# FLAT PLATE SOLAR
# THERMOELECTRIC GENERATOR SYSTEM CONCEPT

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## Abstract

This paper presents details of flat plate solar thermoelectric generator research results and discusses the concept operation from a systems standpoint. The converter concept discussed is that which was investigated by General Atomic Division under Air Force Contract 33(616)-7676. Systems factors and potential are based on completed research and the author's estimate of concept potential if the concept is developed to the point where operational feasibility is established.

## Introduction

This paper presents what are considered the most pertinent details of the flat plate solar thermoelectric generator from both the converter concept and operational systems standpoint. The discussion is divided into sections on the basic converter concept, research results, and systems factors and potential. The consideration is made that the concept is directed toward space application as a flight vehicle power supply. Systems factors and potential are based on completed research and the author's estimate of concept potential if the concept is developed to the point where operational feasibility is established.

The requirement stimulating flat plate research is the need for a highly reliable, lightweight, long life, low cost, radiation resistant static solar device which has a wide orientation tolerance. It is anticipated that the flat plate solar thermoelectric concept will meet all these requirements, if fully developed, for the power range from 5 w to 10,000 w.

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## Technical Discussion

### Basic Converter Concept

There are many types of flat plate solar thermoelectric converter concepts; however, this discussion is concerned only with the concept as investigated by General Atomic (Division of General Dynamics) under Air Force Contract 33 (616)-7676.

The aforementioned concept utilizes the four basic converter components of collector, thermoelements, honeycomb converter support structure, and radiator. Referring to Fig. 1, the collector is aluminum foil coated with alternate layers of metallic aluminum and silicon monoxide for solar radiation absorption. The radiator is also aluminum foil but is coated with a flat-black lacquer for maximum radiation emittance. The radiator is attached to but electrically insulated from the aluminum honeycomb structure. The thermoelements are bonded to the collector and radiator through holes drilled in the honeycomb. Thus, the honeycomb supports the radiator which supports the thermoelements which support the collector foil strips. This results in a relatively flexible device with the potential of good mechanical and thermal stress characteristics.

Referring to Fig. 2, the P- and N-type thermoelements are in alternating rows and are electrically connected by proper slicing of the collector and radiator sheets. Referring again to Fig. 1, the areas between thermoelements in a given row on the collector are in themselves partially slotted to give additional thermal stress relief. Also, small embossments on the collector leading to the thermoelements give added collector foil rigidity.

Some present characteristics of the concept are interesting. The thermoelements used are P-type zinc antimonide and N-type lead telluride with nickel-disc caps on each element end to provide a surface for bonding the elements to the radiator and collector surfaces. Normal temperatures experienced approximate 300°C on the collector side and 100°C on the radiator side. A feature of the thermoelements in themselves is that they are very small -- typical dimensions being 1 mm by 1 mm in cross section and 2.5 mm in length.

### Research Results

A thorough treatment of the program conducted under Contract AF 33(616)-7676 by General Atomic is given in report number Aeronautical Systems Division TDR 62-214 entitled "Flat Plate Solar Thermoelectric Conversion Panels." The report is available through both the Armed Services Technical Information Agency and the Office of Technical Services. This discussion summarizes the major problems and solutions or possible solutions as related to the experimental results and general research findings.

One of the major converter problems was that the silver-solder bonds between the thermoelements and collector and radiator as well as the junction between the zinc antimonide and its nickel cap all tended to separate under thermal cycling conditions. Both spot-welding and gold-cement bonding of the thermoelements to the collector were found to be better than silver soldering -- although the processing in all cases was fairly critical. Silver plating the radiator foil before silver soldering the thermoelements and paying closer attention to the soldering techniques fairly well solved that bonding problem. The zinc antimonide-nickel cap difficulty was resolved in the main by use of a better basic thermoelectric material.

Another major problem was that thermocouple resistances were as much as twice those anticipated. Although this discrepancy was not traced to a single factor, a general speculation based on ordinary engineering relationships and normal occurrences can be reasonably formulated. This is that the excessive resistance was caused by such factors as incomplete or inconsistent bonds, inhomogeneities and general inconsistencies in the thermoelements, normal problems due to personnel becoming familiar with the experimental fabrication techniques, and apparent resistance increases due to the mismatching caused by thermoelement property variations. Although the problem still has not been fully resolved, it has recently been proven that gold bonds on both the collector and radiator sides provide not only better thermal cycling capabilities but also consistently lower resistances than with collector spot-weld bonds and radiator-solder bonds.

Other problems existed with trying to reduce thermal and mechanical stresses, obtaining better collector selective coatings for more energy absorption, reducing overall weight, and obtaining better thermoelements not only with respect to consistency but also with higher performance characteristics. These problems have not been completely resolved, but solutions are possible as evidenced by the collector foil slots and embossments for stress relief which did not completely eliminate stress problems but which did greatly improve the situation.

In all respects but power output, the experimental results were encouraging. Table 1 gives the results of a performance test on a 4 in. x 4 in. converter panel (18 couples, 36 thermoelements). Note that the observed values are only approximately 60% of those expected from measured properties and only 45% of those based on intrinsic properties. This is due not only to the excessive resistance and other factors previously noted, but also to measurement technique inconsistencies. The solar simulator used for performance tests was a search light modified to incorporate a vacuum system with liquid-nitrogen cooled walls. The unit had to be hand focused and oriented. Undoubtedly, hot spots thus caused plus normal variations in the solar spectrum and operational use caused experimental discrepancies. An example of the parameter measurement discrepancies is shown in Table 2 where a 17% increase in solar intensity caused only an 8% increase in power density output.

Other experimental results were more encouraging. Life tests of 800 hr on PbTe and ZnSb thermoelements showed no deterioration due to sublimation at a hot junction temperature of 300°C with the cold junction at 120°C. Similar life tests up to 10,000 hr under another program also have indicated that sublimation is not a problem at temperatures up to 375°C.[1]

Thermal cycling tests were conducted in air and in vacuum. A 4-element panel was cycled 690 times in vacuum with no significant degradation occurring. Thermal cycling in air of 17 parallel-connected couples in a 12-in. strip resulted in several elements breaking and the panel warping. A large factor contributing to this deterioration was undoubtedly that air between the collector and honeycomb-radiator structure conducted excessive heat to the upper structure face. This caused the structure to warp and resulted in the thermoelement fractures. Tests on 2-element modules under another program have indicated that thousands of thermal cycles can be obtained without significant thermocouple deterioration. An interesting sidelight to this is that when an element or couple is operated continuously for thousands of hours and then thermally cycled, it tends to fail rather easily.[2]

In summation, the program conducted under Contract AF 33 (616)-7676 has developed the basic techniques required to fabricate a lightweight flat-plate solar thermoelectric energy converter and has determined some of the characteristics and problems of such a conversion concept. The performance characteristics of test panels were not as good as calculations had indicated were possible; however, it is anticipated that significantly improved panels can now be produced by taking advantage of the understanding of materials, improved fabrication techniques, and technical skills developed during the course of this and other similar programs.

## Systems Factors and Potential

The flat plate converter is presently not feasible for incorporation into a generator system for a flight vehicle supply. This is due to three main factors; namely, low efficiency and consequently low power/unit area; lack of a suitable size working experimental model of a typical system concept which includes the system support and deployment structure (as opposed to the converter honeycomb support structure), attendant control equipment, and long-term system concept test data; and, unavailability of specific cost information to prove the contention of flat plate low cost with respect to conventional power devices such as solar cells. However, sufficient progress has been made to indicate very good potential for a system concept.

When discussing a flat plate thermoelectric system, it is inevitable that it be compared to solar cells because of the likeness in configuration (excluding cells placed on the side of a vehicle) and missions. Solar cell systems are expensive and encounter severe radiation damage in earth orbit. However, they are reliable and have good power output characteristics. The discussion thus leads to future space mission requirements including maximum power requirements and orbital environment. The limitation of earth orbit missions shall now be placed on the discussion; other missions will be mentioned briefly later.

In order for the flat plate to become as fully useful as solar cells have been and will continue to be, the present belief is that it must be capable of at least 5 w/ft$^2$. Otherwise, the required area is prohibitive due to packaging and orbital drag factors. The 5 w/ft$^2$ corresponds to an efficiency of approximately 4%. Although even this is very low, there are advantages of the flat plate at such an efficiency which still make the concept desirable in place of or to supplement solar cells or other power devices and override the area-drag factor. These advantages are the high power/weight ratio and operation in radiation environment. Table 3 presents anticipated characteristics of the flat plate as a system concept. It must be remembered that concept and component reliability and long life are presently being investigated and have shown promising results. And even at an efficiency of approximately 1%, the 4 in. x 4 in. panel previously discussed (reference Table 2) did result in 10 w/lb exclusive of systems support structure.

It has been stated that a flat plate system should cost less than a comparable solar cell system by a factor of 8 to 10.[3] Present costs of a solar cell system are typically about \$400 per watt whereas small experimental flat plate thermoelectric models presently cost approximately \$4000 per watt. Mass production would, of course, dramatically reduce this figure as would anticipated improved fabrication techniques and use of higher performance thermoelectric materials. However, a futuristic cost comparison relative to solar cells cannot be realistically made at this time. It can only be said that the cost <u>should</u> be less based on present limited knowledge.

The last factor necessary to establish systems concept feasibility is a laboratory model of sufficient size to prove the feasibility. Such a working model must have all necessary support structures and power-voltage output electronic controls. Tests must be conducted on the unfolding mechanism and system vibration, shock, and acceleration. Complete simulated earth orbits are probably impractical for large areas (i.e., 10-20 $ft^2$), but relatively large (1 $ft^2$) representative panels could be simulated through 500-1000 earth orbits after being evaluated under simulated launch conditions. If small panels can be orbited successfully, the larger laboratory system model should not have to be orbited for acceptance of the concept -- unless, of course, there is great concern for the operation of unfolding the system in space and/or the operation of a large system with respect to the actual effects that support structure and miscellaneous support equipment have on the system characteristics and reliability in space.

The systems considerations so far have been directed toward earth orbit application. In truth, the flat plate concept may have its best use as a relatively small power supply for interplanetary travel (especially toward the sun) -- either to supplement the power supplies anticipated from MHD, thermionics, high-temperature thermoelectric, or dynamic systems or to be a reliable auxiliary power supply.

Considering earth orbits, there will be many future applications for small power systems from 5 w to 10 kw where low cost, high w/lb, and good radiation resistance are required such that batteries by themselves, solar cells, and other conversion devices are lacking in one or more of the aforementioned prerequisites. Of course, the same is true of missions other than earth orbit.

With respect to system potential capability, the maximum power output will probably be limited to approximately 3 kw in earth orbit because of the area considerations. At 4% efficiency, the required area for 3 kw is approximately 600 $ft^2$. In reality, systems between 5 and 3000 w seem reasonable for earth orbit while the 3000 to 10,000 w systems seem more logical for lunar or interplanetary travel.

## Conclusions

Investigation of the flat plate solar thermoelectric generator was stimulated because of its possibilities as a low cost, lightweight, reliable solar power system for space flight vehicle power supplies. Such a system would augment solar cells in missions which require lifetimes of up to five years in high-radiation orbits and could possibly be competitive in many nonradiation missions. Also, the flat plate performance would improve with missions such as Venus explorations.

Research results to date have indicated that the converter concept has considerable promise; however, system feasibility cannot be established until efficiency is increased, a systems concept experimental model is fabricated and extensively evaluated, and the system costs are more definitely established. Typical performance requirements for feasibility are at least 5 $w/ft^2$, 15 w/lb with systems structure, and capability of 5000 earth orbits with no more than 10% degradation.

## References

[1] Jansen, H., Overmeyer, R., and Shoemaker, H., Thermoelectric Materials and Fabrication, Third Quarterly Rept., Contract NOBs 84776, General Atomic Div., General Dynamics Corp. (February 26, 1962).

[2] Roes, J. B., Thermoelectric Materials and Fabrication, Second Quarterly Rept., Contract NOBs 84776, General Atomic Div., General Dynamics Corp. (December 1, 1961).

[3] Campana, R. J., Preliminary Design and Performance Study of a Sandwich Thermoelectric Converter of Solar Energy, GA-1922, General Atomic Div., General Dynamics Corp. (January 9, 1961).

Table 1 Performance test results, 4-in. x 4-in. panel

| | Calculated Intrinsic Properties | Measured Component Properties | Panel Test Results |
|---|---|---|---|
| Collector Temperature, °C | 282 | 302 | 252 |
| Radiator Temperature, °C | 82 | 76 | 21 |
| Collector Efficiency, % | 63.5 | 60.5 | ... |
| Converter Efficiency, % | 2.3 | 1.8 | 1.0 |
| $w/ft^2$ | 2.95 | 2.3 | 1.3 |
| w/lb | 23 | 19 | 10.5 |

Table 2 Performance measurement discrepancies, 4-in. x 4-in. panel

| Incident Energy $w/meter^2$ | Collector Temp, °C | Radiator Temp, °C | Seebeck Voltage Per Couple, mv | Resistance Per Couple, mohm | Power Density, $w/ft^2$ |
|---|---|---|---|---|---|
| 1200 | 253 | 60 | 58.5 | 102 | 1.23 |
| 1400 | 252 | 21 | 63.5 | 130 | 1.33 |

Table 3 Anticipated flat plate thermoelectric system concept characteristics

| | 1964 | 1967 |
|---|---|---|
| Collector Temperature | 300-325°C | 300-350°C |
| Radiator Temperature | 75-125°C | 75-125°C |
| Generator Efficiency | 4-6% | 5-8% |
| w/lb with Structure | 15-20 | 20-30 |
| Reliability | | |
| Lifetime | 5000 earth orbits | 15,000-25,000 earth orbits |
| Radiation Resistance | very good | very good |

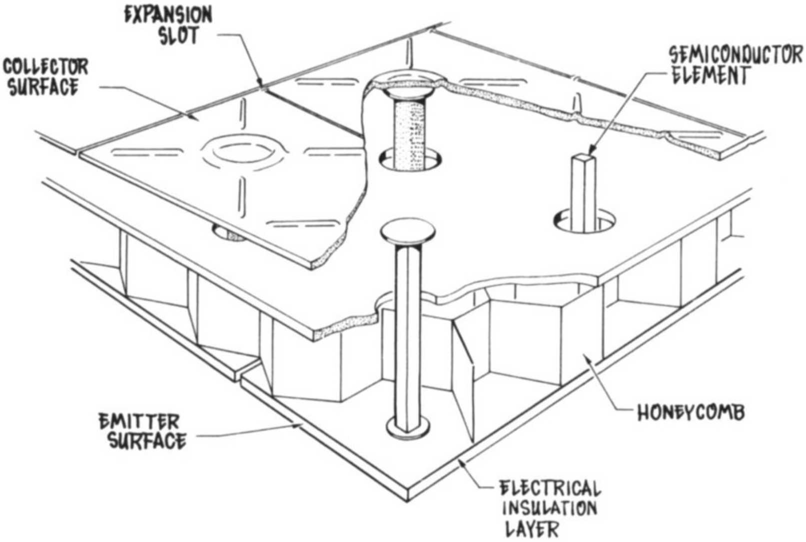

Fig. 1 Section of flat plate converter

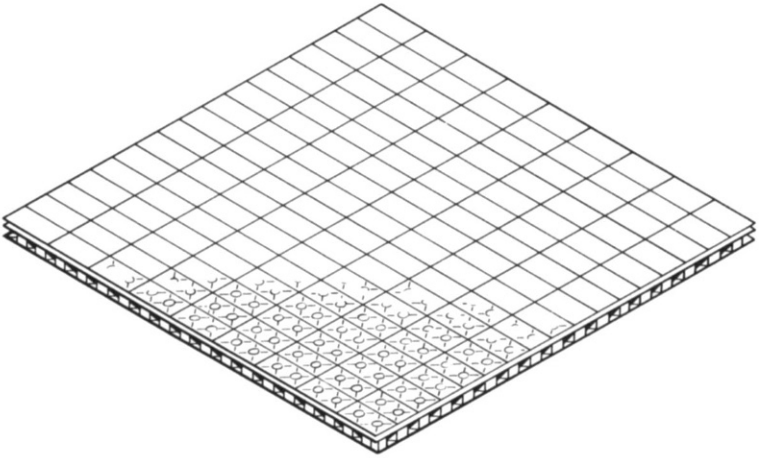

Fig. 2 Typical converter panel