Advanced 80 W\textsubscript{e} Stirling Convertor Phase II Development Progress

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Abstract. This paper reports on the 80 W\textsubscript{e} Advanced Stirling Convertor (ASC) being developed under NASA NRA funding for potential use in advanced radioisotope space power systems. The ASC uses a high temperature heater head to allow for operation at 850 °C. Progress in the development and fabrication of the ASC is presented, as well as continued efforts on an earlier developmental unit, the Frequency Test Bed (FTB). The FTB has demonstrated 36% efficiency (based on AC electrical out) at a temperature ratio of 3. The efficiency of the ASC is expected to approach 40%. Also presented are research efforts being performed to better understand losses within Stirling convertors, as well as efforts being performed to address long life reliability.

I. Introduction

Sunpower assisted by Boeing/Rocketdyne, and further aided by a group of Stirling consultants, is developing the 80 W\textsubscript{e} “Advanced Stirling Convertor” (ASC) under a three-year NASA NRA funded program. The project goal is to develop a safe, reliable, highly efficient, low mass Stirling convertor. The life requirement for the ASC is specified as 14 years. Phase I (year 1) of the program was very successful, resulting in an early developmental convertor, the FTB, that achieved 36% efficiency (AC out/ heat in) at a temperature ratio of 3.0 (650°C hot end, 35 °C reject). This is record setting efficiency for any free-piston Stirling convertor.

The ASC-1 now being developed under Phase II, will also operate at a temperature ratio of 3, but at increased overall temperature levels. The ASC-1 will use advanced high temperature materials in the hot end to allow operation at up to 850°C. The design heat rejection temperature of the ASC-1 is 90°C, but the ASC-1 will have the capability to operate well above this reject temperature. Thermodynamic improvements, as well as increased alternator efficiency in the ASC-1 are expected to further improve conversion efficiency above that already achieved with the FTB.

Four ASC-1 convertors are to be built and tested during Phase II. Testing and development will be performed on both single and dynamically opposed units. Later in Phase II a single unit will be vibration tested on a shaker-table at Boeing/Rocketdyne. Additional component reliability testing will be performed during Phase II. The ASC-1 is scheduled to have its first run during September of 2005.

Phase III of the project involves the development of the final hermetically sealed ASC-2 convertor. Four ASC-2 convertors are also to be built. Vibration testing will again be performed on the ASC-2 at Boeing/Rocketdyne. All ASC-2 units will eventually be run in dynamic opposition, resulting in two pairs of opposed ASC-2 convertors. Reliability testing of components will continue during Phase III. The breadboard controller will also be integrated with the Stirling convertors under this Phase.

The ASC program has been described earlier by Wood and Lane\textsuperscript{1}, Wood and Carroll\textsuperscript{2}, Wood, Carroll and Penswick\textsuperscript{3} and Wong\textsuperscript{4}. The following describes the development progress to date, as well as future plans in the development of the ASC.

FIGURE 1. FTB Convertor (shown next to soft-drink can for scale).
II. FTB Convertor

The Frequency Test Bed (FTB) convertor shown in Figure 1 was a quickly designed and fabricated unit that was operational during the fifth month of Phase I. The purpose of the FTB was to gain early experience with a convertor of the power level intended for the ASC. The heat input is fixed in this application with the convertor intended to operate on the heat supplied by a GPHS of nominally 220 W after insulation losses. To speed hardware fabrication, the FTB was designed with a stainless steel heater head, resulting in a hot end temperature limit of approximately 650°C. Also the FTB was not a fully optimized design with some design compromises made because of the uncertainty of losses in particular areas.

The performance obtained with the FTB was outstanding, demonstrating 36% efficiency (AC electrical out / heat into the head) at a temperature ratio of 3.0. After accounting for the alternator efficiency (of slightly over 90%) the engine-only efficiency is 60% of the Carnot efficiency at this temperature ratio. Also of note is that this performance was achieved at a high operating frequency of 105 hertz. The high operating frequency is important in allowing high specific power in the final ASC units. More information on the measured performance of the FTB can be found in Wood, Carroll and Penswick.

The FTB was an important development step toward the design of the more advanced ASC convertor to be developed in Phase II and III of the current program. The FTB was a significant achievement, demonstrating the remarkable efficiency and low mass possible with small high frequency Stirling machines. It largely put to rest several concerns related to increased perimeter/area effects of small machines which could lead to increased losses in areas such as seals, the regenerator walls, and the displacer appendix gap. Now based on testing experience gained with the FTB, the ASC is expected to have even higher efficiency.

III. ASC-1 Convertor

External views of the ASC-1, including dimensions, are presented in Figure 2. Noticeable in the perspective view is the ribbed flat plate that is used for the transition section between the engine (smaller diameter region) and the larger diameter alternator portion of the machine. This ribbed transition section will also include a brazed-on cover plate (not shown) to add further strength in this area.

Not shown in Figure 2 are 2 sets of clamping flanges which will be used on the ASC-1 with one set for attachment of the heater head to the rejector section, and the second set to attach the pressure vessel to the transition section. O-ring type seals are used in these areas so that the ASC-1 can be disassembled for inspection and modification.

The original plan was that the ASC-1 units would utilize a heavy test vessel similar to that used with the FTB and evident in Figure 1. However because of the success of the FTB, the ASC internal design is not radically different in size or details from the earlier unit. This similarity of internal details has to a large extent allowed more attention to the design of a lightweight external vessel. While the ASC-1 will have clamping flanges as described above, the ASC-2 is expected to look much like that shown in Figure 2 where the flanges are non-existent and the unit is welded shut to produce a hermetically-sealed unit.

The most significant thermodynamic changes from the FTB to the ASC is the use of a longer regenerator and thinning of the outer regenerator wall (possible because of the higher strength material in this area) to further reduce solid conduction losses. Conduction losses are quite significant in small machines. The high efficiency of the FTB was achieved with 27 watts of conduction through the machine out of the total heat input to the head of 220 watts. Thus over 12 percent of the input heat was directly conducted through the solid walls and internal gas of the machine. Conduction losses for the ASC have been reduced by 40 percent compared to the FTB and are predicted to total 16 W.

Reduced conduction losses as well as reduced displacer shuttle heat transfer resulting from the longer regenerator are expected to increase efficiency by approximately 2 percentage points. We also expect a slight increase in conversion efficiency (approximately 0.5 percentage points) due to alternator improvements, even though the ASC alternator will operate approximately 60 °C hotter than the FTB alternator. Improvements here are the use of stronger magnets and increased copper winding mass to reduce electrical resistance losses. Finally, the more effective longer regenerator and improved heat exchanger geometries are predicted by computer simulation to provide a further efficiency gain of approximately 1 percentage point. Current projections place the ASC efficiency (AC out / heat in) at between 39 and 40 percent. The current mass estimate of the final ASC-2 convertor is very close to 1.0 kg.
As stated earlier, the ASC is being designed for a hot end temperature of 850°C. This is approximately 200°C above the current practice which utilizes Inconel 718 for the hot end of the machine. To achieve long life at the high design temperature of the ASC, numerous issues must be addressed in addition to the selection of the heater head material itself. At extended time at high temperature inter-diffusion of adjacent materials, having different compositions, can lead to changes in important properties such as creep strength. Also besides the heater head, other parts within (or near) the hot end are also required to operate at elevated temperatures. The displacer, displacer radiation shields, heater head liner (hot cylinder), acceptor heat exchanger, and the hotter parts of the regenerator all increase in temperature, more or less in proportion to the increase of the head temperature. Thus operation at high temperature requires consideration of all components affected by the increase in operating temperature. Hot end materials are discussed in a later section of this paper.

The ASC offers very significant reductions (between 4 and 5 fold) in the amount of plutonium required compared to state of the art radioisotope fueled power systems. Typical current systems fall in the range of 6-8 percent efficiency. The ASC has been designed for 14 year life which is determined by the creep strength of the heater head. The stress level for the head has been set at 1% creep over the 14 year time period. This amount of creep is predicted to not affect the efficiency of the convertor, as the small increased volume in the hot end has no substantial affect on performance.

Long life reliability of Stirling convertors is yet to be proven, but all indications are that this is not an insurmountable problem. The cold end of the ASC is based on the same technology used in Sunpower cryocoolers, primarily including gas bearings and a highly efficient (and lightweight) linear alternator design. Sunpower coolers have flown on the Space Shuttle (STS-60) and a Sunpower cryocooler cools the sensor on the RHESSI satellite which has been operating in orbit for 2.5 years. (launched on February 5, 2002) The cryocooler aboard RHESSI was also operated for approximately 15,000 hours before launch. The following section describes the reliability efforts which are being performed to insure the long life of the ASC.
IV. Reliability Study

While the ASC project is an advanced technology development effort, it was understood from the beginning that reliability and lifetime performance would need to be adequately addressed to insure potential users of the soundness of the basic technology. To accomplish this, a task was included in the project plan with the goal of insuring that reliability / lifetime degradation concerns were addressed and resolved throughout the development effort. It should be noted that the convertor is made up of two fundamental elements that must operate together to meet system requirements. These are the controller / power conditioning electronics and the free-piston engine itself (including linear alternator). The controller reliability issues can be addressed with conventional, well-established techniques. The engine represents the unique element in the system from the reliability standpoint.

The approach employed for the engine involves a five-step process that is continually updated as the project progresses. The specific steps are: 1) evaluation of fundamental reliability issues based on past and current development efforts, 2) development of reliability evaluation tools to be employed in the design of the ASC, 3) evaluation of areas of potential degradation and their impact on performance, 4) define and carry out ASC component testing to better understand factors driving reliability / degradation, and 5) institute an ongoing reliability plan. The results of this effort to date in specific areas are briefly discussed in the following sections.

A. Reliability Assessment Data Base

The focus of this effort has been to acquire and evaluate the results of a wide range of Stirling and similar free-piston hardware from the viewpoint of basic reliability, failure modes, and an understanding of any problems encountered and how these were resolved. While this investigation looks at all styles of Stirling devices, the primary focus is on long life free-piston systems employing linear electric alternators or motors.

Because of the similarity of the components within the cold sections of engines to those in the warm portions of cryocoolers, the latter provides an excellent source for reliability / failure mode information. Wherever possible in the evaluation of failure/degradation modes involving the convertor’s moving components, an attempt was made to employ information relevant to the gas bearing technology employed in the ASC design. This effort utilizes data from ongoing Sunpower testing, Sunpower licensee data, and extensive testing by MTI and NASA / GRC over the years\(^5\). In areas generic to all free-piston converters such as working gas contamination, regenerator degradation, leakage, etc., the above work in addition to the results of past and ongoing work by STC\(^5\) and the extensive hardware testing underway at NASA / GRC \(^7,8\) were evaluated whenever possible.

Results of the evaluation of the basic ASC convertor moving component configuration and gas bearing / seal concept indicate a high degree of confidence in the robustness and reliability of the ASC design. STI, a Sunpower licensee, has developed and successfully put in commercial use a cryocooler for cooling superconducting electronics for cellular communications which employs the same technology as used in the ASC design. In addition, the physical size and power levels of the STI unit are quite close to those of the ASC. Several thousand STI units have been produced with some units having in excess of 5 years of continuous operation. Total running time accumulated to date is nearly 100 million hours with failure numbers in the single digits. In addition to these units, other Sunpower licensees and on going Sunpower testing has accumulated an additional 800,000+ hours of run time with a lead unit having in excess of 9.5 years of trouble free operation. In all cases when a failure occurred it was fully evaluated and corrective actions taken, this latter work provided an excellent understanding of the failure / degradation mechanism. Other issues resolved in these efforts included unit processing, Q/A system development, hermetic sealing, and burn-in testing requirements.

While the evaluation of existing information has provided a high degree of confidence in the ambient temperature portions of the ASC design, a number of engine specific aspects were found to be lacking. One key item was the extremely limited amount of long term testing of hermetically sealed free-piston engines employing matrix style regenerators. The lack of hermetic sealing represents a serious issue since outside air can permeate through O-rings into the higher pressure internal helium working gas\(^7,8\). The introduction of air into the system compromises the evaluation in the areas of regenerator matrix durability, possible effects on seals / bearings, and potential impact on heater head materials.

B. Critical Convertor Component Evaluation

The combination of high efficiency, high specific power, and a 14 year life target of the ASC requires the use of high performance, low mass linear alternators, refined cycle thermodynamics, highly effective heat exchangers, and high heater head operating temperatures. While all of the items noted are critical to the success of the ASC and are being evaluated in the current reliability assessment effort, the high heater head temperature clearly introduces a number of reliability / design challenges.
Table 1 below indicates the critical ASC components constantly under evaluation. The relative priority in this list is often changed based on the results of ongoing analysis, materials testing, hardware evaluation, etc. Recent emphasis has been on aspects of the heater head design, displacer fabrication issues and the ongoing evaluation of regenerator materials and fabrication issues. Examples of a selected number of these items are discussed in more detail below.

### Table 1. Critical Component Listing

<table>
<thead>
<tr>
<th>Item</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater head</td>
<td>Materials and fabrication</td>
</tr>
<tr>
<td>Working gas contamination / regenerator</td>
<td>Impact of material selection, potential debris generation,</td>
</tr>
<tr>
<td>Controller / sensors</td>
<td>Hot end temperature sensors – durability and long term accuracy</td>
</tr>
<tr>
<td>Displacer cap</td>
<td>Materials and joining</td>
</tr>
<tr>
<td>Fasteners</td>
<td>Design margins under normal and worst case conditions</td>
</tr>
<tr>
<td>Linear alternator</td>
<td>Margins and failure / degradation modes particularly at temperature above design values</td>
</tr>
<tr>
<td>Working gas leakage</td>
<td>Non-conventional leak paths</td>
</tr>
<tr>
<td>Moving components</td>
<td>Seal / bearing effects at &gt; design temperatures</td>
</tr>
<tr>
<td>Controller / power conditioning</td>
<td>Electronics</td>
</tr>
</tbody>
</table>

1. **Heater Head**

The ASC heater head operates at a temperature of about 850 °C which is 200 °C higher than that of comparable long life free-piston convertors. At these temperatures the potential materials are extremely limited and emphasize the cast nickel-based superalloys such as the Mar-M-247 selected for the ASC. To address heater head reliability issues from the start, a probabilistic evaluation approach was employed. In addition to incorporating statistical factors involving the Mar-M-247 properties, this model also includes the statistical / accuracy issues concerning the heater head temperature measurement system (sensor and electronics), variations in mean charge pressure, and manufacturing tolerances. The use of this model allows the impact of various parameters on reliability to be evaluated. As expected, the limited Mar-M-247 database plays an important role, however the accuracy of the temperature sensing system is also very important in defining reliability. Current estimates of the sensor system accuracy at the 850 °C operating temperatures are in the range of +/- 15 to 25 °C. The importance of this effect can be appreciated by the fact that a high side temperature error on the order of 10 to 12 °C can decrease heater head life by 50%.

Incorporating all the effects discussed above in the probabilistic model allows the determination of material operating temperature limits at specific thickness values for a defined reliability level. This information can then be incorporated into the design. For the design of the ASC heater head and regenerator wall the reliability criteria has been set at >0.999. While these results provide a confidence in the basic design further work is required in defining the specific properties of the Mar-M-247 in the operating conditions of interest. The ASC reliability evaluation task has allowed identification of specific conditions for material sample testing which will maximize the information return from the viewpoint of improving the statistical data or reliability modeling. This work has been under way at Boeing / Rocketdyne and has received support from NASA / GRC based on their ongoing material testing efforts as described in Ref. 9 as well as in ongoing personal communications with Bowman at NASA-GRC.

2. **Displacer Dome**

In a similar manner, the displacer cap assembly has been evaluated from the viewpoint of identifying the critical parameters impacting reliability. As with the heater head, the high temperatures eliminated the use of currently employed materials for the displacer dome assembly. The selected Udiment 720, while better defined in some areas than the Mar-M-247 is still a material with a limited database at the temperatures and operating times of interest. These factors combined with the thin walls, the cyclic loading, and the potential impact of fabrication effects, such as braze alloy diffusion, have all been factored into the probabilistic reliability evaluation of this component.

C. **Component Testing**

As part of the reliability / lifetime performance effort it was important to identify areas where critical reliability data was lacking and define and carry out various component testing efforts to provide this information. As examples of this effort, two areas of investigation are described briefly below.
1. **Regenerator**

The regenerator plays a critical role in determining the overall thermodynamic efficiency of the Stirling cycle. Current regenerators are fabricated from small (20 to 40 micron diameter) random fiber matrix with effective porosities on the order of 90%. The effective surface area of these fibers is in excess of the total surface area of the remaining components exposed to the helium working fluid. This makes the high temperature portions of the regenerator extremely susceptible to the presence of gas contamination products such as O\(_2\), H\(_2\)O, and trace out-gassing species from various non-metallic or adhesive compounds employed with the ASC. The results of these interactions can be debris generation (broken fibers), blockage of the regenerator flow passages, and shrinkage of the bulk material. Current stainless steel regenerator materials have had problems with contamination-related effects at temperatures well below the ASC operating temperatures. In efforts to overcome these reliability issues the ASC project in carrying out regenerator sample testing under ASC like operating conditions. In addition, on going work by NASA-GRC is also supporting this effort. Based on results of tests to date it has been determined that the existing Sunpower regenerator fabrication scheme should continue to be employed and a special fiber material used for the reference ASC regenerator.

2. **Linear Alternator**

To demonstrate the robustness of the Sunpower linear alternator and its performance at extreme operating conditions (>>100°C) an ASC alternator will be subjected to high temperature durability / destructive testing. In this, a mechanically resonated stock Sunpower cryocooler linear motor (operating at room temperature) will be used to drive the tested alternator that will be pushed to various elevated temperature levels during testing. The hardware to be employed is shown below in Figure 3. The driver for this is identical to a unit currently being used by NASA-GRC\(^{10}\) to test various linear alternators. Testing will involve determination of the onset of non-recoverable losses in the magnetic material properties, performance degradation as a function of temperature, and in the final phase of the tests actual test to destruction to identify the hardware mechanical limits.

![Figure 3. Hot Alternator Test Rig Components](image)

(Front Row: outer ASC stator, magnet can assembly, inner iron)
(Back Row: mechanically resonated driver, insulation can)

V. **Heater Head Materials and Design**

Boeing/Rocketdyne is developing the heater head for the ASC. As stated earlier the heater head requires reliable operation at 850°C for the design life of 14 years. After examining data for a number of alloys, Mar-M-247 was selected based on creep strength, alloy maturity and fabrication requirements. The heater head also includes an internal nickel 201 acceptor heat exchanger.

Optimum casting parameters have been selected, microstructures and properties are being verified, and heater head fabrication is currently proceeding. Mar-M-247 was procured as 1.8-inch-diameter x 4-inch-long vacuum-
investment-cast bars. Figure 4 shows four of these cast bars. The alloy could have been procured as near-net-shape castings, but the ASC schedule did not allow the time required for mold fabrication and casting development. Near-net-shape investment casting is a straightforward improvement to pursue in the future.

Three lots of castings, four per lot, were fabricated over a range of pour temperatures. The highest and the intermediate pour temperatures provided castings that were porosity-free following hot isostatic pressing (HIP). The lowest pour temperature provided castings having fine grain size, but surface-connected porosity in these castings was not healed during HIP. Figure 5 shows representative microstructures for the highest pour temperature, intermediate pour temperature and low pour temperature castings.

Helium must not permeate the Mar-M-247 heater head to any significant degree over the 14-year operating life of the ASC. Leak paths cannot be tolerated. Intermediate and high-pour-temperature castings appear to have the potential to meet this requirement. Helium leak inspection was carried out on castings segments. In castings from the preferred lots, helium permeation was below the detection level of a sensitive mass-spectrometer-based leak detection system.

Figure 5. Mar-M-247 cast bar microstructures, upper end of cast bar approximately 1 cm from side wall.
The heater heads are in the process of being machined. Acceptable, low helium permeation levels will be verified throughout the sequence of fabrication steps, with a test setup and calibration that enables extrapolation of total pressure drop over the life of the heater head. An early test machining, to verify that the required details and thin wall desired in the regenerator section could be achieved, is shown in Figure 6. Figure 7 shows a sectioned sample showing the heater head to internal acceptor diffusion bond.

Udimet 720 was selected for the displacer dome and baffles. The displacer dome maximum temperature is lower than that heater head, and the pressure difference across the dome is low, allowing the use of Udimet 720 which is a more processable wrought alloy compared to cast Mar-M-247. Table 2 lists the compositions of Mar-M-247 and Udimet 720. Figure 8 shows the stress versus Larson-Miller parameter, for 1% creep, for Udimet 720 and Mar-M-247. The creep strength advantage of Mar-M-247 is evident, as is the fact that Udimet 720 also has notable creep strength.

Baffles are being brazed to the displacer dome in the near term to expedite fabrication. Diffusion bonding is the preferred approach for long-life joints, and is to be developed as soon as development of the higher-priority processes has been completed.

Table 2. Compositions of Mar-M-247 and Udimet 720.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Comment</th>
<th>Ni</th>
<th>Co</th>
<th>Cr</th>
<th>Al</th>
<th>Ti</th>
<th>Mo</th>
<th>W</th>
<th>Ta</th>
<th>C</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar-M-247</td>
<td>Cast Ni-base superalloy. Excellent strength and upper use T.</td>
<td>70.6</td>
<td>8.5</td>
<td>5.5</td>
<td>1</td>
<td>10</td>
<td>3</td>
<td>0.15</td>
<td>1.3</td>
<td>Hf</td>
<td></td>
</tr>
<tr>
<td>Udimet 720</td>
<td>Wrought or P/M Ni-base superalloy. Excellent strength and upper use T.</td>
<td>57.4</td>
<td>14.7</td>
<td>16</td>
<td>2.5</td>
<td>5</td>
<td>3</td>
<td>1.45</td>
<td>0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Stress vs. Larson-Miller Parameter for 1% Creep](image)

**Figure 8.** Stress versus Larson-Miller parameter for Mar-M-247 and Udimet 720.
VI. Investigation of Losses

In addition to development of the convertor itself, efforts are underway to better understand thermodynamic losses which can influence the performance of the ASC convertors. These efforts are being performed by Sunpower as well as by the two universities which are part of the ASC team; Cleveland State University and the University of Minnesota.

A. Regenerator Perimeter Effects
Regenerator perimeter (wall and entrance) effects are being studied by Professor Terry Simon at the University of Minnesota using an existing large scale test rig. Figure 9 shows a large scale regenerator test section (built under the current NRA program) which includes a wall electrical heater and numerous wall thermocouples attached along the length. A special small diameter thermocouple probe (not shown) has also been developed to measure local temperatures gradients near the wall within the gas of the regenerator. This probe is traversed in the near wall region of the regenerator and the test results used to determine local heat fluxes. Additionally the flow at the ends of the regenerator (where the flow enters from the adjacent heat exchanger) are also being studied using this large scale rig.

(b) End View (regenerator is 178 mm diameter).

FIGURE 9. Large Scale Regenerator Test Section at the University of Minnesota.

B. Displacer Internal Losses
The investigation of displacer internal convection losses was completed during the Phase I effort. The concern in this area was that the high frequency oscillatory motion of the displacer might result in large internal convection losses. Displacer interiors are essentially closed containers of the cycle working gas operating at the mean pressure of the convertor. The displacer interior cavity is also divided axially with radiation shields to reduce direct radiation from the hot to the cold ends of the displacer.

(b) DLR Test Section of Displacer Cavity.

FIGURE 10. CFD and Experimental Investigations of Displacer Convection Losses.
The study of displacer internal losses was performed both by CFD modeling (by Professor Mounir Ibrahim at Cleveland State University), and by use of a special Displacer Loss Rig (DLR) which was built at Sunpower. The DLR was used to perform testing on a single closed cavity of gas, representative of the section defined by two adjacent radiation shields within a displacer. This single cavity of contained gas, was oscillated at various frequencies and amplitudes (representative of ASC operating conditions), using a Sunpower linear drive motor.

These analytical and experimental studies showed that the high speed oscillation was found to suppress natural convection losses that otherwise occur within a gravitational field. Figure 10 presents a typical CFD modeling result as well as a drawing of the test section used on the DLR. As a result of this study the number of baffles used in the displacer for the ASC has been significantly reduced.

C. Displacer Appendix Gap Loss
Displacer appendix gap heat transfer effects (including shuttle heat transfer) are the subject of a second CFD study now underway using CFD modeling at Cleveland State University. The displacer appendix gap analysis is rather complicated because of the numerous processes occurring in this area; leakage, compression/expansion of the gas, and the moving walls (each having a temperature profile). No final CFD results from this study were obtained in Phase I and this effort will continue into Phase II. However the loss in this area is not believed to be largely significant because of the high performance obtained on the FTB. Figure 11 illustrates the CFD model of the displacer appendix gap and the associated gas spaces.

![FIGURE 11. CFD Model of Displacer Appendix Gap.](image)

D. CFD Modeling of Gas Bearings
While the techniques used in the design of gas bearings for Sunpower’s machines has proven to be very adequate, the design technique is based on simplified models. To better model the gas bearings, Cleveland State University is also developing a CFD model. The intent here is to better model the gas bearing flows and the interaction with working and bounce spaces of the engine, as well as the interaction with the center-porting system used to maintain the piston mean position. Figure 12 below shows a typical result of the gas bearing model.
Boeing/Rocketdyne is developing the controller to convert the AC electrical power of the convertor to DC output which is to interface with the spacecraft. High efficiency of the convertor will be obtained by maintaining a high power factor, therefore reducing alternator losses. The controller is also required to vary the convertor output in order to maintain the heater head temperature within safe limits to provide the required long creep life. The controller also will maintain the phase between dynamically opposed convertors to minimize vibration. A breadboard controller is to be implemented with the ASC during Phase III.

The Phase II effort also includes a study of a passive versus an active dynamic absorber (to minimize vibration in case of a single convertor failure). If an active dynamic absorber is selected, the controller will also be required to control the electric drive of the absorber. In support of the controller development as well as the reliability and lifetime performance effort (discussed in the next section), a dynamic model was developed during the Phase I effort. The dynamic model includes engine and alternator models as well as the controller. The model can also predict the behavior of opposed convertors and address the dynamic behavior with a dynamic balancer.

The ASC is to have its first run in September 2005 and promises to be a highly efficient and low mass convertor well suited to NASA needs for radioisotope convertors. Based on the performance achieved with the FTB, the ASC is expected to approach 40% efficiency (AC electrical out / heat in) at a specific power (minus controller) of 90 W/kg. The ASC-1 has now been designed to be relatively low mass except for the clamping flanges used to allow assembly and disassembly. The reliability of Stirling convertors is anticipated to be high based on the similar design features and power levels of Sunpower’s cryocoolers. To insure reliability Phase II includes a separate task to identify and investigate reliability issues.

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X. References