DESIGN OF THE SMALL COMMUNITY PROGRAM (SCSE #2) AT MOLOKAI, HAWAII

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Abstract

Power Kinetics, Inc. (PKI) is building a solar power station to be installed on the island of Molokai, Hawaii under a contract with the U.S. Department of Energy. The station will consist of five modules to produce 50 kW each. These consist of a 306m^2 point focus collector with polar axis tracking, a ground mounted steam engine driving an induction generator via a cam clutch, an oil fired boiler and superheater, and a water cooled condenser. The steam system will produce 363 kgm of steam per hour at 6.89 MPa. The temperature at the exit of the solar receiver will be 280°C and at the outlet of the superheater, 450°C. The boiler can produce the steam when there is no sun.

Key words: solar thermal power station, solar collector, solar boiler, steam engine.

INTRODUCTION

The US Department of Energy has two projects under the Small Community Solar Experiment (SCSE); one at Osage City, Kansas, the other at Molokai, Hawaii. PKI bid under both programs and was successful with both bids. The orientation in design, however, is quite different for each project.

In Kansas, the site is in rural America but has ready access to cities and technical services. That projetct will provide experience with a four unit 100 kW system, to determine operational characteristics in such an environment. In Molokai on the other hand, the system is exposed to a corrosive ocean atmosphere in a relatively remote site. Additionally, this five unit 250 kWe system produces a significant (6%) addition to the existing electrical output of the Molokai Electric Company (MOECO). This paper describes that project at Molokai.

The Power Kinetics Square Dish solar collector design avoids the structural limitations inherent in fixed parabolic dish shapes, as will be explained later. The reduction of the design constraint has resulted in a unit size growth from 80m^2 of mirror surface in the 1984 SOLERAS desalination project in Yanbu, Saudi Arabia to the 300m^2 unit size being implemented at Molokai. This scale up has brought about a significant weight reduction, a lowered maintenance profile, decreased parasitic losses, and has simplified the system. This has brought about a major reduction in the costs of the collection of solar energy.

An Australian National University (ANU) engine is aptly chosen for the Molokai project because it addresses the design philosophy for a remote site. A similar engine has operated for over 6000 hours in a solar power station which will be described in another paper. Although it operates in the moderate efficiency range, it is inexpensive and has a very low maintenance requirement. Additionally, the use of a fossil fuel superheater system stabilizes output and increases capacity. This affords the utility a firm 250 kWe addition to its own 4 MWe output.

The system is currently undergoing tests at Sandia National Laboratory in Albuquerque, NM, and is scheduled for installation on Molokai in the fall of 1987.

A parabolic dish configuration was required by the Small Community Program because of the assessment years earlier, that this design could provide more than twice the integrated energy output of a parabolic trough configurations or central receiver. The SCSE program also stipulated that each solar collector in the system have its own electric generator, a requirement that was intended to avoid the energy losses inherent in the pipe collection network of a centralized generation system. PKI has implemented both of these requirements at Molokai with a five dish, 50 kWe reciprocating steam engine design. We would have preferred to use a single similar but larger 250 kWe generator because it would be more efficient and cost much less. The existing design will furnish baseline information, however, from which the characteristics of the larger engine system can be extrapolated.

The addition of an oil fired steam generator and superheater provides stability and firm capacity to the system. Because of the large penetration of the grid, however, this seemed a necessary precaution to minimize any deletorious effects from a 6% solar contribution. Additionally, this benefits MOECO because the firm capacity allows them to use the system as a peaking supply between 5PM and 7PM when the solar input is low or non existant.

SYSTEM DESCRIPTION

The solar collector field will use two acres of land adjacent to Molokai Electric Company's current operations located about 1/4 mile from the sea. Water is obtained from nearby wells to supply cooling water. The plant is to be operated when the solar input is sufficient for tthe combined input of solar and oil to produce more output than a diesel engine would when using the same amount of oil as the burner.

A central plant control turns on and off each of the five identical modules and monitors their status. Each module consists of a series connected solar collector and fossil fired boiler and superheater, a steam engine, condenser and a heat rejection loop, condensate conditioning unit, and integrating controls. Water supply, cooling pond, and fuel oil storage are shared by the individual power modules while the solar collectors and the engines have individual controls which enable their automatic operation and fault detection. When a module is turned on, the solar collector concentrates the available energy to produce steam. The oil burner then brings this wet steam to the conditions required by the engine. Without the sun, the boiler can produce all the steam. The steam engine can operate with wet steam but it is much more efficient when running on superheated steam. This flexibility allows continuous stable operation through clouds and variable weather conditions with the use of simple controls.

SQUARE DISH SOLAR COLLECTOR

The PKI Square Dish Solar Collector (Figure 1) consists of 392 mirrors, 0.6m (25") x 1.2m (48"), mounted on 28 identical open web triangular shaped mirror support beams, each of which supports 14 facets. The dish is aligned parallel to the earth's axis to simplify tracking. The rotating frame consists of three main girders extending from a central beam which is supported so that the girders clear the ground at all orientations. A 2-member boom extends from the frame to support the receiver (Figure 2) 15m (50 ft) from the mirrors. The collector can operate in an 18 m/s (40 mph) wind.

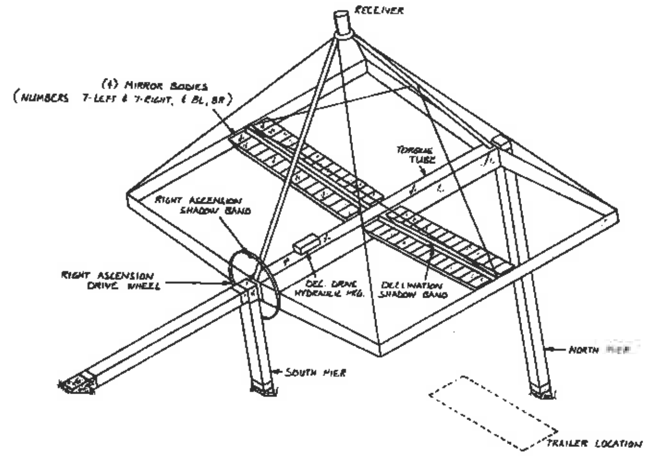

FIGURE 1 The Square Dish collector structure

The mirror supports shape the surface of each mirror to an approximate paraboloid which will produce an image of the sun0.25m (10") in diameter at 15m (50 ft). The 14 mirrors on each beam are aligned to project the image at a focal point 15.2m (50 ft) away. Each facet group (14 mirrors) can be aligned independently by means of an adjustable connection which is locked after alignment. Once the 28 mirror rows are adjusted, the images remain within 25 mm (1") from the focal point (i.e, the point where the controller "thinks" the image is).

The collector has dual-axis tracking and permits focusing of sunlight throughout the day. Right Ascension tracking is accomplished by rotation of the entire collector in an east to west polar sweep, about its center of gravity. Declination tracking is accomplished by simultaneous rotation of all mirror support assemblies, also around their centers of gravity.

The collector control subsystem is microprocessor-based. Active feedback control of the collector is achieved through shadowband sensors mounted on the collector itself. The controller keeps track of sunrise and sunset times and tracks the sun in Right Ascension without positive feedback when the sunlight is blocked by clouds. It stows the mirrors in an inverted position whenever the sun is obscured for ten minutes. The module controller provides additional signals (such as rainwash command, etc.) that are integrated into the system to provide common safety and convenience.

Except during operation, mirror assemblies are maintained in a stowed position. This protects the mirrors from snow, hail, or dirt build-up. The overall system design emphasizes safe operation. Except during periods of power production or manual override for rainwash, the mirrors are inactive.

FOSSIL BOILER AND SOLAR RECEIVER

The boiler was designed to develop 363 kgm (800 lbs) of steam/hr at 450°C (850°F) and up to 6.89 MPa (1000 psi). It consists of four sections: an economizer, a solar heated receiver, a saturated boiler, and a superheater. These sections consist of only coiled pipe and tubing in bundles, with no headers or pressure containing parts of larger diameter than 3/4 inch pipe. The boiler has been designed using the ASME Boiler and Pressure Vessel Code.

The economizer, the solar receiver, and the saturated boiler sections, since they are water wetted in normal operation, will be made of low alloy steel; but the superheater will be of stainless steel. To insure conservative design and provide operational flexibility, the rating of the boiler (the maximum allowable working pressure) will be applied to all sections even though code allows different pressure levels along the path of water-steam flow. In operation only the boiler feed system and economizer will see the upper pressure limit of 6.89 MPa (1000 psi) and these will be at a temperature below 200°C (390°F). The superheater will be at the lower pressure of around 5.88 MPa (850 psi) at the higher rated temperature of 450°C (850°F). This design is appropriate because of the experimental nature of the application and allows much operational freedom below the set points of the pressure relieving valves.

The receiver (Figure 2) is a cylindrical cavity type with an aperture coil opening to a diameter of 1.5 meters. The cavity is about 1.5 meters deep. The focal plane of the receiver is 15.2 meters from the concentrator. Flux distribution inside the cavity has been kept below 12 watts per square centimeter to insure long life of the absorber tubes. Heat loss from the receiver is estimated at 5.7 kW in a 2 m/s wind and 9.1 kW in a wind of 10 m/s. When the insolation is 1 kW/m^2, the solar input to the steam is estimated to be 260 kW.

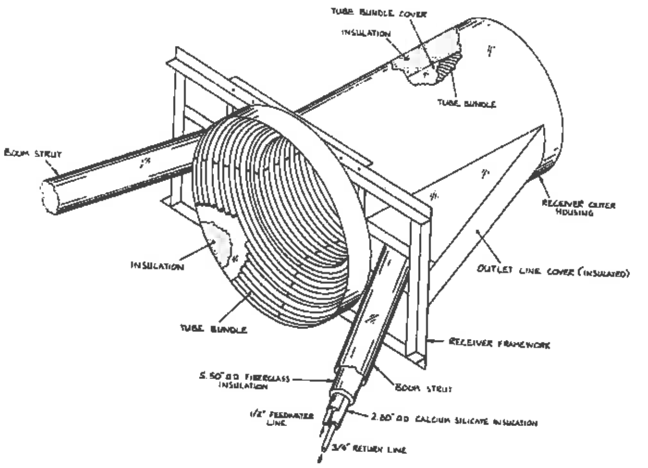

FIGURE 2 The solar receiver. When the insolation is 1 kW/m^2, 260 kW is supplied to the water passing through the 3/4" diaa low alloy steel pipes

While the boiler, (Figure 3) receives an enable signal from the module controller, the burner operates at a preset power interrupted only by an over-temperature signal. The feedwater rate is controlled so that all the absorbed solar energy goes into producing saturated steam and the fossil superheater will bring the steam temperature to 450°C (850°F). The burner has built-in start and ignition controls and adds little complication to the module. Since the engine control and design allows operation on a range of steam conditions, the module can operate without the boiler. Over-temperature or over-pressure conditions of the fossil boiler however, automatically shuts down the module through the module controller.

A hierarchy of control is provided to allow automatic failsafe operation of the plant and maximize the electrical output. The highest level of control allows for operation of one or multiple modules with remote shutdown control by the utility, manual shutdown at the site, or automatic shutdown due to site conditions. Similarly, at the module level, independent controllers allow for maximum safety and reliability. Each controller will function to produce power as long as it receives positive enable signals from the relevant components. Lack of any signal, as well as manual shutdown or central shutdown, stops each component in a safe manner.

FOSSIL HYBRID OPERATIONS

The fossil fired input is controlled by the insolation. When the value is between 500 W/m^2 and 700 W/m^2 the fire adds 100 kW of power to the steam and when it exceeds 700 W/m^2 the superheater operates alone, to provide 50 kW. The flow of feed water is controlled at all times to make the temperature of the steam leaving the superheater 450°C. The superheater is located below the saturated steam generator and is fired by its own smaller burner which is controlled separately.

The switching of the boiler and superheater fires is designed to use a combination of solar and oil whenever the system will produce more output than the same quantity of oil used in a diesel engine. In other locations where waste biomass or crude or bunker oil is used for fuel, the strategy could depend upon the supply and cost of the fuel. The power needed from the burner to achieve this performance depends upon the insolation and the efficiencies of the boiler and engine.

Using a boiler efficiency of 0.85, an engine efficiency of 0.2 and a modern diesel engine efficiency of 0.33, the operation meets the condition that the oil is being used effectively when the solar input is equal to the power of the oil being used.

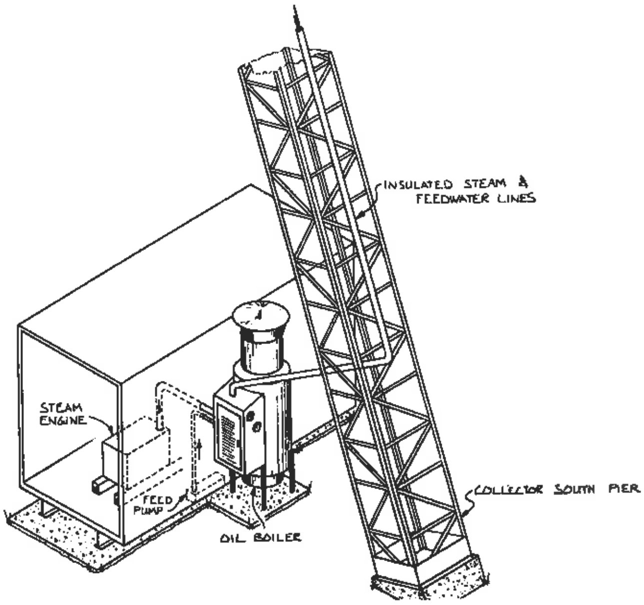

FIGURE 3 The oil fired boiler and superheater in the steam line from the receiver to the engine

The power in the steam entering the engine needs to be 300 kW to produce 60 kW of shaft power. At 430°C and 800 psi this requires a flow of .0913 kgm/s (724 lb/hr). With the 306 m^2 collector and 40 kW from the superheater, that water flow results in the production of dry steam at 331°C when the insolation is 900 W/m^2. The flow will be controlled electronically to produce steam as near to 450°C as possible with oil used mainly for superheating.

The graph of steam temperatures, Figure 4, shows the temperatures that would occur if the flow were 0.090 kgm/s.

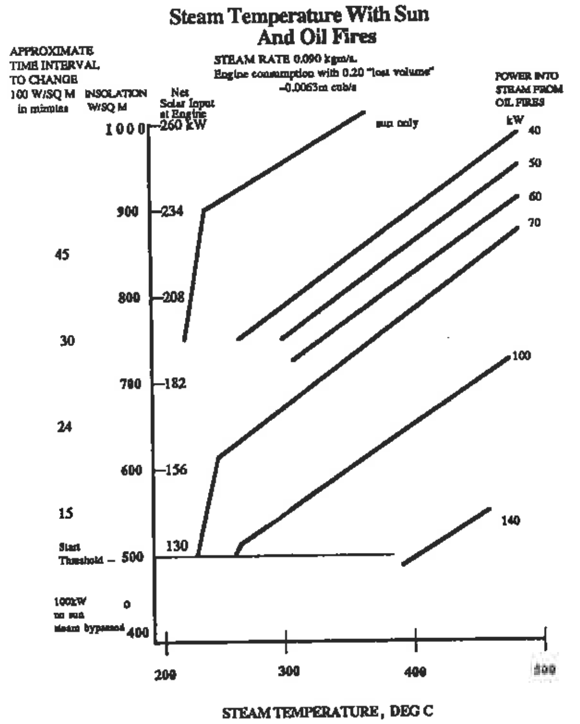

FIGURE 4 The temperature of 0.09 kgm/s of steam supplied to the engine running at 1800 rpm. The lines show the temperature produced by the sun and the oil power. The steam pressure is set by the engine consumption and increases with temperature.

POWER CONVERSION SUBSYSTEM

Most of the engine is made from parts of two diesel engines which are on the market. The crankcase, sump, crankshaft, flywheel, connecting rods and starter are from a Lister Diesel. The cylinder liners and pistons are from a GM diesel. The engine is started by a standard electric starting motor. Steam is admitted to each cylinder through ball valves which are opened by fingers attached to the crown of the pistons. The steam expands until the piston exposes the exhaust ports in the cylinder liner, which was made for a two stroke diesel engine. The engine is started automatically when the incoming steam is hotter than 180°C and the pressure reaches 2.74 MPa (400 psi). The full supply of steam being produced by the collector is used whenever the engine is running. When the power from the collector drops due to lack of sunshine, the engine stops and the starting circuits are reset to monitor the steam and await the starting conditions. The engine is not sensitive to water in the steam, it gives partial output from wet low temperature steam when the sun is attenuated and not supplemented by the oil fired boiler, and a maximum net output of 53 kWe when the insolation is 1 kW/m^2 and the superheater is supplying 40 kW.

The engine configuration is as follows:

Bore	98.4 mm
Stroke	114.3 mm
Number of cylinders	4
Max. steam press.	6.89 MPa (1,000 psi)
Max. steam temp.	450°C (850°F)
Condenser press.	24.5 kPa (abs)
Expansion ratio	25
Lubrication	as in Lister engine
Lubricant	Mobil oil XRN 1301C

Initial water treatment will be done on a plant basis providing deionized water to each module. Each module will utilize a closed loop steam Rankine cycle with only incidental evaporation from the oil skimming tank and occasional boiler blowdown having to be made up. Water supply at the site will be required for both boiler feed and cooling.

Figure 5 shows the interconnections between the components of the steam system. The exhaust steam line enters the upper end of a cylindrical vortex chamber tangentially. Oil and water droplets are stopped by a gauze sleeve on the inner surface and drain to the bottom of the chamber, the steam passes up through the top plate of the vortex chamber to the condenser. The smallest oil drops pass into the condenser with the steam, and the condensate carries these as a very fine suspension to compartment 1 of the feedwater tank. This dispersion of oil in the condensate must be removed before the water is returned to the boilers. It cannot be removed by conventional filters or the centrifuge. The method used is to pump water from compartment 1 of the feedwater tank and deliver it to a 5u filter bag which is packed with non-absorbent cotton wool and mounted in compartment 2 of the feedwater tank. The oil coalesces on the cotton wool and the partly cleared water passes over a weir into compartment 1 from where it is recirculated through the filters. The filter pump delivers about 180 ml/s while the feedwater pump draws 90 ml/s from compartment 2 of the feedwater tank. Beads of oil form on the non-absorbent cotton wool and float to the surface in compartment 2 from where they are carried over the weir into compartment 1.

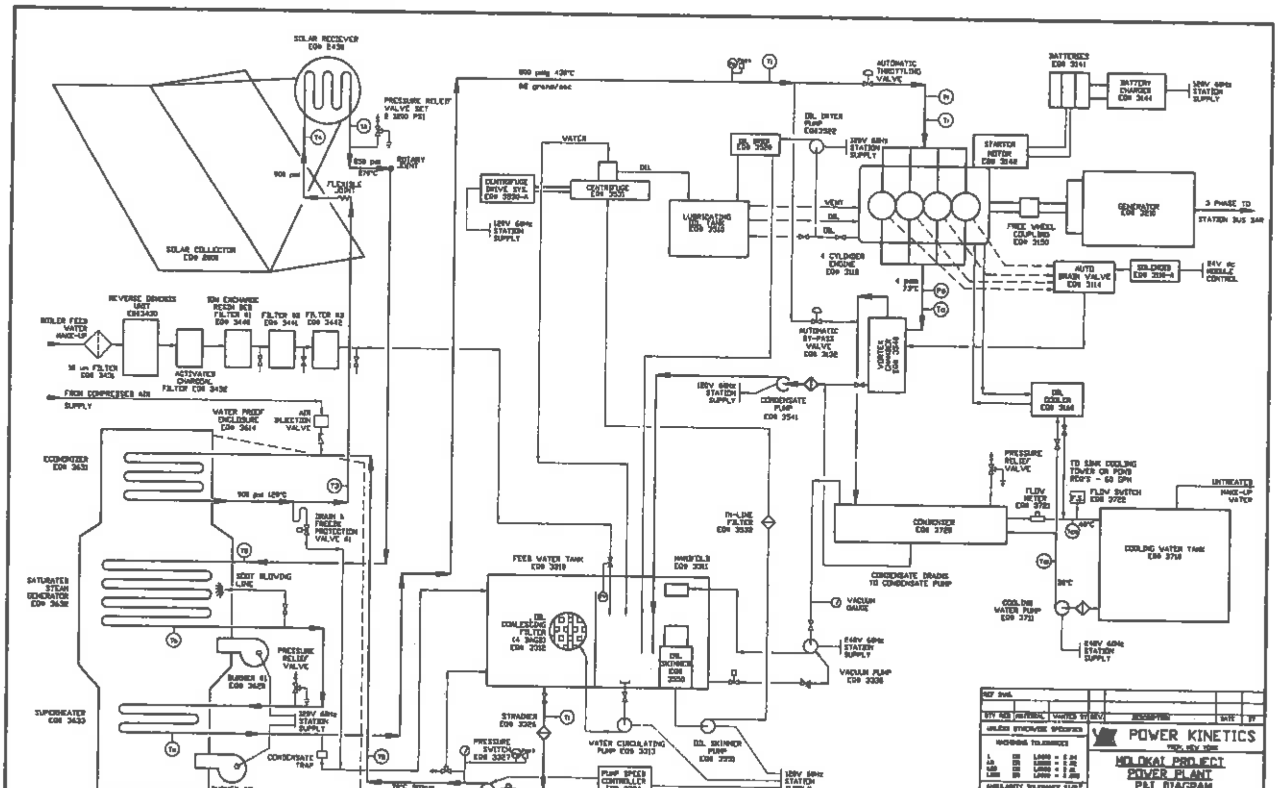

FIGURE 5 The interconnection of components of the power plant

Level switches in the vortex chamber control the operation of the condensate pump which delivers the oil-water mixture to compartment 1. There the oil collects on the surface of the water which varies in level depending upon the amount of water or steam in the return line from the collector. A special skimmer, which floats to the level needed to skim at the rate determined by the flow into the skimmer pump, is used to collect the oil with water. The skimmer pump delivers this mixture to the centrifuge. About 2 ml/s of oil is recovered from the engine exhaust with the complete condensate treatment. The oil is washed and cleaned by this process, leaving solids in the various filters and the centrifuge chamber.

A small quantity of steam leaks to the engine crankcase and condenses. This water must be removed from the lubricating oil in the sump. The wet oil is pumped at 35 ml/s from the sump and through filters to remove the water. It then returns to the oil tank. Oil cooling is also required to remove the heat conducted to the sump oil by the crankcase.

Engine operation starts when the module controller sends an enable signal to the engine controller. This signals the central plant controller and the module's concentrator both to allow operation. As in all cases, a manual shutdown can override the enable signal.

While the engine is stopped, each cylinder is drained of water and steam by a valve. Interlocks prevent the starter from functioning unless the drain is open. As soon as the engine starts, the drain valve is closed by a signal based on engine speed. When the engine is running, any water in the steam is diverted via a steam separator and trap.

The engine controller monitors fluid temperatures, pressures and levels to detect out of limit conditions. The out of limit signal shuts down the whole module at the module controller level and a light signals the reason for the shutdown.. The module controller relays the shutdown status of the module to the central plant controller without affecting the other modules. The independent engine controller allows the module to safely produce electric power as long as there is steam and no shutdown condition.

An induction generator is specified for delivering the electrical power to the utility. It is driven from the engine via a cam clutch which allows the generator to run as a motor when the engine stops due to a passing cloud. At sunset or when continuous clouds develop, the generator is disconnected from the bus after the engine has stopped. When compared to a synchronous generator, the induction generator offered several advantages to the project:

- No voltage regulator is required. Voltage and frequency are controlled by the utility
- Simple construction; no brushes or collector rings
- No synchronizing circuit for paralleling to the utility
- Lower maintenance costs
- Large power swings do not pull the generator out of synchronization with the system.

The generator chosen for the project obtains a high efficiency through use of heavy rotor bars, a close tolerance rotor, extra copper in the stator windings, and an efficient fan. It is a 240/480 VAC, 3-phase, 60 kW/90 HP size at 1800 RPM nominal speed. Actual operating speed is 5% faster with an expected efficiency in the .95-.96 range.

HEAT REJECTION SYSTEM

The condenser of the power conversion subsystem is designed to be cooled by water from a holding tank. On a sunny summer day, heat can be transferred to the water increasing the temperature about 10°C. The heat is lost from the tank by evaporation and some convection to the air at the surface. Evaporation is enhanced by spraying the return water into the pond. At night the heat gained during the day is lost and the temperature drops to a few degrees above that of the air temperature.

The condenser is a shell and tube design with the water in the tubes. The condensate drains from the shell to the vortex chamber and condensate pump. The vacuum pump is a liquidring sealed rotary vane pump for which the flow of cooling and sealing water required is 33 ml/s which is circulated from the feed water tank.

When the engine is not operating, a bypass valve allows water or steam from the solar collectors to pass to the condenser until the steam conditions are correct for the engine to start.

STATUS OF PROJECT

The system design for the Molokai Small Community Program optimizes flexibility. The heavy requirement for reliability because of the remote nature of the site, added significant engineering challenges, but most hurdles have been surmounted under the design phase of the program. Although the 306 m^2 Square Dish has not been approved for manufacture at this time, engineering prototypes indicate that the large size can be produced economically with great gain to system economics. This planned gain permitted the inclusion of fossil hybrid operations.

A pre-production engine similar to the one in operation at White Cliffs in Australia has already been run with a prototype boiler for more than 600 hours. The large risks have been engineered out of the program through suitable equipment design, leaving the more routine risks related to responding effectively with a remote site.

ACKNOWLEDGEMENT

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