated robotic system controlled by a computer, so the desired design is implemented without human errors and at low cost.

4.2 Commercialization Potential

The potential for commercialization of utility-scale and distributed generation solar power systems has been significantly enhanced by the results of this project. SAIC has demonstrated a new system previously unavailable to utilities, and has improved the cost-effectiveness of that system by reducing its production and operating costs and improving its efficiency.

4.3 Recommendations

Through this project, SAIC has proven that the solar concentrating dish, tracking system, and controls are a technical success and are reliable. They also have the potential of being cost competitive in commercial production. The Stirling engine receiver was not shown to have accomplished the same results. Development is continuing on Stirling engines as well as high concentration photovoltaic receivers and Brayton engines. As soon as one of these receiver options shows success in the R&D phase, it is recommended that a project be supported to integrate it with the proven SAIC solar dish concentrator.

The path to commercialization of solar hybrid dish/Stirling systems is from demonstration to pre-commercial application to full commercial system sales. The next step would be to implement a pre-commercial project to allow economies of scale and long-term operation to be demonstrated. An appropriate size would be a 1 to 2 MW project, consisting of 50 to 100 systems. Such a project could be implemented by providing economic incentives to a utility or commercial entity to allow them to justify the risk of the new technology.
4.4 Benefits to California

The immediate benefits of this R&D is in furthering the knowledge base of the solar dish/Stirling technology, quartz window application for Stirling receivers, dispatchable solar/gas hybrid operation of a dish/Stirling system and proof of an advanced mirror concept developed by SAIC with its headquarters in California.

If the results of this project become widely used, California would benefit in two ways. First, SAIC production and engineering facilities are based in California and further development and implementation of these systems would result in job growth and economic activity in the state. Second, since California is one of the most likely locations for implementation of these systems, widespread use of these systems would result in direct benefits to the state in terms of reduced pollution, increased sustainability, and stability of the state’s electric generation system. Increased energy security would be achieved by increasing the use of distributed energy from solar, thus reducing the need to import energy.
GLOSSARY

AC
Alternating Current. An electric current that reverses direction (sine wave). In the United States, most household current is single-phase AC at 60 cycles per second. Many businesses in the U.S. that have larger electrical needs use 3-phase AC at 60 cycles per second, or Hertz (Hz).

Amps
The unit of electrical current. Can be thought of as the "flow rate" of electricity.

APS
Arizona Public Service Company

BCS
Beam Characterization System – A system for measuring the solar flux on a target by imaging the target with a camera system and digitizing the resulting images.

Components
Refers to other devices used and needed when building a solar system.

DC
Direct Current. An electric current flowing in one direction only.

Grid-Connected
A solar system in which the array supplies power directly to a load center (i.e. AC Service Panel) in a home or commercial facility. There is no on-site storage device included with a grid-connected system. Instead, all the kilowatt-hours generated by the system are either used by the loads connected to the load center in the building or they are pulled into the utility grid power lines via the utility kilowatt-hour meter attached to the building.

Inverter
An Electronic Device that changes direct current (DC) to alternating current (AC).

kW
Kilowatt, 1000 watts; an incandescent light bulb uses 40-100 watts.

MW
Megawatt, 1,000,000 watts.

NREL
National Renewable Energy Laboratory

Peak Power
Maximum power rating for some particular device.

PCS
Power Conversion System – Acronym for the entire engine-generator package

Photovoltaic (PV)
Direct conversion of light into electrical energy.

Photovoltaic Cell
The treated semiconductor material that converts solar irradiance to electricity.

PWM
Pulse-Width Modulation – Control system used for variable-speed control of DC motors.

SAIC
Science Applications International Corporation.

Solar
Energy from the sun.

Solar Collectors
A device designed to capture light or heat
energy from the sun. Solar thermal collectors are used in solar hot water systems (often found in homes) and photovoltaic collectors are used in solar electric systems.

<table>
<thead>
<tr>
<th>Solar Panel</th>
<th>Another name for a single module or a group of solar modules that are part of a solar electric PV system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swashplate</td>
<td>Used to convert the up-and-down motion of the four axial pistons into rotary motion of the crankshaft.</td>
</tr>
<tr>
<td>UNLV</td>
<td>University of Nevada at Las Vegas – Host site for NREL concentrating dish / PV development project</td>
</tr>
<tr>
<td>Volts</td>
<td>The unit of electromotive force that will force a current of one amp through a resistor or one ohm.</td>
</tr>
<tr>
<td>Voltage</td>
<td>The measurement of the force of electricity.</td>
</tr>
<tr>
<td>Watts</td>
<td>A measure of electrical power that is determined by multiplying the voltage by the amperage.</td>
</tr>
</tbody>
</table>