Directed Reflectivity, Long Life AMTEC Condenser (DRC)

Final Report of Phase II SBIR Program
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1. Project Summary

The Alkali Metal Thermal to Electric Converter (AMTEC) is a static energy conversion device that operates at high thermal to electric conversion efficiencies that are essentially independent of size, have reached 19% and are expected to reach 25% to 30% in 1997. AMTEC systems have been chosen by NASA and DOE for spacecraft applications and have considerable promise for a wide variety of terrestrial applications. Reduction of parasitic heat losses in AMTEC systems related to radiative heat transfer from the hot side to the condenser can make a substantial contribution to system efficiency. Through design, analysis and the fabrication and testing of cells and systems, the proposed program to develop a Directed Reflectivity Condenser (DRC) has investigated the feasibility of an improved AMTEC condenser component. Phase 1 work showed the potential for adding from 4% to 7% to overall system efficiency for identical operating conditions using the concept. A detailed thermal analysis of several DRC capped cell designs was carried out and some of the conditions under which a DRC, used as the condenser at an end cap of a cylindrical converter, can reduce thermal radiation related losses were determined. A model experimental converter was built and tested to compare DRC and planar condenser surfaces. The results of both analysis and experiment indicate that for moderate aspect ratios of a cylindrical, end-condensed converter, the DRC can reduce overall thermal losses by up to 4%. The initial effort in Phase 2 extended the analysis to a novel 150 watt radial AMTEC cell design. This analysis indicated that for the effective aspect ratio of this new converter design, the system performance at the 100+ watt level was not significantly improved by use of a DRC type condenser surface. Further analyses however showed that for cylindrical, end-condensed converters, optimized for use with internal radiation shields, the use of DRC surfaces on the side walls of the converter could be more effective than on the condenser end surface itself. The experimental work in Phase 2 was intended to incorporate a DRC into this cell design and use its measured performance to refine the state-of-the-art AMTEC analytical models. Because the analysis had indicated that the new radial converter design, which may be useful for systems at the ~ 100 watt level was not much assisted by the DRC properties, this program was redirected toward the simpler cylindrical converter design with the corner cube surfaces on the side walls.

The Phase II program was proposed and planned with a funding level substantially below the maximum potentially available for Phase II programs at that time. At the time, there were two other funded government sponsored programs at AMPS for which positive results of the analyses described in this report were expected to lead to incorporation of the DRC concept into converters scheduled to be built for these programs. The programs of interest were the Air Force program titled "Radiation Tolerant, Eclipse Compatible, Solar AMTEC System" (F29601-99-C-0132) and the DOE/NASA Advanced Radioisotope Power System (ARPS) program. Shortly after its start, the Air Force program was cancelled due to elimination of AF SBIR funds at AFRL and the ARPS program was reduced to a level that could not support introduction of novel concept testing. As a result of these two circumstances, the direct testing of the DRC concept in a full up converter was not completed in the Phase II period.

2. Background of Directed Reflectivity Condenser (DRC) Concept

The basic concept behind the DRC approach is to use the properties of 'corner cube' reflectors to return thermal radiation from a hot source directly back to it. It is desirable for many applications to minimize thermal radiation transfer from hot surfaces to cooler regions. In general circumstances, such radiation leaves the hot surface, proceeds to cooler surfaces, often by a series of reflections and absorptions. Often the radiation is partially or mostly reflected from the first surfaces it encounters and then is progressively absorbed at the subsequent surfaces it encounters during multiple reflections. This principle is the basis for the design of standard "black body" radiation standards which use the opening of a highly polished, reflecting, narrow angle cone as the standard. In order to minimize transfer from a hot surface, it is desirable for the first surface the radiation encounters to preferentially reflect that radiation directly back to the hot source. So-called "corner cube" or "retro" reflectors have precisely this property and at optical frequencies they are used for high efficiency reflectors in applications from highway signs to retro-reflectors for laser ranging of the moon's surface. In the DRC approach investigated here, we apply retro-reflectors to internal surfaces of AMTEC converters upon which the thermal radiation from the AMTEC hot zone falls in order to send the maximum amount of thermal energy back to the source, without scattering or reflecting it to other absorbing surfaces. Even highly specular reflection of thermal radiation from any other surface configuration is unlikely to return the radiation to the source. whose radiation loss it is desired to reduce.

A corner cube or retro-reflector consists of the intersection, at right angles, of 3 planar reflecting surfaces. The geometry of such a corner is such that incoming rays are reflected back in the direction from which they come. The returning ray will be translated laterally by an amount determined by the distance from the cube apex at which it first hits the corner. In the corner cube array shown in Figure 1, a light ray impinging on any point within the opening of any one of these corners undergoes 3 reflections from intersecting planar surfaces and is returned as a ray parallel to the incoming ray. It is generally desirable to minimize the lateral translation of the rays and this can be done by reducing the pitch (distance between the apices) of the surface. Figure 2 shows a schematic drawing of a planar array of corner cube reflectors of the sort used in the initial testing.

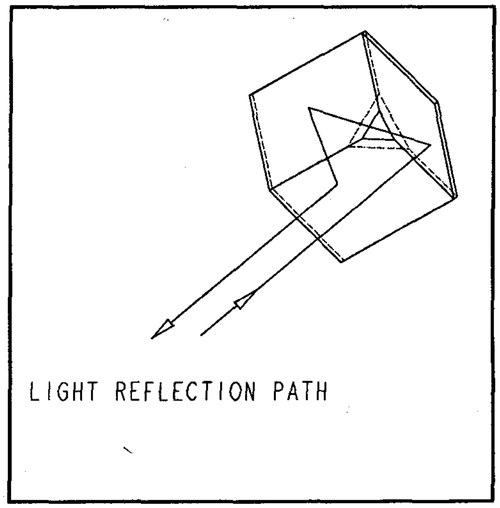

Figure 1 Light Ray Path at Retroreflector.

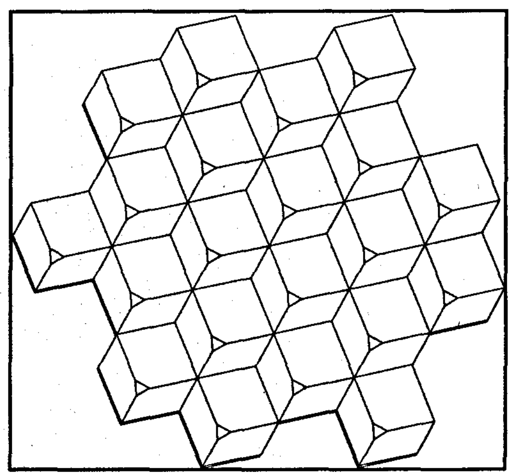

Figure 2 Array of Corner Cube Reflectors.

<u>Other Applications</u>

3. Summary of the Results of Phase I Work

The overall Phase 1 program objective has been to determine whether it is feasible to use a Directed Reflectivity Condenser (DRC) in an AMTEC system to provide enhanced electric power density, efficiency and reliability for space power applications. If these enhancements can be confirmed, it should be possible to establish the potential utility of the DRC concept for enhancement of the efficiency of AMTEC cells/systems suitable for a wide variety of practical space and terrestrial applications. Specific task objectives were to prepare a simulated AMTEC cell in which the thermal transfer properties of a cell configured with a DRC-closed end could be investigated. DRC properties were to be analyzed for typical AMTEC cell configurations and the results compared with preliminary experiments. Based on the results of the experiments and analysis, the potential contribution to enhancement of the efficiency of spacecraft power systems was to be assessed and a decision whether to proceed with a possible Phase 2 program made. These tasks were performed successfully and the results were encouraging and are described in this section.

DRC Analysis

In order to analyze the potential benefit accruing from use of a DRC in an AMTEC cell, calculations were made using cell dimensions and relevant basic emissivity data for conventional cell materials exposed to the thermal radiation environment in an operating cell. For each cell configuration, the analyses were carried out for both a DRC condenser surface and for a flat plate condenser with the same material properties. In each case a detailed mechanical drawing of the cell was created in AutoCAD and this file used with the standard RADCad and SINDA analysis tools to carry out the thermal transport calculations. It should be noted that while radiation is a major loss mechanism, it is coupled to the thermal conduction down the walls of the cell through the thermal isolation region as indicated in Figure 3 Radiation from the hot zone containing the BASE tubes at the bottom of the cell impinges on walls and the fraction absorbed is then conducted down the walls to the condenser region. Under these conditions, the thermal conductance of the converter wall, its length and its emissivity all bear on the parasitic cell thermal losses that can be affected by the choice of a DRC vs. a Flat Plate Condenser (FPC).

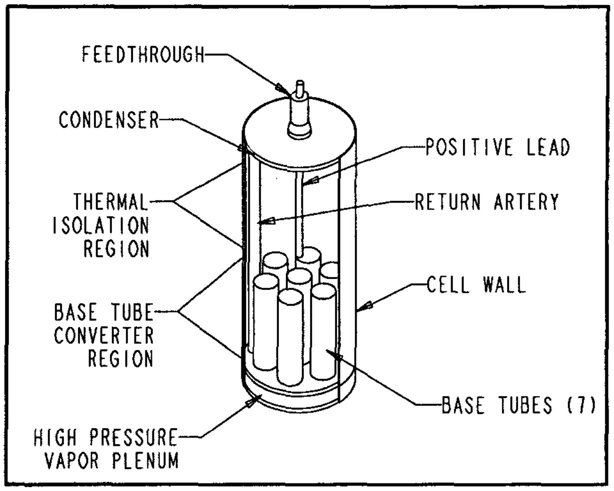

Figure 3 Schematic Diagram of Multi-Tube AMTEC Cell.

<u>Summary</u> Thermal models of simple, cylindrical, multi-tube AMTEC converters with Flat Plate Condenser (FPC) and Directed Reflectivity Condenser (DRC) were studied. Conduction and radiation losses for converters with the two types of condensers have been compared. For the converters studied, those with a DRC appear to require up to 11 % less thermal energy input than for similar ones with FPCs. DRCs were found to be effective in converter configurations for which radiation plays a dominant role in the parasitic heat losses and the view factor from the hot zone to the cold is large. A 'DRC number', defined as the product of the view factor and direct radiation heat loss from the hot end to the condenser as a percentage of the total heat loss, is found to be useful as an indicator of the effectiveness of a DRC in comparison with an FPC. With this definition, a system in which 100% of the radiation goes directly to the condenser, has a DRC number of 100. The relative importance of radiation and conduction heat losses depends on the view factor from the hot end to the cold end, cell wall thickness, material and surface properties and operating temperatures. It was found that DRC is net effective only when the DRC number is greater than 3. Preliminary calculations for the proposed advanced radial converter show that it has a DRC number of about 26. Detailed analysis of this design became a Phase II task.

<u>Assumptions</u> The objective of the analysis is to compare thermal performance of the DRC with that of an FPC. For simplicity, cells without any internal components (BASE tubes, heat shields) were studied. Three different aspect ratios (diameter/height) of the cells were considered to see if the view factor from the hot zone to the cold end has a substantial effect on the performance of DRC. The aspect ratios chosen were 1,

5/7 and 3/7 corresponding to hot end to cold end view factors of 0.314, 0.103 and 0.042, respectively. The cold end was kept at 573 K and three different hot zone temperatures, 873 K, 1073 K and 1223 K were studied. The output of each analytical run was the total energy input to the hot end required to maintain its set temperature for a given cold end temperature. The analysis also yields separately the energy gained by the condenser through conduction as well as direct radiation.

Analysis Procedure

The tools used to perform the DRC analysis were AutoCAD, RadCAD and SINDA. AutoCAD was used to create a surface model of the cell. The model is shown in Figure 4. The side walls of the cell were divided into 14 rings (one is shown) each representing a radiation surface. The hot end was represented as a circular plate. For the Phase 1 effort the complication of including all of the BASE tubes and their support structure was omitted. The condenser surface was taken to be a simple flat plate for the flat plate condenser and a set of inside corner surfaces in the DRC case. RadCAD is a radiation calculation software package that is fully integrated with AutoCAD. For these radiation heat transfer calculations, it was assumed that the surfaces are all specular. Typically, a specularity number of 0.95 was used for the condenser surface and a value of 0.5 was used for the stainless steel surface of the side wall. The surface properties, emissivity and specularity are input in RadCAD which writes out radiation and conductor data for a SINDA input file. The converter side wall is generally made of stainless steel. The material properties, essentially the thermal conductivity and material wall thickness, are used to define the conductors between different nodes. Each RadCAD surface represents a node in SINDA. As one output, SINDA determines the total heat input to the hot end required to maintain the set temperatures. It also breaks out the heat lost/gained by the hot end/cold end via conduction and radiation paths.

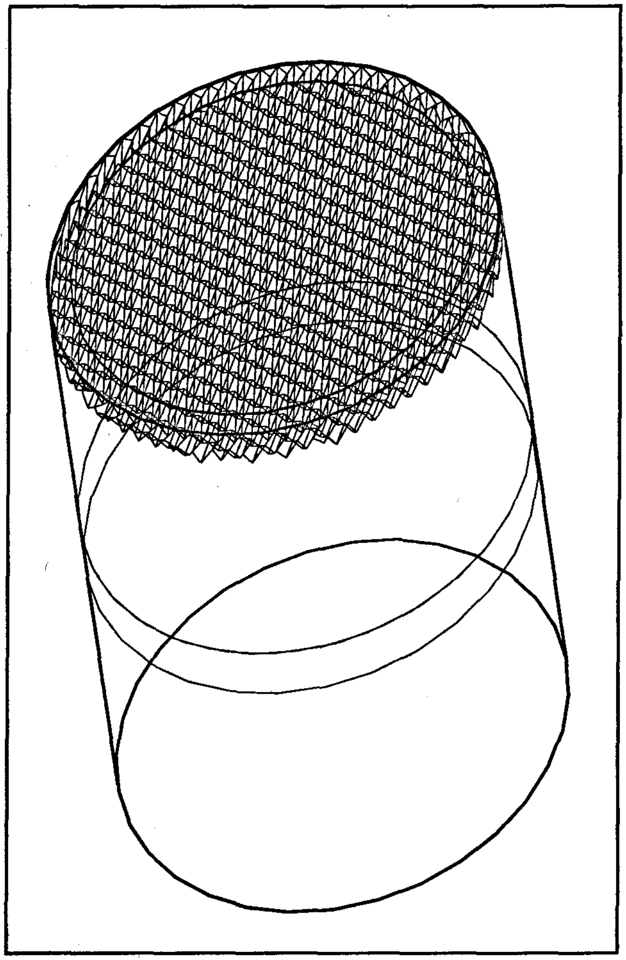

Figure 4 Sketch from the CAD Model for DRC Calculation. A Typical Band for View Factor Calculation is Shown.

Analysis Results Tables 1-6 give the heat input required for the Flat Plate Condenser and the DRC. In Table 1, the effect of the emissivity of the condenser surface on the performance of DRC is given for one cell design. An emissivity range from $\epsilon = 0.01 - 0.05$ was selected to model the emissivities of a sodium coated surface ($\epsilon \approx 0.03 - 0.05$) and the emissivity of copper ($\epsilon \approx 0.02$) in the infrared region. Note that the experimental DRC surfaces are made of copper. The results show that the DRC can reduce the required heat input to maintain the hot zone temperature by about 2 to 3 percent below that of a flat plate condenser of comparable material. The aspect ratio (diameter/length) for these cells was 5/7 and the view factor from the hot zone to the cold end is 0.1027. The other cell parameters are indicated in the table caption.

Table 1: Effect of Condenser Emissivity

	Emissivity	Heat Loss, Watts			%	%
		Conduction	Radiation	Total	Radiation	Improvement
Flat Plate	0.05	101.87	32.21	134.08	24.0	N/A
	0.02	100.98	31.46	132.44	23.7	N/A
	0.01	100.59	31.22	131.81	23.6	N/A
DRC	0.05	-	-	-	-	-
	0.02	99.66	29.81	129.47	23.0	2.28 %
	0.01	98.97	29.48	128.45	22.9	2.64 %

Cell thickness: 0.165 cm, Diameter = 6.35 cm, Length = 8.9 cm, View factor = 0.1027, Steel emissivity = 0.3. Hot end temperature = 600 C, Cold end temperature = 300 C.

One should note that in these cases, the hot zone 'surface' loses about 76% of its heat via conduction and only 24 % is lost via radiation. This is due to the fact that this cell wall is very thick and the conduction losses are therefore high. These results suggested examining the case for a cell with thin side walls for which it is expected that radiation will play a more important role. A DRC with a thin cell wall more closely represents the current production cells which have a wall thickness of about 0.013 - 0.030 cm.

Table 2 gives the relative performance of the DRC with respect to the FPC for a thin cell wall at different operating temperatures. For cells with a 0.030 cm wall thickness, the hot surface loses about 36% of its heat via conduction and 64 % by radiation. The DRC performs better than the FPC in these cases by about 4.5 % in terms of required heat input to the hot end.

Table 2: Effect of Operating Temperature

	Hot end	Heat Loss, Watts			%	%
		Conduction	Radiation	Total	Radiation	Improvement
Flat Plate	600 C	23.32	27.13	50.45	53.7	N/A
	800 C	42.50	62.67	105.17	59.6	N/A
	950 C	57.66	102.16	159.83	63.9	N/A
DRC	600 C	22.45	26.02	48.47	53.6	3.92 %
	800 C	40.65	59.89	100.55	59.5	4.39 %
	950 C	54.94	97.35	152.28	63.9	4.72 %

Cell thickness: 0.030 cm, Diameter = 6.35 cm, Length = 8.9 cm, View factor = 0.1027, Steel emissivity = 0.3. Condenser emissivity = 0.01.

Note that radiation plays an increasingly dominant role in comparison to conduction for higher temperature differences between the hot zone and cold end. This is due to the fact that radiation transfer is $\propto (T_h^4 - T_c^4)$ while conduction transfer is $\propto (T_h - T_c)$. Since DRC helps in cutting down radiation losses, the performance advantage of a DRC is expected to increase with increasing hot end temperature. This is exactly what the results in Table 2 show. This implies that DRC can be an effective choice for ultra-high efficiency cells which are intended to operate at high temperatures.

Since a large view factor from the hot zone to the cold end may also be expected to increase the role of radiation, the DRC performance for a cell with an aspect ratio of 1 was examined. For this cell, which simulates the configuration of current state of the art flight cells, the bottom half of the cell (hot end side) has a wall thickness of 0.030 cm and the top half wall thickness of 0.013 cm. The analysis results for this cell are given in Table 3. The flat plate condenser cell data shows a radiation loss of about 71 %. While the DRC cell shows a similar fraction of loss by radiation, the total heat input required is lower by 11.5 %. The view factor from the hot end to the cold end for this cell is 0.3138.

Table 3: Results for Cell with Aspect Ratio of 1

	Heat Loss, Watts			%	%
	Conduction	Radiation	Total	Radiation	Improvement
Flat Plate	83.00	206.08	289.09	71.3	N/A
DRC	72.05	183.68	255.74	72.0	11.5 %

Cell thickness: 0.030 cm and 0.0127 cm, Diameter = 8.9 cm, Length = 8.9 cm, View factor = 0.3138, Steel emissivity = 0.3. Condenser emissivity = 0.02. Hot end temperature = 950 C, Cold end temperature = 300 C.

In a third case, DRC performance was studied for a cell with an aspect ratio of 3/7. Other than the aspect ratio, all other parameters for this cell were the same as those for the analysis of the cell with an aspect ratio of 1. The flat plate condenser results in Table 4 show radiation losses at 54% of the total heat loss. For this cell, the DRC performed worse than the flat plate condenser by about 1.7% in terms of thermal energy input. This results from the very low view factor in this cell, since little direct radiation reaches the condenser and the radiation which does reach the condenser suffers 3 reflections rather than the one reflection from the FPC.

Table 4: Data for Cell with Aspect Ratio of 3/7

	Heat Loss, Watts			%	%
	Conduction	Radiation	Total	Radiation	Improvement
Flat Plate	7.64	9.08	16.72	54.3	N/A
DRC	7.82	9.18	17.00	54.0	-1.67 %

Cell thickness: 0.030 cm and 0.0127 cm, Diameter = 3.81 cm, Length = 8.9 cm, View factor = 0.042, Steel emissivity = 0.3. Condenser emissivity = 0.02, Hot end temperature = 950 C, Cold end temperature = 300 C.

Note that for this cell, radiation loss fraction is about 54 %. The view factor from the hot zone to the cold end is very small (≈ 0.042) however, and a smaller view factor will make theDRC contribution less important. Also note that in the case of DRC, each electromagnetic ray undergoes three reflections at the condenser surface as compared to 1 for the flat plate. This increases the effective emissivity of the condenser surface. It is thus possible that for cases in which the hot end does not see the cold end enough, there may be no gain from a DRC. The DRC may well perform worse than the FPC in such cases. In order to illustrate this further, we define a new parameter, the DRC number, D_{rc} as

$$D_{rc} = F_{h\text{-}c} \bullet \alpha$$

where $F_{h\text{-}c}$ is the View Factor from the hot zone to the cold end of the cell and α is the radiation heat loss from the hot zone as a percentage of the total heat loss for the FPC. It is the product of the view factor from hot end to the cold end and radiation loss as a percent of total heat loss for FPC. A graph showing the percentage reduction in cell heat input vs. DRC number is plotted in Figure 5. Plotted on a semi-log scale, the results yield a nearly straight line. The graph indicates that DRC gains an advantage if the DRC number is above 3. With this definition, the maximum value of DRC number is 100. Extrapolation of the graph to 100 gives an upper limit of about 20% reduction in required heat input to this cell. This value corresponds to the reduction in the parasitic heat loss.

This graph gives a rule of thumb for considering the utility of a DRC for cells of different configurations. One such design, the radial converter, is shown schematically in Figure 12. Given the typical dimensions of the radial converter (inner diameter = 9 cm, outer diameter = 20 cm, cell height = 4 cm), the view factor from the hot end to the cold end is approximately 0.371. This view factor is close to that for the cylindrical PX style cell with an aspect ratio of 1.0. Assuming a comparable radiation loss fraction of about 70 % of the total heat loss, this gives a DRC number of 26. This projected value is plotted as the single point in Figure 5. One can expect that the use of DRC will reduce the energy input required to compensate for parasitic heat losses by about 12%. This implies that the use of a DRC could increase the projected converter efficiency from 30 % to 31+ % for a fully populated radial converter, a significant improvement for critical applications. Additional gains should be possible through the enhanced uniformity of BASE tube temperatures that would result from use of the DRC.

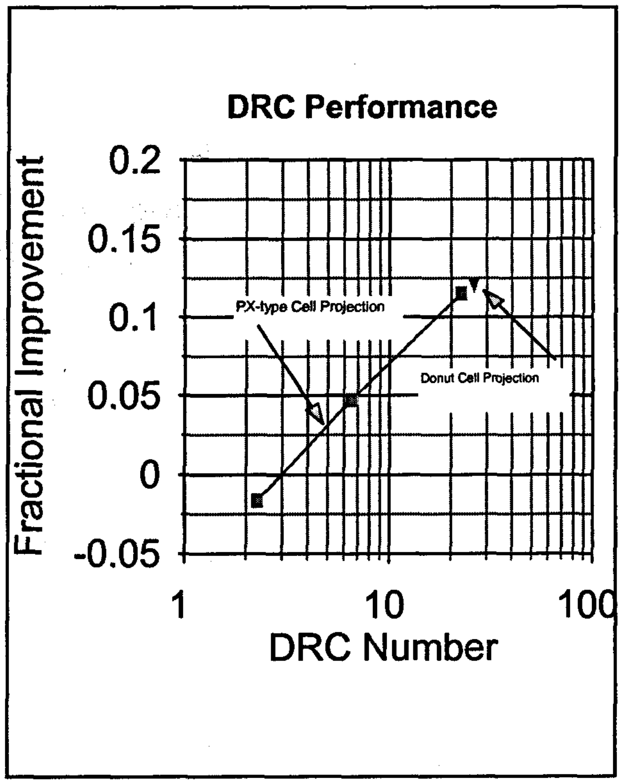

Figure 5 Reduction in Parasitic Heat Loss As a Function of DRC Number.

During this investigation, additional observations were made. The data given in Table 5 shows that even though the hot zone loses a large amount of heat via radiation, the cold end receives relatively little heat directly via radiation. Most of the heat received by the cold end arrives via conduction because most of the radiation heat lost by the hot zone goes first to the side walls and then is conducted to the cold end. Therefore, it was anticipated that reducing the emissivity of the side walls would also help reduce overall heat input to the cell. In principle, a lower emissivity ($\epsilon = 0.1$) can be achieved by coating the stainless steel surface with Tungsten, a metal compatible with Sodium at high temperatures and with lower emissivity. A analytical run was made with this low value of emissivity and it resulted in about 11.5% reduction in energy input as shown in Table 6.

Table 5: Comparison of Heat Inputs at Hot and Cold Ends for FPC

	Heat Gain/Loss, Watts			%
	Conduction	Radiation	Total	Radiation
Hot End	100.98	31.46	132.44	23.7
Cold End	130.36	2.14	132.50	1.6
Side Wall	29.38	29.38	0.00	N/A

Cell wall thickness: 0.165 cm, Diameter = 6.35 cm, Length = 8.9 cm, View factor = 0.1027, Steel emissivity = 0.3. Condenser emissivity = 0.02, Hot end temperature = 873 K, Cold end temperature = 573 K.

Table 6: Effect of side wall emissivity corresponding to Tungsten Coating on FPC vs. SS

	Total Heat Loss, Watts		% Improvement
	ϵ = 0.3	ϵ = 0.1	
Flat Plate	132.49	117.12	11.6 %
DRC	129.47	114.54	11.5 %

Cell thickness: 0.165 cm, Diameter = 6.35 cm, Length = 8.9 cm, View factor = 0.1027, Condenser emissivity = 0.02, Hot end temperature = 873 K, Cold end temperature = 573 K.

Conclusions The analysis predicts that the DRC concept can work to reduce significantly the parasitic heat losses from the hot zone of an AMTEC cell to the condenser for well chosen converter configurations. It appears to do so by a combination of reduction in direct radiative heat transfer and a reduction in the secondary transfer (via conduction) of the radiation which impinges on the cell walls. Based on a simple extrapolation of the analysis done, the maximum reduction in parasitic heat loss that could possibly be gained appears to be approximately 20% for a large view factor from the hot zone to condenser. View factors for some advanced cell designs are such that reductions of 12% appear to be feasible.

Phase I Experiments

Two principal experiments were carried out to examine the performance potential of the DRC concept.

1. A mock-up cell without BASE tubes was designed to use interchangeable 'condenser' end plates. Two plates were prepared, one as a simple flat copper plate and the other a machined copper array of right angle corners forming a DRC surface. While an impractical approach for a production scheme, the DRC end cap was assembled from a set of machined, notched, Cu strips with the thickness chosen to produce the corner cube reflectors desired. A drawing of an array of the type used is shown in Figure 6. This cell was operated in several modes to exhibit any changes in the heat transfer from the hot zone to the 'condenser' end.

2. A standard 'PX' series AMTEC cell was assembled with a machined copper DRC in place of the conventional condenser. This cell was run in standard operational modes and its performance measured for comparison with cells having a conventional condenser.

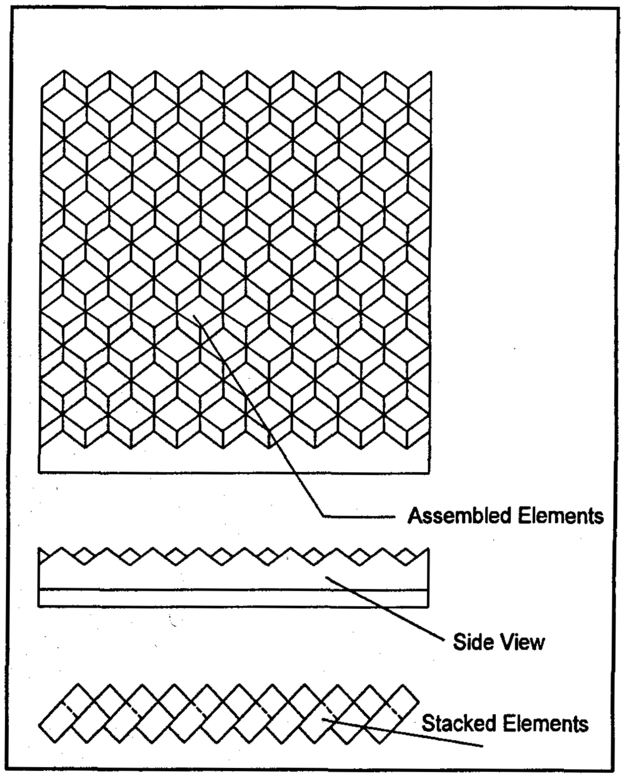

Figure 6 DRC Perspective View also Showing Component Stack View.

Mock-Up Cell A mock up cell based on the actual AMTEC cell dimensions was built and investigated to conduct a separate effects test without complications due to sodium handling. A photograph of directed reflectivity condenser (DRC) dummy test cell is shown in Figure 7. The cell was made out of stainless steel and the wall thickness was 0.165 cm. The condenser end cap had an O-ring on the inside and the cap was removable. Two condenser surfaces were built, one was a simple, flat copper plate and the other was a copper corner cube surface simulating a DRC. The surfaces of both were polished to improve their reflectivity. Copper was chosen as the surface material to provide a reasonable simulation of the infrared reflectivity of a wall wetted by a liquid sodium surface film. The mock up cell was put together and evacuated to eliminate any effects of convective transfer and to prevent oxidation of the copper at the high operating/test temperatures. The O-ring provided a removable vacuum seal and allowed for easy changeover from flat plate to DRC 'condenser' surfaces. The hot zone of this cell was a produced by a cartridge heater installed in a stainless steel heater well. To eliminate uncertainty in operating conditions between the flat plate and the copper cube surface, the temperatures of the cold (condenser) end and the cell wall were also controlled using Thermcraft electrical heaters and electronic temperature controllers.

To study the effect of the DRC, the 'condenser' temperature and the input power to the hot end were held constant and the hot end temperature was monitored while the condenser type was changed. For a given heat input, the hot end temperature in the mock cell with the DRC at the condenser end is expected to be higher because the DRC redirects the radiation headed toward the cold end back to the source, the hot end in this case. The advantage in terms of the difference in power required, with and without the DRC, to the keep hot end at the same temperature was then investigated. The condenser temperature for a constant power source with and without the DRC was also measured. For the same hot end temperature, the condenser temperature is expected to be lower with the DRC inside the mock up cell than with the FPC.

Type-K thermocouples were used to monitor the temperatures and for ease of power measurement, a regulated DC power supply was used to drive the heater input to the hot end. The results of the testing are presented in the following. Table 7 shows the type of cold end surface, cold end temperature, hot end temperature, the power input to the hot end, the difference in the temperatures between the flat and DRC case and the reduction in power input in the DRC case when the temperature difference between the two cases is reduced to zero. Results are presented for two different cold end temperatures and 3 different power inputs. In each of the five cases listed in Table 7, the hot end temperature for the DRC case was higher by 5 - 10 degrees and the difference increased with increases in power input. The reduction in power required to bring the hot end temperature for the DRC case back to the temperature value observed for the flat plate was about 5 - 7 %. Table 8 shows the change in cold end temperature with the input power held constant. In these two cases, FPC and DRC, the hot end temperature is almost the same, but the condenser temperature for the DRC is 5 - 6 degrees lower.

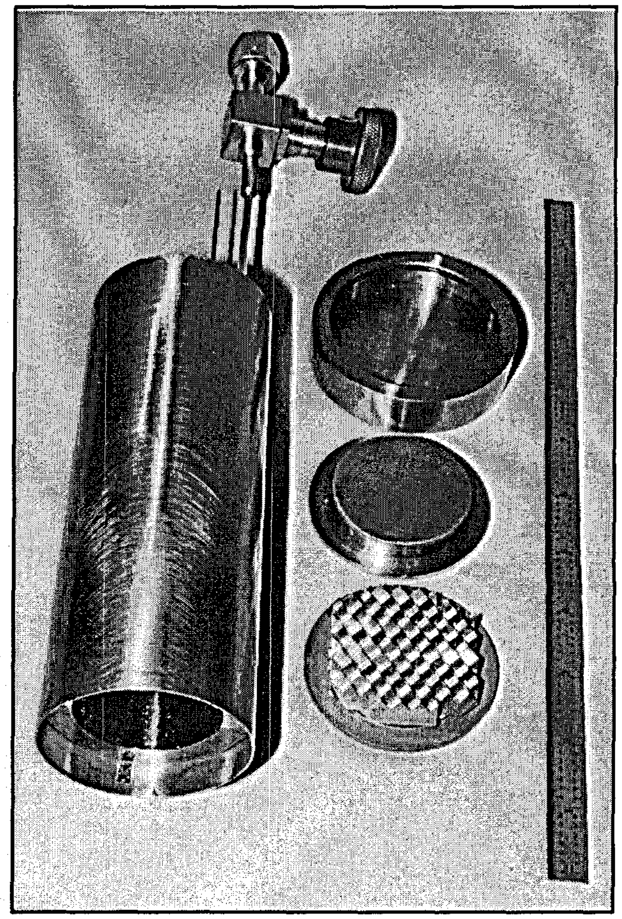

Figure 7 Photograph of DRC 'Dummy' Test Cell, Showing both FPC and DRC End Caps.

There is a relatively simple method for determining the relative contributions of parasitic heat losses that are contributed by thermal conduction and by radiation. One isolates the coefficients of the radiative transfer and conduction terms in the loss by plotting the heat input values required to maintain hot surface and cold surface temperatures. For purely independent radiation and conduction, this plot gives a straight line whose slope and intercept give the radiation and conduction coefficients. The approach is shown here.

The coefficients of the two terms in Eq. 1 can be determined from measurements of the steady state input power vs. simulated hot zone (SHZ) surface temperature at a constant condenser temperature. The data was plotted for the heat input in terms of the coefficients A and B as given in Eqs. 1 and 2 below. One simply plots the data arranged as in the left hand side term in Eq. 2 as a function of $[T_2^2 + T_1^2][T_2 + T_1]$. Examination of the resulting plot for slope and intercept yields directly the radiation and conduction coefficients A and B for the practical case at hand.

$$Q = A[T_2^4 - T_1^4] + B[T_2 - T_1] \tag{1}$$

$$\frac{Q}{[T_2 - T_1]} = A[T_2^2 + T_1^2][T_2 + T_1] + B \tag{2}$$

If Eq. (2) is written simply in the form $y = Ax + B$, then y is equal to $Q/(T_2 - T_1)$ and x is equal to $(T_2^2 + T_1^2)(T_2 + T_1)$. Values of y and x for the first three cases described in Table 7 are tabulated in Table 9 for both cases, with and without DRC. The data are also plotted in Figure 8. For purely independent radiation and conduction, the plot gives a straight line with the slope and intercept identifying the coefficients in Eq. 2. The curvature apparent in the curves plotted in this way as seen in Figure 8 indicates that there is a substantial coupling between the radiation transfer and conduction. This is to be expected under AMTEC circumstances in cells for which radiation to the cell structural walls contributes significantly to the heat that arrives at the cold end by conduction. The lower values for the DRC case do indicate the advantage of using a DRC to reduce thermal radiation-related losses. It is expected that Phase 2 efforts will be made to collect additional data to illustrate the coupling described and to enable a reliable determination of the slope and intercept for the A and B coefficients in Eqs. 1 and 2.

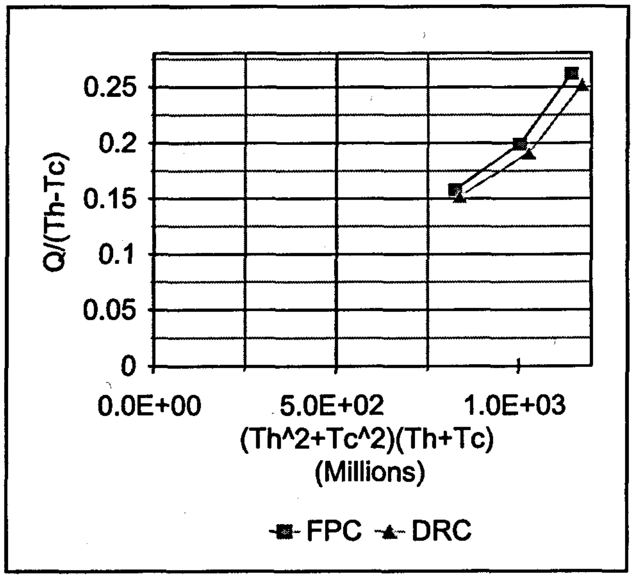

Figure 8 Plot of Thermal Transfer Data for DRC and FPC End Caps.

Table 7. Change in Hot End Temperature For Constant Input Power and Cold End Temperature.

No.	Cold Surface	Cold End (T1)	Hot End (T2)	Power (W)	Delta Temp.	Delta Power
1	Flat	250	381	20.75		
	DRC	250	386	20.75	5	
	DRC	250	381	19.36		1.39
2	Flat	250	456	40.6		
	DRC	250	462	40.6	8	
	DRC	250	457	38.08		2.52
3	Flat	250	506	67.05		
	DRC	250	516	67.05	10	
	DRC	250	506	63.8		3.25
4	Flat	150	451	40.6		
	DRC	150	457	40.6	6	
	DRC	150	451	38.08		2.52
5	Flat	150	377	20.75		
	DRC	150	382	20.75	5	
	DRC	150	377	19.36		1.39

Table 8. Change in Cold End Temperature While Holding Input Power Constant

No.	Cold Surface	Cold End (T1)	Hot End (T2)	Power (W)	Delta Temp.
1	Flat	132	465	52.8	
	DRC	126	466	52.8	6
2	Flat	136	503	67.08	
	DRC	131	502	67.08	5

Table 9. Parameters for Radiation Coefficients

No.	Case	y	x
1	Flat	0.158	8.253×10^8
2	Flat	0.199	1.002×10^9
3	Flat	0.262	1.146×10^9
4	DRC	0.152	8.366×10^8
5	DRC	0.191	1.029×10^9
6	DRC	0.252	1.175×10^9

PX - Cell Testing

A fully recirculating AMTEC cell with a DRC condenser was fabricated and assembled for testing. The cell is in the standard 'PX' configuration with 6 BASE tubes, a cell wall with 0.030 cm wall thickness at the hot end and a 0.013 cm wall thickness at the condenser end. The cell length is 8.9 cm and its diameter is 3.8 cm and the BASE tube length is 3 cm. The aspect ratio is ~ .84. The 6 BASE tubes are connected in series and a single positive lead withdrawn from the cell through an insulated feedthrough in the condenser. The corner cubes have small holes in their vertices to allow sodium to pass through to a wick structure behind the condenser and then to the artery which returns the sodium to the plenum which feeds it again to the individual BASE tubes. A picture of the cell prior to final assembly is shown in Figure 9.

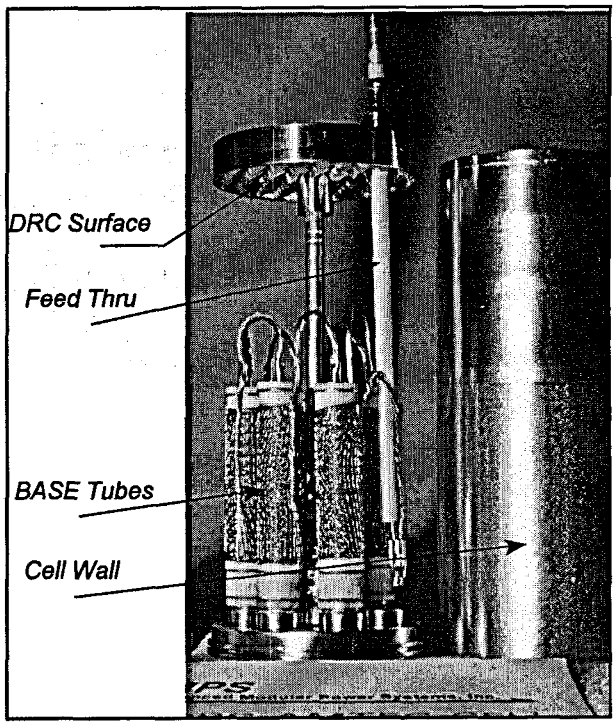

Figure 9 PX - Series AMTEC Cell with Direct Reflectivity Condenser.

The cell was heated using electrical heaters for convenience and for ease of controlling temperatures. Eurotherm controllers were used with Variac autotransformers to supply power to commercial wire-wound heaters from Thermcraft. A series of current-voltage curves were taken both at a number of points in steady state and in rapid passage through the full current range. The cell was an excellent performer throughout the temperature range studied. The current - voltage and power curves for a BASE tube temperature of 1019 K and a condenser temperature of 623 K are shown in Figure 10. The measured power output of this cell is better than other cells of this type fabricated with conventional felt condenser surfaces. The usual peak power density under these temperature conditions is $P_{max} \sim 3.5$ watts. In spite of this very favorable result, we do not yet believe it is possible to attribute the entire or even the majority of the performance improvement directly to the use of the DRC in this cell. Other considerations, including some variability in individual tube performance may have affected these results. Nevertheless, their encouraging nature indicates that a follow-up experiment should be performed since an analysis of the temperature profile leveling and its effect on power has not yet been carried out.

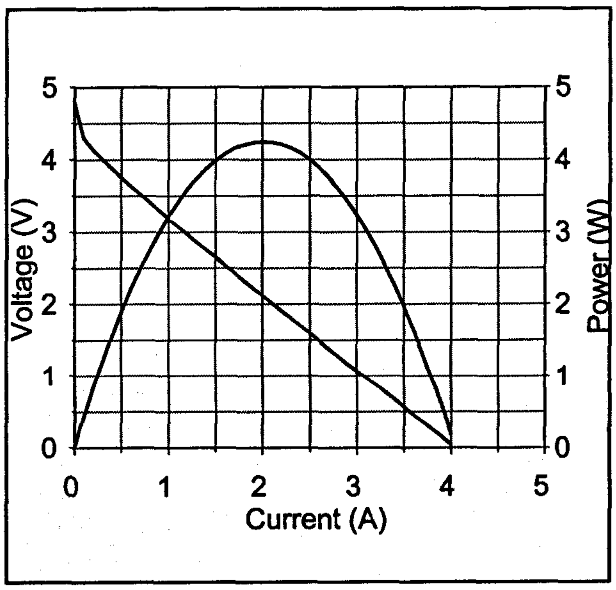

Figure 10 Current - Voltage and Power Relations for the PX-DRC Cell with DRC End Condenser.

Phase I - Conclusions

The DRC concept appears to work. The two experimental test cells built and run give results consistent with the full thermal analyses we have carried out. The analysis predicts a significant reduction in the parasitic thermal losses in AMTEC cells, and it would presumably also work in other applications for which radiation-based thermal transfer is important. For the cylindrical geometries examined, the maximum reduction in thermal transfer is expected to be limited to approximately 20%. The Phase 1 program funding and time limits did not permit investigation of the more complex geometries involved in the Series 3 AMTEC cell designs. While a 20% reduction in parasitic losses appears to be the limiting value, a reduction of ~12 % is predicted for a first cut analysis of current cell designs.

In a cell designed to operate at 30% efficiency, the reduction of 12 % in parasitic thermal losses leads to an improvement in cell efficiency to about 31% if one considers only the overall thermal loss effect. Under design constraints which arise at these efficiency levels, modifications which can add 1% to efficiency, merit consideration, particularly when a number of modifications can act independently with each adding several percent to the efficiency.

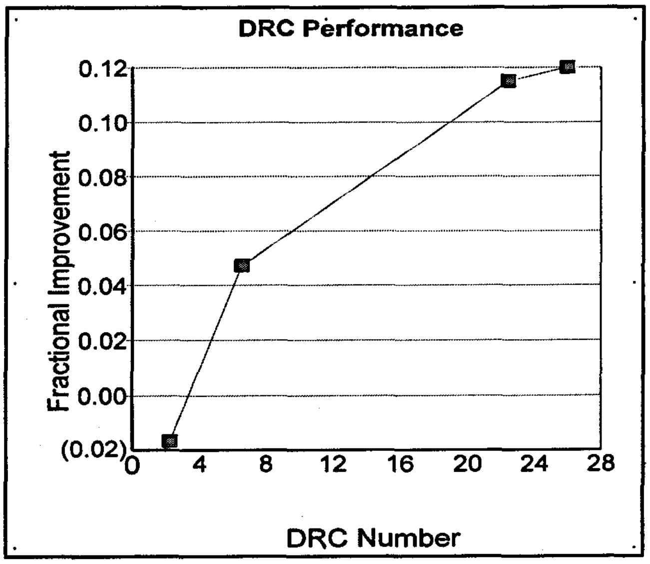

Figure 11 Relationship Between Improved Efficiency and DRC Number.

A second effect, however, may be more significant. In operation of vapor-vapor AMTEC cells, a limitation in power output for a given heat input surface temperature arises due to temperature gradients along the BASE tubes. As the tubes are heated from the 'bottom' (as seen for example in Fig. 1), and heat is withdrawn along their length by the sodium working fluid and radiated from their upper ends, the upper end of the tubes is colder than the bottom end which is closest to the hot surface. The lowered temperature reduces the output toward the tube end and lowers overall performance. The DRC offers the potential to reduce the thermal radiation loss from the 'top' ends of the tubes, to level the temperature distribution and thereby increase the power output. Increased power output has a larger effect on efficiency than a comparable decrease in the parasitic losses. This effect may contribute to the high performance observed for the PX-DRC cell. A similar effect on the BASE tube temperature profile can be achieved by interposing radiation shields between the hot zone and the condenser, but such shielding invariably produces a restriction in the sodium flow path, increases the vapor pressure at the cathode and reduces the power output in that way. Use of a DRC, which accomplishes the radiation-based thermal transfer reduction without benefit of constricting shields may offer a very significant advantage.

4. Phase II Work

Radial Converter

For intermediate system power levels of order 100's of watts, converter design configurations are heavily influenced by the need for efficient combustor performance. The radial or donut converter configuration offers a central cavity for combustion and a modular capability in that converters can be stacked, preserving the central combustion space while increasing the system power level in defined increments. A schematic diagram of the radial converter design is shown in Figure 12 and a photograph is shown in Figure 13. This design uses a large number of small BASE tubes arrayed around the central heated core with the condensing surface at the outer circumference. As shown the power is extracted through a pair of feedthroughs located on opposite sides of the converter in order to minimize the voltage presented to the interior of the converter. It can be seen that in this geometry, radiation from the hot zone impinges first upon the flat top and bottom walls. Analysis of converters in this basic configuration showed that the major parasitic loss was from conduction of heat radially by the 'flat' converter wall plates and further that the major effective contribution from thermal radiation transfer was due to absorption of radiation on these side walls and the subsequent conduction of the received heat radially to the condenser surface.

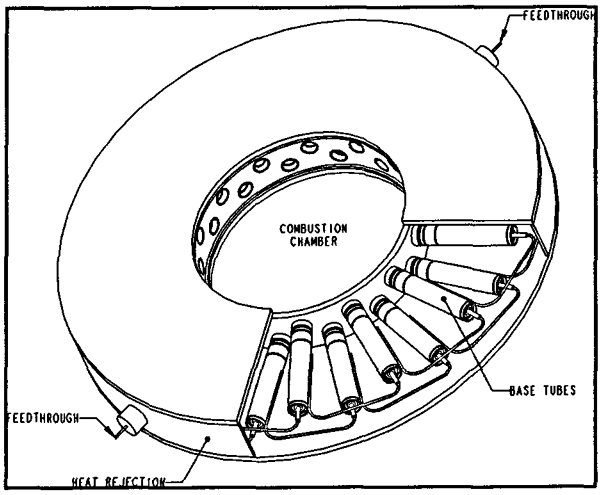

Figure 12 Overall View of Donut Test Converter Design

AMPS built a single row version of the radial converter and demonstrated its functioning with both electrical and combustion heating. A photograph of the converter is shown in Figure 13. This design, when implemented with the large number of BASE tubes shown in these figures, is both difficult and expensive to build. Nevertheless, an example was built and tested and the design concept offers a dramatically different structure for analysis of the DRC (DRW) concept. It was, for the Air Force a pausible approach for the spacecraft missions they had anticipated. Some design issues arose, principally having to do with the large number of component parts and the anticipated reliability and assembly issues that raises.

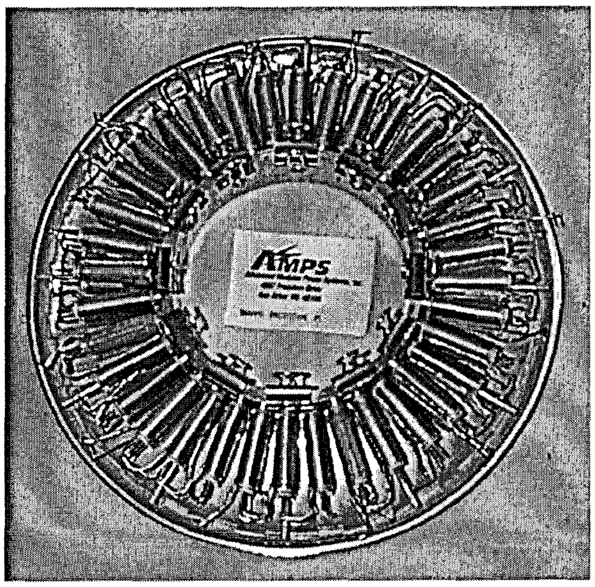
Figure 13 Photograph of Radial Cell Fabricated for the Air Force RATEC Program Showing Central Channel for Heat Input.

5. Analytical Approach

The detailed geometry of the two AMTEC converter designs considered in this program was drawn up in Pro-Engineer software. RadCad was then used to calculate the view factors for radiation and these values were inserted in a meshed model for analysis using SINDA/FLUINT software. This approach gives a full scale analysis that can be very precise but which is limited by the precision with which we can know the various radiation, emisivity and conductivity parameters. In the case of the DRC surfaces, a fully computerized approach is critical both for fabrication, as noted above, and for the analysis. The results of the analysis are presented below for the radial (or donut) converter and for the PX style, cylindrical, converter. As we shall see, the DRC surfaces do not help the radial converter performance over the range of parameters studied as those parameters are varied singly. For the PX style converter shown in the photograph in Figure 9 and schematically in Figure 3, the efficiency can be enhanced by as much as 1.7 percentage points with only single variable adjustments to the design.

6. Results for Radial Converter With DRC Surfaces

Analysis of the radial converter design was carried out using a detailed CAD drawing of the converter housing and the results were derived based on variations of the key configuration parameters. These parameters are: 1) the converter length in the radial direction from the base of the tube support plate to the condenser at the circumference of the converter; 2) the hot end temperature; 3) the wall emissivity; 4) the condenser emissivity; 5) the side wall thickness. The computer calculations produce a large amount of 'data' which we do not include in this report. The results of the calculations, however, are summarized in the following five charts.

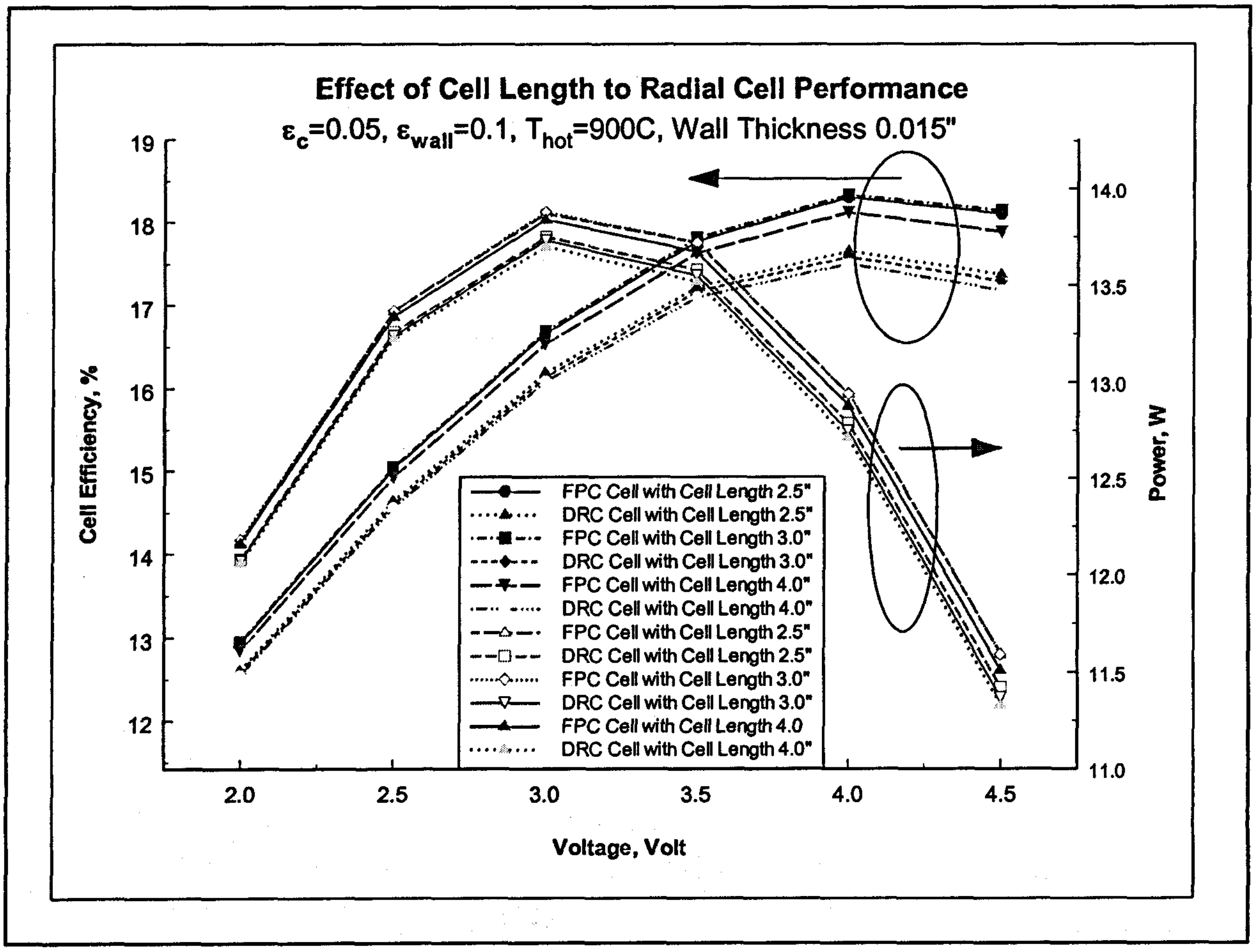

Figure 14 Radial Converter Efficiency and Power as Affected by Radial Converter Length.

Figure 14 shows the predicted effect of changes in the radial length of the converter as shown schematically in Figure 12. It is important to note here that the assumed emissivity of the corner cubes in the cell wall is $\epsilon = 0.1$ so that in a reflection from the wall, generally requiring reflections from all 3 elements of the corner, the net <u>effective</u> emissivity is $\epsilon = 0.27$. The absorption into a 'flat' (FPC) surface, requiring only a single reflection can be much smaller. It may be expected that the effectiveness of a DRC surface will thus be very sensitive to its intrinsic emissivity. The wall thickness of the radial converter ws set at 0.015" to provide adequate strength for operation at a net inward pressure of ~ 1atm. The condenser emissivity of $\epsilon = 0.05$ is expected to be realistic in the near IR for a surface coated with liquid sodium. For variations on the length variable alone, the optimum length appears to be close to 2.5". It also appears that the DRC wall surface does not improve efficiency or power over a "flat" or smooth wall.

The BASE tubes in the radial converter are heated from their open end which is attached, through several intermediate flanges to the hot end, tube support plate which forms the wall of the central cavity in the

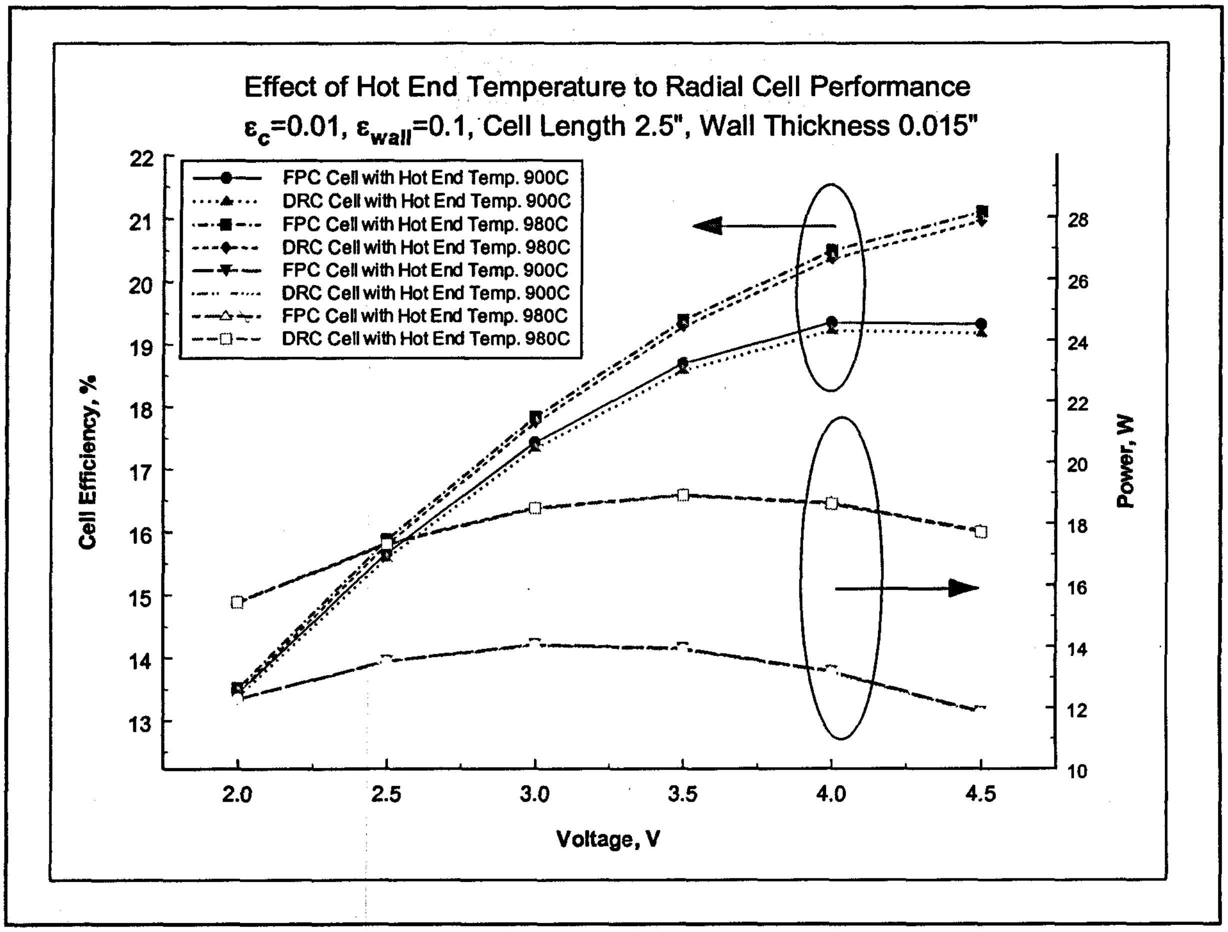

Figure 15 Radial Converter Efficiency and Power as Affected by Changes in Hot End Temperature.

converter. There are, therefore, temperature gradients in the BASE tube wall as well as the converter wall. Figure 15 shows the predicted effect of hot end temperature on both "flat plate" (FPC) and DRC performance. It can easily be seen that higher hot end temperatures dramatically improve efficiency and power output capability but that there still appears to be no advantage to use of the DRC surface configuration. From these curves it can be seen that an 80 C increase in hot end temperature leads to at least a 1.5% to 2% increase in efficiency.

The condenser emissivity is important since it is at this level that the thermal radiation directly from the hot zone or by reflection from a smooth wall, reaches the heat sink as a parasitic loss. In Figure 16 is plotted the predicted performance of FPC and DRC surfaces on the radial cell converter efficiency and power for variations in the condenser emissivity. The converter length was set at 2.5", near the maximum efficiency value as seen for the earlier analysis with respect to that variable. It can be seen that for very low emissivity at the condenser, the two surfaces perform about equally, but for higher condenser emissivity the DRC wall is substantially worse given the other parameters as indicated on the chart..

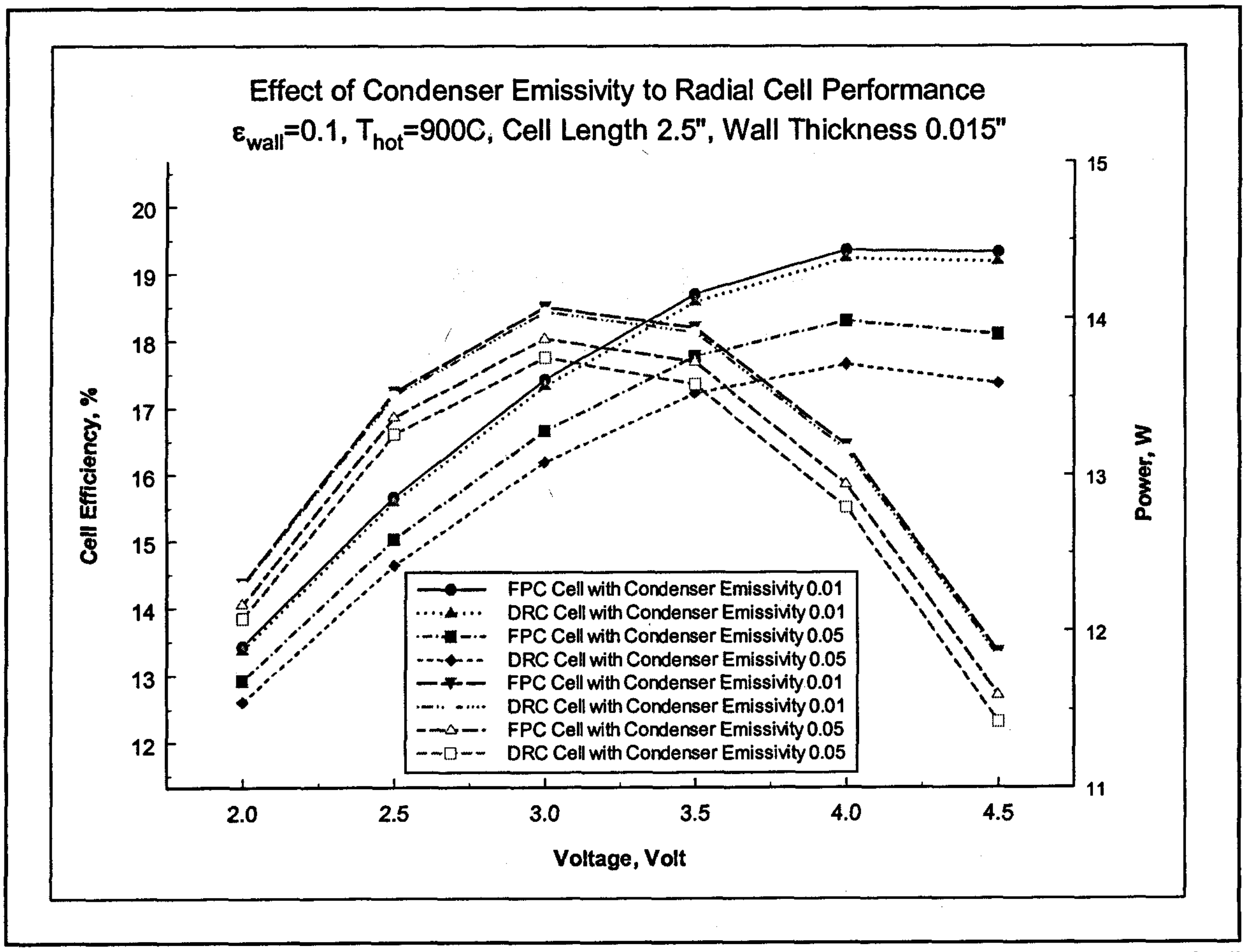

Figure 16 Radial Converter Efficiency and Power as Affected by Variations in Condenser Emissivity for "Flat Plate" and DRC Surfaces on the Converter Wall.

A critical qualitative result of the analysis is that the major contribution to the thermal loss is by conduction down the converter wall of the heat that arrives at the wall by radiative transfer from the hot zone. The effect of changes in the converter wall thickness is suggested for two values in the plots in Figure 17. Clearly reducing the cell wall thickness by 25% from 0.020" to 0.015", improves efficiency by more than 1% as shown. Significantl further improvements can be made if the wall thickness can be reduced further. For a smooth cylindrical wall in a PX-style converter, wall thicknesses of approximately these values are necessary to support the external atmospheric pressure with respect to the vacuum internal to the converter. The DRC surface, is comprised of small segments each of which is joined, at right angles, to 4 adjacent planar segments in a continuous repeating array. This arrangement leads to an extremely stiff structure, with the stiffness increasing as the size of the corner elements is increased. The added stiffness of the DRC surface, may allow converter walls to be made thinner thus further reducing the thermal conduction losses and enhancing the advantage to be gained by controlling the reflections as DRC surfaces can.

Because the amount of radiant energy that is picked up by the converter wall depends on the emissivity of the wall surface, the dependence of power and efficiency on wall emissivity was also analyzed. The results of this analysis are shown in Figure 17. For this case the wall thickness was set at 0.015", a suitable thickness for a smooth wall and the hot end temperature was set at 900 C.. As in the other separate radial converter cases shown in this work, the performance with the DRW wall is slightly below that with a smooth wall. Because the DRW surface requires, of virtually all incoming radiation, a 3-surface reflection, the 'effective' emissivity of the DRW wall surface, independent of its directionality, is $\epsilon = 1 - (1 - \epsilon_0)^3$. The intrinsic emissivity, ϵ_0, of the example presented, at $\epsilon = 0.10$ thus would, for a DRW surface, correspond to $\epsilon_0 = 0.035$. If the scale of the corner DRW surfaces is sufficiently small, it may be feasible for the surface to preferentially hold a liquid sodium film as has been shown to occur for the so called "Creare micro-machined condenser." [1] The Creare surface is machined in such a way as to trap sodium through capillary action. A liquid sodium film can have an intrinsic emissivity as low as 0.02 in the infrared region important for the peak radiation transfer effect so the 0.035 value is plausibly within reach. On the simplest conclusion based on these predicted values and for a 0.015" wall thickness, a DRW with an intrinsic $\epsilon = 0.035$ would have an efficiency value 2% higher than for a smooth wall with the same effective emissivity. A thinner wall and/or a shorter converter length would tend to increase this advantage further.

While a significantly lower emissivity might alter this conclusion, the sample DRC surfaces that we were able to have made, would have emissivities approximately equivalent to those assumed for this plot.

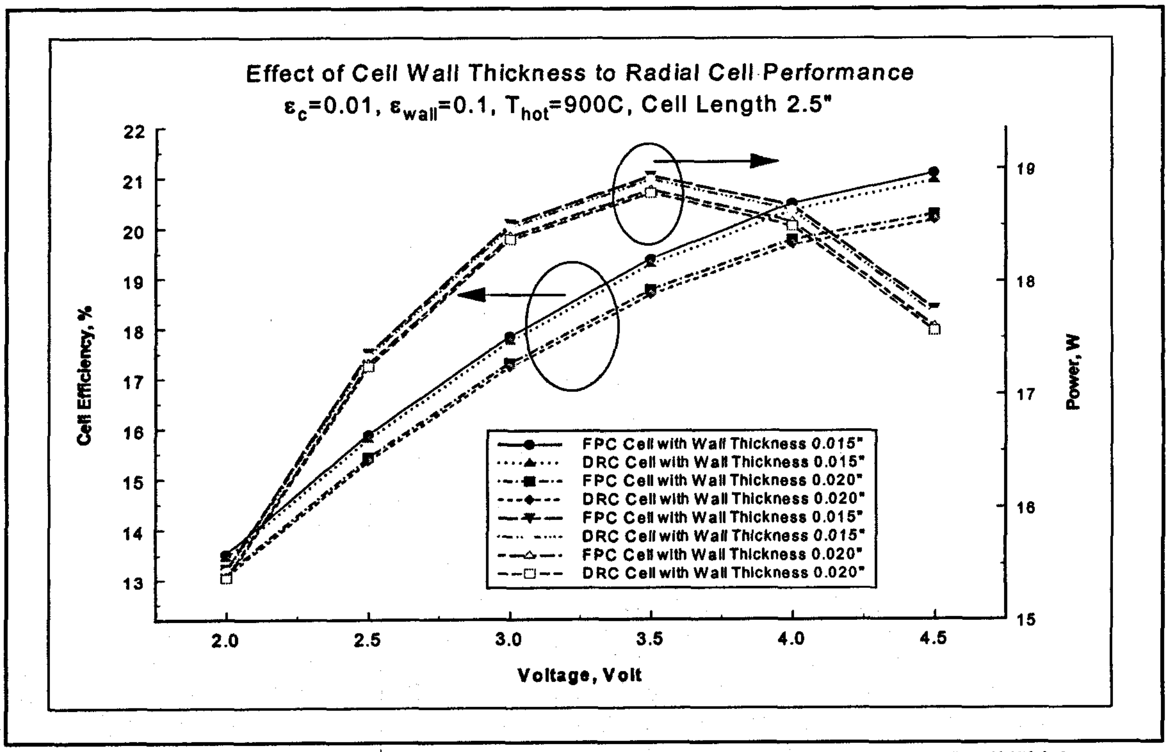

Figure 17 Radial Converter Efficiency and Power as Affected by Changes in Converter Wall Thickness.

[1] 'Condenser Design for AMTEC Power Conversion', Christopher J. Crowley, Proceedings of the 26th Intersociety Energy Conversion Engineering Conference, Vol. 4, p 456 (1991).

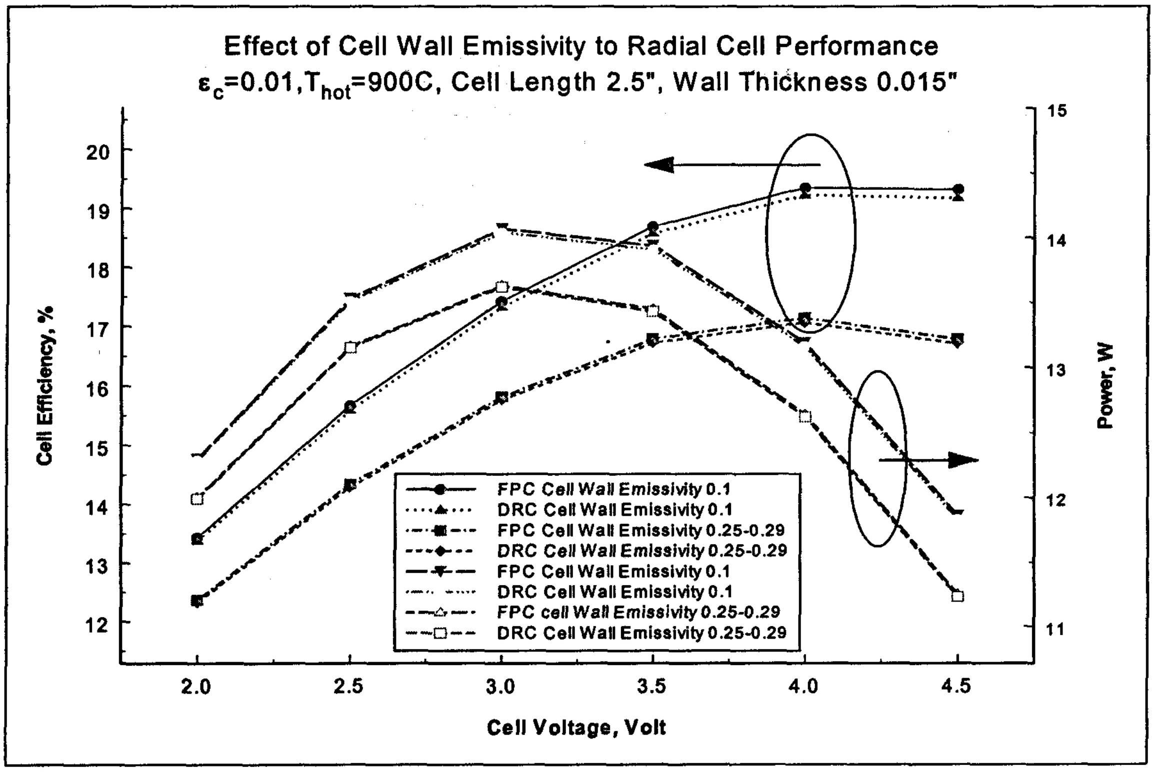

Figure 18 Radial Converter Efficiency and Power as Affected by Changes in the Emissivity of the Converter Wall.

<u>Conclusion</u>

For the radial converter design, the DRC/DRW surfaces can only offer an improvement if the converter configuration is specifically designed to minimize basic thermal conduction parasitic losses so that thermal radiation transfer and the conduction losses that follow from it are dominant and lower emissivity surfaces can be produced in DRW form. Such designs are likely not to be either structurally sound or cost effective for a basically radial type concept. The radial converter was the initial design selected for the "Radiation Tolerant, Eclipse Compatible, Solar AMTEC System" SBIR program for the Air Force under contract F29601-99-C-0132. This configuration, however, was not ideal for more general applications. A more general, high efficiency design has evolved as typified by the PX style converter shown schematically in Figure 3.

7. Results for Cylindrical, PX-Style Converter with DRC Surfaces

The PX-style converters, shown schematically and in the photographs of Figures 3, 7 and 9, were analyzed both for configurations in which the condenser was formed in DRC mode and in which the converter wall was formed as a Directed Reflectivity Wall surface (DRW). While the Phase I experiments indicated a minor improvement for the DRC surface on the end condenser, the improvement was useful only for particular aspect ratios for which the direct radiation from hot zone to condenser was the dominant loss mechanism. The analysis performed here was for a converter with a length of 5 inches, a diameter of 1 inch and a hot zone of 2.5 inches length and a hot zone operating temperature of 900 C. The FPC and DRW converters each had the same 0.015" wall thickness. The results of the analysis for efficiency and power for

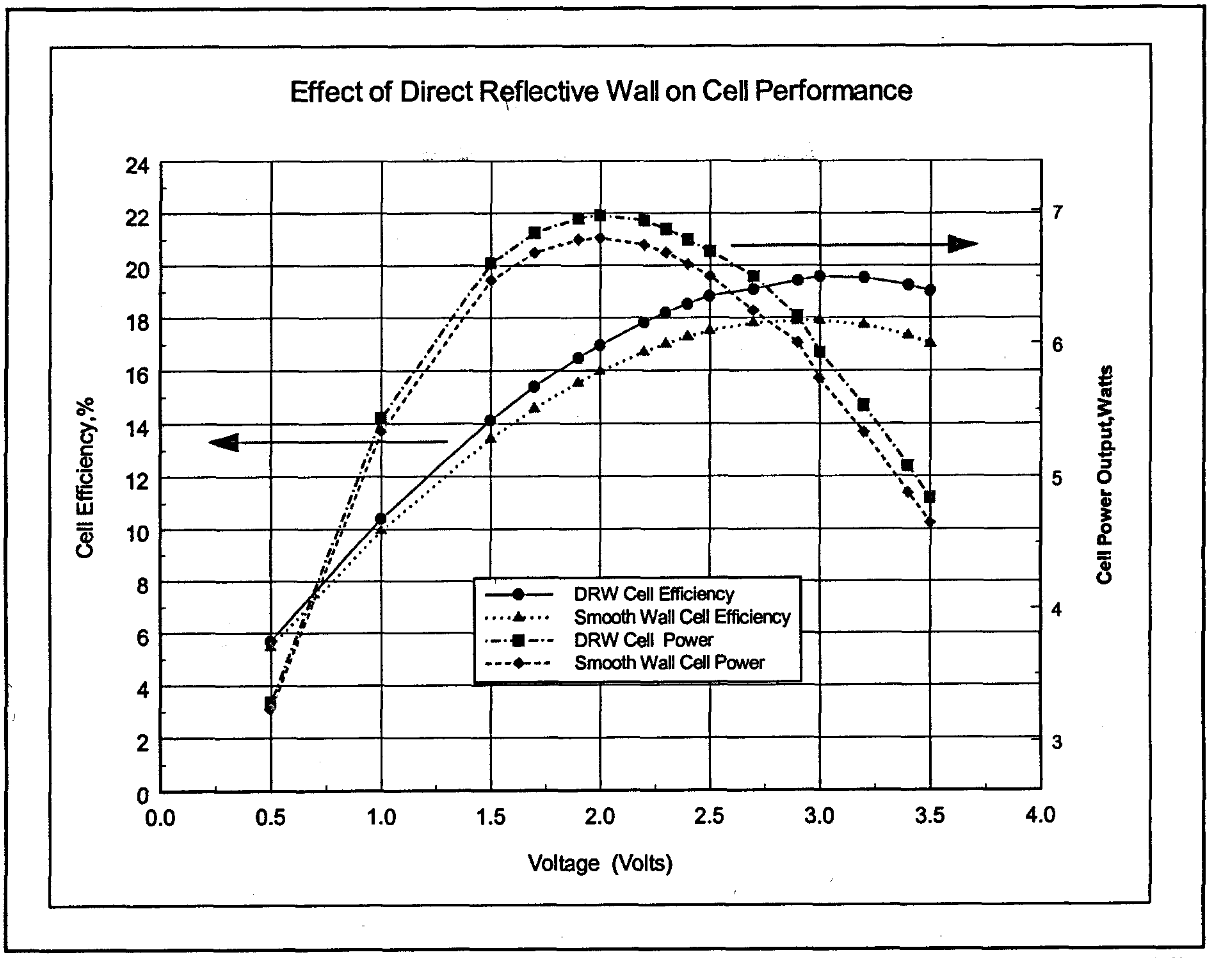

Figure 19 Efficiency and Power for a PX-Type Converter - Comparison of DRW and Smooth Converter Walls.

both smooth wall and DRW are shown in Figure 19. The assumptions for these calculations were similar to those for the radial converter design. The DRW intrinsic surface emissivity was chosen to be $\epsilon_0 = 0.1$ so the effective emissivity of the wall was then $\epsilon = 0.27$. The flat condenser surface was presumed to have an emissivity $\epsilon_0 = 0.05$.

<u>Conclusions</u> The analysis clearly indicates that the use of a DRW can improve the efficiency of a single PX type converter by 1.7% (from ~17.9% to 19.6%) for a simple configuration with no optimization of wall thickness. Optimization of the wall thickness could take advantage of the apparent increased structural rigidity of a converter wall in which the directed reflectivity corners are impressed to reduce the wall thickness. This, in turn, would reduce thermal conduction loss, much of which is fed by the radiation. No allowance furthermore was made for intrinsic reflectivity enhancement if the DRW surface becomes coated with a layer of liquid sodium. We anticipate that optimization of these other parameters could increase the incremental effectiveness of the DRW surface in reducing thermal losses. While additional analysis to investigate the synergistic effects of simultaneous implementation of DRW, thinner walls, shorter (longer) converter lengths could be valuable, any available funding would, at this stage, be more usefully applied to building and testing one or more complete DRW converters.

For commercial, terrestrial applications where cost is the most critical discriminator, the added cost for producing and sealing to a DRW as an external wall is likely to make its use uneconomical. For spacecraft power systems, however, improvements in efficiency of even 1% to 2% can be highly important and the DRW approach appears to deserve consideration. Analysis for specific converter configurations would be required.

8. Experimental Effort

The experimental verification program was designed to measure converter efficiency and produce a direct comparison between that of a converter with conventional radiation shielding and a converter, similar in all respects except for using a DRC shield system inserted inside the outer containment wall. This approach would not allow testing of the advantages potentially to be gained from use of thinner converter walls with the DRW configuration but would allow a fair comparison of the effects of the changes on the total thermal radiation transfer. The task was to place individual converters (with and without DRW's) in the environment they would see if assembled into a complete system with many other, like converters. In such a system, each converter would see a local environment that mirrors its own surface temperature condition, Lateral heat transfer/loss would be minimal and the heat input and removal would occur almost entirely at the hot and cold ends. The lateral conditions are essentially adiabatic and the test apparatus, to be used for individual converters, is designed to produce these thermal conditions so that the efficiency to be expected of converters embedded in a system can be properly assessed. The two converter figurations are shown side by side in Figure 20 and Figure 21.

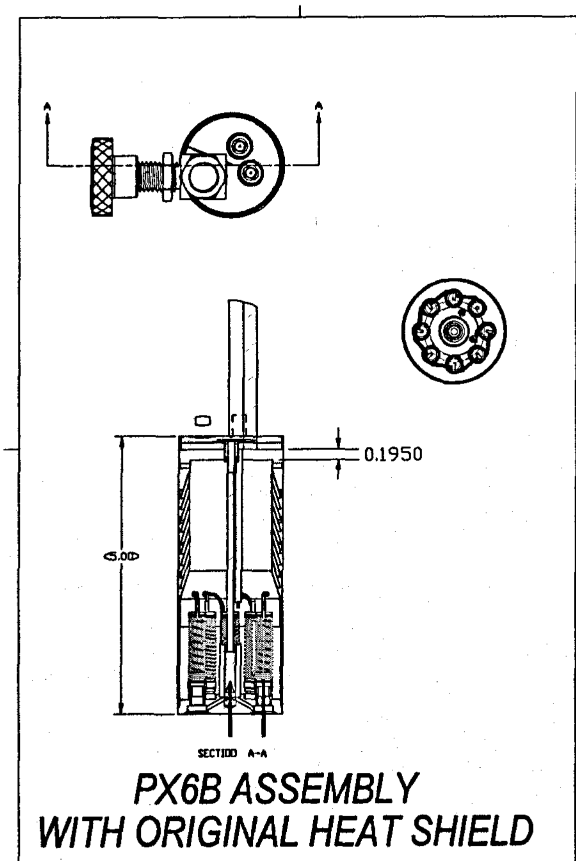

Figure 20 Control Converter Configuration

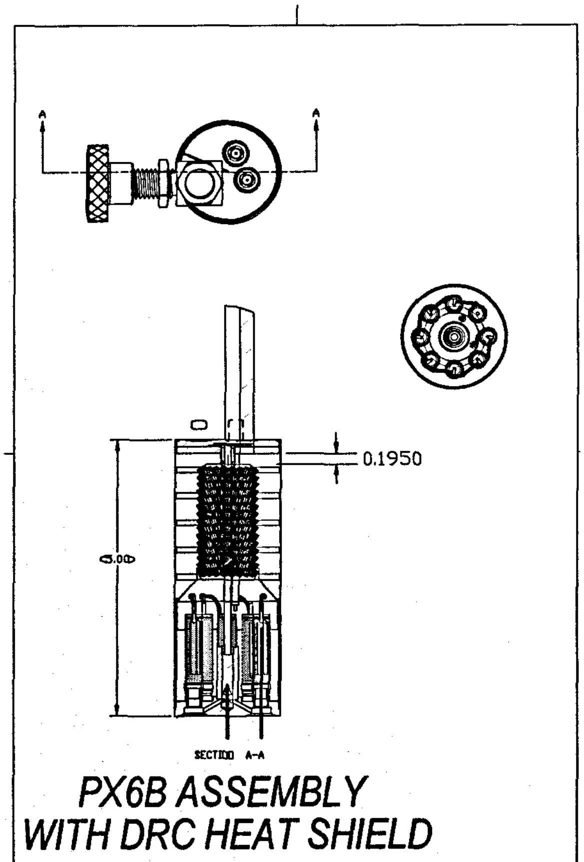

Figure 21 DRW Configuration

The Adiabatic Test Apparatus

In order to simulate AMTEC converter performance in a system, an apparatus designed to produce adiabatic conditions at the converter walls was designed and fabricated. The principle is simply that a series of guard heaters is placed around the perimeter of the converter and when the converter is operating, the heaters (with their controlling thermocouples) are adjusted so that the converter walls are in thermal equilibrium with their surroundings at all points and there is no net heat input or loss from the side walls of the converter. As noted above, this simulates the circumstances the converter would see as an element in a many-converter system in which it is surrounded by identical converters

Guard Heater Test Setup

To test the power output of AMTEC converters experimentally, and be able to vary the thermal environment an AMTEC converter is exposed to, a guard heater enclosure was created. Here we describe the test setup, including the design and functionality of the guard heater, the instrumentation used to control and measure temperatures, and possible future modifications that could be made to the guard heater system to increase its flexibility.

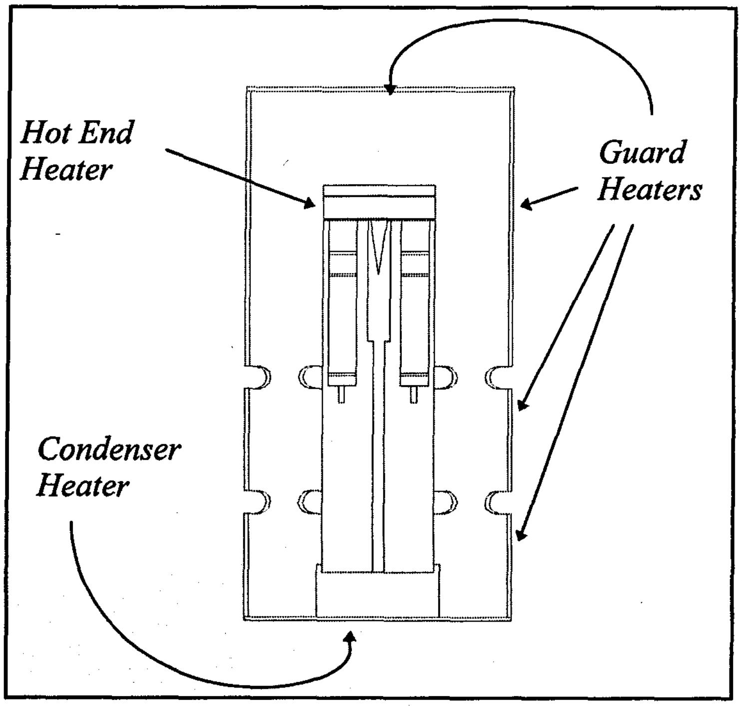

Figure 22 Guard Heater Canister with PX Cell Inside.

Figure 22 and Figure 23 show cross-sections of the guard heater with a PX converter mounted inside. With the PX converters being cylindrical in shape, this was the obvious choice for the shape of the guard heater. Thus, to surround the 3.8 cm diameter x 10.16 cm long converter, the guard heater canister is 7.6 cm in diameter x 15.2 cm long. It is made of 1.6 mm thick stainless steel, and has several cuts to thermally segregate different portions of it in the axial direction. Heating elements are attached to the three zones of the curved wall to control the heat transfer at the converter wall. Another heating element is attached to the flat top plate to guard the hot end heater. Finally, it is easier to control a heater than a fan, so the cold end of the converter is kept at a constant temperature by the combination of an over-cooling fan and the cold end heater. The converter is mounted in such a way that the part of the converter wall surrounding the BASE tubes is guarded by the largest guard heater section (the topmost section in Figure 22), while the two smaller guard heater sections guard the remainder of the converter wall. Void spaces between the guard heater canister and the converter are filled with Fiberfrax insulation, a refractory wool type material made by Unifrax[2]. The entire guard heater canister is also surrounded by 2" of Fiberfrax, then covered with a fiberglass blanket.

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[2] Unifrax Corporation, 2351 Whirlpool Street, Niagara Falls, N.Y. 14305-2413

The hot end converter heater is a coiled Kanthal wire cast in ceramic. Voltage leads are attached to the lead wires at the point where they enter the ceramic casting to measure the voltage drop in the heater. Using this voltage and the current, the electric power being converted into thermal power can be determined.

As many as 22 thermocouples are used to measure temperatures as follows. Four are used to measure and control the temperatures of the four zones of the guard heater. Seven are spot-welded in place at various locations on the converter and the hot end heater; two of these are used to control the cold end heater and the hot end heater. There are also two built-in thermocouple "wells" leading to points inside the BASE tube and in the throat of the evaporator. The remaining eight are mounted to a moveable stage and are inserted into eight wells made from 1.6 mm O.D. x 0.812 mm I.D. tubing (see Figure 23). Four of these wells are fastened to the wall of the AMTEC converter to insure good thermal contact with the walls; the other four are fastened to the guard heater so that they lie on the same radial line as the four on the cell. The moveable stage is supported on a threaded rod, and by turning this, the stage and all eight thermocouples move lengthwise along the cell/guard. The threaded rod has 7.09 threads per cm, giving a locating accuracy of 0.35 mm. The experimental data taken with this device indicate that the data is highly repeatable. During the experiment, these eight temperatures along the cell/guard are measured every 1.27 cm from the condenser to the hot end.

Experimental Procedure

Data collection during the performance testing is divided into two major procedures. First, temperatures are measured at numerous locations to analyze the flow of heat energy into and out of the converter. Once it has been determined that the converter wall is in an adiabatic environment, the power output is measured. These routines are repeated with the converter under various loads and with the hot end (T_{hot}) of the cell at 1023 K, 1073 K, and 1123 K. In all cases, the temperature of the cold end (T_{cold}) of the converter was set to 623 K.

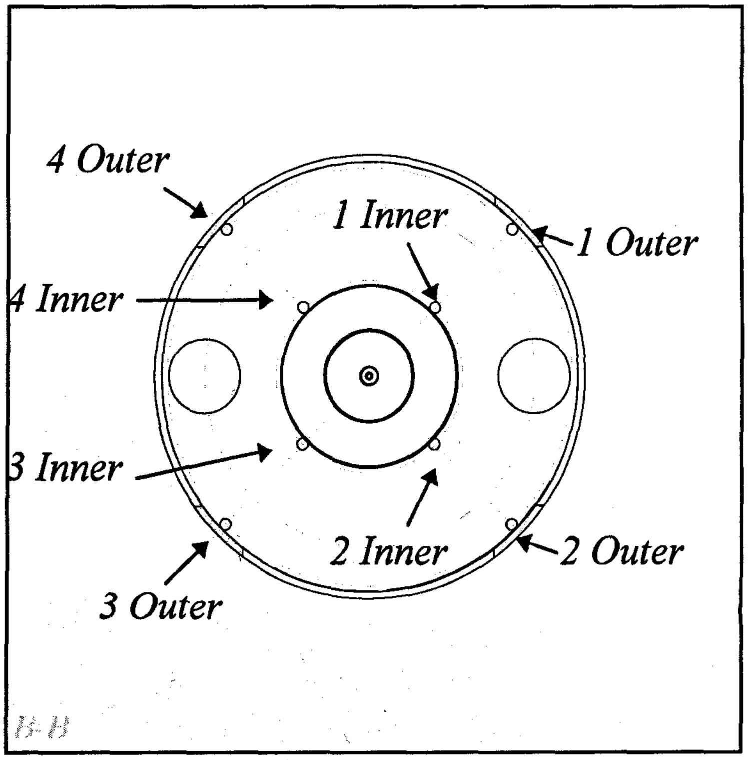

Figure 23 Midplane Cross Section of Guard Heater, PX Cell, and Thermocouple Wells

For the first part of data collection, the heated converter is connected to a constant resistive load, and the hot and cold end temperatures are controlled to within 2 K of their set points. Next, using the eight thermocouples along the converter wall and the guard heater, eight temperatures are measured longitudinally every 1.27 cm from the cold end of the converter to the hot end 10.16 cm from the cold end. In all, 96 measurements are made, and the data is analyzed as in Table 1. At each longitudinal position, the four guard heater temperatures are averaged, and the four converter wall temperatures are averaged, then the difference between the averaged guard heater and converter wall temperatures is found. Next, using data from the manufacturer of Fiberfrax, a mathematical expression is used to determine the thermal conductivity at an appropriate average temperature for each longitudinal position along the converter wall. Finally, assuming one-dimensional radial heat transfer, the heat transfer in the radial direction can be calculated. Summing the

Table 1 Example Data Set for the PX-5B Converter With T_{hot} = 1123 K and T_{cold} = 623 K and Heat Input = 37.7 Watts and Power Output = 4.01 Watts

Longitudinal Location [cm]	Average Guard Heater Temp. [K]	Average Cell Wall Temp. [K]	Difference Between Guard Heater and Cell Wall [K]	Fiberfrax k [W/(m K)]	Radial Heat Transfer [Watts]
0	643.3	627.0	16.3	0.08	0.06
1.27	713.0	749.0	-36.0	0.10	-0.34
2.54	820.5	829.3	-8.8	0.12	-0.10
3.81	878.8	887.3	-8.5	0.14	-0.11
5.08	926.5	941.5	-15.0	0.15	-0.21
6.35	978.3	979.3	-1.0	0.16	-0.02
7.62	1021.0	1020.3	0.7	0.17	0.01
8.89	1065.0	1072.5	-7.5	0.18	-0.13
10.16	1112.3	1149.5	-37.2	0.20	-0.35
			Total Radial Heat Transfer		-1.19

radial heat transfer at all positions as in the lower-right cell in Table 1, one calculates the total radial heat transfer. A negative radial heat transfer indicates that heat is transferred out of the converter.

In practice, setting the guard heaters so that the total radial heat transfer is exactly zero is never possible; however, reducing it to within ±1.5 watts is quite feasible. Figure 24 shows that the guard heater temperature profile can be made to match the converter wall temperature profile very closely. After taking this set of data, if too much radial heat transfer is found, the guard heaters are adjusted accordingly, and the data is

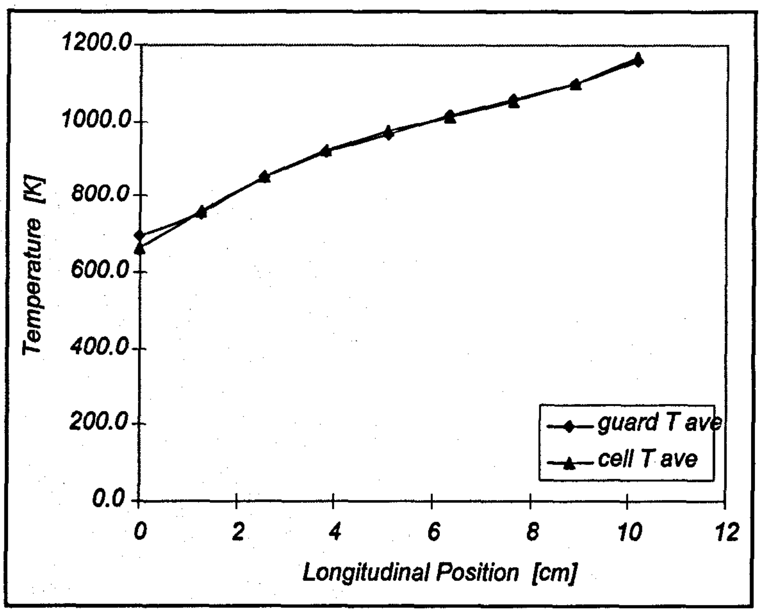

Figure 24 Temperature of the Cell Wall and Guard Heater At 1.27 cm Longitudinal Intervals, Demonstrating the Adiabatic Condition.

taken again once thermal equilibrium is re-established. The time between these data sets is between 20 and 30 minutes. Finally, once adiabatic conditions are reached, four measurements are made. The voltage and current coming from the AMTEC converter gives the converter power output. Likewise, the voltage across the hot end heater and the current going through it give the thermal power input by the hot end heater.

Control Converter Testing

The experimental program was begun with a conventional PX-6 converter having the usual complement of radiation heat shields attached to the side wall at the cold end of the converter shell. Figure 25 shows a plot of data taken on the DRC control converter using a fast sweep of the current from open circuit to short circuit current and return to open circuit. The two-valued curves occur because under load the temperature

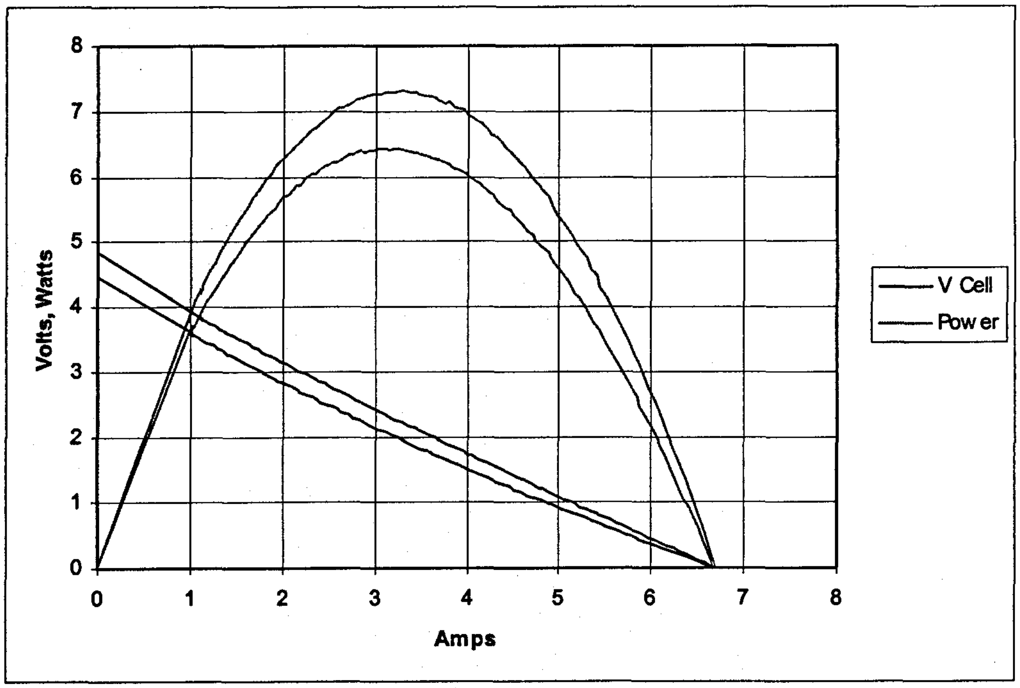

Figure 25 Power and I-V Data for DRC-2 Converter at 800 C Hot End and 350 C Cold End. The Lower Curves in Both Parameters are the Response to the Drop Below Starting Temperature Under Load.

of the BASE tube and cathode drops rapidly and in the time of a short sweep does not have time to recover. Tests at equilibrium reflect the lower temperatures appropriate for each current setting given that the input surface temperature is kept constant. The tests run in this way are shown in the plots in Figure 26 and Figure 27. The effect of the lowered BASE and evaporator temperatures under full load is apparent in a comparison of these two sets of plots. The power and current-voltage relations determining the output in the efficiency experiments correspond directly to the equilibrium values shown here in the "step test' plot in Figure 26.

Efficiency Measurements

The efficiency of operation of the PX-6 converter was measured using the adiabatic test apparatus described above. In operation, the temperatures of the thermal input and output surfaces are controlled to specific values and a set converter current is established. The multiple thermocouples measuring the temperatures of the converter wall (at several positions as indicated above) and the adjacent insulator surfaces are brought very close together by adjusting the power in the several external heaters. When the temperatures of the heaters and converter wall are essentially balanced, the power input to the heaters and the power output of the AMTEC converter, determine the efficiency as Efficency = electric power out/thermal power in. An assessment of the quality of the temperature matching and thus the direction of any net heat flow is determined by noting the small residual temperature difference which, together with the thermal conductivity of the insulation package, yields the net parasitic heat flow. Thermocouples are arrayed around the converter perimeter so that average temperature differences can be used for these evaluations. The results of the efficiency experiments taken on the PX-6 converter are shown in Figure 27. This curve does not resemble the classic, calculated efficiency relation which shows a double-valued region at currents below that for the peak power. In those calculations, constant BASE and evaporator temperatures are presumed whereas here those temperatures adjust to satisfy the current demanded (load impedance) with a regulated input surface temperature at the hot end of the converter. The two odd points at 1.6A may reflect that for them, the reservoir temperature was substantially higher than the measured BASE tube value. This could well have introduced liquid anode conditions which can enhance power output density substantially and thus improve efficiency. If follow on experiments are to be carried out care must be taken to ensure that both vapor-vapor mode and liquid-vapor modes are properly recognized so that comparisons between normal and enhanced area electrodes can be made unequivocally.

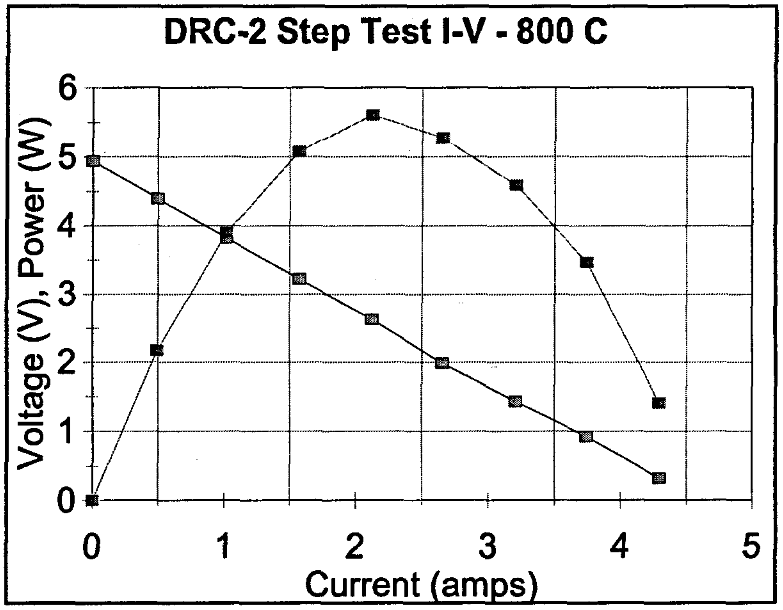

Figure 26 Equilibrium Current-Voltage Test Data

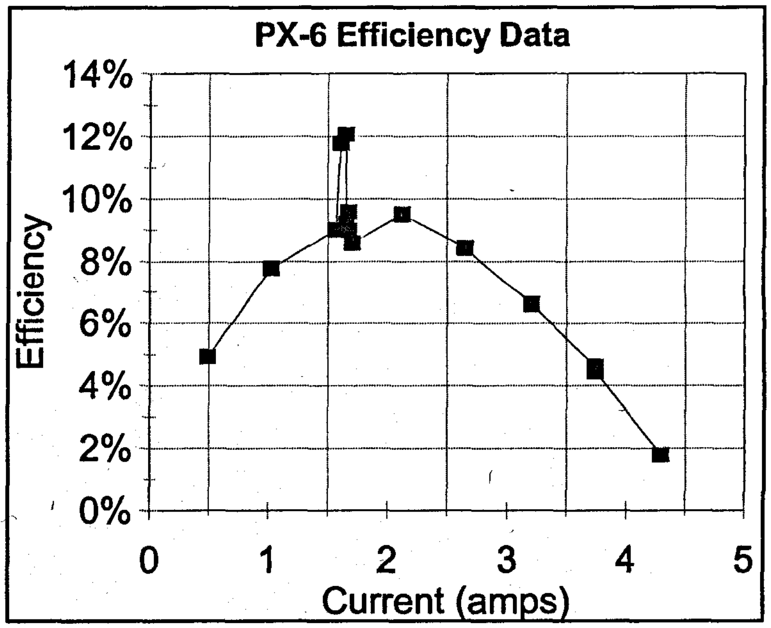

Figure 27 Data for PX-6 Efficiency at Constant Input Temperature.

Fabrication of DRC cylinders.

Fabrication of DRC surfaces was first carried out as planar arrays because this is a simple geometry to make. For use on the walls of cylindrical cells, where we expect it to be effective based on the analysis described above, it is necessary to use a different approach. Clearly this cannot be achieved by wrapping a planar array around a cylindrical form. The initial step taken, was to produce a CAD drawing of the part in which all of the right angles could be directly specified, with the constraint that the apices of the corner cubes must lie on the surface of a right circular cylinder. This was done in AutoCad and the drawings converted to IGES format so that they could be used to drive an electrodischarge machine (EDM) automatically. The fabrication was carried out by 3-Dimensional Services [3] (3-D) on a purchase order. While the details of the process were kept proprietary by 3-D, it was basically a multi-step process in which 1) a mold was initially EDM cut on the inside of 3 nesting pie shaped sections of a cylinder; 2) this mold was used to cast a 'positive' mandrel using a low melting alloy - probably one of the Cerro-Bismuth alloys (Bismuth, lead, tin, cadmium with melting points well below 100 C); 3) a layer of nickel (approximately 0.10 mm thick) was then electroplated onto this mandrel; 4) the cast object was then heated to melt and remove the mandrel leaving the finished hollow cylinder with the corner cube pattern impressed on the inside (and outside) forming a DRW. In this way the expensive, EDM cut parts could be reused multiple times.

3-D made 6 cylindrical shells for us. Two of these were not usable since they had deformed edges. For each of the 6, the surface finish was quite poor by optical standards, but with the angles made as required, they should be usable for testing and for establishing the proof of principle. These shells remain available for incorporation into PX style converters. Two of them are shown in the photograph in Figure 28 .

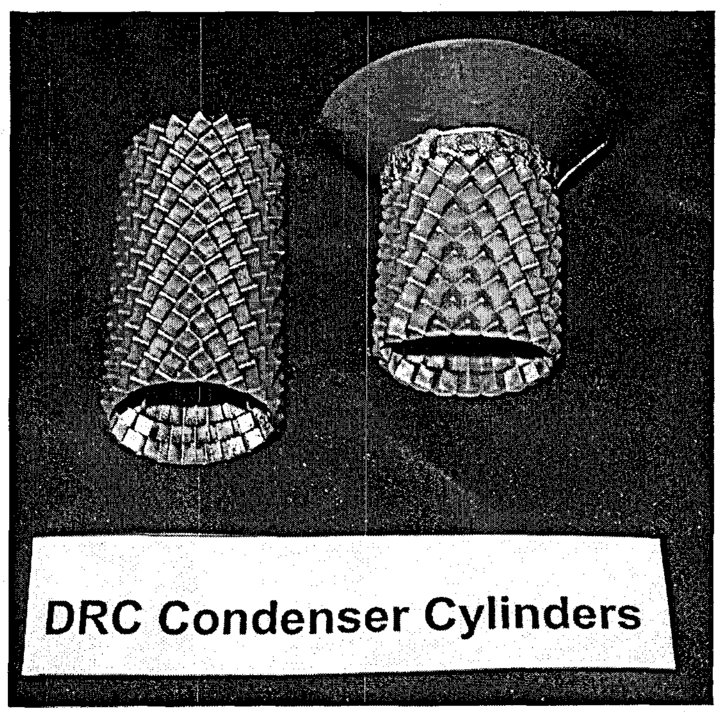

Figure 28 Nickel Corner Cube Cylindrical Converter Wall Liners.

9. Remaining Tasks

In order to complete a proof of principle for the directed reflectivity radiation transfer control strategy, an experimental test of the efficiency gain possible with the DRW concept should be carried out. This should be done first with a DRW surface inserted into the colder end of the low pressure region of a standard cylindrical AMTEC converter on which substantial efficiency data has been or can be obtained. The data obtained in the experiments should then be compared to the predictions of the analytical models generated in this program. If the experimental results are in reasonable agreement with the analysis, further experiments and analytical effort would become worthwhile in the context of high performance AMTEC systems for high value added applications. Spacecraft power for technical missions to deep space destinations may be the best example of this sort of application. If the analytical approach is verified successfully it can then be used to investigate the potential

[3] 3-Dimensional Services, Inc, 2547 Product Drive, Rochester Hills, MI 48309.

for improvement in the performance of the current generation of AMTEC spacecraft converters. A brief outline Statement of Work for a continued effort on the DRC concept is given in the appendix to this report.

Why is the Experimental Work on the Program Unfinished

When the Phase II proposal for this program was submitted, the funding level proposed was $357,000 of which $90,000 was AMPS cost share, substantially less than would have been required to complete all experimental tests. These funds were expended on the analysis and initial experimental portions of the program. As the proposer I reasoned that if the analytical results, which were the heart of the program, indicated a significant advantage for the directed reflectivity concept, one or both of two other programs that were already funded, would be delighted to take on the cost of the final experiments to confirm the modeling since in both cases efficiency rather than cost was the major driver for success. This coordination was deemed particularly likely to be simple since the analytical teams for this program and the other two were comprised of the same engineers. The two programs were the "Radiation Tolerant, Eclipse Compatible Solar AMTEC System", under Air Force contract # F29601-99-C-0132 and the "Advanced Radioisotope Power System", under Department of Energy contract # DE-AC03-98SF21559.

Unfortunately, the Air Force program was cancelled on 24 November 1999, and the ARPS program was operating at an extraordinary pace in attempting to meet extremely tight declared deadlines with no time available for attempting further advances in the technology. Further the ARPS program was cut back severely in August of 1999. The funds, both from DOE and from AMPS cost share were fully expended on the analysis and the control converter experiment as described above. Because the funding request was so conservative and we later lost the promised support from each of these 2 independent government programs on which we had counted for supplemental effort, it was not possible to conduct the experimental proof of principle efficiency test for a PX-6 converter with a directed reflectivity wall. The critical DRW elements are still available for use, if and when additional funding for the tests can be found. The outline of a modest effort to complete the experiments is given as an appendix to this report.

10. Conclusions

The analyses of the radial converter design indicated that the DRC/DRW surfaces, for the converter configurations considered, would have minimal impact on the converter efficiency and for some choices of dimensions would be worse than smooth surfaces. The analysis for a simple straight wall cylindrical converter design, however, showed a probable efficiency gain of at least 1.7% for use of the DRW configured converter wall.

The analysis of this cylindrical, PX type converter design, indicates that with the parameters chosen, the efficiency with a Directed Reflectivity Wall (DRW) can be greater by at least 1.7% relative to the same converter with a conventional smooth wall surface. In achieving this gain, the analysis assumed a converter wall thickness substantially larger than is currently deemed necessary for structural integrity. The mechanical properties of a DRW cylinder were not directly measured during this program, but the DRW surfaces fabricated with a thickness of 0.004" for this program appear to show a very high stiffness for this basic thickness . It appears probable that converters made with walls having the DRW configuration can be made lighter and with a significantly longer heat conduction path than if made with smooth walls having equivalent and adequate strength. The incremental improvement indicated in the analysis may be treated as the minimum change to be expected in a converter whose overall design is optimized to take advantage of the DRW surface..

Appendix A - Statement of Work for DRC Completion (8 months from start)

Outline

1. Adapt new efficiency test apparatus for PX-6 style converters
   - 1.1 Fabricate heater/insulation package to accommodate non-chimney converter
   - 1.2 Verify thermal loss analysis with dummy cell (probably done with PX-8 already)

2. Fabricate remaining components for DRW converter
   - 2.1 Identify inventory of usable components from Phase II test build
   - 2.2 Select 8 BASE tubes
     - 2.2.1 Complete BASE tube assembly by standard manufacturing instructions
     - 2.2.2 Identify or fabricate the BASE tube support plate, converter wall, artery/evaporator and feedthroughs
   - 2.3 Install DRW shield and attach to converter wall to prevent movement during handling and operation

3. Assemble PX - DRW converter
   - 3.1 Conduct He leak tests
   - 3.2 Finish weld
   - 3.3 Bake out and load sodium

4. Install converter into new efficiency test station
   - 4.1 Instrument and verify data acquisition system operation and calibration

5. Carry out efficiency experiments as a function of temperature, current and power

6. Repeat these operations with a smooth wall converter of the same configuration.

7. Compare performance with analytical model results and draw possible conclusions on effectiveness of the DRW.

8. Prepare and submit report on conclusions to DOE and to NASA/JPL for interest.

9. Prepare paper reporting results for publication

Task Description

1. Since the initial efficiency testing in Phase II, a new test apparatus has been constructed that allows for much more rapid data collection. The new apparatus relies on direct measurements of the temperature gradients in an insulation package and following initial calibration, does not attempt to track all longitudinal gradients since they can be established for the apparatus at the outset. The new efficiency apparatus insulation package was built to accommodate primarily the "chimney" converter described by the A. Schock group at Orbital Sciences and now proposed for use in the ARPS program. Some modification of the insulation package will be required to fit the cylindrical PX series converter to be tested here.

2. Many of the components for the DRW test cell are still available for use. The BASE tube support plate and artery and converter wall would need to be built. The critical DRW cylinders are available.

3. Assembly of these components with the exception of the attachment of the DRW liner can proceed according to well established procedures. The use of a standard converter design will reduce the cost of this assembly step.

4. Installation of the DRW converter into the efficiency test station will be straightforward based on the modifications to an insulation package described above. The instrumentation will be checked out and calibrated using the procedures put in place for the other program which funded construction of the apparatus. The computerized data acquisition system (DAS) will be rechecked/calibrated against company maintained standards.

5. The converter will be operated at a series of output power levels and the heat input, lateral losses and temperature gradients will be measured using the DAS checked out in task 4. The data will be checked first against the historical data taken on the PX-6 converter measured as described in the report above. While this will give and indication or progress, it will not be sufficient since the change in the efficiency measurement apparatus used may have introduced an inconsistency.

6. The efficiency measurement operation will therefore be repeated using s smooth wall converter of the same basic construction as the DRW converter.

7. The two data sets from the two sets of efficiency tests will then be compared both with each other and with the model results described in the report above in Section 7. Conclusions will be drawn as to the effectiveness of the DRC/DRW concept for AMTEC efficiency enhancement.

8. A supplementary final report will be prepared and submitted to DOE and to NASA/JPL. If the conclusions warrant it and sufficient interest is shown by NASA and/or DOE, the project will be pursued under other funding mechanisms for a Phase III effort.

9. If no objections are made by program sponsors, a paper will be prepared for publication describing the work and conclusions.

<u>Projected Cost to Complete</u>

The currently estimated cost to complete the experimental work on a DRW, a dummy converter for calibration of the thermal paths in the efficiency apparatus and a control converter to allow validation of the modeling carried out under this abbreviated program is $175,000. A more detailed statement of work and discussion and a detailed cost proposal will be prepared on request.