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# Results of the Boeing/DOE DECC Phase I Stirling Engine Project

Kenneth W. Stone
Boeing
5301 Bolsa Ave.
Huntington Beach,
CA 92647
PH: 714-896-1164
FAX:714-372-2394

Terry Clark
Coni C. Thamann
Stirling Energy Systems
6245 North 24th Pkwy
Phoenix, AZ 85016
PH: 602-957-1818
FAX: 602-957-1919

Hans Nelving
Kockums
S-205 55 Malmo,
Sweden
PH: 46-40-34-80-00
Dir: 46-40-34-82-75
FAX: 46-40-97-32-81

Richard B. Diver
Sandia National Laboratories
P.O.Box 5800
Albuquerque,
NM 87185-0703
PH: 505-844-0195
FAX: 505-844-7786



## ABSTRACT

Phase I of Boeing Company/DOE Dish Engine Critical Component (DECC) Project started in April of 1998 and was completed in 1999. The Phase I objectives, schedule, and test results are presented in this paper. Test data shows the power, energy, and mirror performance are comparable to that when the hardware was first manufactured 15 years ago. During the Phase I and initial Phase II test period the on-sun system accumulated over 3,800 hours of solar-powered operating time, accumulated over 4,500 hours of concentrator solar tracking time, and generated over 50,000 kWh of grid-compatible electrical energy. The data also shows that the system was available 95 % of the time when the sun's insolation level was above approximately 300 w/m$^2$, and achieved a daily energy efficiency between 20% and 26%. A second concentrator was refurbished during Phase I and accumulated over 2,200 hours of solar track time. A second Stirling engine operated 24 hours a day in a test cell in Sweden and accumulated over 6,000 test hours. Discussion of daily operation shows no major problems encountered during the testing that would prevent commercialization of the technology. Further analysis of the test data shows that system servicing with hydrogen, coolant and lubricating oil should not be a major O&M cost.

## INTRODUCTION

McDonnell Douglas (now Boeing) and United Stirling AB (USAB) of Sweden (now Kockums) formed a joint venture in the early 1980 to develop and market the Dish Stirling System shown in Figure 1. McDonnell Douglas Corporation (MDC) designed and build the solar concentrator (dish) for the USAB 4-95 Stirling engine. The system was manufactured, installed, and tested through the late 1980s (Lopez, 1993). The market for alternative sources of electricity generation disappeared in the mid-1980s, causing both companies to divest the program. Stirling Energy Systems (SES) obtained the concentrator rights and hardware, and has obtained a license to manufacture the Kockums 4-95 Stirling engine. In April of 1998, Boeing received a cost-share contract from the Department of Energy (DOE) to

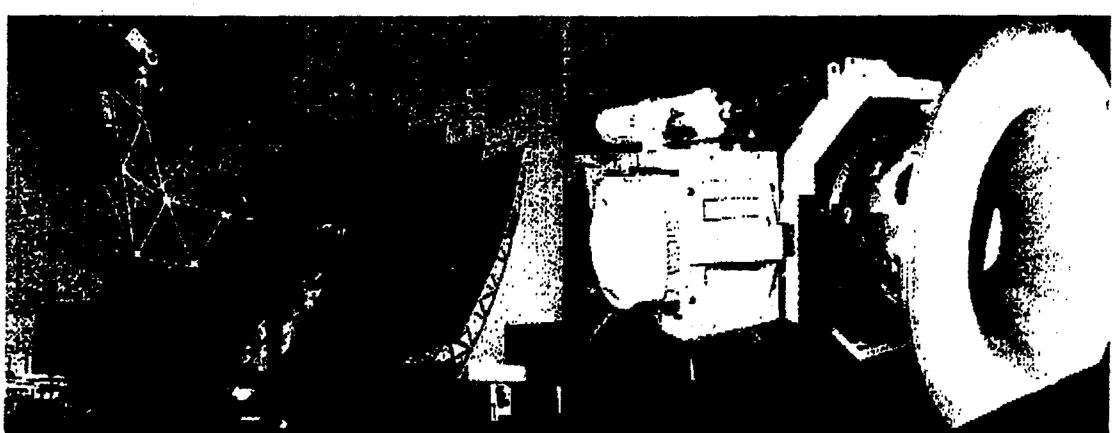

Fig. 1. Dish Stirling System

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continue testing this system (Stone, et al.,1999) in order to revalidate the technology, evaluate new engine seals, and update performance benchmarks. The primary objective of the Dish Engine Critical Component Project is to commercialize the technology. The objective of the first phase was to enlarge the reliability database needed for commercialization and to demonstrate the performance of the system. Two Power Conversion Units (PCUs) consisting of an engine, generator and auxiliary equipment were refurbished by Kockums in Sweden using equipment manufactured in the early 1980s. PCU #1 was mounted on the concentrator at the Boeing/SES Solar Test Facility in Huntington Beach, CA and has operated on-sun since July of 1998. PCU #2 was installed in a Kockums test cell in November 1998 and has operated nearly 24 hours a day for 13 months using a combustion heat source. The 4-95 Stirling engine was first solarized and tested in the early 1980s by USAB/Kockums for the Department of Energy and Jet Propulsion Laboratory (JPL). Since that time a dozen engines have been used in several programs (Droher, 1986 & Livingston, 1985) and these have accumulated over 20,000 hours of on-sun operating time, generated over 169 MWh of grid electricity and completed over 124,000 hours of test cell time, as shown in Table 1.

**Table 1. Power Generating Time and Generated Energy.**

**On-sun operating time**

| PROGRAM | TIME (h) |
|---|---|
| Boeing DECC Phase II* | 505 |
| Boeing DECC Phase I | 3,322 |
| MDA/USAB/SCE | 13,752 |
| USAB/Vanguard | 2,412 |
| USAB/JPL | 420 |
| TOTAL | 20,411 h |

**On-sun generated energy**

| | |
|---|---|
| Boeing DECC Phase II | 6,491 |
| Boeing DECC Phase I | 44,838 kWh |
| MDA/USAB | 118,000 kWh |
| TOTAL | 169,329 kWh |

**Test cell operating time**

| PROGRAM | TIME (h) |
|---|---|
| Boeing DECC Phase II* | 762 |
| Boeing DECC Phase I | 5,278 |
| MDA/USAB | |
| - Simulated solar | 50,707 |
| - Bench | 35,578 |
| USAB/Vanguard | |
| - Simulated solar | 17,577 |
| - Bench | 5,030 |
| USA/JPL | |
| - Simulated solar | 700 |
| - Bench | 8,480 |
| TOTAL | 124,112 h |

***Through 1/23/00**

## OPERATING TIME

The first dish/engine unit has been operating since July of 1998 and has accumulated over 3,300 hours of on-sun operating time in Phase I and continues to operate in Phase II. The weekly on-sun operating time and total accumulated operating time are shown in Figure 1. The average weekly operating time of about 50 hours per week has primarily been a function of the weather conditions. The maximum weekly on-sun operating time in 1998 was 70 hours, and 80 hours in 1999. There have only been three outage periods, discussed below. Since the Boeing/SES Test Site is close to the ocean, it is subject to considerably more cloudy weather than would be experienced in a desert location. In order to increase the concentrator operating time both of the units at Huntington Beach were placed into the track mode of operation even on cloudy days starting in 1999. The accumulated track time for Concentrator #1 was

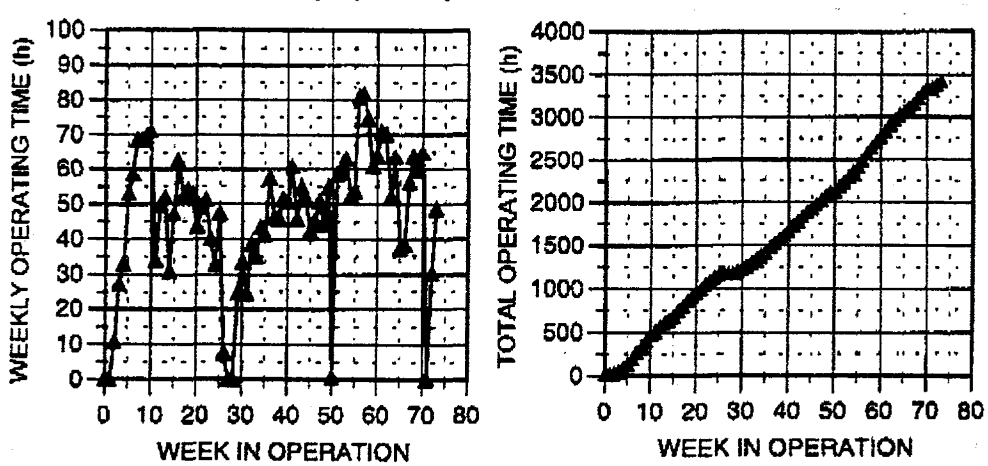


**Fig. 2. Weekly and accumulated on-sun operating time for PCU #1.**

4,500 hours as shown in Figure 3. The second concentrator was made operational during Phase I in order to generate a larger concentrator reliability database and to prepare for the next PCU. The accumulated track time of over 2,000 hours for the second concentrator is also shown in the right side of Figure 3. The flat portions in the accumulated track time curve for Concentrator #2 are not due to problems but because the unit was taken off-line for wiring modifications, mirror alignment, or special testing. Both of these concentrators were fabricated in the McDonnell Douglas/United Stirling 1980s Dish Stirling program. Since no major changes were made to the concentrators (same drives, mirrors, structure, controls), the total accumulated concentrator operating time since 1984 is far in excess of the accumulated tracking time shown for the DECC program.

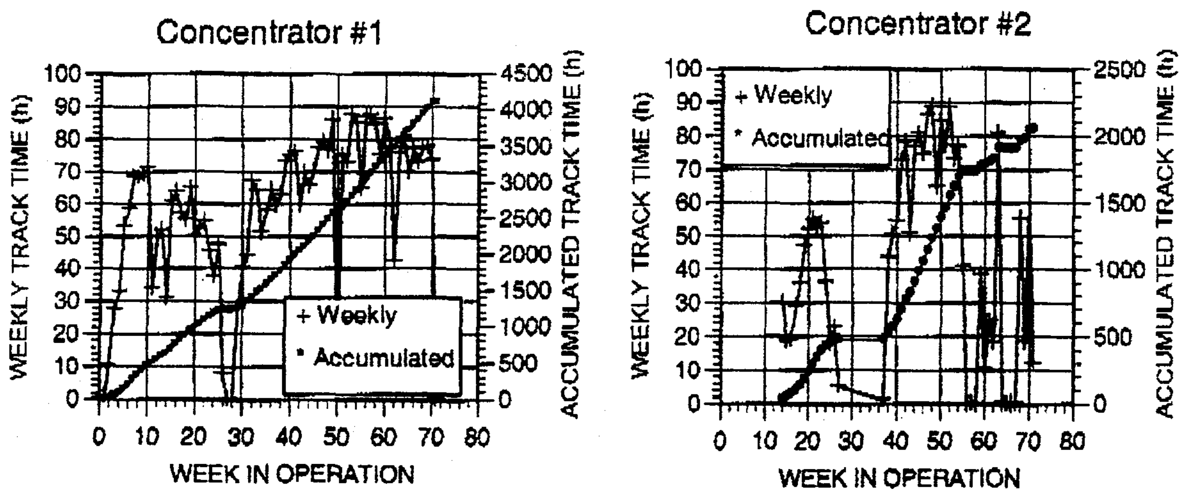


**Fig. 3. Tracking time for concentrator #1 and #2.**

The second Stirling engine was installed in an engine test cell at the Kockums plant in Sweden. The solar-type heater head was removed, replaced with a combustion heater head, and liquid fuel burned to provide heat to the engine. The test cell was located in an enclosed area, therefore the radiator was removed and the coolant lines were connected to an external cooling system. Initially the test cell unit only operated about eight hours a day during weekdays. Later safety systems were installed and checked out for use in extended operation, and after week 18 (March 1999) the test cell has had the capability of operating 24 hours a day, seven days a week. The weekly and accumulated operating time is shown in Figure 4. Most of the outage periods have been caused by non-engine components such as the combustion system, and facility utilities.

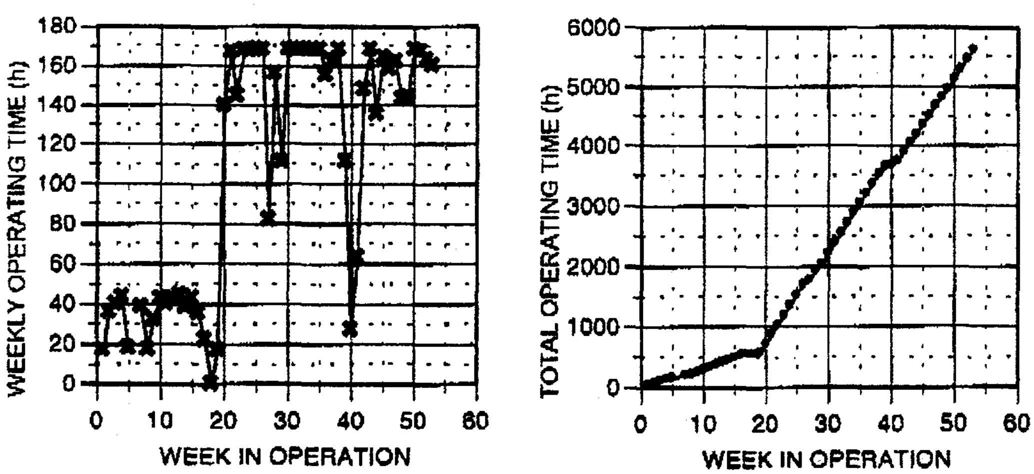


**Fig. 4. Test cell operating time for PCU # 2 at Kockums.**

## On-Sun Performance

One of the objectives of the DECC Phase I project was to establish an updated power and energy performance benchmark for the Dish Stirling system. This benchmark could then be used to establish annual performance parameters for Huntington-Beach-type solar conditions, and to compare the performance to that obtained in the 1980s. The net weekly and accumulated energy generated for the project is shown in Figure 5. The weekly average energy generated is approximately 800 kWh with a maximum of 1500 kWh. Again, the average weekly energy is low for because of the close proximity of the test site to the ocean, which results in more cloudy days than would occur in a desert location. The net daily generated energy as a function of the incident sun energy is shown in Figure 6 as a function of the sun daily incident energy. The top, or maximum, performance line shown in the left portion of this figure defines the maximum net daily energy that could be expected at a given sun incident energy level. Also shown is the average performance (or least- squares-linear line) of all data points, and a lower performance boundary line. The variation of the data points between the upper and lower line boundaries are the result of variation in reflectivity due to mirror soiling, and to some extent, variations in ambient temperature, wind speed, etc. The right-hand plot of Figure 5 shows the daily net energy efficiency as a function of the sun daily incident energy. The efficiency is calculated by dividing the daily energy by the concentrator glass aperture area.

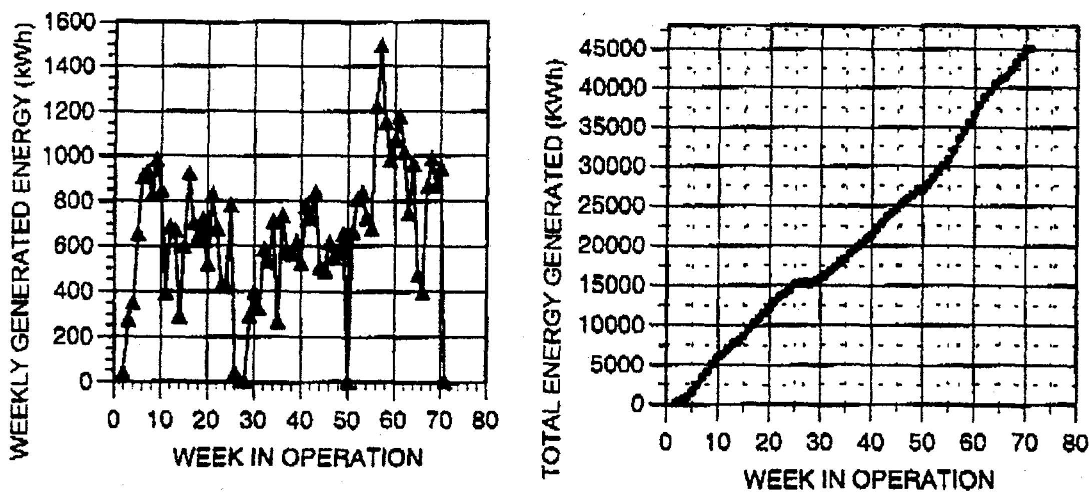


**Fig. 5. Weekly and accumulated net on-sun generated energy for PCU #1 at the Solar Test Site.**

The sun's daily incident energy (kWh) is the amount of direct normal insolation incident on the concentrator glass aperture area each day. The three performance lines shown in the left-hand plot were also converted into an efficiency curve, and are shown in the second figure. The daily energy efficiency ranges from 20 % to 26 % for a high daily incident sun energy level.

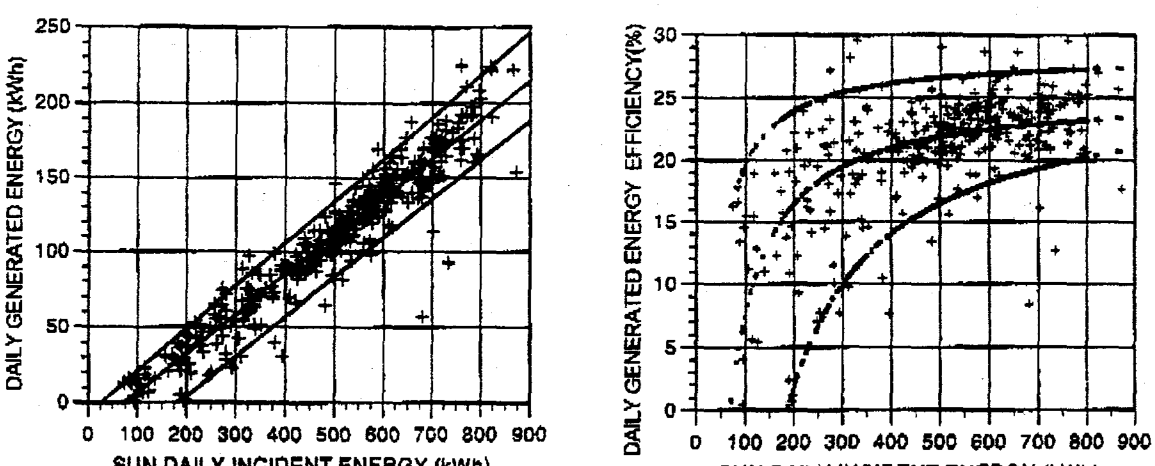


**Fig. 6. Daily net generated energy and daily energy efficiency, for PCU # 1 AT Solar Test Site.**

## SYSTEM AVAILABILITY

Several parameters were used in order to quantify the system availability. An "incident" was defined as an event where an operator had to take some action either in the control room or in the field to correct an operating situation. Incidents were recorded for the PCU, concentrator, and balance of plant. An outage period is defined as a time period when the system was not available to generate power. An incident does not necessarily mean there was an outage period, i.e., some situations could be corrected without taking the system off-sun. A summary of the incidents and outage times is shown in Table 2. Also shown are the number of days the system produced positive power (POW) during the day, the number of days there were no problems while the sun was available (NP), and days there was no sun (Clouds). There have been 365 days where the system operated without any problems when the sun was available (NP) out of a total of 412 operating days (POW + Clouds).

**Table 2. Summary of Incidents and Outage Time**

| MONTH | NO. OF INCIDENTS | | | NO. OF DAYS WITH | | | OUTAGE TIME (h) | | |
|---|---|---|---|---|---|---|---|---|---|
| | PCU | Concen'r | Bal. Of Plant | NP | Pow | Clouds | On-Sun | Sun above $2^0$ | h/mo* |
| AUG '98 | 15 | 1 | 0 | 28 | 30 | 1 | 0.2 | 3.4 | 6.2 |
| SEPT | 4 | 0 | 0 | 29 | 25 | 5 | 0.0 | 0.7 | 1.2 |
| OCT | 3 | 1 | 0 | 29 | 30 | 1 | 2.0 | 3.0 | 3.5 |
| NOV | 5 | 0 | 1 | 26 | 28 | 2 | 1.1 | 1.6 | 4.8 |
| DEC | 2 | 0 | 1 | 13 | 14 | 0 | 12.0 | 14.0 | 14.0 |
| JAN '99 | 14 | 2 | 1 | 13 | 21 | 4 | 24.2 | 44.1 | 102.6 |
| FEB | 6 | 1 | 0 | 25 | 22 | 5 | 0.1 | 3.2 | 4.15 |
| MAR | 7 | 3 | 0 | 28 | 30 | 1 | 1.2 | 10.2 | 13.2 |
| APRI | 6 | 0 | 0 | 25 | 29 | 1 | 7.7 | 13.2 | 18.4 |
| MAY | 4 | 0 | 0 | 30 | 29 | 2 | 11.0 | 18.2 | 29.2 |
| JUN | 10 | 0 | 1 | 16 | 24 | 0 | 48.3 | 90.3 | 153.3 |
| JUL | 19 | 0 | 1 | 26 | 29 | 1 | 4.9 | 15.0 | 21.3 |
| AUG | 7 | 0 | 0 | 27 | 31 | 0 | 5.1 | 5.9 | 7.9 |
| SEPT | 5 | 0 | 0 | 26 | 21 | 2 | 5.5 | 11.1 | 12.1 |
| OCT '99 | 1 | 0 | 1 | 24 | 24 | 0 | 57.0 | 69.8 | 161.0 |
| | | | | | | | | | |
| TOTAL | 108 | 8 | 6 | 365 | 387 | 25 | 180.4 | 303.6 | 552.5 |

*Based on a 24-hr day, see definition of AV.24 below

Three system availability measures were defined. The first is the availability when the sun was shining (SUNAV) so power could be generated. That is, when the sun's insolation was above 300 $W/m^2$. It is defined as:

$$SUNAV = (\text{Time power was generated})/(\text{Time insolation was above } 300\ W/m^2)$$

The second availability is defined as the time the sun was above $2^0$ elevation (SUNAB) less the outage time. It is defined as:

$$SUNAB = (Tsa - Tosa)/Tsa$$

where Tsa is the time the sun was above $2^\circ$ elevation, and Tosa was the time the system was not available to generate power (outage time). There were some problems that did not stop the system from operating but required some maintenance action. These types of problems were normally corrected after sunset and therefore no outage time would be accounted for in either of the above definitions. Therefore, a third type of availability is based on an entire (24 h) day. It is defined as:

$$AV.24 = (T24 - To24)/T24$$

where T24 is 24, and To24 is the time in a 24-hour period that the system was not available to generate power. The three system availabilities are shown in Figure 7 for the period of August 1998 to October 1999. The average availability over this test period was 95 to 96 %.

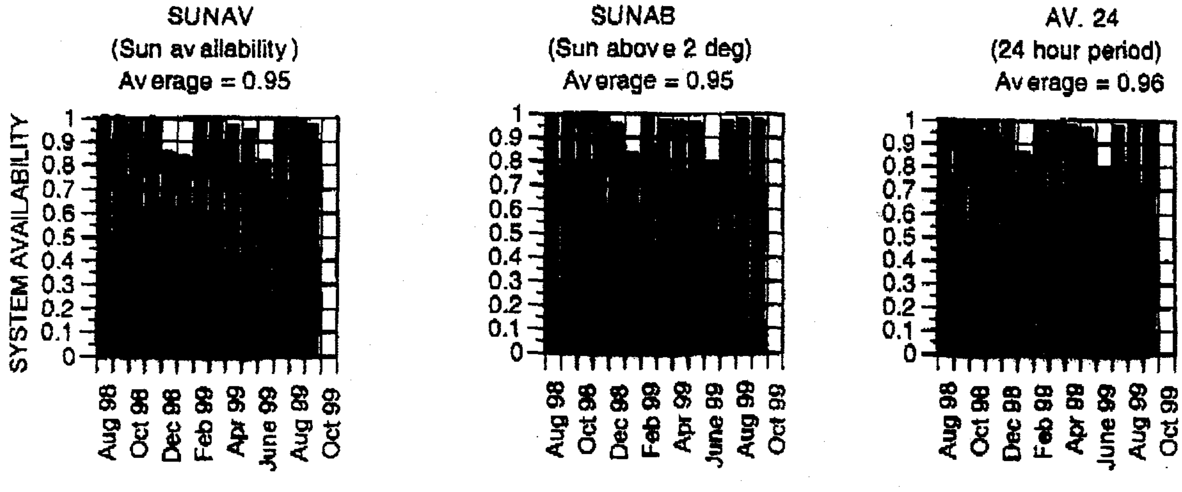


**Fig. 7. System availability for PCU #1 for the period of August to October 99.**

The probability density function of the outage times for the three types of availabilities defined above are shown in Figure 8. The mean outage time for each type of availability was approximately 30 minutes, and 60 to 70 % of the time the outage time was less than an hour. Over 40 % of the time the outage was less than six minutes for the sun available outage time (SUNAV). The reason for this short outage time will be discussed in the next section.

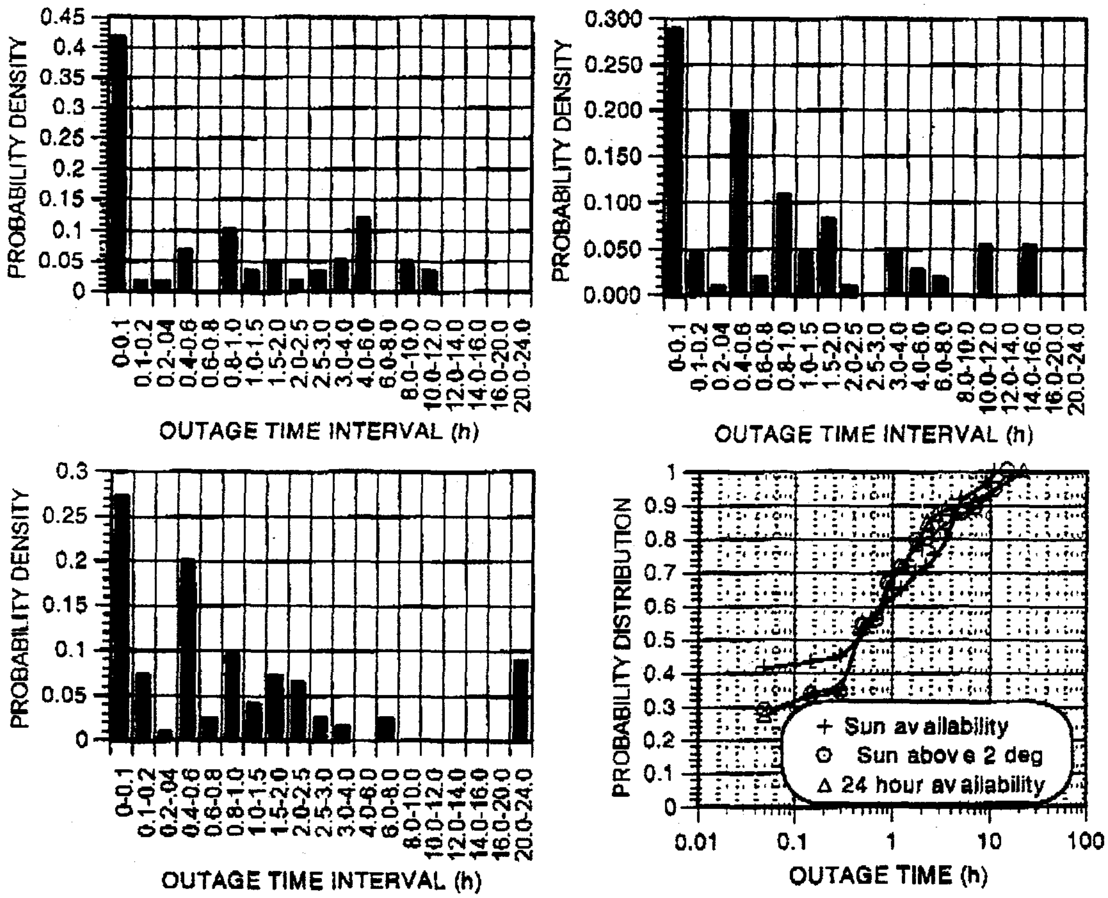


**Figure 8. Availability density and distribution function of outage time for PCU # 1.**

## INCIDENT AND OUTAGE ANALYSIS

A goal of DECC Phase I was to start a reliability database for the moving parts of the engine and other key engine components. Thus far, there have been no major problems with any moving part (bearing, seals, rings, etc.), or with key components such as the heater head, regenerators, and gas coolers. There were problems with a number of external components, discussed below, which resulted in most of the incidents. The frequencies of occurrence for the different causes are shown in Table 3.

The most frequent problems were oil leaks from around plugs called "oil vanes" and detrack signals, often false, from the control software. Although the oil vane plug leak was easy to fix, the PCU would have to be removed which would result in loss of on-sun time. Since the oil leak was not causing any loss of on-sun operating time, it was tolerated until the PCU was removed for an other reason. False detrack signals resulted in a very small loss of on-sun operating time because the alarm could be cleared in many cases before the engine stopped. Kockums believes the cause of false alarms resides in the software and are investigating the problem. A number of incidents were the result of the compressor valve becoming clogged with a black powder. This happened a number of times and resulted in cleaning or replacement of the valve. The problem is still under investigation but the source of the black powder appears to be inside the valve. There was also a problem with a small gas leak through the external tank valve. This problem did not result in any loss of on-sun time or loss of gas from the system so it was also tolerated in order to

**Table 3. Summary of Causes of PCU Incident/Outages**

| Incident | Description | Comment |
|---|---|---|
| Oil leaks | Oil leak out oil vane plugs<br>Gasket material dried out<br>Problem: Improper threads & plug during mfg./assembly. | Accounts for 26 of 108 incidents.<br>No loss of on-sun time.<br>Management decision not to fix during initial test period. |
| | Oil film from crankcase breather | Change to longer tube with right angle bend. |
| Detracks | False alarm signal of:<br>"Too many refills between wake-up" | Accounts for 20 of 108 incidents.<br>Minor loss of on-sun time.<br>Apparent software problem. |
| | Various detracks. | Accounts for 8 of 108 incidents.<br>5-6 hours loss of on-sun time. |
| Compressor valve | Black powder clogs valve and causes excessive compressor duty cycle. | Accounts for 5 of 108 incidents.<br>Minor loss of on-sun time. |
| External tank valve | Leak into compressor circuit, the gas pumped into supply tank which causes "high tank pressure" shutdown. | Accounts for 2 of 108 incidents.<br>2-3 hours loss of on-sun time. |
| Water pump failure | Shorted field winding. | Accounts for 2 of 108 incidents.<br>Designed for 50 Hz but 60 Hz power used 1-2 hours of loss on-sun time. |
| Generator #1 | Shorted field winding.<br>Oil seal leak (minor problem). | Accounts for 1 of 108 incidents.<br>Cause: Defective insulation due to vage/water/grease.<br>6 days of outage. |
| Generator #2 | Oil seal leak. | Accounts for 1 of 108 incidents.<br>Less than a day outage. |
| Thermocouples | Burned out thermocouples.<br>Not required for operation. | Accounts for 2 of 108 incidents.<br>2 hr of lost on-sun time. |
| Gas leak | Manual valve on supply tank. | Accounts for 10 of 108 incidents.<br>No loss of on-sun time.<br>Valve replaced. |
| | Buildup of material under piston rod seals. | Accounts for 1 of 108 incidents.<br>57 hours of lost on-sun time.<br>Cleaned seals/engine. |

investigate the cause and corrective action. The leak was eliminated by rework of the valve. The water pump was replaced once due to a short in the field winding. Upon investigation it was found that a European 50 Hz pump was operating at 60 Hz, and the supplier indicates this contributed to the failure. There were two generator problems during this phase of testing. The first failure was caused by a short in the field winding. The present generator is a 15-year old on open frame design and the problem is believed to be the result of excess grease, age, moisture, and perhaps a manufacturing problem. The second generator was replaced because of a oil leak between the engine and generator seal. There were two thermocouple (T/C) incidents, the first was a gas manifold T/C that burned out. In the second incident, two receiver tube T/Cs were replaced because the leads failed from exposure to direct solar insolation that resulted when the protective thermal insulation eroded.

A manual hand valve on the supply tank had to be replaced after it began to leak excessively, it was found the seat material had failed after 15 years. The valve and also the tank were replaced with components selected for mass manufacturing. Otherwise there were no leak problems from external lines, filters, fittings, etc. In late October of 1999, a higher than normal hydrogen gas loss was noticed. The top part of the engine was disassembled and a buildup of residue was found in different parts of the engine. This residue had collected around one of the piston rod seals and had worked its way down into the seal thereby allowing gas leakage. The residue was removed, the affected parts thoroughly cleaned, and the engine was reassembled and operated normally without replacing any seals or parts. The composition and source of the residue is under investigation.

No significant problems were encountered with the concentrator. Early in Phase I, there was an intermittent elevation position signal problem. This problem was first thought to be a defective elevation incremental encoder, but turned out to be a faulty electrical connector.

## ACKNOWLEDGEMENT:

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## SUMMARY

The SES Dish Stirling system that was developed by McDonnell Douglas and United Stirling AB has accumulated significant operating time since it was first developed in the early 1980s. The 4-95 Stirling engine has accumulated over 140,000 hours of operating time and has generated over 164,000 kWh of on-sun grid-connected energy. The concentrators have accumulated over 6,000 hours of tracking operation during Phase I of the DECC program and many more hours in previous programs. Availability during the time the sun was shining averaged 95 % and the system efficiency was nearly the same as measured when the units were first placed in operation in the 1980s. Any problems that have occurred have been resolved at the Solar Test Site, and the solar and fuel versions of the engine will continue to be tested during Phase II of the DECC project. These data show that the Boeing Dish Stirling system is durable and can reliably produce electricity from the sun.

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