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A High-Efficiency Refractive Secondary Solar Concentrator for High Temperature Solar Thermal Applications

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Note that at the time of research, the NASA Lewis Research Center was undergoing a name change to the NASA John H. Glenn Research Center at Lewis Field. Both names may appear in this report.

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A HIGH-EFFICIENCY REFRACTIVE SECONDARY SOLAR CONCENTRATOR FOR HIGH TEMPERATURE SOLAR THERMAL APPLICATIONS

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Abstract

A refractive secondary solar concentrator is a non-imaging optical device that accepts focused solar energy from a primary concentrator and redirects that light, by means of refraction and total internal reflection (TIR) into a cavity where the solar energy is used for power and/or propulsion applications. This concept offers a variety of advantages compared to typical reflective secondary concentrators (or the use of no secondary at all): higher optical efficiency, minimal secondary cooling requirements, a smaller cavity aperture, a reduction of outgassing from the cavity and flux tailoring of the solar energy within the heat receiver. During the past 2 years, NASA Lewis has been aggressively developing this concept in support of the NASA Marshall Shooting Star Flight Experiment. This paper provides a brief overview of the advantages and technical challenges associated with the development of a refractive secondary concentrator and the fabrication of a working unit in support of the flight demonstration program.

INTRODUCTION

Over the years, NASA Lewis has developed a variety of technologies that support the use of solar thermal power for space systems. The refractive secondary solar concentrator described within this paper is a key element of that technology thrust. The secondary concentrator unit, when used in conjunction with a large primary solar concentrator, focuses the sunlight into a heat receiver cavity. The energy absorbed within this cavity can then be directly converted into electrical energy for use by the spacecraft or used to heat a propellant to provide thrust for orbit transfer and on-orbit maneuvering. This concept of solar thermal propulsion is currently being developed under NASA and US Air Force programs. Under the auspices of the NASA Marshall program, the "Shooting Star Experiment" (SSE) is a short-term space flight demonstration program to study and quantify the benefits and operational implications of solar thermal propulsion (Curtis 1998). In cooperation with NASA Marshall, the NASA Lewis Refractive Secondary Concentrator Team is fabricating a prototype secondary concentrator for ground test and evaluation. Successful testing of this prototype unit should allow for its inclusion in the final flight hardware design. This paper will briefly describe the progress made on the design, fabrication and testing of this first prototype.

For solar thermal energy applications in space, the secondary concentrator provides major benefits. It maximizes the input of solar energy within the heat receiver cavity, while minimizing the size of the aperture necessary to capture the light. This is important since a larger aperture increases the amount of heat lost through radiation. This is extremely critical for cavities operating at high temperatures, i.e. 1500K to 2500K. Most large-scale solar thermal designs have proposed using reflective secondary concentrators. A single crystal refractive secondary provides a number of advantages over the traditional hollow reflective compound parabolic concentrator (CPC). The primary advantages are higher efficiency, higher concentration ratio, flux tailoring, and the ability to function without requiring elaborate cooling features. These advantages and a more detailed analysis of the design have been described in a previous publication (Soules 1997).

CONCEPT DESIGN

DTIRC/Flux Extractor

There has been extensive research over the past 30 years in the design and application of secondary concentrators. (Winston 1995). One specific type of secondary is the Dielectric Total Internally Reflecting Concentrator (DTIRC). (Ning 1987). The secondary concentrator being developed under this program is based on the DTIRC concept. The DTIRC by itself cannot efficiently pass all of the solar energy that it accepts into a lower index media (i.e. a heat receiver cavity in air or vacuum). A DTIRC that is shaped for maximum concentration ratio will reflect, at the exit

surface of the DTIRC crystal, as much as 50% of the solar energy that it accepts at the inlet surface. In order to achieve a high optical efficiency, the secondary is connected to a flux extractor. The flux extractor is a dielectric rod with facets of various size, shape, quantity and finish that is attached to the exit of the secondary. It projects into the heat receiver cavity and permits nearly complete extraction of the solar energy from the DTIRC. It is typically made of the same material as the concentrator but may be made from another material with a different index of refraction (preferably higher). A sketch of a refractive secondary concentrator and flux extractor, as it would be installed in a typical solar thermal propulsion engine, is shown in Figure 1.

Flux Tailoring

The flux extractor, through changes in the design shape and surface, can provide variation in the solar flux distribution within the cavity. This feature may be desired for certain applications, such as solar thermal propulsion, where maintaining a proper thermal profile is important for efficient operation. Figure 2 shows a 3D trace for a finite number of randomly distributed rays that enter the DTIRC within the design acceptance angle. As shown in the ray trace, the majority of the light passing through the DTIRC stays in the flux extractor via TIR until it can exit the extractor by striking the facets at angles that are less than the TIR angle. The corresponding flux distribution pattern for a specific design is presented in Figure 3. It has been shown by Opticad analysis that the flux pattern can be controlled by varying the extractor facet length, number and surface finish (specular or diffuse). Analysis and testing is in progress to identify the surface treatments and shape alternatives possible that would provide efficient solar flux distribution for a typical solar thermal propulsion engine.

Material Selection

Currently, four "man-made" single crystal materials have been identified as possible candidates for use in this application. Each material has temperature, environmental and/or fabrication limitations that would constrain its use for certain mission application. This data is summarized in Table 1. Since the "Shooting Star" flight experiment is planned for temperatures of 2000K or below, sapphire or YAG are presently the material of choice. Further material evaluation and coating analysis is necessary to identify the best material (or combinations of materials) for operation at cavity temperatures of 2500K and above.

TABLE 1. Secondary Concentrator Material Characteristics

Material	Size Availability	Melt Point	Index of Refraction	Est. Thermal Conductivity (Watts/cm ² •K)	Optical Absorption Cutoff	Chemical Stability
Al ₂ O ₃ sapphire	33 cm dia. x 15 cm long boules	~2300K	1.76	100 @ 20K 0.25 @ 300K 0.1 @ 1000K 0.06 @ 2300K	~5μ	Stable at high temp. in air or vacuum
MgO magnesium oxide	10 cm dia. x 15 cm long irreg. shapes	~3000K	1.76	30 @ 20K 0.6 @ 300K 0.08 @ 1500K	~7μ	Reduces in air due to H ₂ O, stable at high temp. in vacuum
ZrO ₂ zirconia	10 cm dia. x 15 cm long irreg. shapes	~3000K	2.16	0.1 @ 300K	~6μ	Reduces at high temp. in vacuum, stable in air
Y ₃ Al ₅ O ₁₂ yttrium/aluminum/garnet (YAG)	13 cm dia. x 20 cm long boules	~2240K	1.82	0.1 @ 20K 0.08 @ 1000K 0.07 @ 1500K	>4μ	Stable at high temp. in air or vacuum

PROTOTYPE HARDWARE FABRICATION & TESTING

Design Implementation

Current refractive secondary concentrator and flux extractor designs have focused on solar thermal propulsion engine applications. Under operational conditions, these engines will operate at temperatures approaching 2500K. Figure 1 shows the "Shooting Star Experiment" engine concept discussed earlier. While the engine is designed for use with hydrogen propellant at 2500K, the short-term SSE flight will heat nitrogen as a propellant at temperatures approaching 2000K. The ultimate goal of the Refractive Secondary Concentrator Program is to develop the technology necessary to support the high temperature applications envisioned for future space systems; however the program's immediate concern is the initial demonstration and testing of this concept within the confines of SST operational conditions.

The first secondary concentrator ground test articles were made from zirconia. Zirconia was selected due to its size availability, lower manufacturing cost, and high melt point temperature. Zirconia is ideally suited to demonstrating and quantitatively measuring optical performance of the DTIRC/flux extractor unit. However, as indicated in Table 1, zirconia reduces at high temperature in vacuum (i.e. changes color with time) and therefore has a limited useful life for space applications. Following discoloration in vacuum, the zirconia can be restored to its original color by heat treating in air at elevated temperature. Tests have shown that zirconia retains its original qualities and can be reused as a test article. This time/temperature relationship is being studied to determine ground test limitations for the prototype hardware. Although the SST experiment is a short duration test, it remains to be seen if zirconia is a suitable material for flight hardware demonstration.

Component Test Results

Researchers at NASA Lewis have evaluated a variety of sample materials and coatings in an effort to optimize system performance within the given optical, thermal and mechanical constraints. Coupons of sapphire, zirconia, and magnesium oxide were fabricated and polished to "best effort" flatness in an attempt to achieve 1/20th wave or better. Early analysis indicated that the contact surfaces between the flux extractor and concentrator would require 1/20th wave flatness or better (depending upon index of refraction of the DTIRC/flux extractor) in order to efficiently transfer the solar energy from the concentrator into the extractor. To date the best efforts have produced only 1/10th wave flatness.

It was also believed, early in the program, that mechanically contacted optical surfaces would provide a thermal resistance in vacuum that would reduce the conduction heat loss from the high temperature extractor to the cooler concentrator. Contact resistance tests were conducted under contract to Texas A&M University using sapphire wafers polished to ~ 1 wave and MgO wafers polished to 1/10 wave. No appreciable thermal resistance was achieved. (Mirmira 1998). As a result of this testing, a decision was made to pursue diffusion bonding as a means of joining the extractor to the concentrator. A successful diffusion bond should result in a lossless optical connection. Coupons of all candidate materials are to be bonded and tested for optical and mechanical performance. The samples will involve bonding like as well as dissimilar materials. Diffusion bonding of like materials is reported to result in bonds as strong as the parent material. For unlike materials small differences in the coefficient of thermal expansion (CTE) may have an adverse effect on the strength of the bond.

Prototype Hardware Fabrication & Assembly

The fabrication of two sets of zirconia crystals was recently completed by the Optikos Corporation for use in ground testing at NASA Lewis and at the University of Alabama, Huntsville (UAH) Solar Laboratory. The first crystal set was designed to optimize optical performance based on specifications provided by NASA Marshall for the primary solar concentrator. The first prototype unit is shown in Figure 4. The secondary concentrator DTIRC has an 8.9 cm. inlet diameter, a 1.9 cm. exit diameter, and is 12 cm. long. The flux extractor is 15 cm. long and has 3 equilateral facets. The DTIRC accepts a light beam with a 22 degree entrance half angle. The second crystal set was designed for a 42 degree entrance half angle. This design variation from the SST requirements allows the second unit to be tested with primary concentrators at the Lewis Research Center's Tank 6 Facility and at the Edwards Air Force Base's Solar Laboratory. In addition, the second prototype unit incorporates a 4 facet diamond shaped extractor for improved efficiency. The DTIRC and flux extractor from the first crystal set will be diffusion bonded

and then tested for throughput efficiency and high temperature operation at the UAH Solar Laboratory. Present plans are to hold the second set as a spare until preliminary test results are acquired at UAH.

The design of a crystal holder that will support the concentrator/extractor assembly at the DTIRC inlet, see Figure 1. is in process. The current design has the flux extractor cantilevered from the DTIRC into the solar thermal engine cavity through an opening in the engine insulation. Launch load survival tests are planned to verify that the crystal mass can be supported in this manner and survive the high G forces associated with a Space Shuttle launch.

SUMMARY

Significant progress has been made in the past year in developing a refractive secondary concentrator design to support the SST and other future solar thermal power and propulsion applications. The feasibility of this concept has been demonstrated and design tools have been developed to assist in design optimization. Candidate materials have been identified along with sources for raw materials and fabrication. Crystal material issues, specifically for high temperature and long-term space applications, still need to be addressed. Two prototype DTIRC/flux extractor units have been fabricated and are awaiting test. These units, fabricated from zirconia, will be used to verify predicted performance (optical, thermal, and mechanical).

An important area remaining to be pursued is the development of specialized high temperature coatings that can enhance the overall performance of the secondary concentrator. One such coating is an infra-red (IR) block coating that could be applied to the crystal inlet surface. Such a coating would reflect back the majority of IR radiation losses from the hot cavity while rejecting a much smaller amount of the incoming solar radiation.

The high temperature refractive secondary concentrator concept offers many advantages over other secondary concentrator systems. The NASA Lewis Refractive Secondary Concentrator Team plans to continue the development of this technology for a variety of solar thermal propulsion and power applications.

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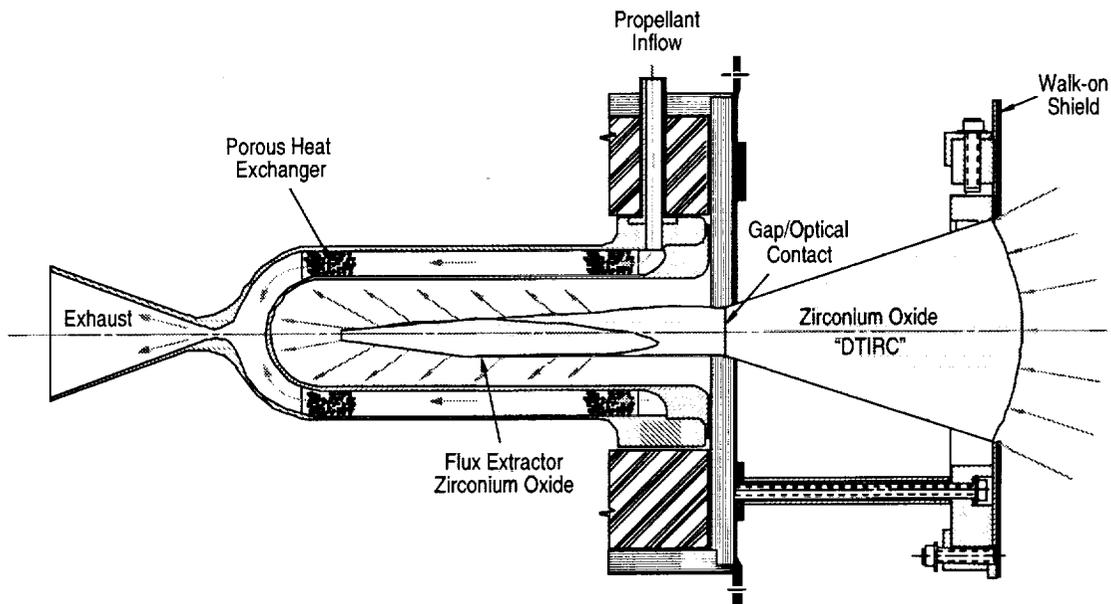


FIGURE 1. Schematic Drawing Showing a Refractive Secondary Integrated into a Solar Thermal Propulsion Application Concept.

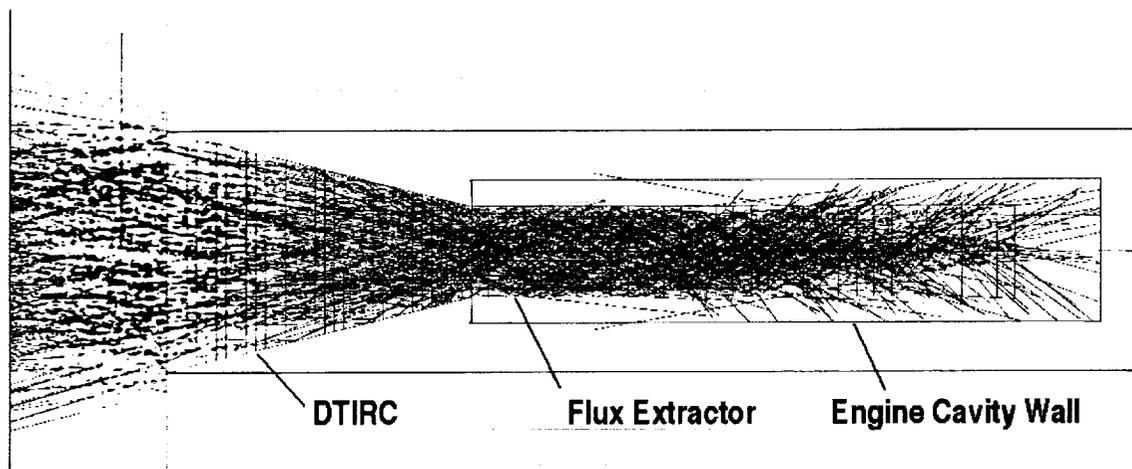


FIGURE 2. Ray Trace Showing Light Rays Entering DTIRC, Exiting Flux Extractor and Impinging upon the Heat Receiver Cavity Wall.

Secondary Concentrator Demonstrator - Flux on Cavity

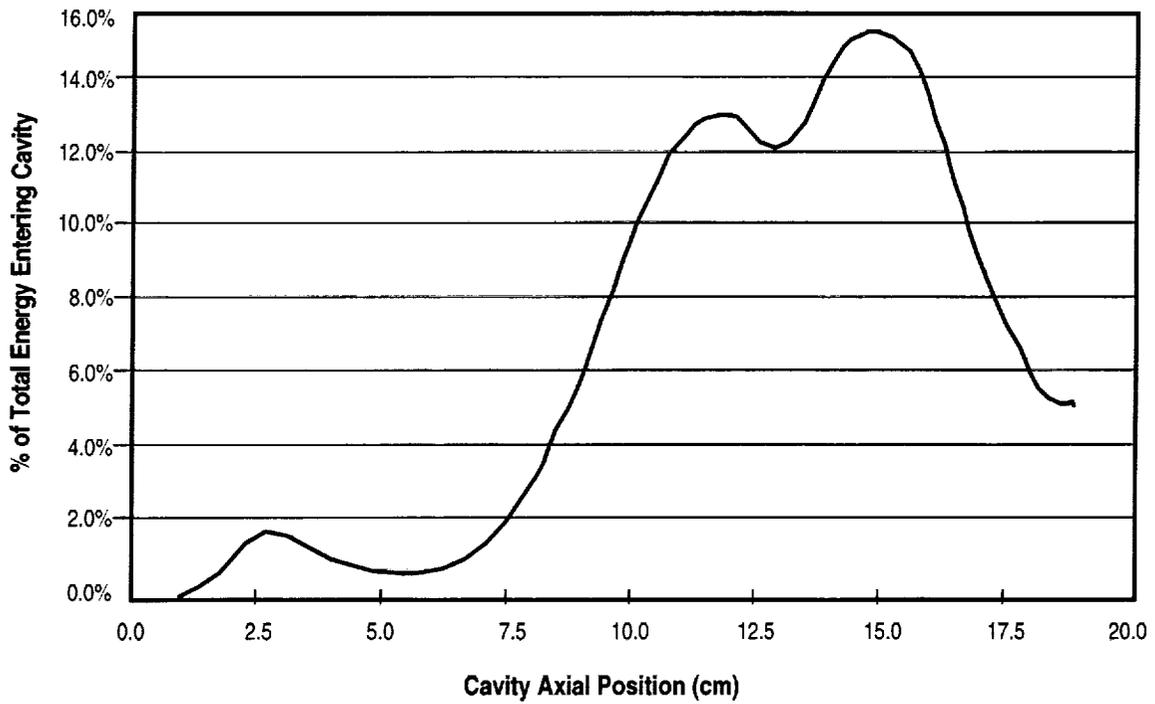
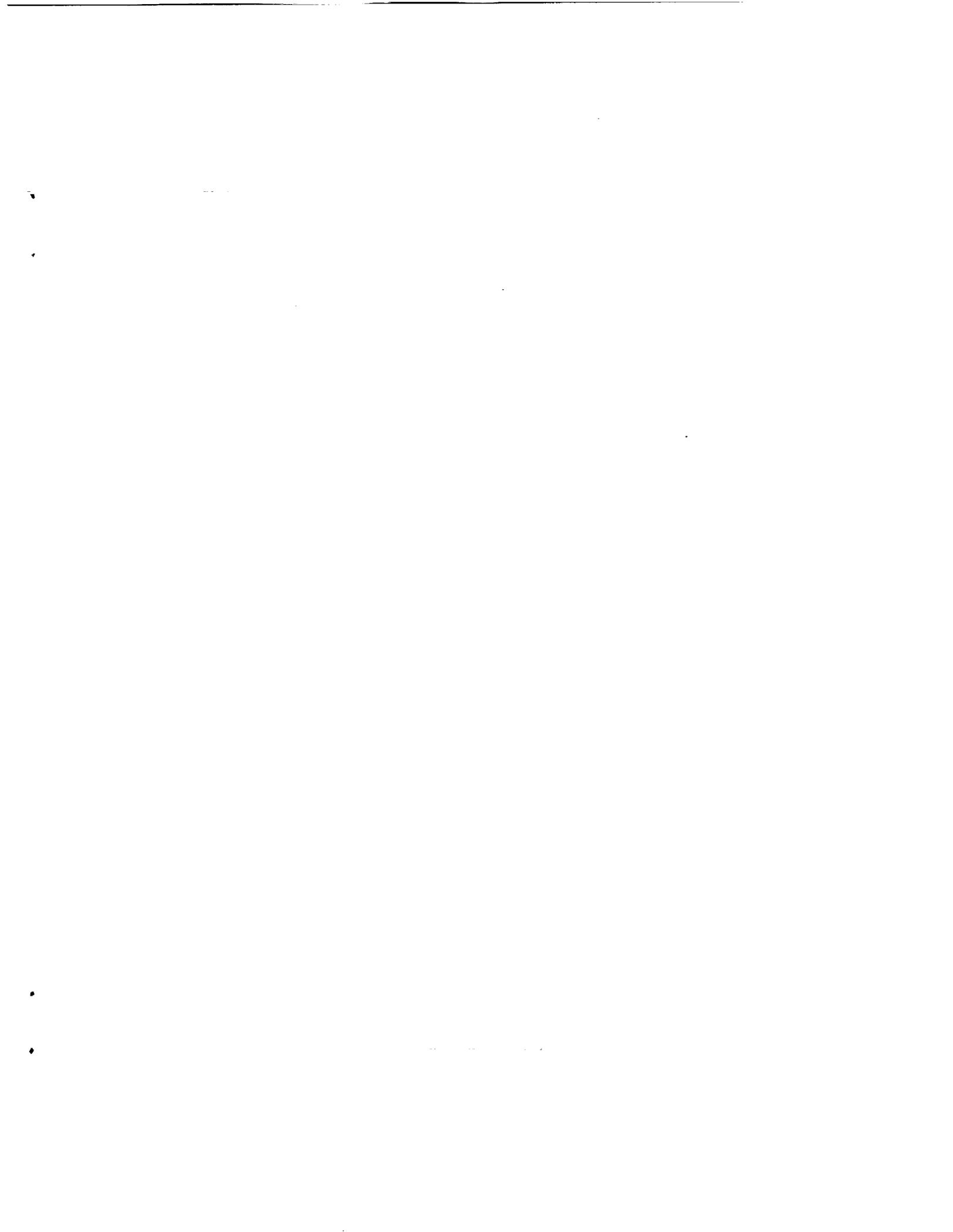


FIGURE 3. Solar Flux Intensity Distribution within the Heat Receiver Cavity for the Current Secondary Concentrator Design. (0.00 = Cavity entrance).



FIGURE 4. Secondary Concentrator and Flux Extractor Made from Single Crystal Zirconia.



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