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Rolling Thunder-Integration of the Solo 161 Stirling Engine with the CPG-460
Solar Concentrator at Ft. Huachuca

Abstract. Project "Rolling Thunder" is a dish/Stirling demonstration project at Ft. Huachuca, a U.S. Army fort in southeastern Arizona. (Huachuca means "rolling thunder" in Apache.) It has been supported by the Strategic Environmental Research and Development Program (SERDP), a cooperative program between the Department of Defense (DoD) and the Department of Energy (DOE). As part of a 1992 SERDP project, Cummins Power Generation, Inc. (CPG) installed a CPG 7-kW_e dish/Stirling system at the Joint Interoperability Test Command (JITC) in Ft. Huachuca, Arizona. The primary objective of the SERDP "Dish/Stirling for DoD Applications" project was to demonstrate a CPG 7-kW_e dish/Stirling system at a military facility. Unfortunately, Cummins Engine Company decided to divest its solar operations. As a direct result of Ft. Huachuca's interest in the Cummins dish/Stirling technology, Sandia explored the possibility of installing a SOLO 161 Stirling power conversion unit (PCU) on the Ft. Huachuca CPG-460. In January 1997, a decision was made to retrofit a SOLO 161 Stirling engine on the CPG-460 at Ft. Huachuca.

Project "Rolling Thunder - The SOLO 161 Demonstration at Ft. Huachuca" has been a challenge. Although, the SOLO 161 PCU has operated nearly flawlessly and the CPG-460 has been, for the most part, a solid and reliable component, integration of the SOLO PCU with the CPG-460 has required significant attention. In this paper, the integration issues and technical approaches of project "Rolling Thunder" are presented. Lessons of the project are also discussed.

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1. INTRODUCTION

Dish/Stirling systems use a tracking array of mirrors to concentrate solar energy onto a Stirling engine. This technology holds the record for conversion efficiency of sunlight to electricity and continues to show promise for producing low-cost electricity from the sun. Dish/Stirling technology development has been supported by DOE since the late 1970s and is described in detail in Stine and Diver [1]. In 1991, DOE and Cummins Power Generation, Inc. (CPG), a wholly owned subsidiary of Cummins Engine Company, entered into the Dish/Stirling Joint Venture Program (DSJVP) to develop and commercialize 5-10kW_e dish/Stirling systems for remote power applications [2].

In parallel with the DSJVP with support from the Strategic Environmental Research and Development Program (SERDP), Sandia contracted with Cummins Power Generation, Inc. (CPG) for the installation of a CPG 7-kW_e dish/Stirling system at Ft. Huachuca, AZ. The primary objective of the SERDP "Dish/Stirling for DoD Applications" project was to demonstrate a CPG 7-kW_e dish/Stirling system at a military facility. In October 1995, a CPG-460 solar concentrator was installed at the Joint Interoperability Test Command (JITC) at Ft. Huachuca, AZ, and in January 1996, a Clever Fellows Innovation Consortium (CFIC) free-piston Stirling engine was installed on the CPG-460. Unfortunately, dynamic imbalances in the CFIC displacer pistons limited system output. Maximum net output was less than 2-kW_e. Even more unfortunate, Cummins Engine Company decided to divest its solar operations in June, 1996. Retrofit of new displacers during the summer of 1996 was, therefore, canceled [3].

As a direct result of Ft. Huachuca's interest and excitement about the Cummins dish/Stirling technology and its long-term potential for DoD installations, Sandia explored the possibility of installing an alternative Stirling engine power conversion unit (PCU) on the Ft. Huachuca CPG-460 solar concentrator.

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The SOLO 161, an improved version of the proven V-160 kinematic Stirling engine, was identified as the only viable alternative in this power range (5-10 kW_e). Following correspondence with Schlaich, Bergemann, und Partner (SBP), the license holder of the V-160 technology; Solo Kleinmotoren GmbH, the engine manufacturer; and discussions with the SERDP sponsors; Sandia program managers; and Ft. Huachuca personnel, a decision was made to proceed with project "Rolling Thunder" in January 1997. (Huachuca means "rolling thunder" in Apache.)

In addition, within Task 1 of the International Energy Agency (IEA) Solar PACES, plans for an "engine exchange" involving the testing of a SOLO 161 Stirling engine in the United States and a Stirling Thermal Motors (STM) STM 4-120 Stirling engine in Europe were being discussed. The possibility of integrating a Thermacore, Inc. reflux heat-pipe solar receiver (Thermacore supplied heat-pipe receivers to CPG) with the SOLO 161 engine was also of interest to Sandia, Thermacore, SBP, and SOLO. Project "Rolling Thunder", therefore, was an opportunity to satisfy many objectives. The following paper describes the project, integration issues, technical approaches, experiences, test results, and status of project "Rolling Thunder". Lessons are also discussed.

2. PROJECT PLAN

The objectives of project "Rolling Thunder" were primarily to demonstrate dish/Stirling technology and to provide Ft. Huachuca JITC with a functional dish/Stirling system. Performance objectives were to significantly increase power and demonstrate a functional system with good availability. At the same time, it provided an opportunity to facilitate potentially beneficial partnerships within the international dish/Stirling community; to advance the technical status of dish/Stirling technology; and to satisfy one element of the IEA Solar PACES "engine exchange." Testing of both a directly illuminated receiver (DIR) and a heat pipe solar receiver are an opportunity to compare the performance of two receiver designs under similar conditions.

The original project plan for "Rolling Thunder" had three phases. Phase 1, called for integration and testing of the SOLO 161 PCU with direct illumination receiver (DIR) with the Fort Huachuca CPG-460, and operation for at least two months. In phase 2, the SOLO 161 was to be retrofitted with a Thermacore reflux heat-pipe receiver and operated another two months. However, because of the opportunity to perform the receiver testing at the Plataforma Solar de Almeria (PSA) and because of the technical requirements of a heat pipe receiver retrofit, a decision was made to drop phase 2 and conduct continued operation, phase 3, with the DIR.

Project management was performed by Sandia. Through Sandia contracts, Solo supplied a SOLO 161 Stirling PCU, and WG Associates (WGA) designed an interface fixture for mounting the SOLO 161 PCU on the CPG-460. WGA also modified control software and assisted with the PCU and controls installation. The SOLO 161 PCU includes a DIR with a 18-cm (7-inch) diameter aperture, a 3-phase 460-Volt induction generator, cooling system, and, controls. Sandia fabricated the interface fixture and shipped the hardware, along with the SOLO 161 PCU to Ft. Huachuca in July 1997. The Ft. Huachuca JITC modified the PCU tripod supports and the electrical connections with the JITC facilities. New Mexico State University South West Technology Development Institute (SWTDI) was contracted to independently record and report site solar insolation, weather data, and system electrical output.

Because of Cummins divestiture of its solar business, the availability of spare parts and technical expertise was a key consideration in deciding to proceed with "Rolling Thunder". Fortunately, we obtained 12 spare mirrors, computer control boards, drive motors, vacuum pumps, and other spare parts during the Cummins divestiture. In addition, WGA, who had designed the next-generation 10-kW_e solar concentrator for CPG had the structural and controls expertise needed to support the integration of the SOLO 161 with the CPG-460.

Given the proven record of the SOLO 161 and CPG-460, and the availability of spare parts and expertise, we were confident that we could meet the objectives of "Rolling Thunder." The SOLO 161, an alpha configuration kinematic Stirling engine, is an improved version of the proven V-160. The V-160 has been tested extensively at the PSA in Spain [4]. The SOLO 161 is rated at 9-kW_e at 1500 RPM and uses a 3-phase 460-Volt induction generator to provide power to the grid - at a thermal-to-electric conversion

efficiency of 30%. Connection of an induction generator with the grid is straightforward, and the CPG-460, although low power for the SOLO 161 has accumulated over 40,000 hours on 9 systems with good reliability.

For the most part, integration issues occurred at interfaces between the SOLO 161 and the CPG-460, and were anticipated. On the other hand, some issues were subtle and the difficulties of systems integration, particularly at a remote location, made development of solutions difficult and slow. The follow discusses these integration issues and solutions.

3. SYSTEM INTEGRATION

Project "Rolling Thunder" primarily involved the retrofit of the SOLO 161 kinematic Stirling engine on the CPG-460. Because the engine was designed for the SBP stretched-membrane concentrators, the CPG-460 had to be adapted to the SOLO 161 Stirling engine. Principle features of the CPG-460 include 24 aluminized polymer-film stretched-membrane facets, supported on a geodesic space-frame structure. The CPG-460 also uses a polar drive with the power conversion unit is supported by a tripod mount, fig. 1. System components and technical issues of the CPG-460 are described in detail in Bean and Diver [5, 6]. In the process of integrating the two major subsystems, we have had to deal with many minor issues such as oil leaks from the engine, difficulty inspecting oil and coolant levels, and matching European and English connectors. In general, however, we have been able to identify the root cause of problems and develop solutions. Keys have been the robustness of the SOLO 161 PCU, and the capabilities of the CPG-460 controls. The ability to dial-up the system from home, watch the system operate in real time, and review performance data and operational logs has been invaluable. In combination with rapid and expert support from SOLO and SBP, we have been able to work around or resolve virtually every issue. We, therefore, believe that we now have a system that is capable of meeting our original objectives.

The SOLO 161 is intended for gas-fired cogeneration applications and solar application on the Schlaich, Bergermann, und Partner (SBP) stretched-membrane concentrators. The SBP concentrators utilize a skid mount for the SOLO 161 PCU, resulting in an obvious mismatch between the CPG-460 and SOLO 161. The rectangular mounting adapter, fig.2, is relatively heavy and interferes with access to the engine and electronic control panels. As a result, an electric winch and removal of the hinges are needed to hoist the engine cover to perform engine maintenance. To access control and thermocouple panels, it is necessary to remove the panel-cover hinges. Interface of the CPG-460 and SOLO 161 controls was straightforward. Cummins developed their 7-kW_e dish/Stirling system to operate in remote locations. It is extremely sophisticated and is capable of fully unattended operation, including automatic start-up, tracking, and stow. It permits remote monitoring, data acquisition, and control via a dial-up modem, and will safely detrack in the event of faults detected by the concentrator, engine, or operator. The program and operating data are contained in non-volatile flash memory and provide a robust control capability that has been proven in over 40,000 hours of operation on 9 different systems. The system is capable of recovery from loss of power and includes a battery back-up un-interruptible power supply. Sun-tracking features a hybrid system in which open-loop tracking is used to acquire the sun and closed-loop tracking, based on high-temperature thermocouples, provides accurate tracking. Self-alignment algorithms allow the concentrator to account for structural rotation, tilt, sag, and other sources of misalignment. Structural and installation requirements are, therefore, significantly reduced. Interface of the SOLO controls with the CPG-460 controls was straightforward and was similar to approaches used by Cummins with other engines. The SOLO 161 utilizes analog outputs that continually report key engine operational parameters and status. In the event of an engine fault such as loss of oil pressure, over temperature, etc. a detrack signal is sent to the CPG-460 controller and the dish tracks off sun. Errors detected by the CPG-460 controller can also initiate detrack, resulting in a redundant and safe system. The 0-10 Volt engine control signals required resistor bridges to interface with the 0-5 Volt input used by the dish controller. SBP has operated the V-160 on 7.5-meter diameter stretched-membrane dishes and the SOLO 161 on 8.5-meter diameter dishes. While the 7.5-meter SBP concentrator has a comparable projected area to the CPG-460 (43.8 m² vs. 44.8 m², respectively), it has a higher reflectivity. The reflectivity of the thin-glass mirrors used on the SBP concentrators is over 90%, while the reflectivity of the aluminized polymer films are typically less than 80%. In addition, on June 6, 1997 a severe hailstorm at the JITC damaged all of the stretched-membrane

facets. Although the 7-mil PET film is resistant to hail damage, the hail in the June 6 storm was hard and jagged. As a result, we had to use all 12 of our spare mirrors and the salvaged mirrors each needed numerous patches, further reducing power. Although, we expected the output of the SOLO 161 on the CPG-460 to be significantly less than its rating, we did not anticipate the implications for controls.

Figure 1. Photograph of the "Rolling Thunder" Dish/Stirling System operating on-sun at the Ft. Huachuca JITC test site.

Figure 2. Photograph of the SOLO 161 in the rectangular mounting adapter on the CPG-460.

Because of the relatively low power of the CPG-460, the SOLO receiver-temperature controls tend to overcorrect, sometimes resulting in over-temperature faults. To address this issue we are investigating modification of engine control parameters. Operation with a higher over-temperature limit is planned. In addition, the relatively low power of the CPG-460 necessitated adjustment of our operational strategy. Typically, dish/Stirling systems are capable of producing net power at insolation levels as low as 200 to 300 W/m^2 . The Ft. Huachuca system needs over 600 W/m^2 to produce net power. If operated at insolation levels of 300 to 600 W/m^2 , typical of high thin clouds, the SOLO 161 produces heater temperatures below freezing. This sometimes causes fault conditions and is hard on the engine. To avoid this, we changed the operational strategy to enable off-set track when the insolation level drops below 600 W/m^2 for a specified time. We are still tuning parameters to enable smooth operation.

Interface of the aperture tracking thermocouples with the SOLO 161 was also problematic. On the Cummins system, four thermocouples were located in the aperture plane. Two thermocouples each provide closed-loop tracking signals for polar and declination tracking, respectively. For the SOLO 161 PCU, receiver efficiency and receiver flux intensity considerations resulted in geometrical constraints that dictated that the tracking thermocouples be located approximately 11.4 cm (4.5 inches) in front (towards the concentrator) of the focal plane. Placement of the tracking thermocouples in the focal plane either significantly reduced receiver efficiency or required major modification of the PCU. The dynamic response of the closed-loop tracking control was significantly different and resulted in poor tracking and delays in initiating routine operation. In February 1998, we made a significant modification of the thermocouple location and tracking algorithms that have proved to be successful. Refinement of the tracking control parameters is still required to improve closed-loop capture range.

Engine vibrations and their implications on the CPG-460 were also not fully anticipated. The SOLO 161 produces torque variations from its operation that cause 60-Hz vibrations when operated at 1800 RPM. The CPG-460 uses a light-weight, tubular-steel structure that happens to resonate near 60 Hz. In addition, the stretched-membrane mirrors also tend to resonate. This problem was initially discovered in the DSJVP with the unbalanced Sunpower free-piston Stirling engine. In that case, the space-frame tubing oscillated at extreme amplitudes and sometimes fatigued in as quickly as a few minutes [5]. Vibrations on the CPG-460 with the SOLO 161 are significantly less, and we are yet to experience a fatigue failure. However, during the evening of March 19, 1998 after several days of operation, a large structural bolt came loose, apparently

from vibrations, damaging several space frame members and a facet. We were able to repair the structural members and replace the facet. The distant-light-source alignment technique, based on the approaches in Diver [7] was key to the repairs. The technique, which was originally implemented at Ft. Huachuca in November 1997, made it possible to realign and focus the concentrator in one evening. We have made additional provisions for securing fasteners, however, we are concerned about the long-term implications of the engine-induced vibrations on the structural and optical elements of the CPG-460. We are, therefore, evaluating vibration isolators and other approaches for reducing vibrations.

4. RESULTS

To date, system operation has been sporadic and limited as we have identified and dealt with issues. For 1998 through the end of March 1998, the SOLO 161 has accumulated approximately 100 hours of on-sun operation. Figure 3 is a plot showing 11 consecutive days of operation in mid March. Maximum system net output is less than 4-kW_e, while operating with a maximum receiver temperature of 700°C. With the receiver temperature increased to 750°C, maximum system output increased to approximately 4.1 kW_e. The SOLO 161 is capable of operation with a set point temperature of 800°C, suggesting potential additional improvement in system output.

Figure 3. SWTDI data showing system performance during March 1998.

5. LESSONS AND CONCLUSIONS

Project "Rolling Thunder" has been a challenging endeavor. It has involved retrofit of a solar concentrator that is no longer produced or supported in the U.S., with an early production Stirling PCU manufactured in Germany, at a remote U.S. military facility with minimal solar expertise – all on a limited budget. Although, the SOLO 161 PCU has operated nearly flawlessly and the CPG-460 has been, for the most part, a solid and reliable component, integration of the SOLO PCU with the CPG-460 has required significant attention. We have relearned that even simple retrofits can be difficult and expensive and that components not specifically designed to work together, may not necessarily work together – at least in all respects. For example, controls integration was straightforward, however, maintainability of the SOLO PCU was hampered by integrating it with the CPG-460. Another important lesson, is that integration issues can be multidimensional. For example, the thermal mismatch between the concentrator and engine created issues beyond the anticipated low system output. Unanticipated, were the needs to modify receiver temperature

control parameters and to implement a much more complex cloud-transients response strategy. It is also difficult to anticipate all problems. Many are subtle and can only be characterized by testing, e.g. vibration issues, and closed-loop tracking response. In addition, resolution of problems can be equally difficult to plan for and budget. The inclusion of contingencies, both in time and money, when integrating complex systems such as dish/Stirling is, therefore, absolutely critical. For "Rolling Thunder," the cumulative effect of the anticipated and unanticipated problems, the difficulties of working at a remote location, setbacks such as the June 6 hailstorm, all delayed progress and increased costs.

Perhaps the most important lesson is the need to perform dish/Stirling system integration at a solar test facility, not at a remote location. It is especially important to avoid performing system integration at the customer's site. Customers have high expectations and are not interested in anticipating or hearing about integration issues. It is, therefore, very easy for customers to lose patience and faith in the technology. This lesson is hard to learn because there will always be money-paying customers who want the latest technology at their site. The need to "sell" our technology to stay in business also makes this lesson hard to follow.

Despite these "hard lessons", we are more optimistic about the potential to develop viable dish/Stirling systems than when we started "Rolling Thunder." This optimism is partly a result of having the opportunity to work with the SOLO 161 PCU; partly a result of the versatility and robustness of some of the Cummins technology; and partly from the lessons learned from "Rolling Thunder." We believe that the next-generation Cummins DSJVP concentrator, with thin-glass mirror panels, a "skid" type PCU mount, increased mirror projected area, and other features is a ideal match to the SOLO 161 PCU. We hope that we will have an opportunity to build and integrate such as system – at the National Solar Thermal Test Facility in Albuquerque, NM.

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