REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
17 Jul 96

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Prospector VIII: Thermohotovoltaics -- An Update on DOD, Academic, and Commercial Research

5. FUNDING NUMBERS
DAAH0496-1-0340

6. AUTHOR(S)
M. Frank Rose, principal investigator

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Auburn University
Auburn, Al 36849-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
ARO 36179.1-RT-CF

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

14. SUBJECT TERMS

15. NUMBER IF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

PROSPECTOR VIII:

THERMOPHOTOVOLTAICS -- AN UPDATE ON DOD, ACADEMIC, AND COMMERCIAL RESEARCH

July 14-17, 1996

Edited by

M. Frank Rose, Co-Director
For the Prospector VIII Board of Directors

Sponsored by

Space Power Institute
Auburn University, Alabama 36849
&
Army Research Office
Research Triangle Park, North Carolina 27709-2211

Held at the
Washington Duke Inn
Durham, North Carolina

M. Frank Rose, Director
Space Power Institute
Auburn University, Alabama

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PREFACE

The idea for a series of highly focused workshops dealing with key issues associated with the science and technology of advanced power systems had its origin in many conversations with outstanding technologists all over the world. It became apparent that the difference between the state-of-the-art and what these technologists saw for future needs was so large that new approaches to meet these needs were mandatory. Key issues falling into this category are: prime power, thermal management, advanced energy conversion, life support, automated systems and advanced diagnostic techniques. Due to the interdisciplinary nature of power systems, any new and successful approach will likely come from a group with diverse backgrounds rather than those schooled in the "accepted" approaches.

Power systems offer unique challenges to engineers and application specialists. While a capability or mission may be feasible, more often than not, the power technology available determines the total mission profile. As the mission profile expands, the demands on the power technology associated with the mission quickly extend beyond the state-of-the-art. For many advanced concepts, power technology is totally enabling. It is not just the "long pole in the tent", it is the "tent". Often promising concepts are abandoned due to the lack of a foreseeable power technology that could remove it from being a laboratory curiosity. It is insufficient to think totally in terms of system energy density or power density. Due to environmental and safety concerns, the power technologist may be forced to employ non-optimum power systems that drastically limit the performance envelope. Furthermore, the use of exotic materials, exotic fuels, and complexity reliability, etc., further impedes the transition from laboratory curiosity to field workhorse. Recalling that "energy and mass are neither created nor destroyed, but simply changed from one form to another," energy carried within the system, and stored in the chemical bond or in the nucleus, must eventually be used as intended or ejected from the system in the form of "low grade heat". Three options exist for managing waste energy. Having changed its thermodynamic state when useful work is done with it, the excess energy can either be radiated away to space, stored, or convected/conducted into a flowing coolant stream. Each of these techniques has its advantages and disadvantages, almost always adding to the system mass. Clearly, there is a set of tradeoff parameters that must be manipulated to provide an optimum system for a given mission and, of course, it is impossible to simultaneously achieve the optimum in all parameters.

Under sponsorship of The Army Research Office, a workshop dealing with ThermoPhotoVoltaic (TPV) power technology was organized and held at the Washington Duke Inn & Golf Club. This workshop, Prospector VIII, is the eighth in the series. All have dealt with power technology and are interrelated to this workshop. The following is a list of the Prospector Workshops and their individual focus:

- Prospector I, Thermal Management of Space Based Assets,
- Prospector II, Radioisotope Power Systems,
- Prospector III, High Energy Density, High Power Density Power Sources R&D,
- Prospector IV, Small Engines and Their Applicability to the Soldier Systems,
- Prospector V, Microelectromechanical Systems, Their Applicability to the Soldier System,
- Prospector VI, Electric Actuation,
- Prospector VII, Small Fuel Cells for Portable Power, and

- Prospector VIII, Thermophotovoltaics, An Update on DoD, Academic, and Commercial Research.

In addition to the above Prospector series of workshops, The Army Research Office sponsored a workshop entitled "Mobile Battlefield Power," which was conducted in the same format as the Prospector series. All of these workshops produced technical documents that clearly identify key issues that must be addressed to advance the art and also have potential Army applications.

The focus of Prospector VIII is to assess whether or not Thermophotovoltaics is capable of meeting some of the needs of the Dismounted Soldier in the field. The requirements placed on power technology by the "Soldier System" concept are as demanding as that of any spacecraft and share many common requirements such as extreme reliability, safety, minimum weight and volume and, of course, the ever increasing demands due to environmental concerns.

There is always something in a name. Just as the prospectors of old sometimes worked the tailings of old diggings searching for a missed nugget, we too reviewed the current techniques "looking for nuggets," before embarking on a search of new ground. For this, we assembled a wide range of technologists--engineers, physicists, manufacturing specialists, and managers representing the government laboratories, industry and the university community. The groups were charged with evaluating thermophotovoltaic power technologies that might be relevant to the Dismounted Soldier. In addition, safety, environmental risk, manufacturability, fuel availability, and cost were factors that were considered within the framework of a politically viable, workable system. Only then, after a "decent assay of the ore did we file a claim."

In keeping with the tradition of the previous Prospectors, the workshop was patterned after the highly successful Gordon Conferences that have formal morning and evening sessions, leaving the afternoon free for recreation, small group discussions or laboratory tours at the participants' discretion.

The workshop was directed by a group of senior scientists from the Army Research Office, and The Space Power Institute at Auburn University. The broad technical base represented by the Board of Directors resulted in a unique agenda that effectively covered the multitude of both real and potential Thermophotovoltaic power technologies applicable to the Dismounted Soldier. The Board members are Dr. Richard Paur, Dr. J. Kruger and Dr. B. D. Guenther all from the Army Research Office, Mr. C. R. Johnson and Dr. M. F. Rose representing the Space Power Institute.

The workshop organizers would like to express thanks to the administrative staff of the Washington Duke Inn & Golf Club, Durham, NC, and to the Administrative Staff of the Space Power Institute for organizing and managing the workshop. Special thanks are due to Ms. Dana Latham and Ms. Patricia Lassiter, whose efforts contributed greatly to the success of the workshop and to this archival record.

The pages that follow contain a detailed record of the workshop procedures, an Executive Summary, the results and recommendations of the working groups, copies of the individual technical presentations and a list of the attendees. The attendees were key technologists from government, industry and academia. We appreciate their willingness to give their time and technical skills for this meeting and sincerely hope that this document represents an accurate distillation of the workshop deliberations. It is, after all, their collective opinion that is archived here and whatever impact this document has in the future is due to their deliberations.

We hope to see many of you at Prospector IX.

M. Frank Rose, Co-Director
For the Board of Directors

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

Thermophotovoltaics is the technology for photoconverting energy to electricity from an incandescent source which can be heated from any heat source. This technology is unique and has great promise for the development of portable power sources for the Dismounted Soldier. Consequently, a workshop on Thermophotovoltaics - An Update of DoD, Academic and Commercial Research, was held at the Washington Duke Inn & Golf Club, on July 14-17, 1996, sponsored by the Army Research Office.

To accomplish the objectives of the workshop, a group of scientists, active in the field, from government laboratories, industry and academia were invited to lecture on a wide range of topics germane to the emerging field of Thermophotovoltaics. The technical program consisted of plenary and state-of-the-art sessions covering as wide a range of relevant topics as the allotted time permitted.

Recent advances in the technology associated with Thermophotovoltaics suggest that power systems could be built in the range from a few watts to greater than 500 watts which would impact the requirements for the Dismounted Soldier. As the Army becomes more mobile, a premium is to be paid for capability, reliability and minimal mass systems. Improvements in photovoltaics and emitters, in terms of reliability, size, weight, and energy efficiency might translate immediately into increased capability and, perhaps, reduced cost. For example, a fueled system only has to convert the energy stored in the fuel at an efficiency less than 2% (JP - 8) to produce a power supply that is as energetic as existing batteries. Fieldable technology rarely equals laboratory prototype or theoretical capability. Obstacles sometimes are fundamental and perhaps can be finessed through appropriate R&D, innovative techniques, and skillful engineering. This workshop attempted to explore some of the possibilities. As confirmed by the plenary speakers and the working groups, there are a number of potential applications of Thermophotovoltaics for the military and the civil sector.

Thermophotovoltaics is multi-disciplinary. For example, solid state converters must be combined with a radiant element, which is heated from a fossil fueled combustion source. Further, the need for recuperation is paramount for efficiency. As confirmed by the plenary lecture from the Army Research Office, ARO is already investing in technologies which tend to define the state-of-the-art. The ultimate utility of Thermophotovoltaics may not reside in the fundamentals of the device itself but in such issues as: can it be manufactured in mass from affordable materials; can it be made robust enough and provide the reliability needed to function in a hostile environment; can it be engineered into a package with minimal signature, and will it provide an enhanced capability to the Soldier in the field.

As the workshop progressed, several pacing ideas emerged which were used to guide the workshop process. These are:

- There is a potentially large civil market for TPV;
- It is only necessary to convert the heat of combustion of diesel fuel at a rate of 1.3% to equal the energy storage values of the Army's BA5590 Battery;
- There does not appear to be any "fundamental physical reasons" why TPV systems cannot be built with modest efficiencies;

- There is a definite lack of engineering experience with TPV systems;
- There is a definite lack of standards and "agreed upon" test procedures; and
- A concerted program could field a device within 3-5 years.

Assess the State-of-the-Art of Thermophotovoltaic Systems by Characterizing Innovative Photoconversion Techniques and Determine Their Applicability to ARMY/DARPA/Civil Applications

Within the numerous organizations interested in TPV, there is a wide range of individual components whose principles have been demonstrated on the laboratory scale that would appear to be ready for rapid maturity if the applications are real. Examples include photovoltaic cells with conversion efficiency greater than 20%, blackbody-like emitters with emittance greater than 0.9, selective emitters which emit greater than 50% of the energy in a narrow band, burners with combustion efficiency greater than 90%, cavities where losses are just now being defined, filters with efficiency greater than 80% , coolant schemes which are readily adaptable to cooling the PV cells, and designs for high-temperature recouperators. To date, a few of these components have been assembled into laboratory systems which indicate feasibility and provide only inefficient demonstrators. The most prominent example which can be viewed is the "Midnight Sun™" device from JX Crystals.

Several programs are seeking power output greater than 500 W. Most of these are funded within the DARPA and Army programs and should provide laboratory demonstrations within one year. The emphasis to date has been on the demonstration of capability, materials, and processes for laboratory devices. Packaging issues are only now being addressed and should clarify many of the obstacles which must be overcome before major fieldable devices are possible. Very little attention has been paid to the demonstration of full up systems and the establishment of such engineering parameters as figures-of-merit, performance specifications for each component, range of parameters achievable for each component, etc. Efforts to establish an infrastructure are emerging. Major potential applications in the military are APU power, battery chargers, and direct battery replacement.

Within the civil markets, examples where TPV can potentially compete are in a cogeneration scheme with gas furnaces, gas water heaters and stand-alone auxiliary power for pleasure craft. To date, laboratory demonstrators have been less than 5% efficient. The technology is clearly available to build systems with efficiency greater than 10%. The most optimistic projections for efficiency are on the order of 30%. Until more emphasis is placed on recuperation, it is not possible to specify power density with high confidence. Power densities greater than 100 W/kg do appear reasonable.

Identify the Key Research Issues Pacing the Development (or Limiting Full Development) of Efficient, Mobile, Fieldable, High-power TPV Cells/system With Acceptable Life

The state-of-the-art is such that useful devices can be built with existing technology. However, the research and development issues necessary to optimize and improve performance can be divided into those which effect the materials technologies of the devices, their operating environmental response, and those which influence the manufacturing/packaging technologies.

There are a host of materials of use in TPV technology, especially in the radiating element. Both blackbody and selective radiators are possible and each technique has its advocates. In general, the material of choice has been at the discretion of the particular investigator. Little is known about the degradation (if any) which will occur when these radiators are operated at high temperature for long periods of time. As a result, there is a clear need to study strength, chemical composition, and vapor pressures at the operating temperature.

In order to make efficient TPV, optical recuperation as well as thermal recuperation is necessary. Optically, highly-efficient reflective filters are necessary. Numerous techniques were discussed at the workshop, but many of the techniques are company proprietary and thus only briefly described. Placement of the filter is critical for efficient optical recuperation. In any case, the filters will be subjected to the total radiant thermal flux and must be able to withstand considerably elevated temperatures. Highly efficient and cost- effective filters are key and should be researched in depth. In order to manufacture a TPV power system that is affordable, the cost of photovoltaic cells must be reduced by orders of magnitude. The requisite manufacturing technology will only be put in place if there is an adequate market. To date, the best cell technology is unidentified. GaSb and InGaAs and Si are contenders. Cells based on other materials should be researched. This will provide the necessary data to do a cost/efficiency tradeoff for applications. The difficulty with Si is the large bandgap which necessitates high temperatures within the TPV unit. These temperatures place unique demands on recouperators.

Recouperators are reasonably well established for temperatures compatible with high-temperature metals and alloys. Considerable investigation needs to be done to establish the technologies for temperatures greater than 1700 K. Due to the lack of complete systems, there is little data on subsystems interactions which will have to be overcome before a device can be fielded. As a result, there is a definite need for a model which could accurately predict system performance and subsystems interactions. Issues such as service life can only be discussed within the framework of a specific application and system concept. At this stage in the technology development, there are no specific devices which could be evaluated within the context of the battlefield environment.

Identify the Major Limiting Factors Which Must Be Addressed as Part of Overall TPV Cell/system Design

From the perspective of the Dismounted Soldier, a list of potential applications, as described within the workshop, should be scrutinized from the viewpoint of desirability, probability of successful development, and potential impact to the Dismounted Soldier if widely deployed. From an Army operational Army perspective, cost, reliability, maintenance, power capability, energy storage, availability, etc., are key issues to any large scale deployment. The level of TPV technology is immature and as such it is difficult to assess how well it will function in the Army environment. All of the equipment for the Dismounted Soldier must be enormously compact and rugged. Consequently, issues such as availability of fuel, energy density, power density, minimal signature (both thermal and acoustic), orientation-independence, ruggidization, simplicity of operation, and reliability are the major limiting factors from an operational point of view. Cost is always a limiting factor. These limiting factors translate to the materials issues discussed above as critical research issues since the limits placed on the materials directly determine operational limits.

Since TPV is just beginning to emerge, there is little data which can be used to judge performance within system configurations. These limiting factors are critical and a data base must be established before major fielding is possible. Cost effective photovoltaics will be enabled by sophisticated manufacturing techniques and civil demand which allow mass production with acceptable yield. That infrastructure and manufacturing technology is just now beginning to emerge and is a necessity if wide spread application is to proceed.

Prioritize Research Issues, Indicating the Impact if Research is Successful

TPV is at a stage where it should move into major demonstrations of its promise. The workshop unanimously agreed that the first priority is to develop complete systems. Since most of the components necessary to build a system have been demonstrated separately, it is time to "learn design rules" by trying. The idea is to force rapid learning by the need to rectify mistakes made in the development of systems. There is sufficient capability in several R&D organizations to build prototypic systems which could be evaluated in the field. Only in that mode can priority R&D issues be identified within the framework of application. Concomitant with these demonstrations, the necessary fabrication technology must be established. Research is needed to accurately characterize the capability of each component within the framework of the application to the Dismounted Soldier. The successful application of TPV must result in weight savings, cost effectiveness, added capability, and reliability. At the component level, the priorities are:

- Demonstration of a diesel burner/recouperator/emitter in an integrated unit;
- Development of optimized and affordable photovoltaic cells and;
- Development of the optical cavity consisting of emitter, photocell, and filter as an integrated unit.

Provide Milestones for Research Teams to Attain to Assure Significant Improvements in TPV Technology Over a Near-term and Long-term Development Program

The workshop participants identified several potential applications for the Army. The most promising were:

- Battery chargers/portable power units in the 150-500 watt range;
- Stand alone power which is PV by day and TPV by night, and;
- Direct battery replacement for batteries such as the BA 5590.

Given sufficient funding, the technical community should be able to produce a fieldable device for evaluation within three years. An engineering prototype could be built within one year thereafter. It was also the consensus opinion of the workshop that the prototype should focus on a battery charger/portable power unit since it appeared to be the least risky application.

Identify Operational/environmental Constraints Such as Materials, Signatures, Manufacturing, and Pollution Which Might Influence Applications or Improvements Envisioned

Within the framework of the Workshop, the participants identified the following operational constraints due to the peculiar nature of the requirements for the Dismounted Soldier:

- TPV must not have a signature which can be exploited by a hostile force;
- TPV must be capable of orientation independent operation in many scenarios;
- TPV must be robust and capable of sustaining mechanical shock typical of that associated with the battlefield environment, and;
- TPV must be equivalent or better than the currently deployed devices.

Establish Scaling Laws and, Wherever Possible, Compare TPV Innovations with Other Methods of Powering Army Systems

Simple scaling which can be used as a preliminary "yardstick" can be derived from the response of the photovoltaic cells and assumptions about the efficiency. For a given illumination intensity, the power output scales linearly with the area of the photovoltaic array. The energy scaling is solely related to the system efficiency. The total mass of the system is quickly dominated by the fuel mass. There is a minimum mass of the system which is determined by such items as fuel tank, recouperator, cell array and structure, coolant scheme, and any controls, etc., which are necessary to make the device user friendly. It is impossible to determine how these components effect scaling until some complete systems are built. After fuel mass dominates the equation, scaling is linear in fuel mass. Only within the framework of an application, does size and capability have meaning. As systems emerge, detailed scaling can be established.

Specific conclusions from each of the working groups are included in the working group summaries and have been used to generate the response to the objectives of the workshop as listed above. There are several general conclusions as stated below:

TPV has the following positive attributes:

- Capable of using logistic fuel directly;
- Inherently quiet operation;
- Intrinsically lightweight;
- Low emission;
- Multifuel capable;
- No moving parts in the main power stream;
- Cogeneration compatible;
- Tolerant of low temperatures;
- Moderate efficiency;

- Simple to start, and;
- Throttleable.

TPV has the following negative attributes:

- TPV must operate at elevated temperatures for efficient conversion;
- Limited industrial base;
- Poor systems experience, and;
- May have thermal signature.

There was a general consensus that the highest priorities are not research issues. The major issues are associated with systems engineering. There is a strong need for standards, good systems models and demonstration devices from which detailed scaling laws can be verified.

It was the general opinion of all of the working groups that the 100-500 watt units were far easier to engineer than those intended to be "worn" on the individual solder as a battery replacement.

Successful development of military units would be a means of developing a large civil market which would support further development. It was estimated that the cost of a 2 kW " Honda Generator" would be on the order of $0.75/W and would be the technology to beat for many markets. Optimistic projections of the ultimate cost of TPV were on the order of $0.35/W.

It was the unanimous opinion of the participants that "TPV" is capable of providing significant and useful power sources for both civil and military applications.

INTRODUCTION

INTRODUCTION

Prospector VIII is the eighth in a series of workshops dealing directly with advanced technologies applied to the individual soldier's needs. Recent advances in ThermoPhotoVoltaics (TPV), as presented at the NREL Conferences, have suggested that TPV might play a key role in future power systems for the Dismounted Soldier. As the Army becomes more mobile, a premium is to be paid on reliability and minimum mass systems. Improvements in power technology and systems in terms of reliability, cost and maximum energy/power density translate immediately to increased capability and reduced cost.

In November, 1990, the first workshop on Mobile Tactical Battlefield Power Technology was held at the request of the Army Research Office. One of the major findings from this workshop was the need for research and development to improve the Army power technology at the low end of the scale. Power technology up to about 500 W and man portable are absolute keys to the effectiveness of Army mobility. Further, issues of autonomy time, reliability, scaling and cost were not clearly defined and pointed to the need for other workshops dedicated to subsets of the Army's power needs. The second power workshop on key issues in Electrochemical Power Technology was held at the Auburn University Hotel and Conference Center on May 27-28, 1992. That Workshop was requested by the Department of the Army, Assistant Secretary of the Army for Research, Development and Acquisition (ASARDA), and was sponsored by the Army Research Office. The focus for that workshop was the peculiar challenges for power technology associated with the Soldier as a System and the ability of electrochemical power sources to meet the requirements.

The enormous energy stored in the nucleus is an attractive source if means can be invented to access this energy in a cost effective and environmentally safe way. To assess this technology, Prospector II studied Radio isotope powered (RTG) systems with emphasis on whether they could meet any of the Army's needs. Since small combustion driven engine-generator systems also appear capable of performance within the requirements for the soldier system, the focus of Prospector IV was on the capability of these small engine-generator systems and the problems which must be solved prior to placing in the inventory. Within the scope of the Soldier as a System, there is a wide range of power requirements depending upon the mission duration and the capability needed for the mission. At Prospector IV, it was pointed out that there was a new and emerging technology of miniature machines or "systems on a chip" which could be applicable to all of the technologies discussed in the Prospector series of workshops and might also provide new capability. For that reason, Prospector V explored the application of "MIMS" technology to Army needs with special emphasis on the Soldier System. Prospector VII focused on small fuel cells which are even now being evaluated for use in a battlefield environment. Since TPV is emerging and could use battlefield fuels, a workshop in this area was highly desirable to assess the potential of TPV and to put its attributes in perspective with respect to competitors such as batteries, fuel cells and small motor-generator sets. *The goals of the workshop are to draw the participants' attention toward three major sets of criteria -- requirements, key research issues, and projected capabilities and development opportunities.* The specific goals, as determined by the Board of Directors, are to:

- *Assess the state-of-the-art* of thermophotovoltaic systems by characterizing innovative photoconversion techniques and determine their applicability to ARMY/DARPA/civil power applications;

- *Identify the key research issues* pacing the development (or limiting full development) of efficient, mobile, fieldable, high-power TPV cells/systems with acceptable life;

- *Identify the major limiting factors* which must be addressed as part of overall TPV cell/system design;

- *Prioritize research issues*, indicating the impact if research is successful;

- *Provide milestones for research teams* to attain to assure significant improvements in TPV technology over a near-term and long-term development program:

- *Identify operational/environmental constraints* such as materials, signatures, manufacturing, and pollution which might influence applications or improvements envisioned; and

- *Establish scaling laws* and, wherever possible, compare TPV innovations with other methods of powering Army Systems.

To accomplish these goals, a group of scientists and engineers, active in the field, were invited to present current perceptions of the state-of-the-art in ThermoPhotoVoltaics. A plenary session was organized to present a government and industrial perspective on the potential of TPV and to provide insight into the state-of-the-art. The plenary agenda is shown in Figure 1.

PLENARY SESSION - PERSPECTIVE
Chairman: Mr. C. Johnson (AU)

- "Why Are We Here Anyway?," Dr. Dick Paur (ARO)
- "TPV Research Sponsored by ARO," Dr. Jack Kruger (ARO)
- "TPV: An Industry Perspective," Dr. Paul Baldasaro (Lockheed-Martin)
- "Why Should NASA Care, Where Should We Go?," Dr. Dennis Flood (NASA Lewis)
- "Competing Technologies for TPV," Dr. M. Frank Rose (Auburn)

Figure 1.

As confirmed by the plenary speakers, the interest in TPV is wide spread and there are potential military, space and civil applications. Many of the applications would appear to be near term if cost is not a factor.

To accurately determine the applicability of TPV, it is necessary to attempt to define the state-of-the-art in the relevant technologies. Therefore, to assist in the workshop process, scientists and engineers, active in the field, were invited to present technology summaries describing the state-of-the-art, near-term-state-of-the-art and to give their opinions of ultimate limits with some considerations for practicality. The agenda for the technology sessions is shown in Figure 2.

TECHNOLOGY UPDATE SESSION I

Chairman: Dr. Frank Rose

- "Liquid Fuel Combustion," Mr. Malachy McAlonan (Teledyne-Brown)
- "Recouperates for TPV Systems," Mr. Fred Becker (Thermo Power, Tecogen)
- "Systems Aspects of TPV Energy Conversion," Mr. Ed Doyle (Tecogen)
- "Small Radioisotope TPV Generators," Mr. Al Shock (Orbital Sciences Corp)
- "NREL TPV Activities & Capabilities," Dr. Tim Coutts (NREL)
- "Status of JPL TPV Research Effort," Dr. Amy Ryan (JPL)
- "Advanced Detectors," Mr. David Wilt (NASA Lewis)
- "Minimal Losses in TPV Systems Using Line Emitters and Selective Filters," Dr. Ed Horne (EDTEK, Inc)

TECHNOLOGY UPDATE SESSION II

Chairman: Dr. Henry Brandhorst

- "Selective Emitters," Dr. Don Chubb (NASA Lewis)
- "Status of TPV Research at SPI," Mr. Peter Adair (Auburn)
- "Emitter Fabrication," Dr. Zheng Chen (Auburn)
- "A Model for Predicting TPV System Performance," Mr. Ken Schroeder (Auburn)
- "Cell Fabrication," Dr. Paul Sharps (Research Triangle Institute)

Figure 2.

The remainder of the workshop was spent in small working groups centered around:

- Customer Requirements, Specific Mission Needs, State-of-the-Art
- Key Research Issues, Major Limiting Factors, Constraints
- Strategies & Technologies, Priorities, Near & Long-Term Developments, Milestones to Achieve Priorities

In a final session, the working group chairmen presented a summary of their group's deliberations and findings to the general assembly of participants. As usual, considerable lively discussion attended each report and was incorporated as accurately as possible in the executive summary results.

The 50 participants were drawn from Industry (26), Academia (10), and Government Laboratories/National Laboratories (14) and represented an adequate cross-section of scientists and technologists working, or interested, in the field. The remainder of this document is a collection of the workshop presentations and summaries from the working groups.

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WORKING GROUP DELIBERATION SUMMARIES

WORKING GROUP 1 SUMMARY

TPV: An Update on DoD, Academic, and Commercial Research

Washington Duke Inn & Golf Club
July 14-17, 1996

Charge to the Working Groups

General to All Groups:

- Where possible, compare with other (competing) methods of powering Army systems.
- In general, the focus of the workshop is toward the dismounted soldier.
- Power range of interest is from about 5 Watts for chargers to roughly 500 Watts for a "one man portable" device.

TPV: An Update on DoD, Academic, and Commercial Research

Washington Duke Inn & Golf Club
July 14-17, 1996

Charge to the Working Groups

Group 1:

- **Address the state-of-the-art in terms which describe capabilities, performance, cost, technological limits. Project growth in capabilities if evolutionary, or if revolutionary.**

- **Who are customers? What are their requirements? What are the military and civil "mission scenarios?"**

- **Suggest innovative concepts or designs which should be pursued by defining their scope relative importance, timing. Compare and contrast options/tradeoffs suggested in your plan.**

Prospector VIII: "TPV - An Update of DoD, Academic, and Commercial Research"

Working Group #1 Summary

Customer Requirements, Specific Mission Needs, State-of-the-Art

INTRODUCTION

The Customer Requirements, Specific Mission Needs and State-of-the-Art Group (Group 1) examined the state-of-the-art in ThermoPhotoVoltaic (TPV) devices, and attempted to assess their present cost and technological limits. In addition, the group did an extensive comparison of TPV with other sources of power and delineated its advantages and disadvantages. System testing was proposed as the next logical, essential step in the evolution of TPV technology. Specific charges to the group were:

- Address the state-of-the-art in terms which describe capabilities, performance, cost, and technological limits. Project growth in capabilities, if evolutionary, or if revolutionary.
- Who are the customers? What are their requirements? What are the military and civil "mission needs"?
- Suggest innovative concepts or designs which should be pursued, by defining their scope, relative importance, timing, and to compare and contrast options/tradeoffs suggested in our plan.

A common, general charge to all working groups included the following:

- Where possible, compare with other (competing) methods of powering Army systems.
- In general, the focus of the workshop is toward the dismounted soldier.
- Power range of interest in from about 5 watts for chargers to roughly 500 watts for a "one man portable" device.

WORKING GROUP PARTICIPANTS

The working group participants were drawn from military, industrial and academic organizations allowing a broad perspective of the issues involved. The group was heavily weighted by industrial producers of TPV technologies and systems. Thus insights into the technological issues and drivers for the technology were at hand. Of significant benefit were the insights of a major supplier of commercial equipment fielded in difficult locations. The participants were:

• **Henry Brandhorst, Chair** (Auburn)
•• Peter Adair, Recorder (Auburn)

Guido Guazzoni (U.S. Army)
John Szentes (Caterpillar)
Ed Horne (EDTEK)
Al Schock (Orbital Sciences)
Al Newhouse (Newhouse Consulting)
Malachy McAlonan (Teledyne-Brown)
John Remo (Quantametrics, Inc.)
Linda Garverick (Essential Research)
Harvey Serreze (Spire Corp.)
Steven Flammang (Tecstar, Inc.)
G.H.B. Schaffer (Quantum Group)
Don Hindman (Babcock & Wilcox)
Norbert Elsner (High Z Tech.)
Jack Kruger (ARO)

DISCUSSION

Specific Applications and Requirements

Initial discussions focused on Army requirements for some TPV-potential applications. The applications included a 300-500 W battery charging station using liquid or gaseous fuels and weighing roughly 10-15 lbs. Another was a replacement for the hand-cranked generator, able to supply 20-30 W at night (PVs would be used to power the system when sunlight was available). A replacement for the 5590 Battery that could supply 5 W continuous and 50 W peak was also examined. Other applications that could take advantage of the cogeneration (able to supply both heat and electricity) capability of TPVs were discussed in lesser detail. These included shower and laundry equipment and kitchens. Radiant heating (using the emitters' narrow spectral emissivity to more efficiently dry products) was also discussed as an example of a market using TPV-related technologies. Finally, some discussion was devoted to larger power requirements such as APUs and UPSs, but the discussion was limited as these systems generally exceeded the workshop guidelines.

Design Issues

Design issues specific to TPV systems for these applications were discussed and these served to identify some technological issues that must be addressed before reliable TPV systems can be fielded. Issues included: emitter strength and lifetime, outgassing/fogging of optical elements, nonuniform illumination and/or heating of the photovoltaic cells, reliable ignition and combustion of liquid fuels and ability to meet milspec requirements.

Markets

It was generally recognized that a TPV system includes many items that are marketable on their own. Successful marketing of these byproducts of TPV efforts could be important to the overall success and continued development of thermophotovoltaics. Some of the items included recouperators, emitters, burners, filters, photovoltaic devices and fuel atomization schemes.

Concern was expressed that Army applications were insufficient to fuel a large market for TPV systems. It was easily concluded that other segments of the DOD could equally benefit from TPV systems given successful demonstration. Remote power for Air Force and Navy systems were a topic of discussion, but no specific applications were delineated. Substantial discussion was devoted to potential civilian customers. Applications discussed in limited detail included auxiliary power on yachts, sailboats etc., recreational vehicles and small motors such as for snowmobiles and other small motors in the 1 to 10 kW range. It was also noted that the marketplace was not constrained to the U.S., but that many international opportunities exist.

Many applications discussed would take advantage of the quietness of TPV power systems and their ability to be fueled by conventional liquid fuels. Specific other attributes of TPV systems included: simplicity of design, tolerance to long periods without use, portability (smaller systems), potentially low thermal signature, low EMI and cogeneration of heat and electricity.

Competing Technologies

Extensive discussion was devoted to uncovering the advantages and disadvantages of TPV systems compared to other competing technologies. Specific competing technologies included: thermoelectric generators (TEG), fuel cells, solar PV/batteries, Stirling, motor/generators, batteries and small turbines. In general, the main advantages of TPV were application dependent but included: higher efficiency and power density potential, direct use of logistic fuels, simplicity, ability to exploit waste heat, small footprint, no vibration or noise, DC output, and wide turndown. The disadvantages included: low maturity, higher cost, operating temperature, and lower efficiency (for some applications). The attached charts detail the specifics for each competing technology. The opinion was expressed that small turbines were the main competition for TPVs in view of recent advances in that technology.

TPV System Validation

In order to overcome some of the disadvantages outlined above, the group felt strongly that system level demonstrations were essential. They believed that the technologies had matured to the point that such demonstrations could also be used to uncover the strongest of the competing technologies, whether they be emitters, optical filtering/processing, cell and thermal designs, recouperator designs and cogeneration schemes. The recommended size for these demonstrations was in the range of 500 W to 2 kW. While this was mostly outside the range of the guidelines provided, the group believed that somewhat larger demonstrations were appropriate. However, any size demonstration was certainly preferable to no demonstration. The purpose of these demonstrations would be to demonstrate efficiency, reliability, and technology option viability.

A concern expressed was that the TPV community has many disparate entrepreneurs and organizations that support it. In general, these organizations remain separated from each other to foster their competitive positions. It was strongly expressed by the group that this separation actually promotes weakness and lack of focus in the industry. Furthermore, because of the limited capitalization of many of the organizations, privately sponsored demonstrations of reasonable level are impossible. Thus the following approach was proposed:

> "The government should offer substantial funds (~$10M) to both validate competing consortia and to select at least two of them to deliver a DOD acceptable product in 4 yrs."

In this manner, a companies could define a competitive TPV system for a specific application and seek out the best industrial teaming arrangements that would allow implementation of that concept. The government, through a validation process conducted while detailed proposals were being developed, could be assured that credible teams were assembled and could deliver the system in the time frame. Additionally, the requirement that the consortia have an organization in the DOD that agreed with the product and would procure such systems upon successful demonstration would ensure relevance. Overall, the development of the consortia and the variety of technologies proposed for various systems would allow determination of the strongest technologies and system designs. This would have the effect of consolidating and thereby strengthening the entire field.

Cost of TPVs

Due to the relative immaturity of the field, it was not possible to obtain reliable, valid and conclusive information as to the cost of TPV systems. The group did suggest that the descending order of cost drivers was: cells, emitters, filters and recouperators. There were differences of opinion as to the exact order after cells, however. Some felt that recouperators were next in line. In view of the absence of system level demonstrations, such cost driver ordering appears speculative.

Some cost goals were suggested for TPV systems. These were based on the ability to compete commercially with small motor/generator sets in the few kilowatt range. While this may be an optimistic market and there may well be others that will tolerate higher cost, the group preferred the strong challenge. Thus a goal of 35¢/W was proposed.

SUMMARY

Several Army applications were used to set the stage for discussions of TPV systems and state-of-the-art. Subsequent comparisons of TPV systems against competing technologies including thermoelectric generators, fuel cells, solar PV/batteries, Stirling, motor-generators, batteries and small turbines for a range of applications were made. These comparisons allowed clarification of TPV attributes and limitations. It was concluded that the absence of system level demonstrations has not allowed a downselection of the strongest technology options and system concepts and the strongest industrial teams. Nor has it allowed potential users to ensure themselves of TPV system viability and competitiveness. Thus credible, government-sponsored demonstrations conducted though validated consortia with assured DOD customers were proposed in order to validate this technology. It was also observed that many of the separate elements of the TPV system may also be separately marketable to provide cash flow. Applications such as radiant heating to dry things (e.g. crops, laundry) was noted as a specific application to highlight that possibility. It was noted that the international marketplace should be a strong consideration. Optimistic cost goals of 35¢/W were suggested.

WORKING GROUP 2 SUMMARY

Charge to the Working Groups

General to All Groups:

- Where possible, compare with other (competing) methods of powering Army systems.
- In general, the focus of the workshop is toward the dismounted soldier.
- Power range of interest is from about 5 Watts for chargers to roughly 500 Watts for a "one man portable" device.

TPV: An Update on DoD, Academic, and Commercial Research

Washington Duke Inn & Golf Club
July 14-17, 1996

Charge to the Working Groups

Group 2:

- Address key issues, limiting factors, constraints, & objectives of TPV technological improvements (cell or sys).

- Answer as many discussion questions as possible, i. e.

  - What must be done to influence specific improvements in TPV technologies? What kind of investment(s) helps? What are valid test and evaluation criteria? Does "it" scale?

  - Does "what must be done" change when military or commercial applications are considered? Is so, how, what, when?

Prospector VIII: "TPV - An Update of DoD, Academic, and Commercial Research"

Working Group #2 Summary

Key Research Issues, Major Limiting Factors, Constraints

The working group consisted of a balanced mix of the participants representing the University, Government Agencies, and Industry. The group consisted of the following:

- **Frank Rose, Chair**
- •• Ken Schroeder (Auburn)

Margaret Ryan (JPL)
Aleksandr Kushch (Quantum Gp)
Brian Zelinski (Univ of Arizona)
Paul Sharps (Research Tri Inst)
James Phillips (Univ of Delaware)
W. F. Micklethwaite (Firebird Semicon)
Bob Guenther (ARO)
Navid Fatemi (Essential Research)
Ed Doyle (Thermopower Corp)
Don Chubb (NASA Lewis)
Charles Blatchley (Pittsburg State)
Paul Baldasaro (Lockheed Martin)
Mike Timmons (Research Tri Inst)
Lewis Fraas (JX Crystals)
Jerry Beam (Wright Labs)
Robert Rosenfeld (DARPA)
Brian Good (NASA Lewis)
Mark Goldstein (Quantum Group)

The sessions began with a detailed discussion of the requirements and applications which were envisioned for the military. In terms of energy, the "technology to beat" was judged to be batteries which have a specific energy on the order of 175 Whrs/kg(BA-5590) and a specific power on the order of 20-50 W/kg. By contrast, it was pointed out that the battlefield fuels had energy densities on the order of 13,000 Whrs/kg and conversion of this stored energy to electricity at an efficiency of 1.33 % would be equivalent to the BA-5590 battery in terms of storage density.

The most demanding application was the need for microclimate cooling. With mission times on the order of 72 hours, the power requirement is about 300 W peak with a total energy budget on the order of 4800 Whr. For the electronics suite only, the power level is on the order of 25-50 W. This 25-50W applies to all of the "fighting" soldiers, which is about 20% of forces. The panel considered the question "Will rechargeable batteries with TPV charger be good enough?" If so, in what scenarios.

The panel assumed that the Army goal is to operate under all conditions. In current scenarios, the microclimate cooling requirement has been reduced from 72 hours to 12 hours.

Within the framework of a light infantry battalion (>200 fighters), the "per week" cost while fighting is approximately $46,000 for batteries. It was estimated that the costs would rise to approximately $151,000 with new systems. A cost of $28.00 per battery was assumed.

The discussions of weight of any proposed system was in terms of the dismounted soldier. Within that context, power systems which he would personally carry would weigh less than 5 kg, including fuel, and the minimum power of interest would be on the order of 5 watts. At the other end of the scale, a "man portable" unit might weigh in excess of

25 kg, including fuel, and be carried as a separate "charger" to a central location. The upper limit on power considered by the group was 500 W but it would be desirable for the converter unit to operate at a power density greater than 20 W/kg. The amount of fuel would determine the total mass. It was the opinion of the panel that the 500 W units were far easier to construct than the smaller units intended to be "worn" on the person of the individual soldier as a battery replacement.

Since the soldier is dismounted, the time for operation of a system of this type is a function of the mission and, as such, was not specified within the panel's discussions. In the limit of long run times, the mass of the system is totally dominated by the fuel mass. For long missions, the device could be refueled by air drop or some other suitable means of delivering fuel to the individual unit. The "shelf" life of individual units should be essentially infinite and require little or no maintenance. In operation, lifetimes greater than 1000 hours were mentioned with limiting factors poorly understood.

Since this technology utilizes the battlefield fuels, the environmental effects would be minimal and on the same order as existing equipment. Several of the panel members did mention the possibility that the combustion process could be controlled sufficiently to minimize NO_x emissions. The units would probably contain a small rechargeable battery which could present minimal disposal problems.

While successful development of commercial markets are a goal, the requirements for a military application are significantly different. The need for ruggedization, minimal mass, reliability, and minimal "hostile exploitable" signature are unique to the military and would require a technological sophistication in excess of that necessary to penetrate the civil markets. Nevertheless, it was judged that the basic components, emitters, PV cells, recouperators, and cooling schemes were common.

Cost was an issue both for the commercial arena and the military. It was estimated that the cost of a 2 kW "Honda generator" would be on the order of $0.75/W and would be the "technology to beat" within some civil markets. The panel judged that some civil markets such as the luxury yacht auxiliary power would not mind paying a premium for a quiet unit. Optimistic projections of ultimate cost, if a sufficient R&D program were completed, was on the order of $0.35/W.

The panel discussed the general attributes of TPV within the context of the state of the art as presented in the workshop sessions. The following are general attributes:

Positive attributes

- Inherently quiet operation
- Intrinsically lightweight
- Capable of using logistic fuel directly
- Low emission
- Multifuel capable
- No moving parts in the main power stream
- Cogeneration compatible
  - Convenient for incidental electric generation on heating systems
- Tolerant of low temperatures
- Moderate efficiency
- Simple to start

- Excellent dormancy
- Throttleable

Negative attributes

- Must operate at elevated temperatures
- Limited efficiency
- Limited industrial base
- Poor systems experience
- May have thermal signature

The panel compared the projected performance parameters with respect to some competing technologies. TPV has the promise of being far more efficient when compared to thermoelectric power generation. Further, the cost of the TPV elements should be less than the thermoelectric elements. The power and energy density is greater than thermoelectric generators.

When compared to fuel cells, the TPV is multifuel capable as well as being able to use logistics fuels. It is, however, less efficient by better than a factor of 2. Both fuel cells and TPV are airbreathers and should have comparable power densities.

When compared to batteries, the TPV technology is far more energy dense and has a low life cycle cost. Further, the ability to refuel and the "infinite" shelf life are attributes that are not achievable for typical battlefield batteries. Their power density is far greater than batteries.

The panel next discussed the general specifications which would determine a system for military applications. From an overall perspective, the panel considered the primary specifications to be:

- Power density
- Energy density
- Efficiency
- Life
- Cost

At the systems level, the panel considered the following to be the characteristics which should be considered within the framework of military applications:

- Use of logistic fuels
- Replenishment scheme
- Weight of fuel needed as recharge

As operational issues, for any system, the panel considered the following issues to be crucial to any successful deployment of TPV technology in the battlefield:

- Start-up issues, the soldier would want only to "flip a switch" for instant on operation
- Automatic shut down and turn on as appropriate in a hostile environment

- Heat rejection, especially in a man portable application since this could increase his thermal load
- Purity of the air supply needed for combustion
- Control of the thermal signature
- Modularity and ease of repair
- All orientation operation

Within the context of determining the above, the panel determined that there was a need for a "working model" of the soldier which could help in determining the best size to develop. The panel also thought that there might be some hesitancy on the part of the soldier to use an unfamiliar technology. The panel thought that soldier input would also help to decide what would be the most use:

- Stand alone battery replacement
- "PV by day, TPV by night power system"
- Battery charger

It was the unanimous opinion of the panel that there were no "fundamental problems" standing in the way of the development of systems which were on the order of 10% efficient. Further, the panel thought that the upper limit on efficiency is on the order of 30% and is governed mostly by the fundamental physics of photovoltaic materials and the wavelengths at which energy can be efficiently photoconverted.

The panel unanimously agreed that the highest priorities are not research issues. The major issues are associated with systems engineering. The following **systems issues** were discussed and judged to be critical:

Good high fidelity systems models which would include

- Systems geometries
- Uniformity of emitter temperature
- Flow paths for fuel and air
- Recouperator design and integration in a compact system
- End effects and reflectors in the cavity
- Systems weight
- Power density/energy density
- Systems tradeoffs such as emitter type, etc.
- Temperature limits within systems
- Scaling capability

Matching of the emitter, filter and photovoltaic cell in a cavity

- Optimize the cavity as a unit
- Materials compatibility
- Effects of thermal cycling
- Effects of material evaporation at high temperature

Burner and recouperator design and fabrication issues

- Fuel versatility, multi-fuel capable
- Fuel injector
  - Liquid fuel atomization
  - Low power
  - Throttleability
- Recouperator
  - High temperature operation
- Coupling to the emitter
  - emitter edge effects
- Orientation independence
- Cold start-up
- Ignition system

Photovoltaic

- Cell cost
  - Materials must not be exotic
  - Processing should be simple
  - Cost models and volume production
- Cell cooling schemes
- Cell coatings
  - Protection
  - Spectral control
- Spectral control within the cell
- Manufacturing technology
- Tolerance to non-uniformity
- Interconnections
  - Integrated
  - Design to prevent arcing
- Fault tolerance
- Multiple designs
  - Need standard designs
  - CAD/CAM systems

At the component level, the following items were judged to be relevant and further research would improve performance. However, improvements in these elements were not critical to "entry level" systems at about 10% efficiency.

Filter technology

- Diffractive filters are emerging
- Cooling of filters
- Performance including losses, efficiency and cut off characteristics
- Thermal sensitivity
- Integration within PV Cells

Emitter

- Effects of continuing high temperatures on the materials
  - Changes in grain size
  - Wear and replacement of emitters
  - Vapor pressures
- Multi-constituent emitter to tailor emission to spectral characteristics of cells
- Emitter support structure
- Physical strength
- Attachment to fuel system and recouperator

The panel agreed that there is a need for standard methods and approaches to defining the performance of TPV components. The panel realizes that this is difficult to do because there is a coupling of the components and many systems choices. It is necessary to develop standards for emitters, both blackbody and selective, which allow systems choices. In order to facilitate standard measurements, there also needs to be an "agreed upon" set of definitions.

Within the research community there is a wide range of entrepreneurs and organizations who are actively engaged in TPV. All have been working under the assumption that there will be applications if the technology can be reduced to practice. It was generally concluded that many of the applications were vague and in need of definition. The efforts within this community have, until now, been primarily concerned with components instead of systems. It was generally acknowledged that there was a general lack of experience in building TPV systems within the community and that there is not enough funds available to adequately cover the field. As a result, there is a distinct need for wide scale collaboration. To that end, the government as the funding source needs to foster the formation of consortia and teams in the short term to define the technology. From these efforts, a substantial funding level needs to be put forth to build real systems which could be tested under simulated battle conditions.

The panel closed its deliberations with the observation that the development of integrated systems has the highest priority. The general idea is to learn the design rules by conceiving systems and trying to build them. In this mode, demonstrators will emerge as well as key R&D items which will extend the systems state-of-the-art. The general approach should be to develop teams. This will force teams to build systems which will have flaws and mistakes and, as a result, stimulate rapid learning.

By developing working systems, the next level of component research needed to improve systems will be identified. By this process, poor approaches will be eliminated, the reliability of components will be established and demonstrated, efficiency will be determined and refined, poorly performing subcomponents will be redesigned, and better methods of fabrication will be established. All these will lead to sample fieldable units within a couple of years and eventually to production.

Specific Panel Recommendation

- Focus on portable generator sets up to about 500 W which could be used as chargers or as stand alone units
  - Probability of near-term success high
  - Meets Army priorities
  - Use as a basis for scaling, life cycle costs, and efficiency determination

- Take a diverse approach in two phases
    - At least two approaches in phase I
    - Compete approaches and downselect
    - Take winner to engineering prototype
- Funding requirements
    - Phase I funds need to be on the order of $15 M over a 3-4 year period
- Phase II funds need to be on the order of an additional $10M
    - Ask for cost sharing from the industrial sector since significant commercial potential exists
- Extensive teaming highly desirable to marshal and conserve resources and to enhance the probability of a successful system

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WORKING GROUP 3 SUMMARY

Charge to the Working Groups

General to All Groups:

- Where possible, compare with other (competing) methods of powering Army systems.
- In general, the focus of the workshop is toward the dismounted soldier.
- Power range of interest is from about 5 Watts for chargers to roughly 500 Watts for a "one man portable" device.

TPV: An Update on DoD, Academic, and Commercial Research

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Charge to the Working Groups

Group 3:

•• Near & Long-term Development: There is keen interest in a portable system which is small enough to fit on a person's belt, as well as one which can be carried on a person's back. Describe, or quantify the specs, critical design parameters, break-throughs required, limitations, etc.

•• What strategy did your Group use to arrive at these decisions? Does it vary from military to commercial? Where do you think the money will be coming from, and why?

•• Provide milestones for research teams to attain or assure significant improvements in TPV tech. What is time-frame involved? Given an urgent need, can one "surge" to production?

Prospector VIII: "TPV - An Update of DoD, Academic, and Commercial Research"

Working Group #3 Summary

Strategies & Technologies, Priorities, Near and Long-term Development, Milestones to Achieve Priorities

Introduction

Background

Working Group 3 focused on the strategies and technologies, near- and long-term development, and milestones necessary to achieve the priorities which it believed represented the direction for the nation's TPV program. The Group also ensured that the Army's priorities would drive the direction of any major TPV development. Initial questions were fundamental -- why should there be a TPV program? What does TPV bring to the playing field that other technologies lack? What price is paid for TPV over other technologies? What is the cost of conversion from other technologies to TPV? What are the limitations to TPV? Are there other markets should TPV become technologically achievable at a reasonable cost? What breakthroughs are required to make TPV viable? How should the Army proceed toward a TPV program, given the assumption that the technology offers great promise? What recommendations would the Group make to Army developers" In what time frame does TPV appear achievable?

Working Group Participants

The Group's representation provided emphasis in the three major areas of TPV development, namely the DoD, industry, and the academic community. An Army Research Office participant offered valuable insight into the Army's priorities and the status of current programs.

- Dennis Flood (NASA Lewis), Chairman
- Cal Johnson (Auburn Univ), Recorder

- Tim Coutts (NREL)
- Dan Krommenhoek (Lockheed Martin)
- Bill Berry (Notre Dame)
- Frank Vicente (Lockheed Martin)
- Eric Barringer (Babcock & Wilcox)
- James Avery (JX Crystals)
- Phillip Jenkins (Essential Research)
- Edward West (Western Washington U)
- Dick Paur (ARO)
- Eric Clark (NASA Lewis)
- Bill Biter (Sensortex)
- Fred Becker (Thermopower)
- David Wilt (NASA Lewis)
- Mark Goldstein (Quantum Grp)
- Zheng Chen (Auburn Univ)

Discussion

Requirements

The Group believed that a major consideration for TPV application was a major Army battery program where TPV could "fit" and would offer such qualities as a marked technological advantage, improved efficiency and reliability, and a competitive cost. The battery program which immediately under discussion was the BA5590 replacement program. After considerable discussion, the Group developed a set of criteria which it believed would ensure that any TPV device could replace the BA5590. That criteria required that any TPV device should have an "instant recharge" capability (i.e., refueling capability), should be a fully integrated unit, should possess a 50W peak power where it could sustain continuous use at less than 5W, and should have a low thermal signature with an outer skin temperature of less than 120 degrees F. Additionally, the device should be suitable for use in close or confined spaces, and it should be operationally usable in water or wet conditions.

The Group had hopes that any such TPV development could find applications in more than 100 different devices, typical of the BA5590 application. Operational requirements were carefully chosen, and it was recognized that further study might modify this initial set of data. In the transmit mode, the TPV should be expected to expend 35W for 20% of time and 3W for the remainder of the duty cycle. Ideally, there should be a load leveling capability inherent within the device.

Attraction of TPV - Pros and Cons

There were a number of attributes which made the TPV technology to participants. First, in comparison to the well-used and well-studied BA5590 in use by today's Army personnel, TPV has a comparatively high energy density. Additionally, when again compared to the BA5590, the TPV could be said to have an "infinite" shelf life. TPV also has, possibly, the ability to be fired using multiple fuels. It is simple, reliable, and robust. Designs point to a typically modular construction. TPV will be considered environmentally benign, a point which many participants said should be taken lightly in today's climate.

When making a life-cycle comparison with respect to batteries, the TPV system is low. One reason was pointed out by a participant from another Group: although it costs approximately $62 to buy a typical Army battery, it costs an additional $28 to dispose of it. Again, a TPV system has a low noise level, an attribute which is favored on the battlefield. Finally, it was believed that high efficiency is not required in order for TPV to be competitive with batteries. Efficiency is an effective selling point, participants, and this attribute should be used to show potentially rapid gains in capability when TPV is employed with improved efficiencies.

Limitations

This particular topic area stirred some interest during the outbrief to the entire Workshop assembly due to the various ways in which load management could be defined and measured (evaluated). For example, turn-down in the burner and/or recouperator could be a problem for the TPV system. One participant discussed the fact that a "hybrid" vehicle presented a real challenge. The general belief by participants was that if one were designing a system for "full load" or "partial load," then load management becomes a significant issue, and might even be considered a "limitation" by some designers. A final comment was that "networking is a very, very important issue when switching from power to full load."

It was conceded that there was really no long-term experience or installed capability which could be used as a benchmark by the Group in its analyses. In addition to load management issues, other limitations included the lack of a component vendor infrastructure, a low peak efficiency in comparison to conventional generator sets, a slow response start-up, and thermal fatigue or creep in ceramics design limitations to be overcome.

Army Priorities

The Army needs a replacement for the BA5590; approximately 300,000 units/year are needed. In the category of portable generator sets, the Army needs approximately 5,000 units/year. The Army recognizes that it does not make the market in this category of units (up to 500W for a TPV replacement). In the category of auxiliary power units (APUs) of 10KW or less, there is a requirement for approximately 1,000 units/year. Finally, in the multi-KW generator sets of 100 or more KW, there is a requirement of approximately 1,000 units/year.

There were a number of bottom-line statements made by the Group at this point in the discussion. For example, it was believed that the TPV community would appreciate the development of portable generator sets and APUs by the Army or other users, since these offered relatively rapid introduction of some current TPV developments. Specifically, with respect to the BA5590, the BA5590 is a very difficult technical problem, and it requires a unique solution. Portable generator sets represent a more attractive path thought the Group participants, and they offer a greater spin-off potential.

Breakthroughs

No technical breakthroughs are required for a technical demonstration. This finding is in sharp contrast to past Workshops in which other programs have been examined.

Commercial Markets

The participants called upon their collective expertise to define the commercial markets available to various TPV system designs. In the competitive programs, batteries had the most potential in terms of numbers -- approximately 20 billion primary batteries are sold world-wide each year. In the recreation vehicle (RV) area, there is a large, lucrative market. The question was posed, is there a military parallel to this market? In the marine market, it was felt that there was an even larger potential than in the RV area. Portable generator sets offer a large market, but that market is cost-driven. This cost factor could plan against the introduction of TPV systems initially. The bottom line: Commercial markets should become more viable as the TPV technology matures and a manufacturing base is established for Army applications.

Strategy

In assessing an overall strategy on behalf of the Army, the Group agreed that a near-term success, whether military or commercial, was needed. Such a success would serve many purposes, from validating the principle to garnering an advocacy for TPV technology. In the strategy, the Army should use its priorities to identify the target application, such as the portable generator sets (up to 500W). In whatever program combination, the Army should meet its declared policies on primary portable power sources and/or generators in the most coherent argument possible. Additionally, the Army should optimize mass, life-cycle cost, and efficiency of the TPV system so as to meet or exceed the requirement for its selected military application. With regard to that efficiency, the issue is whether that efficiency is measured at peak power, average operating conditions, etc. Finally, in its strategy, the Army should consider leveraging Army investment with funds from other branches of the service.

Near-Term Issues

There were believed to be a number of near-term issues, but none were thought to be "show-stoppers" in the classic sense. The most significant issues to be addressed in a design phase, and a *technology demonstration*, included:

- System design/modeling
- Spectral control
- Cavity design
- Emissive system
- Combustion (liquid fuel)
- Thermal management

A *"technology demonstration"* was defined by this particular Working Group to be engineering sufficient to make a working system.

The Group's bottom line was as follows: The Army should fund system demonstrations as soon as possible. In doing this, it must freeze the design at some point, compete some designs, and commence with the demonstration as expeditiously as possible. Participants noted that the Army should consider the requirements already set in the DARPA BAA which was published prior to the conduct of the Workshop.

Long-Term Issues

Long-term issues overlapped with several of the near-term issues. The most prominent issue was believed to be that of thermal management. With the passage of time, and one or more technology demonstrations, it was believed that considerable progress could be made in the long-term areas of cost, lifetime of the TPV system, packaging (to include weight, size, robustness, durability, etc.), and the user interface.

Again, the Group focused on the bottom line. To achieve success in the TPV technology development, designers must provide a cost-effective product to meet customer needs.

Discussion of Questions to Be Addressed

In summarizing the questions which seemed to be remaining after several discussion periods, the Group settled on a set of three questions. First, should the design, or a set of designs, be frozen? The consensus was that a "Technology Demonstration" should be funded, at a system level or an engineering prototype level. The target should be clearly specified, i.e. 150W or 500W. It was thought that the target generates a specific set of competitors and designs. Finally, there should be multiple sets of competing subsystems. This point might ensure inclusion of some competitors which would not otherwise become part of the evaluation process. Secondly, should designs be competed against one another, and then a down-selection made? The consensus was that this should probably be done. In fact, 3 or 4 designs should be chosen for that competition. Third, how long should the evaluation and down-selection process take? It was believed that four years was not too long a period to thoroughly scrutinize the competition and make some selections for TPV development.

As an afterthought, the Group considered the entire Technology Demonstration process to see if it were reasonable and achievable in terms of the total cost involved. The Group believed that the Army should be prepared to fund system studies immediately. Based upon two independent sources, an approximate total cost to field an engineering prototype was estimated to be $10 million.

Time Frame

Discussions revolved around the types of fuels to be used in the TPV system, and that fuel appeared to drive the time frame for prototype product development. For example, in a general case, it was estimated that for any fuel, it would require a maximum time frame of approximately five years to create a prototype. In a gaseous fuel system, that period would probably be reduced to a maximum of four years.

In estimating how this time might be applied in several phases, the Group developed a time line as follows: In the first phase, there would be 30-36 months for a technology demonstration (at a cost of $15 million for three awards). Typical technology specifications might be "less than 2 cubic feet and less than 25 pounds." During the second phase of the program, there would be a period of 15-24 months for construction of a "preproduction device" (at a cost of $10 million for 2 awards).

Surge Capability

When the Group considered whether the TPV development could be surged, the Group concluded that it was only a matter of paying the cost penalty. It was estimated that there would be an approximate doubling of the cost for a one-year decrease in the development period (Phases I and II). That would equate to a total cost of $50 million for a product in 4 years under the former five-year development program.

Recommendations

The Working Group recommended that the Army establish a "two-phase development program," consisting of a Technology Demonstration Phase (Phase I) and a Preproduction (Engineering) Prototype Phase (Phase II). The first phase would be designed to address near-term system issues, and the second phase would address long-term issues which meet specific customer requirements.

In Phase I, there would be a clear technology demonstration to be conducted over approximately a three-year competition period at a cost of $4-5 million. The "optimum program" envisioned by the Group under this phase would yield three or four technology demonstration units. The actual number of competitors would be decided by the Army Research Office's TPV Program Manager. A more modest program could be created, at a higher technical risk, with an investment of $2-3 M. This plan would yield two systems over a three-year competition period. By way of comparison, the members noted that this latter investment would be roughly equivalent to 10% of the current Army investment for BA5590 batteries ($22 M in FY96).

In Phase II, the Army should define individual applications which it wishes the engineering prototypes to meet. The Army should identify requirements for the Engineering Prototype Phase of the Development program. Phase II will require that an additional 12-18 month period be added to Phase I to assure completion of Phase II. The total time to completion of both phases was estimated to be approximately four years. This period of time coincides well with the Army's typical four-year development "window," noted several of the discussion group members.

Other Recommendations

The Group further recommended that the Army establish a Consortium of DoD, industry, and academic institutions. The Army should look at opportunities or unique ways in which cost-sharing could be accomplished to achieve some goals during the Engineering Prototype Phase (Phase I). This is generally not a popular approach during periods of fiscal constraint among industry teams, so definitions of cost-sharing arrangements need to be carefully reviewed by participants.

The Group also recommended that there be established a mechanism for information exchange among interested Consortium members, as well as others in the TPV field. Such arrangements would necessarily protect intellectual property rights of the parties involved in the Consortium, provide access to a "library" of information by some list of subscribers, and prove to be an asset to all who might be interested in pooling resources, or accessing and maintaining a vibrant data base of TPV technologies. A benefit of this data base and information exchange, as stated by the members ion their discussions, would be the ability to promulgate a "common language" to discuss TPV technologies, facilitate the exchange between data banks, and more accurately and efficiently describe new developments in publications.

In late discussions, the Group was advised by other Groups to include the need to establish "standards" for TPV development so that measurable comparisons could be made, so subsystems could be integrated and rated in competition, etc.

Finally, the Group believed that there was a need to promote thermophotovoltaics to other organizations so as to gain a better understanding of the technology's capabilities, to garner advocacy for TPV in new applications, and to educate the users of the technology on ways to better employ TPV in the future.

Summary

In summary, there was substantial discussion on the possible application of TPV as a replacement for the Army's BA5590. The group concluded that, in this example, TPV was not a near-term application and would follow after TPV applications in other areas had been proven reliable, efficient, and cost-effective.

There was considerable discussion among the Group members on the need for power sources of up to 500 Watts. The Group was unanimous in stating that TPV technology was mission-enabling. Additionally, they recommended that a power source of less than or equal to 500 W be developed through a rigid technology demonstration.

The Group members believe that size power source (up to 500 W) would solve a multitude of the Army's power problems over the long term. In time, a TPV device could be developed as a direct replacement for the BA5590. TPV could also serve as a replacement for the engine generator set, again determined through a series of technology demonstrations.

Finally, the Group identified a strategy, cost goals, and time frame to arrive at some near-term and long-term applications for the TPV development program. This newly-created strategy would be effective if there were early successes, visible to potential users of the technology (perhaps through a demonstration), and if a "niche market" were identified so as to assure a successful introduction of the TPV capability. Members believe that cost goals need to be identified and demonstrations and studies should be directed toward achieving those goals. The approximate cost spread was from $15 M for Phase I (technology demonstration) to $25 Million for Phases I & II (development of a "preproduction device"). A surge capability could be attained at double the normal cost ($50 M) which would reduce the total development time by one year (to four years maximum). Time frames were outlined for several phases of the Army's TPV technology demonstration, with time spread of from four to five years. The general guidance stated that a four-year period was considered the optimum for a gaseous fuel system technology demonstration, assuming that TPV development funds and any critical assets were going to be available.

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PLENARY SESSION

Why Are We Here Anyway?

For

Prospector VIII Workshop: Thermophotovoltaics

14 July 1996

Dr. Richard J Paur
ELECTROCHEMISTRY AND ADVANCED ENERGY CONVERSION
CHEMICAL AND BIOLOGICAL SCIENCES DIVISION
ARMY RESEARCH OFFICE

Tel: (919) 549-4208, DSN 832-4208 FAX: -4310
Paur@ARO-EMH1.Army.Mil

The Army needs better power sources!

- Power consuming technologies advancing much faster than power producing technologies

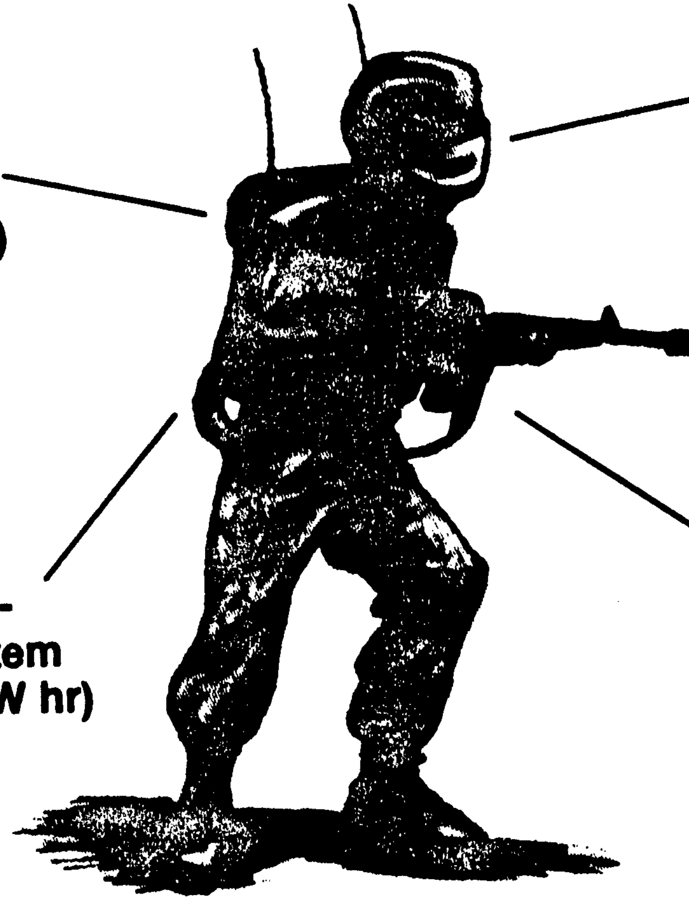
- Emphasis on power projection to reduce cost of maintaining standing Army in Europe, Far East, ...

GEN II Soldier System

Anticipated Power And Energy Requirements
(12 hr mission)

Individual Soldier Computer/Radio (30 W max, 120 W hr)

Integrated Headgear Subsystem (6 W max, 60 W hr)



Refrigerated Micro-Climate Cooling System (150 W max, 4 hr, 600 W hr)

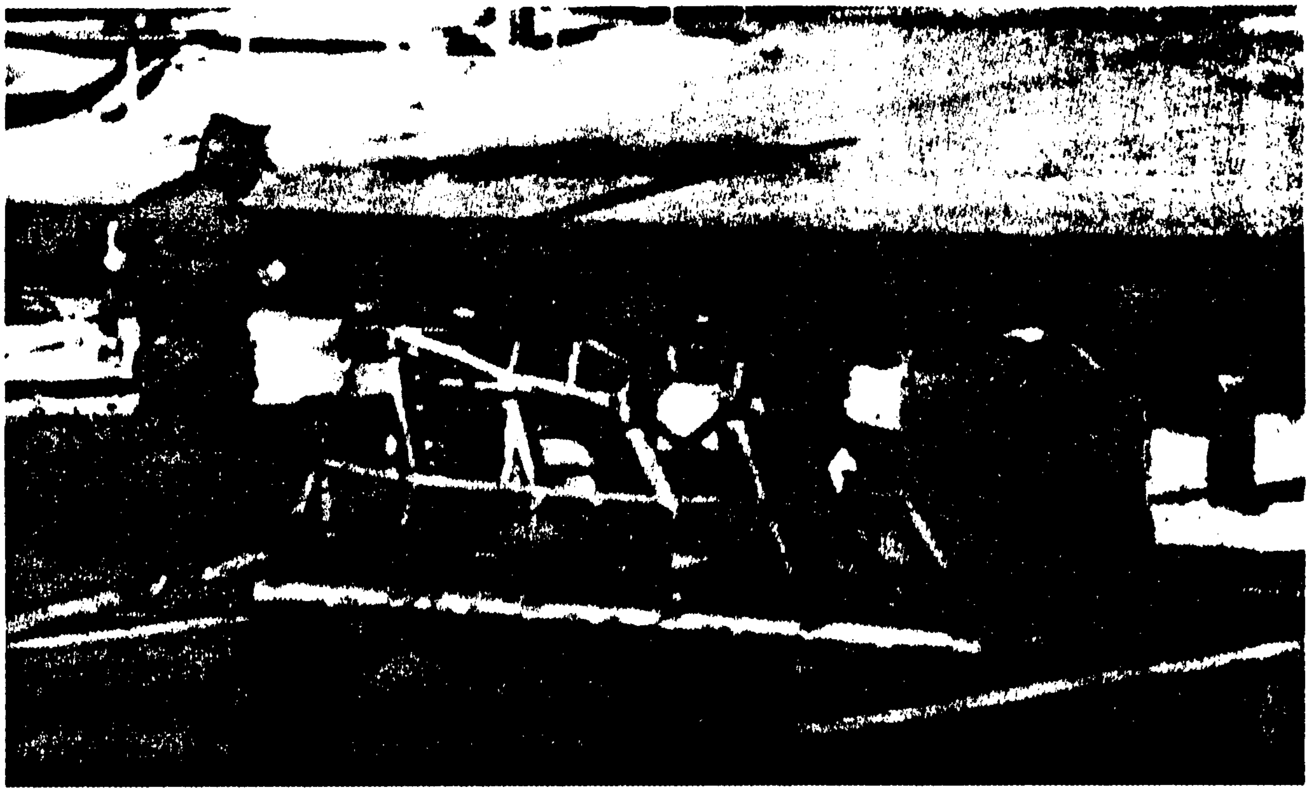
Weapon Interface Subsystem (1 W max, 5 W hr)

"Battery technology is one of the most important areas that we have right now." Army Gen. Leon Salomon, Commander, Army Materiel Command, 11/23/94

ARPA

Marine Corp Air-Ground Combat Center,
7^{th} Marine Regiment, 29 Palms, CA

(Deploying to Kuwait, Oct. 94)



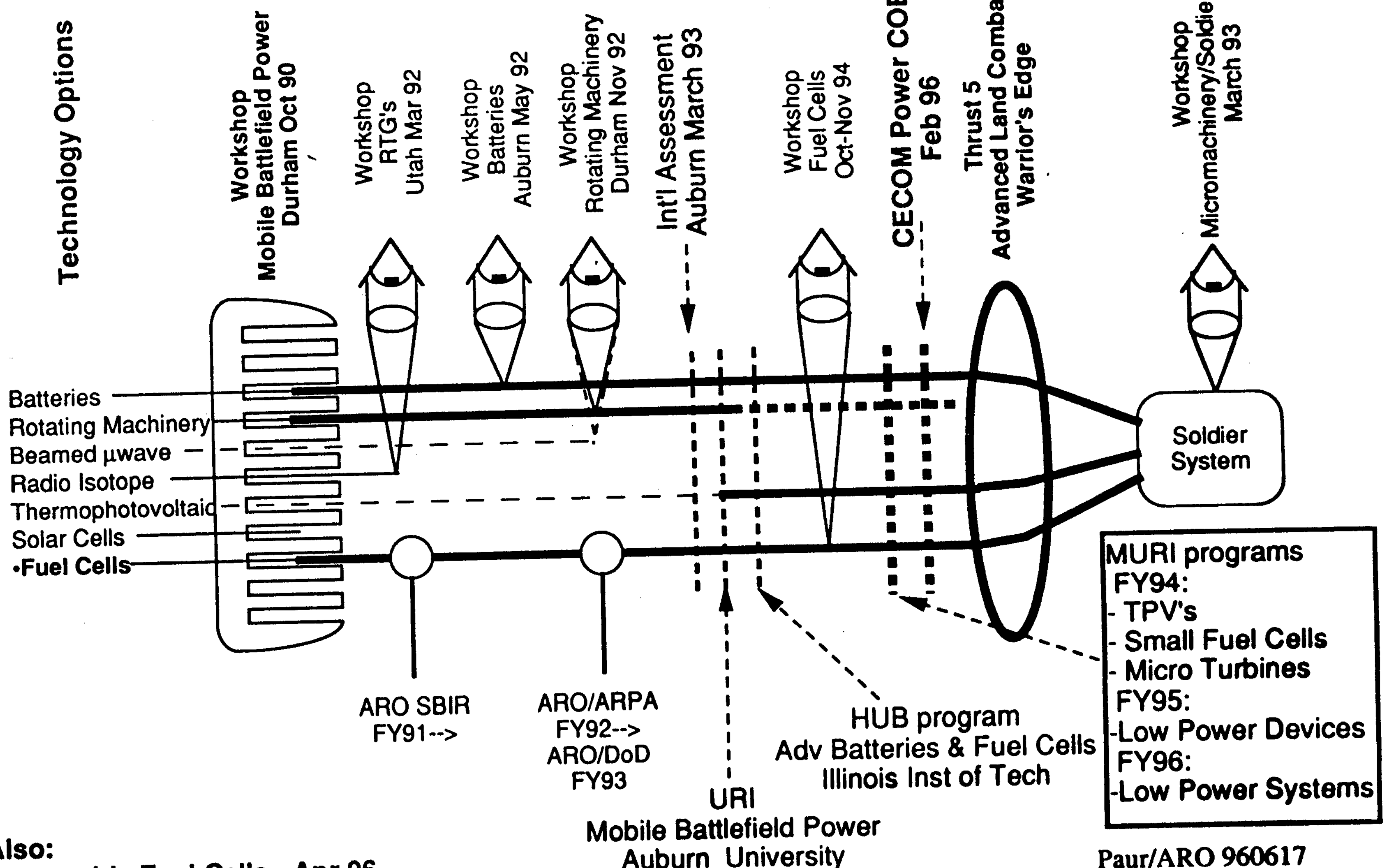
Communications Company Battery Pallet (1 of 2)

100 batteries/drum, 12 drums/pallet,
7 -10 days of operation

ARPA

BAT-014 4/95

Information Assessment & Program Chronology
ARO Mobile Battlefield Power-Soldier System Focus



Also:
Disposable Fuel Cells - Apr 96
Thermophotovoltaics - Jul 96

Paur/ARO 960617

Electrochemistry / Advanced Energy Conversion

Funding Profile:

	FY91	FY92	FY93	FY94	FY95	FY96	FY97	FY98	FY99
SBIR	50	260	300	420	250	400	400	400	400
ARPA		435	490	3371	6627	6472	*3139*	*1453*	---
NSA			150----------------	---------------->	---	---	---	---	
ARO-HUB				5300	0	0	*2000*	*2000*	*700*
MURI '94				3000	---	3000	*3000*	*3000*	*3000*
Other OSD						834	400	400	400
ARO	100	100	100	400	754	495	500	500	500
	150	795	1040	12491	7631	11201			

Tech Transfers ———————— Δ1 ————————

Shadowed Numbers are Projections

Italicized Numbers are Negotiated Options

Δ1 - Transferred program to CECOM/Belvoir via STO

Paur/ARO 960512

1995 Funding vs Power Technology

Fuel Cells		Batteries		Other	
ARPA-TMI	1324	Yang	39	MURI-Epstein	1174
ARPA-IFC	2180	Petrucci	105	(Micro Gas Turbines)	
ARPA-SOFCo	2626	Shriver	110	MURI-Seal	900
IIT/HUB-Smotkin	824	Frech-A	140	(Thermophotovoltaics)	
Linn	56	IIT/HUB-Selman	738	URI-Rose	368
ARPA-IIT	98	Shriver-A	140	(Opening Switches, Porous Electrodes, TPVs)	
Lukehart	158	SBIR-Loutfy	250	STTR	300
MURI-Smyrl	1060			(Thermophotovoltaics)	
Gray	200				
ARPA-H-Power	285				
ARPA-Aspen	114				
	-------		-------		-------
	8925		1522		2742

Representative expenditure; not fiscal year $

Paur/ARO 950828

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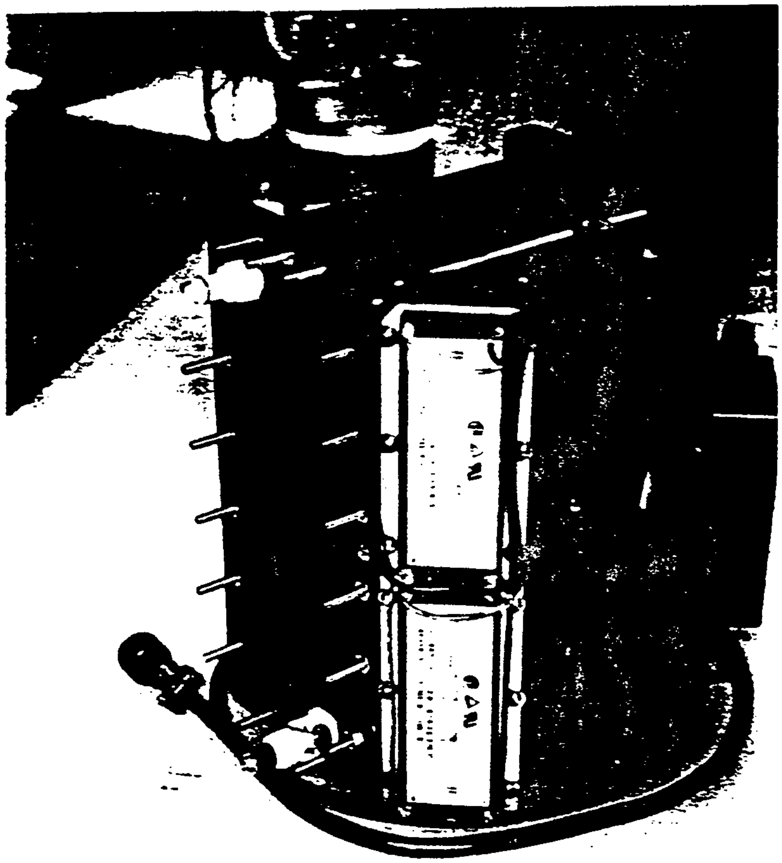
Lessons

- All useful systems contain enough energy to cause considerable damage in the event of an accident - safety engineering is essential
- 'Standard' battery systems can be improved in various ways (ie, cold weather performance, shelf life, performance of rechargeables) but no dramatic improvements (more than doubling) in energy density are foreseen
- Lightweight, high efficiency energy conversion devices which can use air as the oxidizer are the key to making use of the high energy density of convenient liquid fuels --> fuel cells, thermophotovoltaics, micro turbines.... Caveate: systems need to be designed for tactical robustness, i.e., submersion in water...
- The relatively advanced state of the art of hydrogen/air fuel cells and the very high energy density of hydrogen justify the present significant DoD effort to find new ways to deliver hydrogen to the soldier
- Power management through more efficient electronics

ANALYTIC POWER CORPORATION
CENTURY SERIES FUEL CELL POWER SUPPLIES

Analytic Power announces the Century Series Fuel Cell Power Supplies. These power supplies operate on hydrogen and air and produce electricity and water. The hydrogen can be supplied from regulated gas bottles or it can be generated by Analytic Power's Fuel Pacs. The power supplies can be operated between 40°F and 120°F. The natural voltage regulation is about 37% from full to no load. Analytic Power can supply DC to DC voltage regulators if required.



Analytic Power FC-200 Fuel Cell Power Supply

In fuel cells, unlike batteries, the fuel supply and the electrical generator are separate. The fuel cell is similar to an engine and generator set except that the efficiency can range between 56% and 77%. The chemical hydride Fuel Pacs can give the fuel cell energy densities of 800 to 1.400 watt hours/pound.

Based on the same technology used for powering space craft. the fuel cell is silent and pollution free. The Prototype FC-200 in the photograph was developed by Analytic Power for the Army Research Office. It recently powered a three-wheeled scooter and replaced lithium batteries to operate a microclimate cooler.

Mobile Electric Power

Analytic Power Corporation

U.S. Army Research Office

1994
Quality
Award
Winner

"Only with the support of the Army SBIR program could we research and develop this technology."

Future soldiers must rely on portable efficient power sources with silent operation and background - indistinguishable thermal and acoustic signatures. Analytic Power Corporation successfully developed an innovative fuel cell technology which meets these requirements.

The Century Series Fuel Cell operates on hydrogen and air and produces electricity and water.

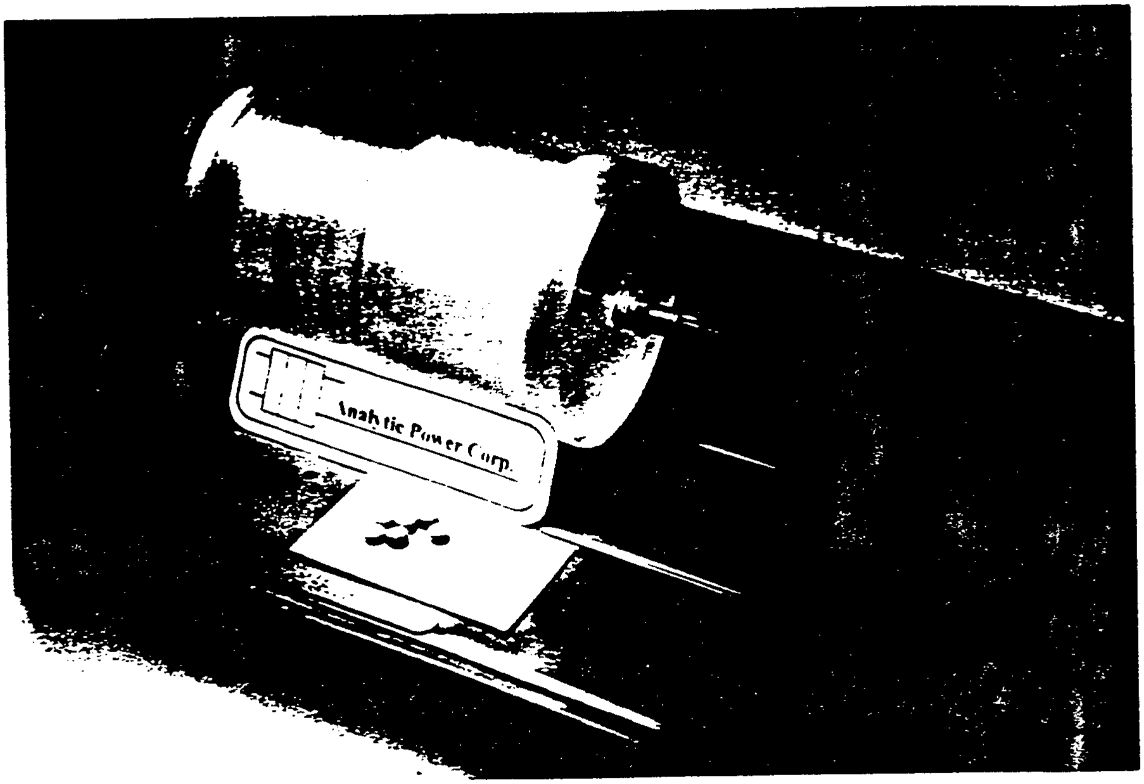
It is compact, silent, and pollution free. Currently the power source is being demonstrated at Natick Research, Development and Engineering Center for soldiers' microclimate cooling systems.

Commercially, Analytic Power Corporation has sold the units to the Niagara Mohawk Gas Corporation and an overseas company.

Phase III Impact

- **Analytic Power Corporation sold two units commercially.**
- **Other commerical uses: medical emergency, natural disaster relief, and others.**
- **$13,000 in sales to date.**

ANALYTIC POWER CORPORATION
FUEL PAC 750



Analytic Power Corporation announces the Fuel Pac-750. The Fuel Pac-750 will produce 15.5 cubic feet (440 liters) of hydrogen, enough for 750 watt hours of energy with Anlaytic Power's Century Series Fuel Cells.

The Fuel Pac produces hydrogen on demand by reacting the chemical hydride fuel cartridge with the water stored in the Fuel Pac. The Fuel Pac can be started and stopped. It is position insensitive, operating equally well on its side or inverted. The Fuel Pac fuel cartridge is available from Analytic Power.

Fuel Pac-750 Specification

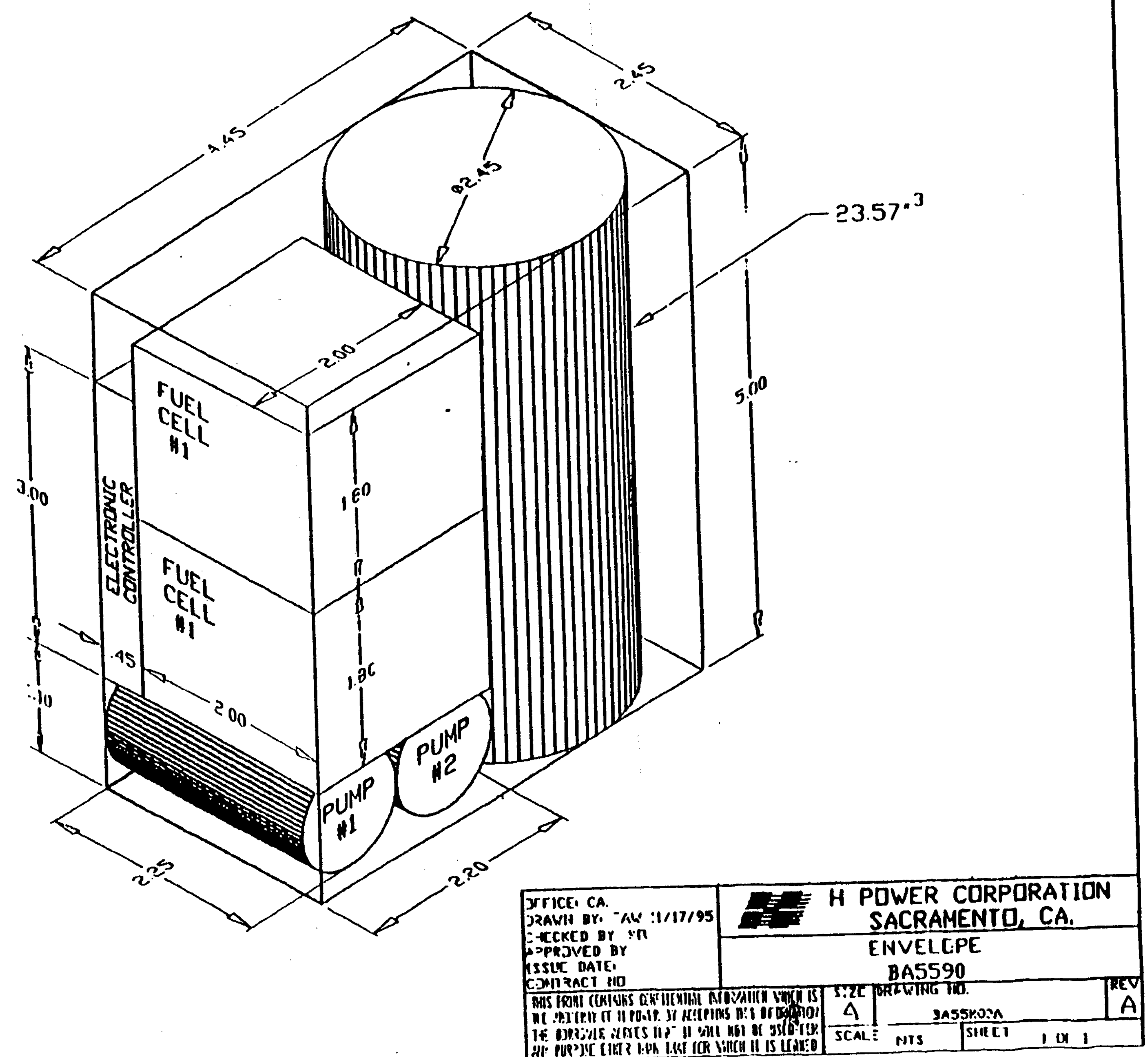
Weight:	*3.5 pounds*
Dimensions:	*4.5" dia. x 6.5" long*
Cartridge Weight:	*80 grams*

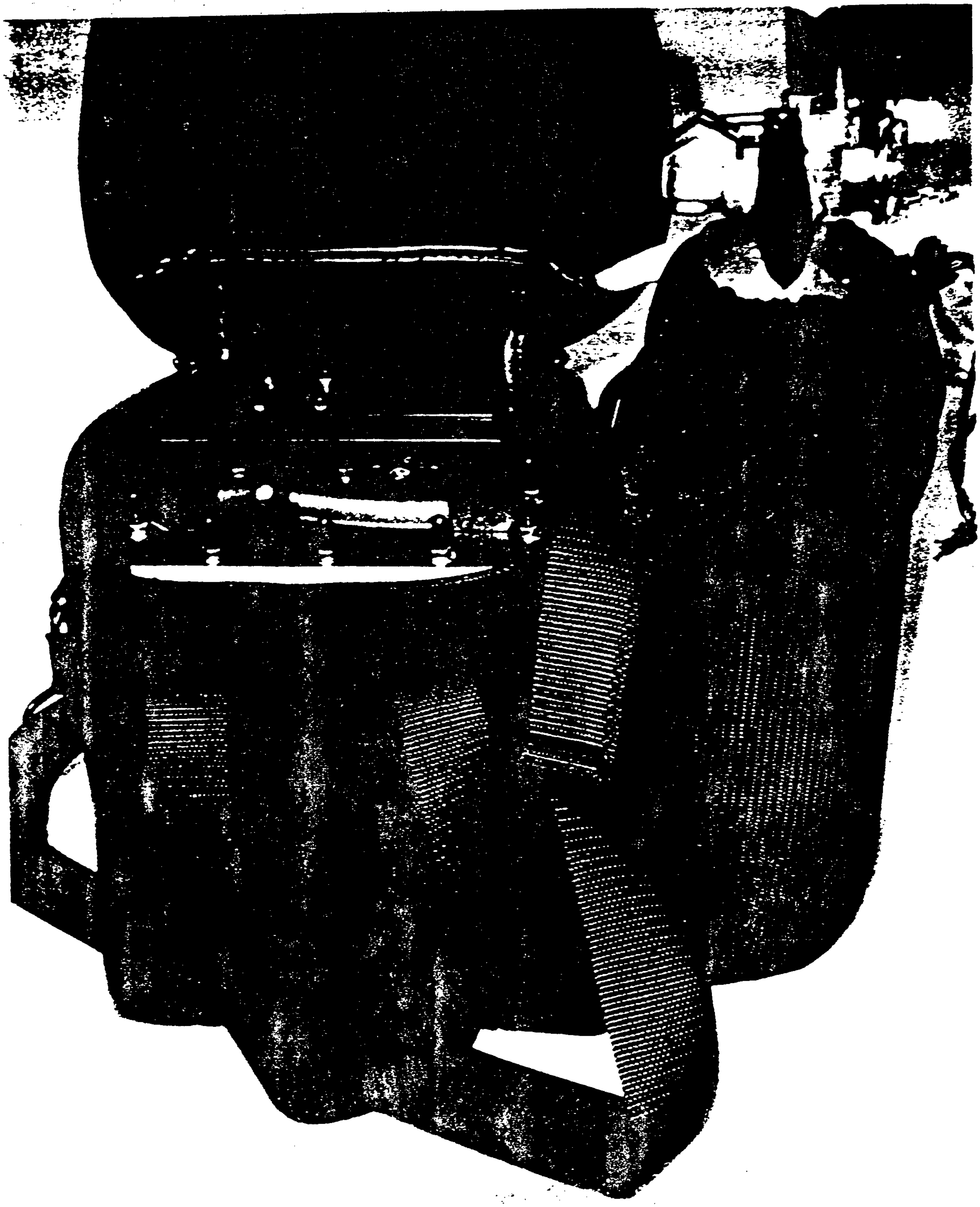
Analytic Power Corp.
PO Box 1189
Boston, MA 02117

Status - Portable Fuel Cells

- ARO/DARPA BA5590 sized fuel cell system from H-Power
- NSA Snorkler program - 100 W cont power - Ball Aerospace/Ballard
  - 27 pounds for 5 kWh using high pressure hydrogen - 408 Wh/kg- can replace 29 BA5590's which would weigh 64 pounds (demonstrated)
  - 30 pounds for 13 kWh using chemical hydride - 950 Wh/kg - can replace 75 BA5590's which would weigh 165 pounds (under development)
- ACT II supported 150 W stack for DBBL - Analytic Power
  - Six units delivered to DBBL
  - Col Canada very supportive of fuel cell power systems
  - MOU - NSA/CECOM - CECOM to be item manager for fuel cells
- Strong industrial support - much commercial interest

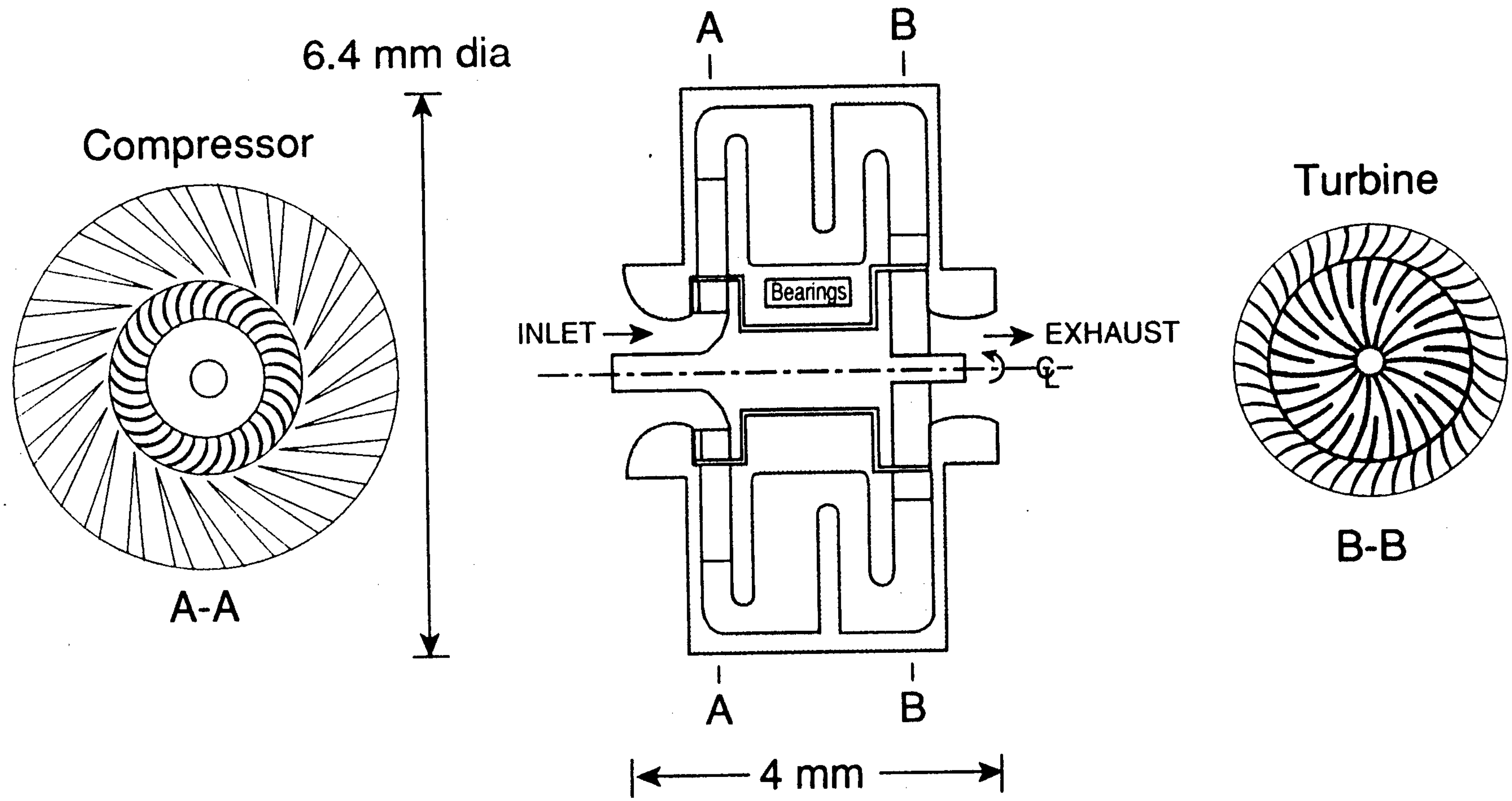
Paur/ARO 960617


4.45
2.45
ø2.45
23.57"3
5.00
2.00
FUEL CELL #1
FUEL CELL #1
ELECTRONIC CONTROLLER
1.60
1.8C
3.00
.45
.10
2.00
PUMP #1
PUMP #2
2.25
2.20
OFFICE: CA.
DRAWN BY: TAW 11/17/95
CHECKED BY
APPROVED BY
ISSUE DATE:
CONTRACT NO
H POWER CORPORATION
SACRAMENTO, CA.
ENVELOPE
BA5590
SIZE A
DRAWING NO.
BA55KO2A
REV A
SCALE NTS
SHEET 1 OF 1




MODELING AND SIMULATION CONCEPT
ANALYSIS AND

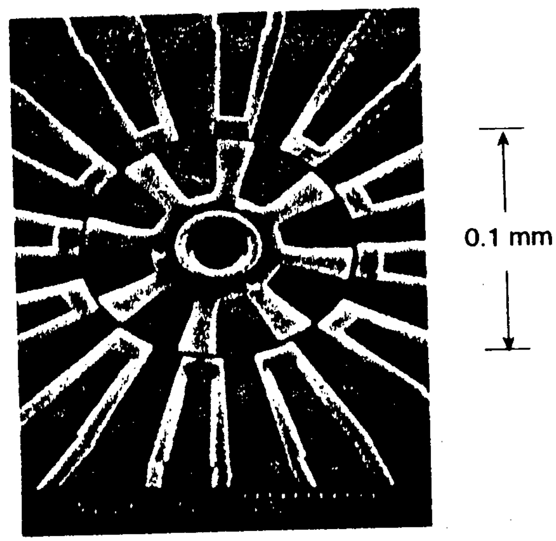
CONCEPTUAL LAYOUT OF μJET ENGINE
(Inlet Flow Area = 1 mm^2)



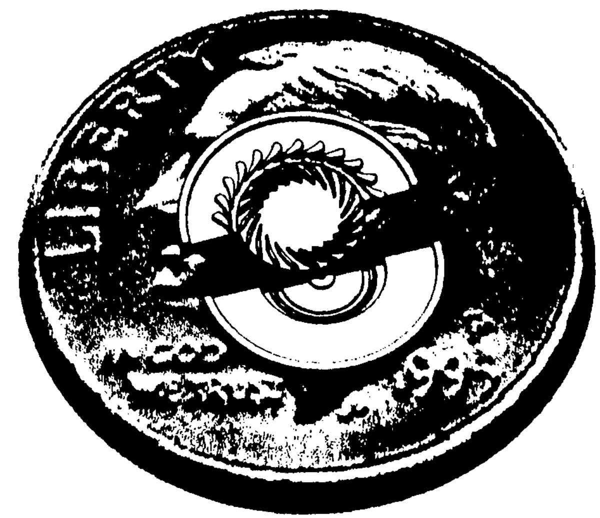
MICRO GAS TURBINE GENERATORS
- Concept -

- μFabrication of refractory ceramics enables the concept of micro gas turbine engines and generators (milli-centimeter dia)
- Power densities can approach those of full-sized engines (100 watts/cc)
- Achieving high performance levels requires
  - High turbine inlet temperature (~1600 K)
  - High speed, highly stressed rotating parts ($3x10^6$ rpm)
  - Low leakage and high tolerances (~1 μm)
- Cost could be very low given sufficient demand (10^8 units/year)
- μEngines can be an enabling technology for new concepts

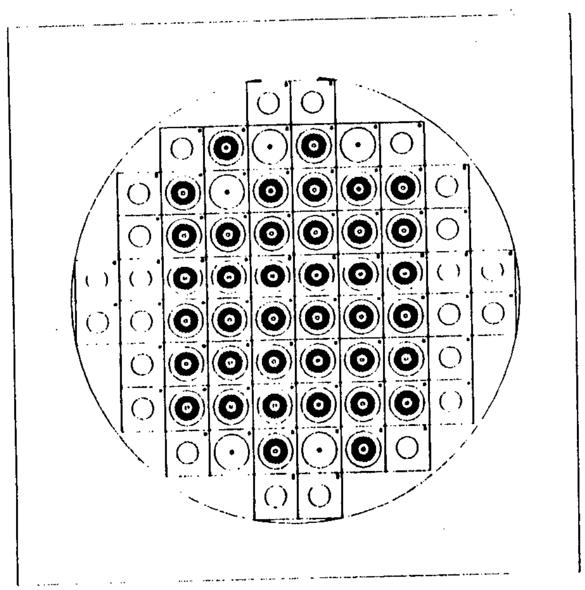
MIT SALIENT-POLE ELECTRIC MICROMOTOR



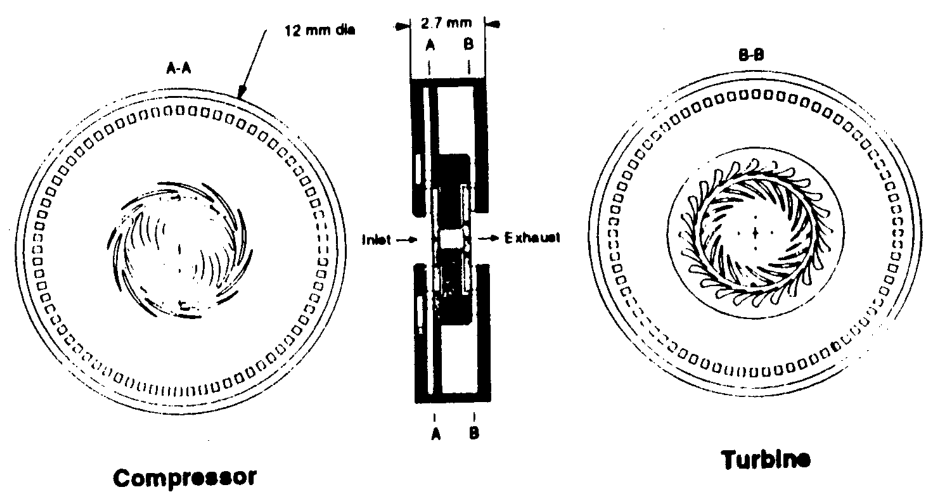
20 WATT TURBOGENERATOR IS FIRST MILESTONE



μ FAB CAN YIELD LOW COST



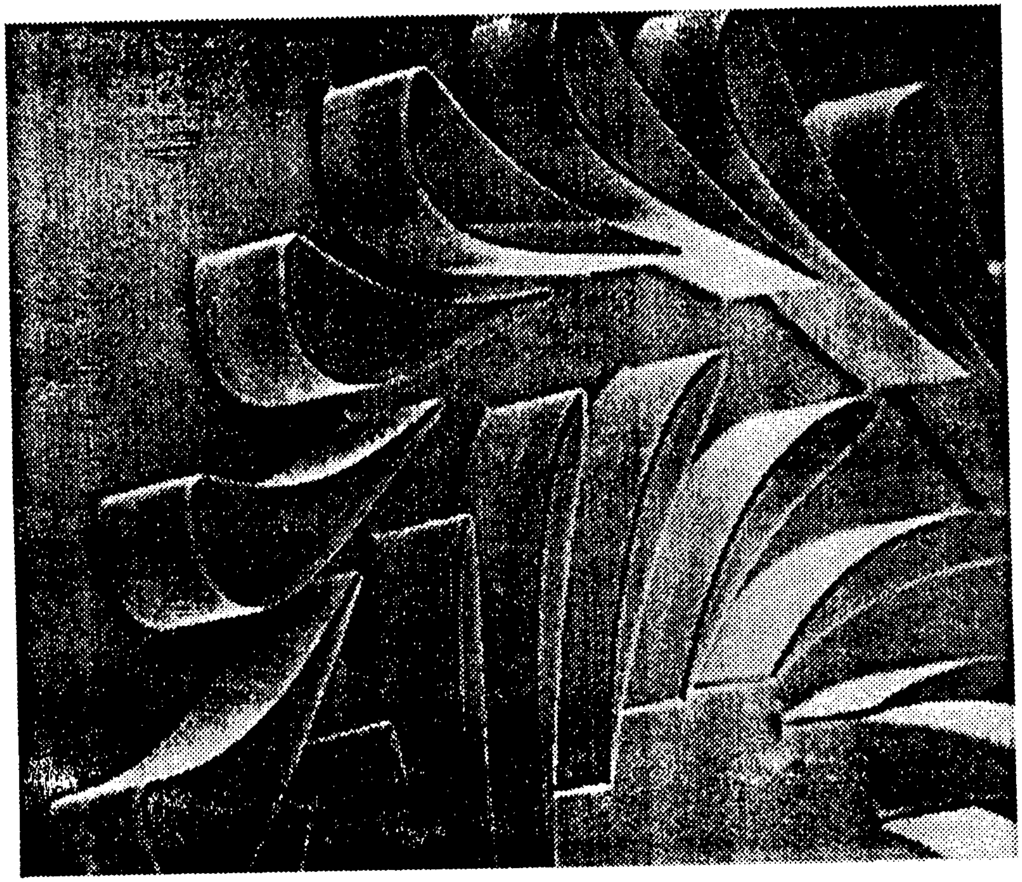
MICRO GAS TURBINE GENERATOR



PERFORMANCE COMPARISON

	μ Turbogen + Fuel	$LiSO_2$ Battery (BA5590)
Power Output	50 w	50 w
Energy	175 w-hr	175 w-hr
Weight	50 grams	1000 grams
Size	50 cc	880 cc
Specific Energy	3500 whr/kg	175 whr/kg
Energy Density	3500 kwhr/m^3	200 kwhr/m^3

Portion of turbine wheel and nozzles showing quality of high-aspect-ratio etching



~2 millimeters

Blades are 200 micrometers high

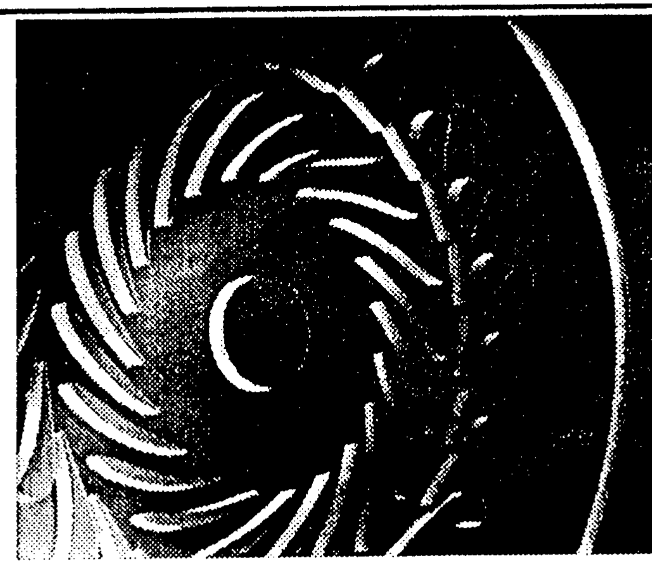
Paur/ARO 960617

Micro Turbo Compressor

Objective:

Develop a small compressor unit sized to support 50 to 200 W fuel cell power supplies

DARPA is providing $1.1 M over FY96-FY98 to support project



Silicon-based micro turbo compressor

Approach:

Using micro turbine technology being developed under the MURI program, design a silicon-based turbine compressor system. Power will be obtained by operating the MURI program generator as a motor.

Anticipated results:

Program will provide early verification of turbine design, generator/motor design, and, most critically, bearing design for MURI program, while producing an intermediate product which will support the small fuel cell community.

Your Challenge! Tell the Army what TPV's are good for...

- Give the Army an honest picture of
  - remaining technical barriers
    - funding limited? idea limited?
    - when will they be available
  - where will we want to use them - hybrids?
  - cost - can we really afford them?
  - fuel - ideal - what can you live with?
  - ...

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Thermophotovoltaic (TPV) Programs Supported by the U.S. Army Research Office (ARO)

presented to the
Workshop on TPV Research &Technologies

14 July 1996

by
Dr. John S. Kruger

Research and technology efforts through the DoD University Research Initiative (URI), Small Business Technology Transfer Research (STTR) and Multidisciplinary University Research Initiative (MURI) Programs are discussed.

The URI Mobile Power Center at the Space Power Institute, Auburn University, Alabama. Much of this investigation is concentrating on TPV because of the promise of efficient electric power from any heat source. This is a very serious technology transfer efforts with lots of patents, publications, and presentations. With about a $400k expenditure each year for the now fifth and final year ARO has been able to leverage 6 or 7 times that amount through industrial partners' support. The direction for the research has been directed now to include gas chromatography of output gases to allow accurate estimates of rare-earth emitter and ceramic lifetimes. Auburn plans to develop a user-friendly computer simulation program that will be useful to TPV R&D efforts.

STTR contracts are designed to link as small business with a research institution such as a university to work on commercialization and military aspects of promising research results. Phase I efforts are typically $100k per year to allow proof of principal. The better efforts may be invited to propose Phase II work at up to $500k total over two years to develop demonstration embodiments, while attracting larger companies for an industrially funded third phase.

ARO is currently supporting three Phase I efforts and has just received proposals for Phase II. Sensortex has teamed with the Institute of Energy Conversion at the University of Delaware to look at TPV generator using existing photovoltaic (PV) cells, copper Indium selenide (CIS). High efficiency is achieved by combining multiple complementary effects: a dielectric stack infrared (IR) reflecting filter; a selective emission surface based on ytterbia; and the thin-film solar cells.

Quantum Group is working with the Optical Sciences Center at the University of Arizona. Their approach includes: multicomponent, multiband emitter materials using both ytterbia and erbia; specialized optical reflectors, thermal isolation and liquid cooling; along with combustion and shock absorbing design. Recently Quantum decided there is no need for two matched-bandgap PV cells so will use silicon alone.

JX Crystals is working with Western Washington University on burning fuel in a ceramic tube, using a proprietary emitter material which is an ideal wavelength match to the gallium antimonide PV cells. They are pursuing a parallel commercial development. The MURI grant with Western Washington University complements the STTR program.

Thermophotovoltaic (TPV) Programs Supported by the U.S. Army Research Office

Workshop on TPV Research & Technology

14 July 1996

Dr. John S. Kruger, ARO

TPV Workshop Expectations

- **Speakers and participants by invitation.**
- **A mix from government, academia and industry (large and small) of researchers and developers.**
- **Assess state-of-the-art.**
- **Identify key issues:**
  - emitters;
  - filters;
  - photocells;
  - thermal management;
  - system considerations.

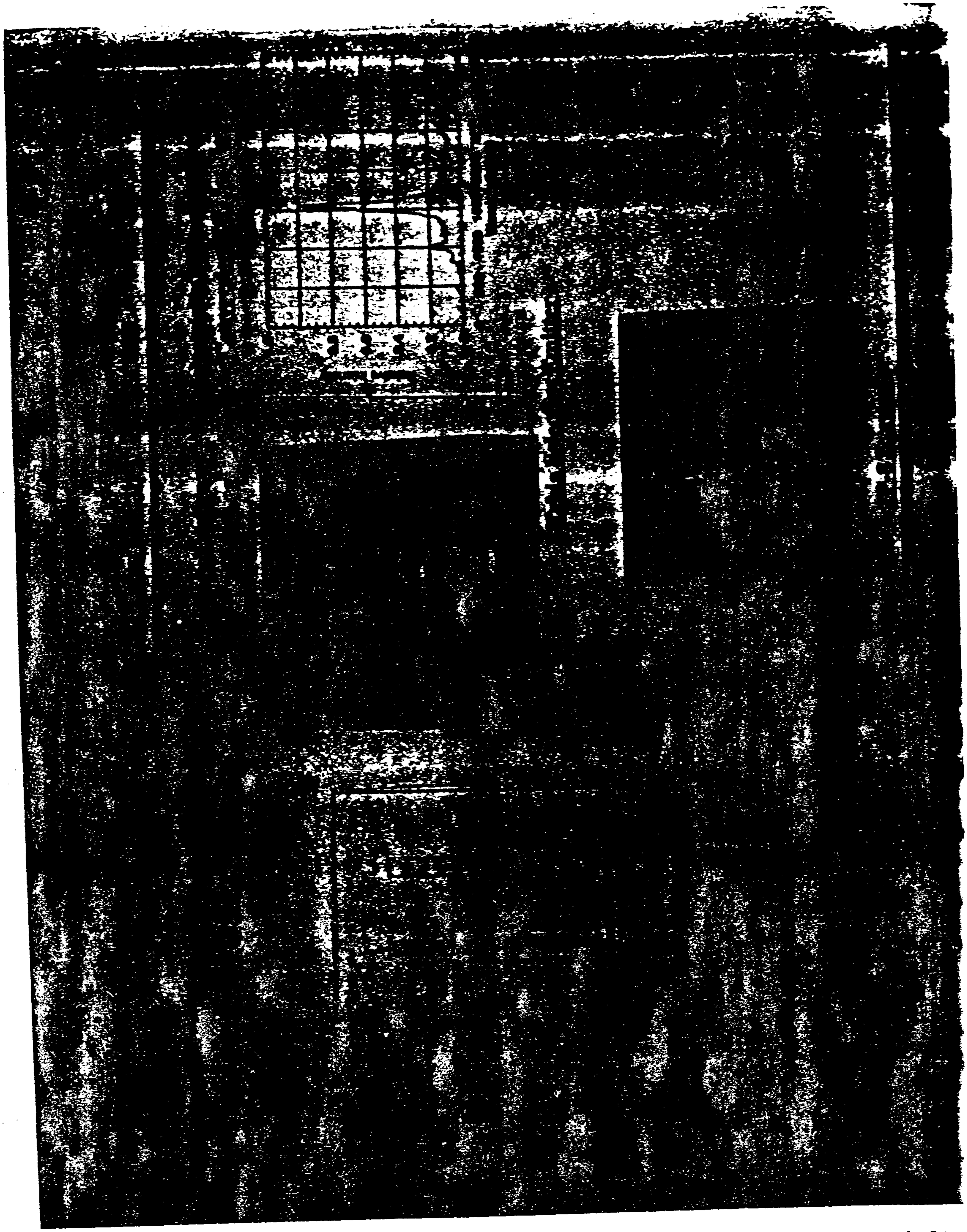
Mobile Power Technology

University Research Initiative

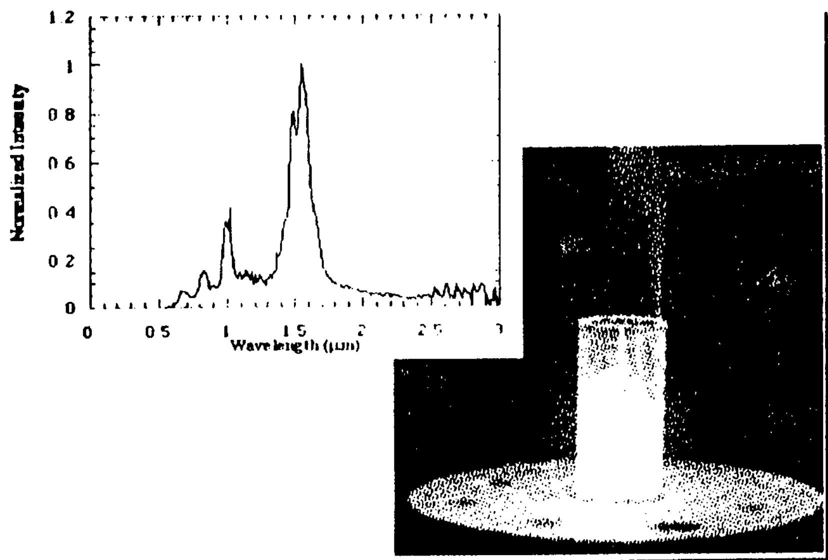
Auburn University Space Power Institute

- A very serious technology-transfer effort, with lots of patents, publications and presentations.
- One of the best bargains around!
- Concentrating on thermophotovoltaics because of promise of efficient electric power from any heat source.
- Emission-line-matched InGaAs photocells.
- New capacitor technology transitioned to Maxwell Corporation.
- Liquid-metal jet work brought to conclusion.

64



Physics: Energetic Processes (OSD4)



OBJECTIVES:

- To study power systems for small platforms such as the soldier

Performer:

M.F. Rose: Auburn

APPROACH:

- Use paper-making technology to produce metal/carbon fiber composites for batteries, capacitors, and fuel cells
- Investigate thermophotovoltaics (TPV)
- Investigate mercury jets for repetitive opening-switch applications

PAYOFFS:

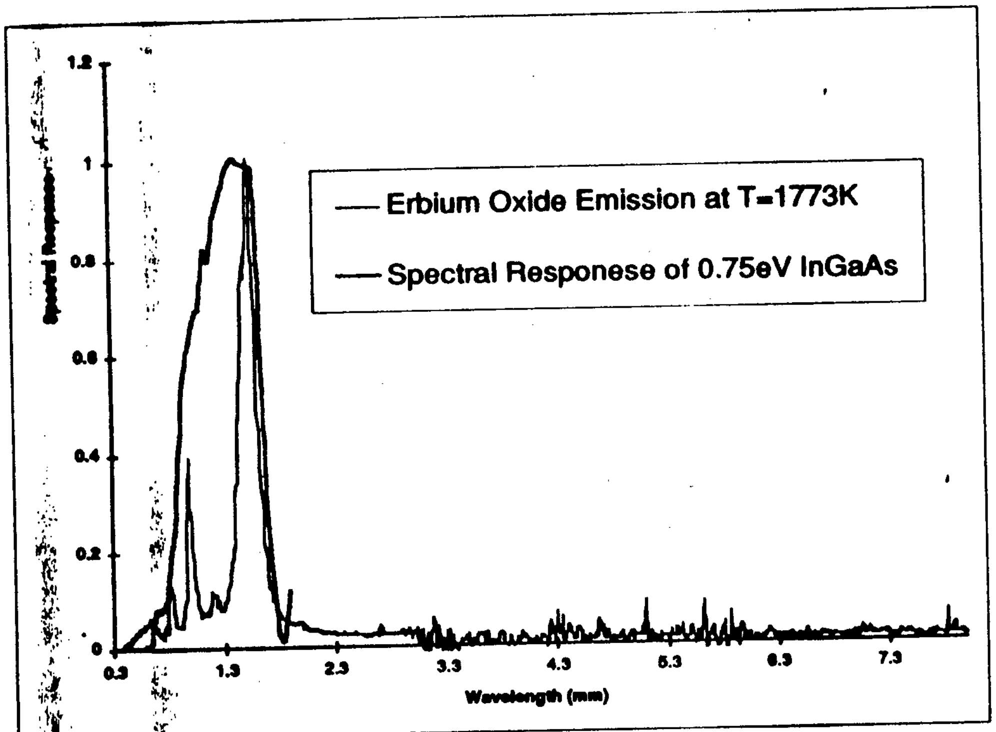
SCIENCE

- Composite filters for chemical agents, advanced battery electrodes, composite selective line emitters for TPV

ARMY

- TPV power for Special Forces, 58 Hz repetitive opening switch demonstrated demonstrated load leveling technique

Thermophotovoltaic



- Reduce blackbody emission from thermal source
- Narrowband emission from Erbium Oxide
- Match InGaAs photovoltaic detector to therma source

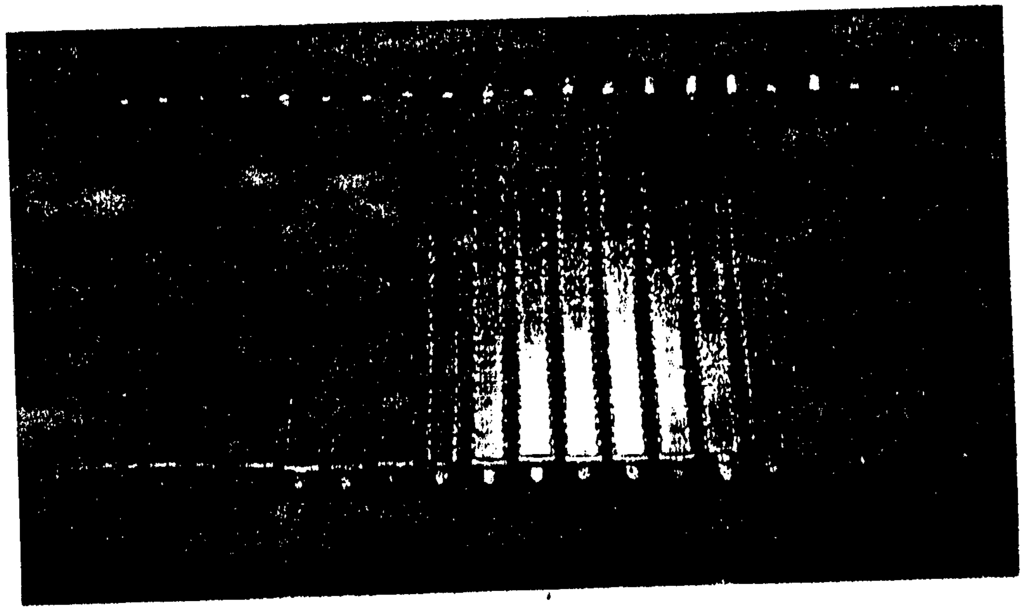
M.F. Rose: Auburn

JX Crystals Inc. and Western Washington Univ.

Small Efficient Thermophotovoltaic Power Supply Using Infrared-Senstitve Gallium Antimonide Cells

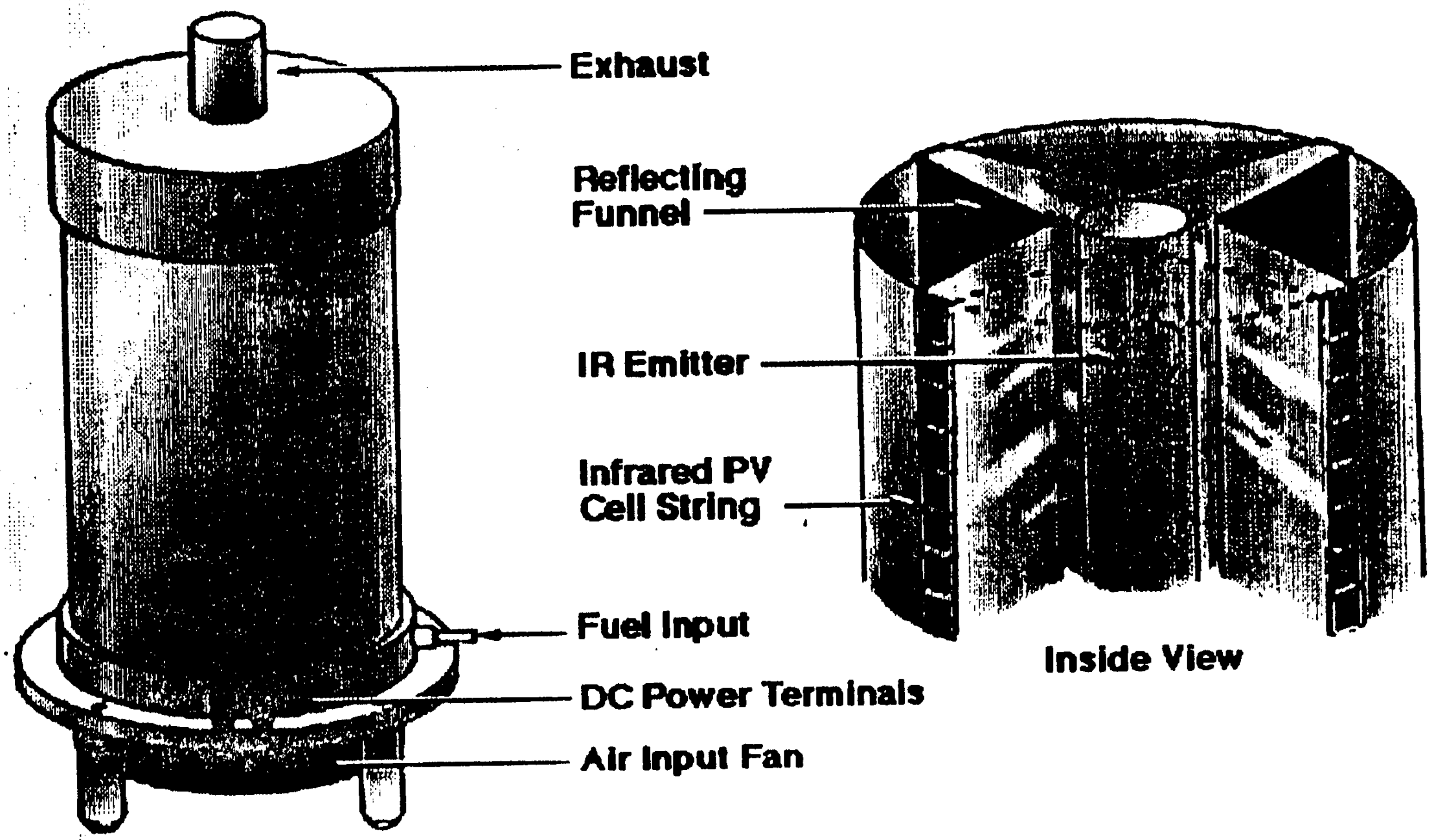
- Fuel burned in a ceramic tube.
- Selective emitter operating at 1750 K.
- New gallium antimonide cells with extended IR response.

STTR Topic ARMY 95T004

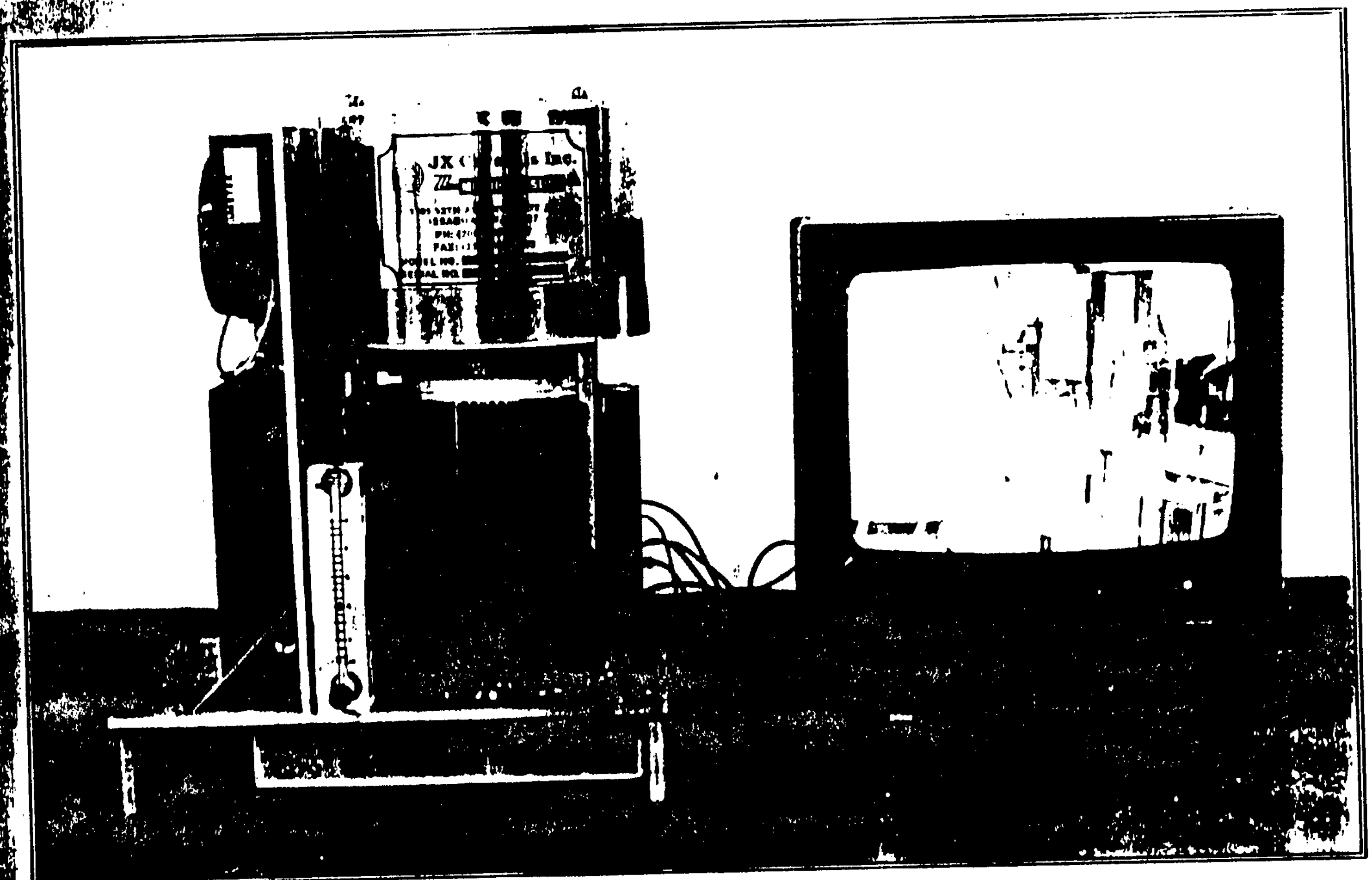


JX Crystals Inc.
20 Circuits
February, 1996

Thermophotovoltaic (TPV) Generator



Midnight Sun™ 130 Watt Generator demonstrated under Phase I



JX Crystals Inc. 4/23/96

Sensortex, Inc. /Univ. of Delaware (Institute of Energy Conversion)

Novel Low Cost Thermophotovoltaic Generator

72

- Uses exisiting photovoltaic cells.
- No requirement for breakthrough technology developments, such as low bandgap solar cells.
- High efficiency by combining multiple approaches that complement each other.
  - a dielectric stack IR reflecting filter;
  - a selective surface emitter based on Yb_2O_3;
  - an existing thin film solar cell (copper indium selenide).

Quantum Group Inc. and University of Arizona

Man Portable TPV Generator System

- Multicomponent, multiband emitter materials using Yb_2O_3 and Er_2O_3.
- Optical reflector and dichroic mirror.
- Combustion and shock absorption system.
- Two matched bandgap photovoltaic cells of Si and GaSb.

Multidisciplinary URI (MURI)

- Vehicle Research Institute at Western Washington University.
- JX Crystals as subcontractor.

APPROACH

- **Increase power from 3 watts/cm^2.**
  - Increase temperature from 1500 degrees C to 1700 degrees C
  - Power increases as the fourth power of temperature
  - Requires ceramic materials
  - Cast and machine ceramics
    - Silicon carbide
    - Zirconium oxide
- **Develop short pass IR filters** (JX Crystals subcontract)
  - Improve efficiency and power
  - Mount at mouth of receivers
  - Mount on cell face
  - Deposit filter material on cell face
- **Extend IR response from 1.7 microns to 2 microns for Quaternary Cells.** (JX Crystals subcontract)
  - Allows efficient use of lower temperature emitters at higher cell cost
- **Develop Burner Geometry for Uniform Cell Illumination**
  - Imperfect high temperature end mirrors require more illumination at ends of string or larger end cells. Both approaches are currently being evaluated.
- **GaSb Crystal Growth** (JX Crystals subcontract)
  - Establishment of Crystal Growing Equipment JX Crystals
  - Wafers are not expected to be in production until year 4 of the contract
- **Weight Reduction**
  - Current burner is being fully instrumented and will be redesigned based on accumulated data to optimize all the parts and reduce weight when possible.

ACCOMPLISHMENTS

- **BURNER RESEARCH AND DEVELOPMENT**

  - New equipment purchased, based at WWU.

    1. Inert gas high temperature furnace purchased and set-up.
    2. Ceramic heat treat oven has been designed and built. (Air atmosphere for large parts.)
    3. CNC mill should be delivered mid Dec. This will allow rapid production of burner parts from design on work station direct to mill.
    4. Silicon graphics works station and ProEngineer software purchased. This will allow 3D design of parts and modeling of components.
    5. Five gas emission test equipment purchased and operational.
    6. Instrumentation bench designed and built.

  - Recuperator parts have been designed, cast and tested. Design optimization is ongoing.

  - Emitter stacks have been designed, cast and tested. Design optimization is ongoing.

  - Initial burner heat trials have shown very low emissions: Total HC below 1 PPM, CO = 100 PPM, NOx = 301 PPM. N.B. Catalyst coating on recuperator can drive NOx even lower.

ACCOMPLISHMENTS (Cont.)

• **TPV CELL PRODUCTION** (JX Crystal subcontract)

- New equipment purchased and based at JX Crystals.

1. Liquid Phase Epitaxy - in place and being modified to produce quaternary cells.
2. Vacuum Desiccator - for use in filter production.
3. Crystal Puller manufactured to order in China.
   - currently being shipped from China.
4. Cell position fixtures designed and built.
5. Hall Effect Measurement System - purchased by JX Crystals.
6. High powered microscope - purchased by JX Crystals.

- New production methods have allowed JX Crystals to develop inventory of 700 - 1cm^2 cells and 80 oversize cells for use on circuit ends in an effort to improve system efficiency.

• **FILTER RESEARCH AND DEVELOPMENT** (JX Crystal subcontract)

- Separate filters at mouth of recievers proved almost impossible to cool.

- Filters are currently being mounted on cell face. (400 in inventory).

- Experiments continue on depositing filter material directly on cell face.

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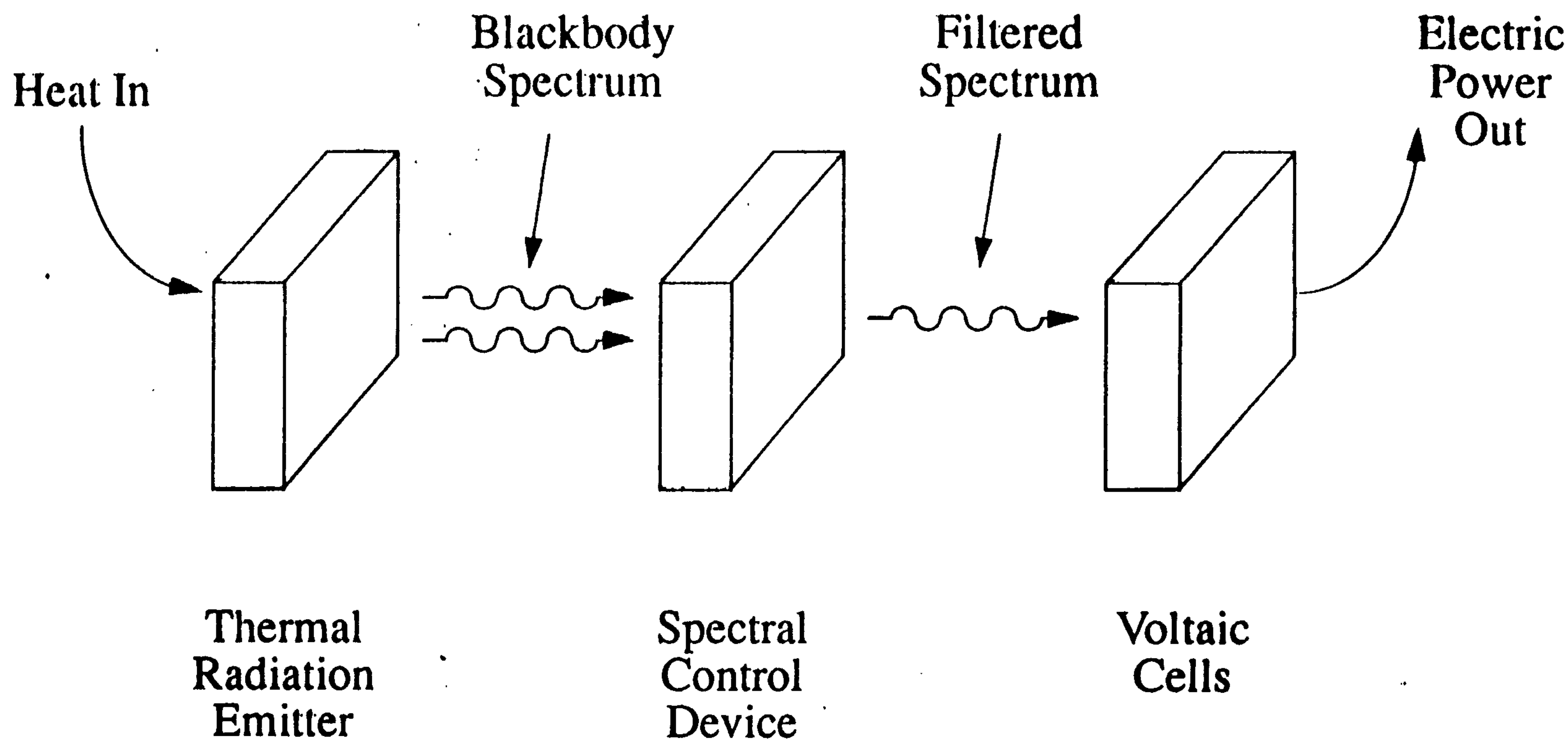
"TPV: AN INDUSTRY PERSPECTIVE"

Dr. Paul Baldasaro

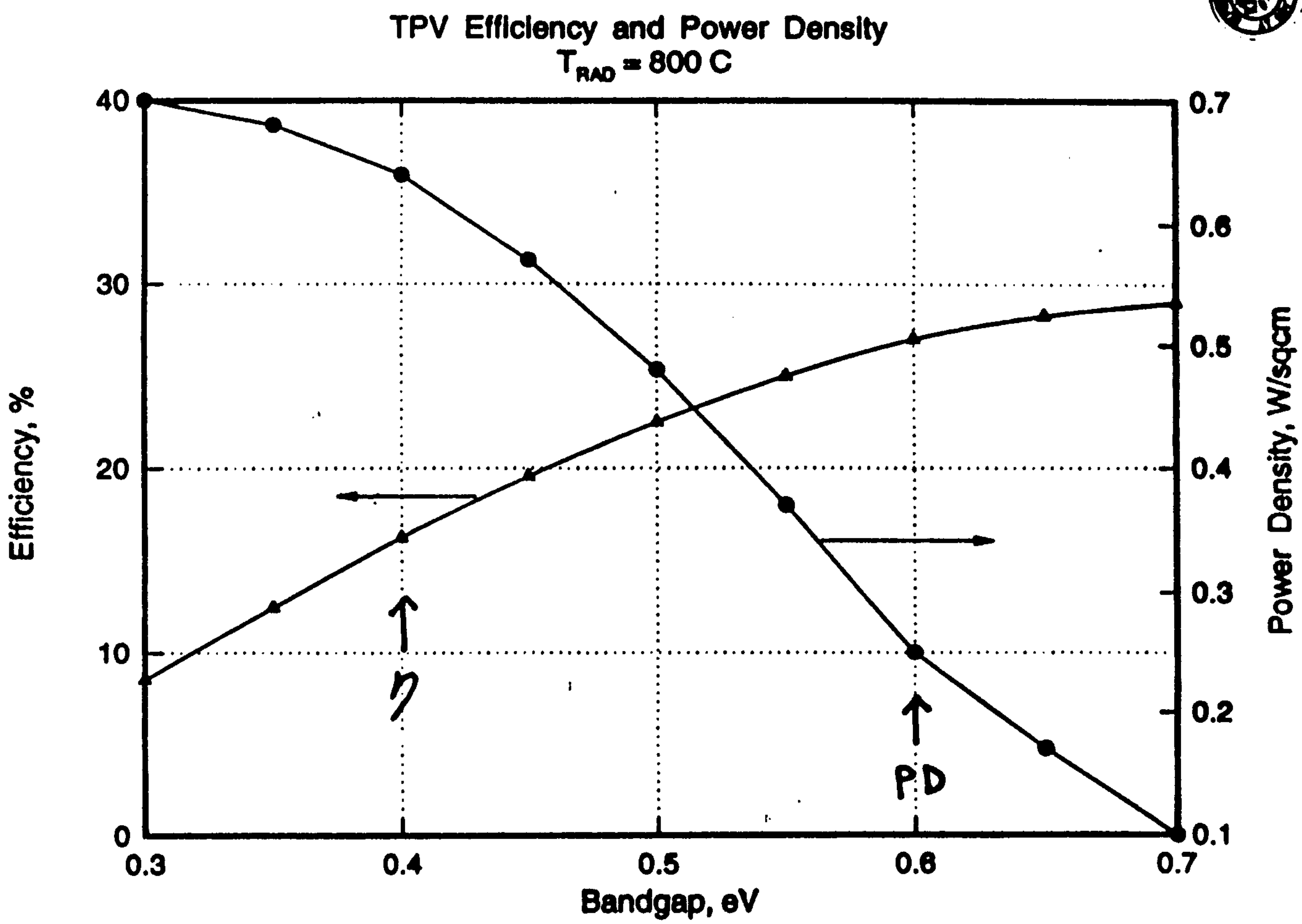
Lockheed/Martin
Schenectady, NY 12301

FIGURE 1

Thermo Voltaic Concept



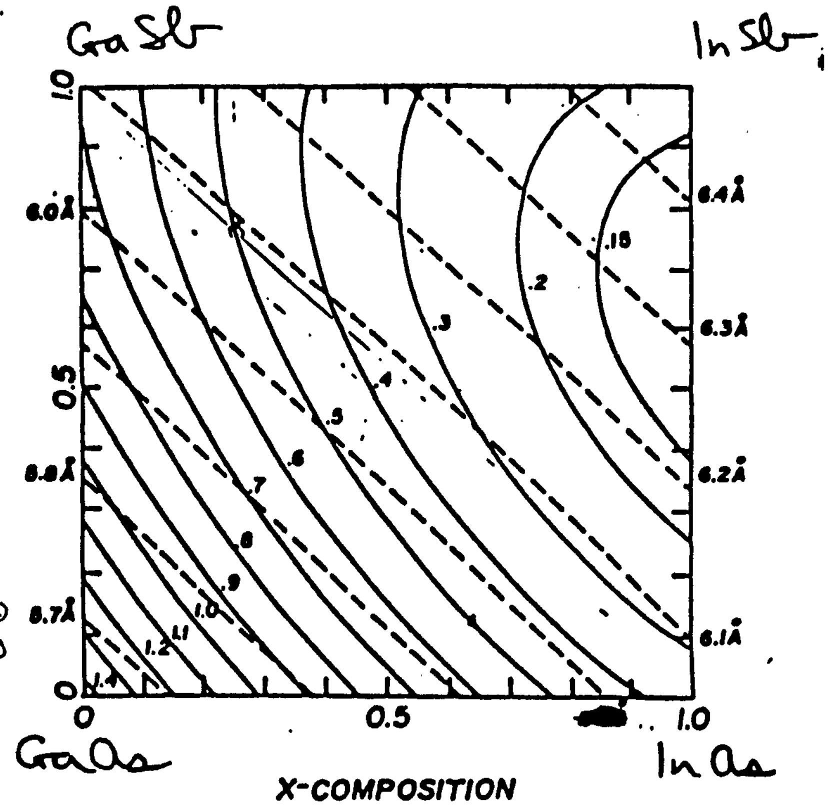
DIODE FEASIBILITY ASSESSMENT



ALLOWABLE BANDGAP RANGE $0.4 < E_g < 0.6$

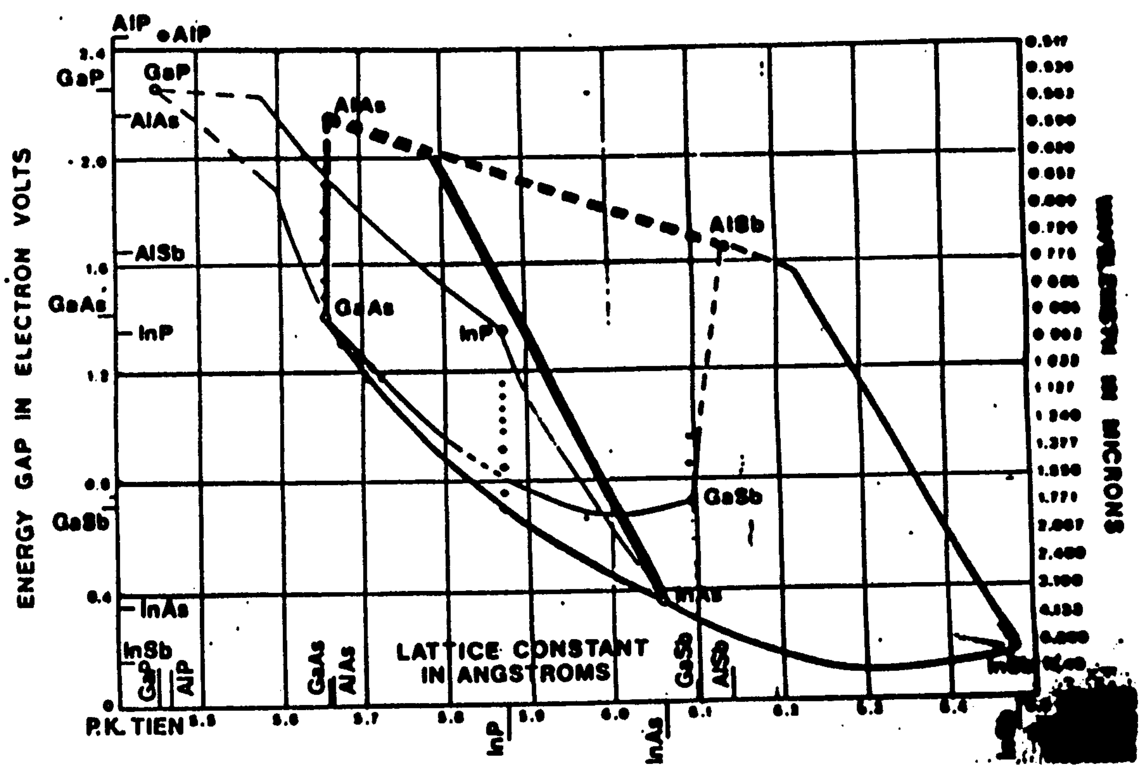
MATERIALS SYSTEM OPTIONS

Ternary system



(1) $Ga_{1-X}In_XAs_{1-Y}Sb_Y$

Quaternary system



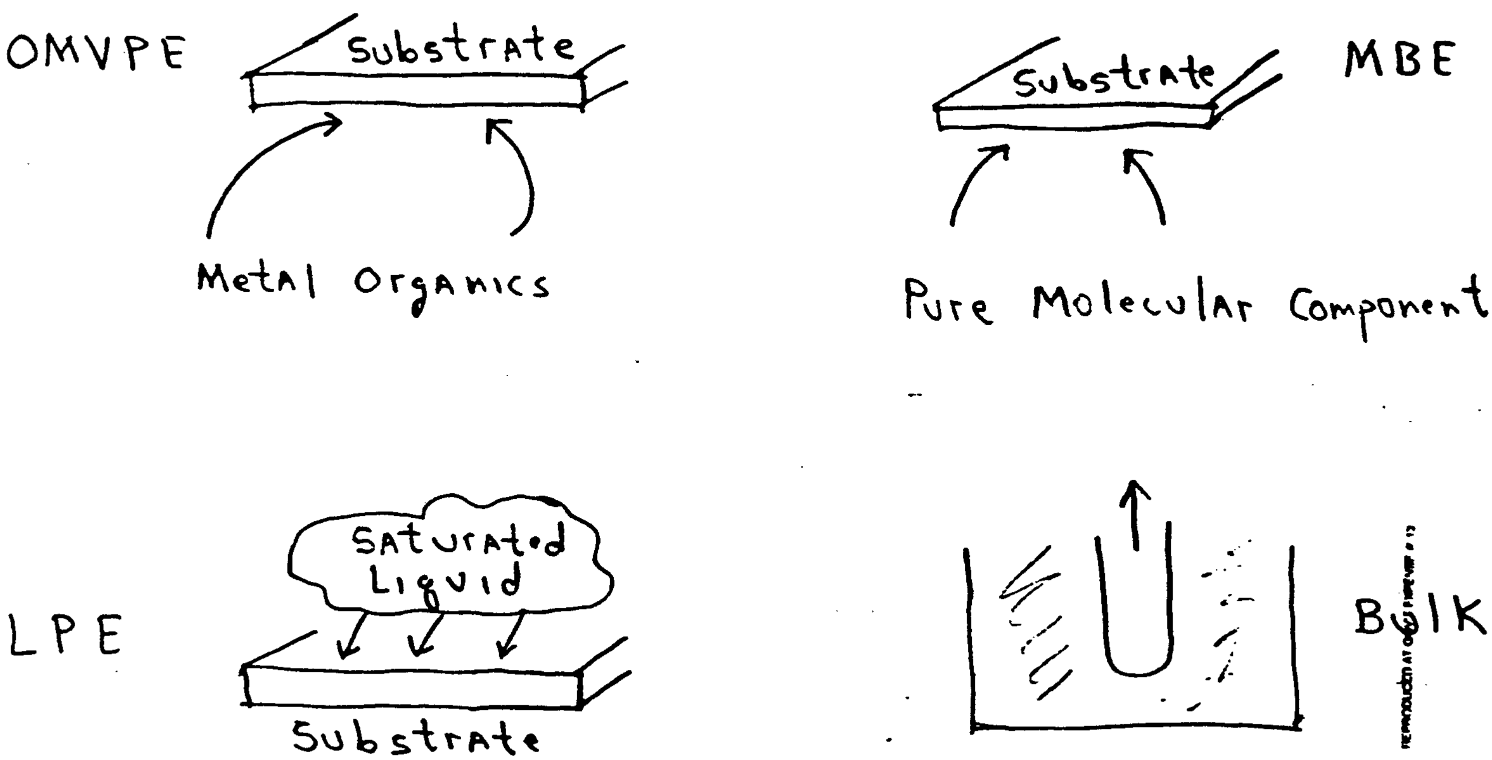
MULTIPLE MATERIALS SYSTEMS AVAILABLE FOR TPV CELLS

MICROFABRICATION TECHNOLOGY

TPV cells and filters require micron size fabrication control. What are the options and experience?

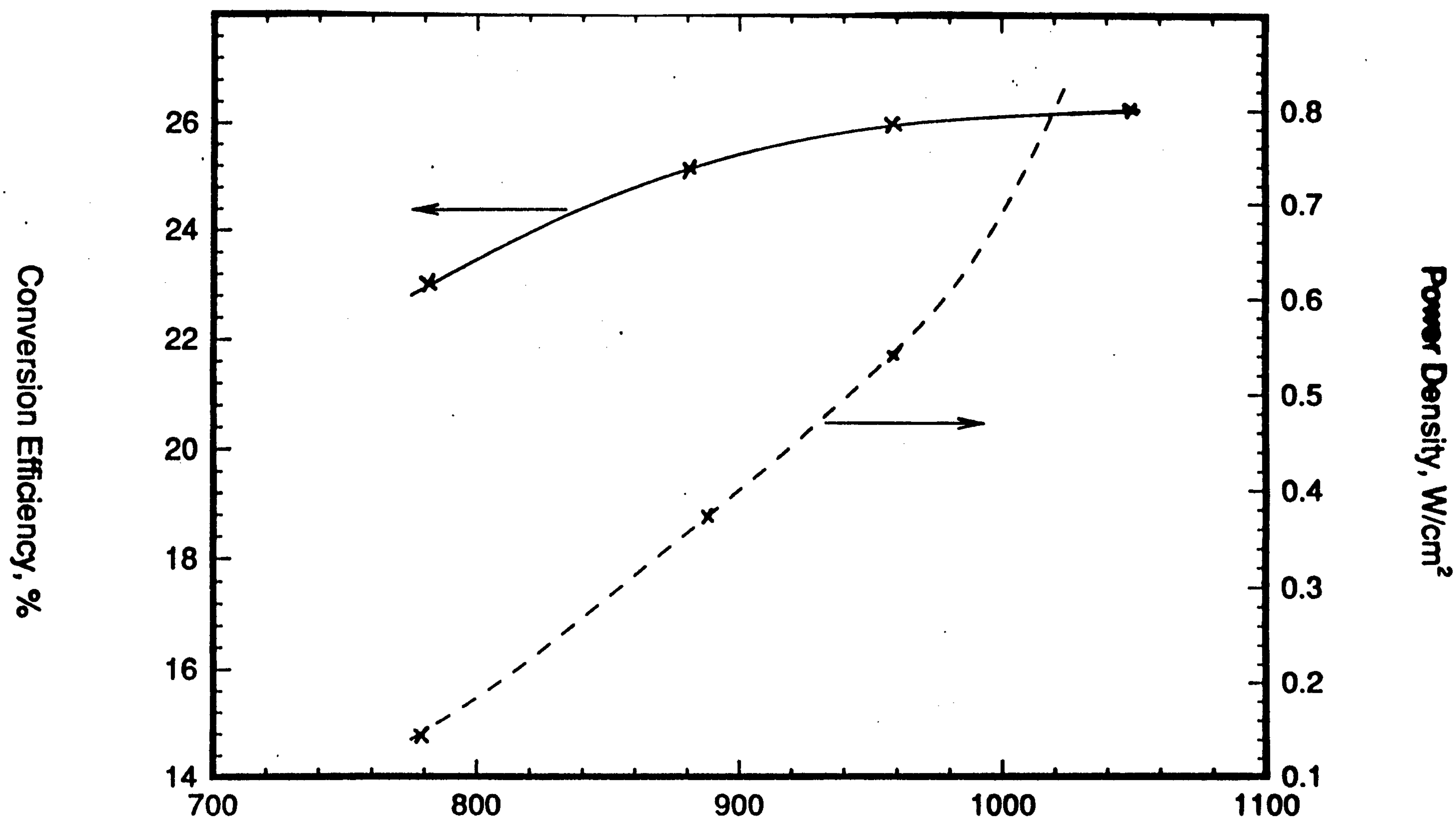
Note that voltaic conversion at the ~~lower bandgaps targeted (~0.5~~ ev) requires **single crystal** devices, which **mandates** epitaxial growth processes.

OPTIONS	1. Vapor phase growth	metal organics (OMVPE)
		pure molecular vapor (MBE)
	2. Liquid phase growth	precipitation (LPE)
		bulk growth



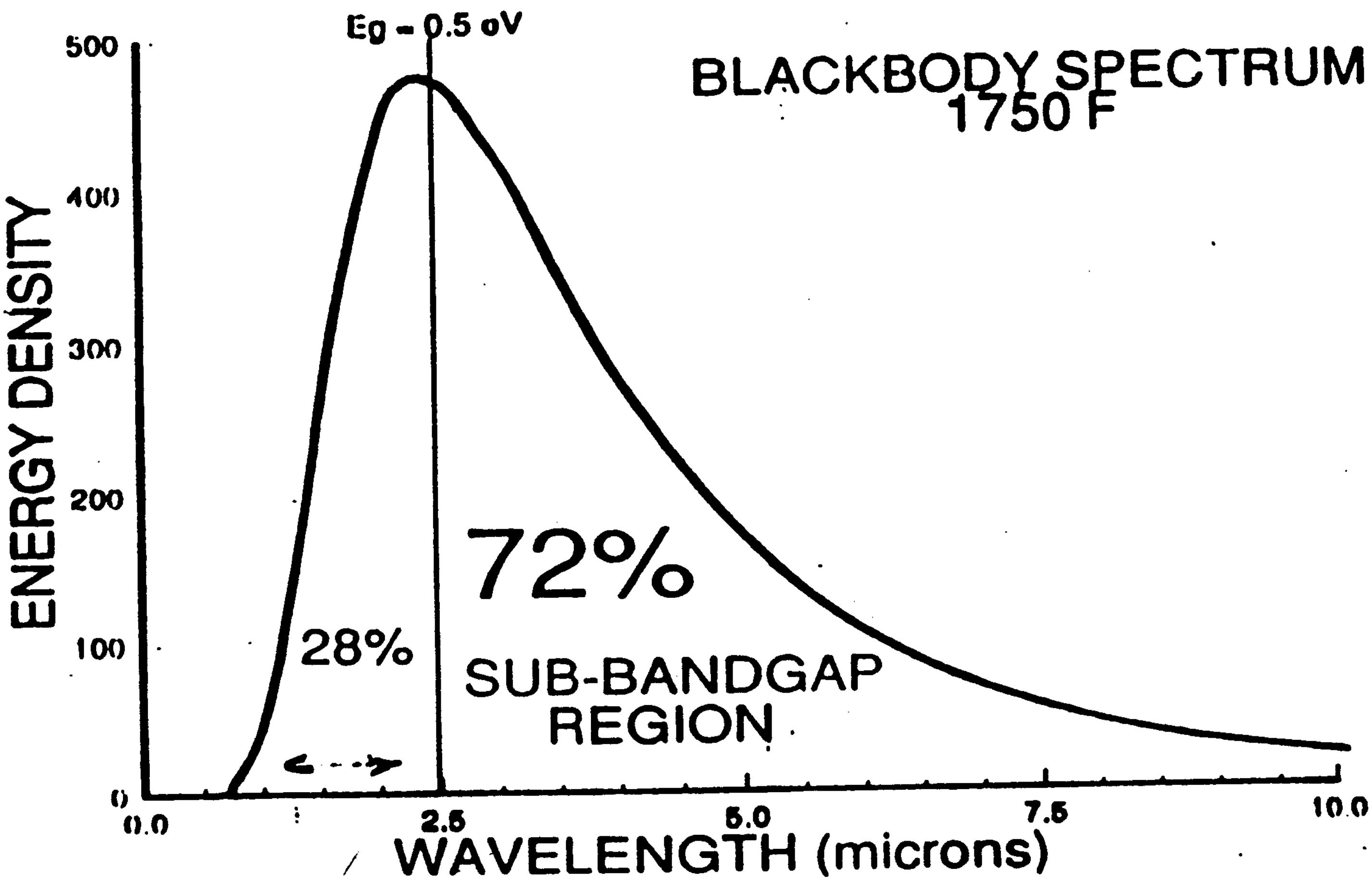
MULTIPLE FABRICATION OPTIONS AVAILABLE

Efficiency and Power Density



FILTER FEASIBILITY ASSESSMENT

SPECTRAL SELECTIVITY



THE MAJORITY OF THERMAL RADIATION IS BELOW BANDGAP

THERMO PHOTOVOLTAICS SPECTRAL CONTROL TECHNOLOGY

1. INTERFERENCE FILTERS

2. SOLID-STATE PLASMA FILTERS

3. TPV CELL DESIGN
   - BACK SURFACE REFLECTION
   - EMITTER/SUBSTRATE PLASMAS

4. EMISSIVITY MODIFICATION
   - SURFACE TEXTURING
   - MATERIAL SYSTEM DESIGN

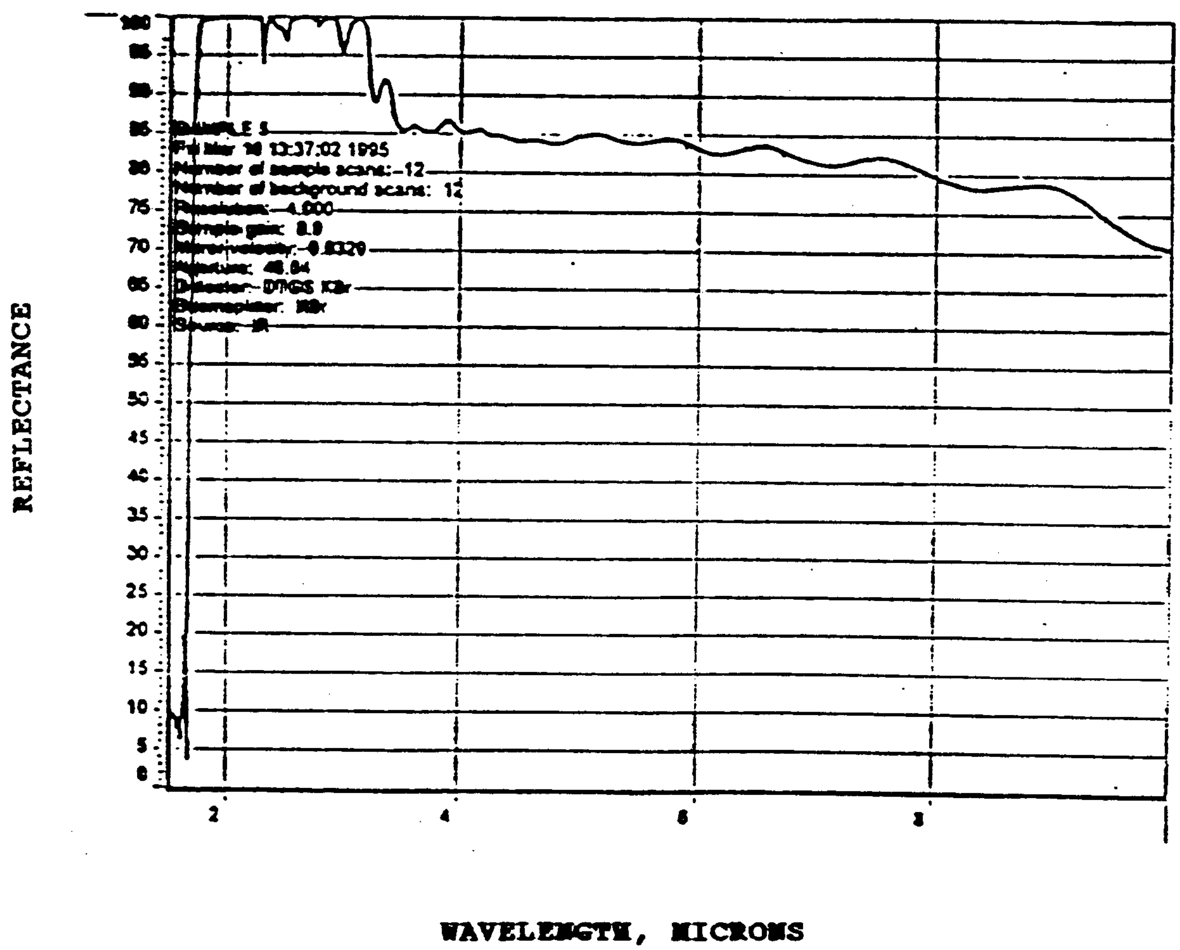
5. THIN METAL/DIELECTRIC FILTERS

6. METALIC DIPOLE FILTERS

7. METALIC GRID FILTERS

8. QUANTUM WELL FILTERS

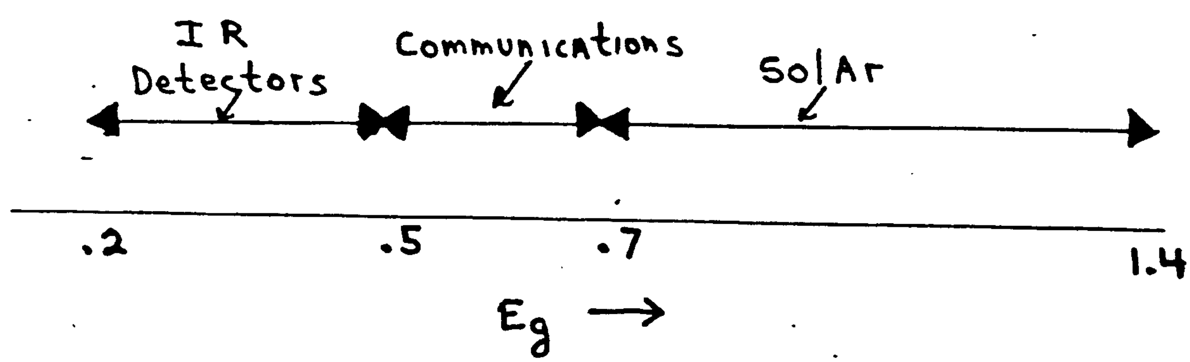
REFLECTANCE SCAN OF A DIELECTRIC/BSR FILTER SYSTEM



SPECTRAL CONTROL DEMONSTRATED

TECHNOLOGY OVERLAP (i.e. REINVENTING THE WHEEL)

PUNCHLINE: Much of the technology required for low temperature TPV has already been developed for other applications.



Note the strong overlap between the communications bandgap range and the desired low temperature TPV cell range.

Identified technologies to date:

- Quaternary voltaic cells grown with OMVPE, MBE, <u>and</u> LPE
- High performance graded ternary voltaic cells of InGaAs
- Plasma filters
- High performance interference filters
- High reflectivity back surface reflector technology (developed for TPV application in the 700's)
- Bulk ternary crystal growth technology

TPV HAS LARGE SYNERGY WITH THE NATIONAL INFRASTRUCTURE.

ENGINEERING FEASIBILITY

Figure 8

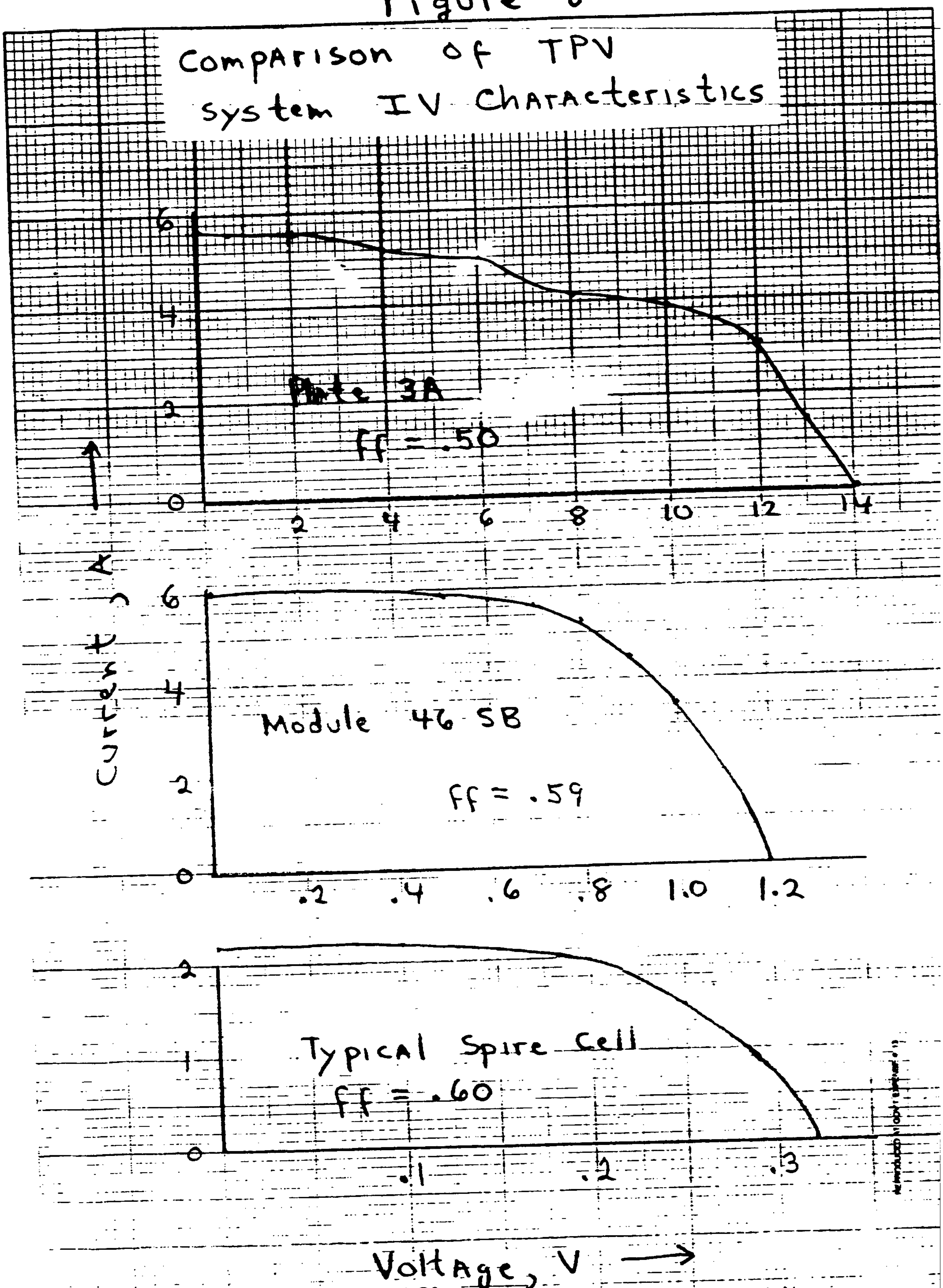

Comparison of TPV system IV Characteristics
Plate 3A
ff = .50
0
2
4
6
2
4
6
8
10
12
14
Current, A
6
4
2
0
Module 46 5B
ff = .59
.2
.4
.6
.8
1.0
1.2
2
1
0
Typical Spire Cell
ff = .60
.1
.2
.3
Voltage, V

Figure 10

Calculated Effect of Measured Illumination Uniformity

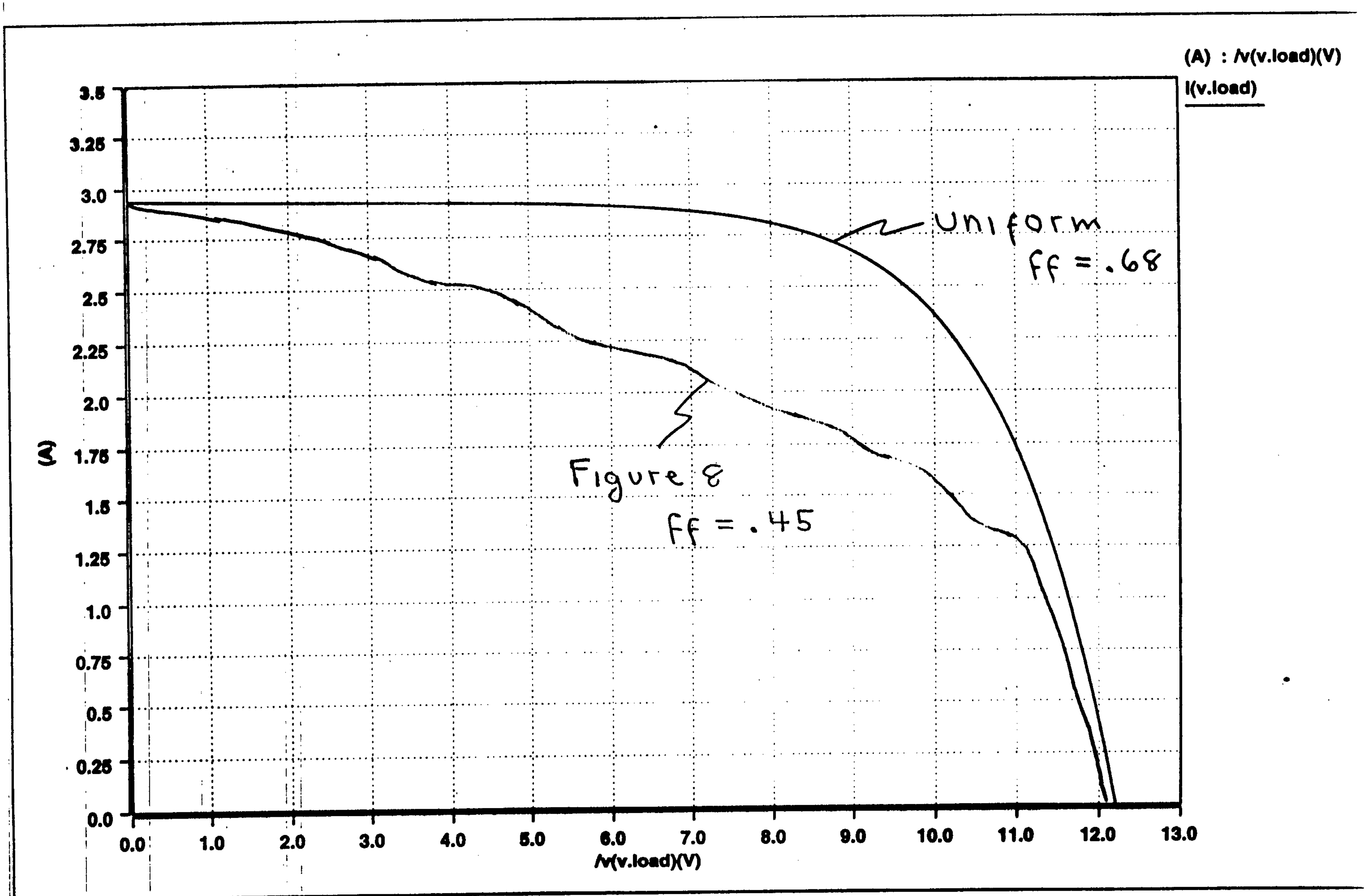
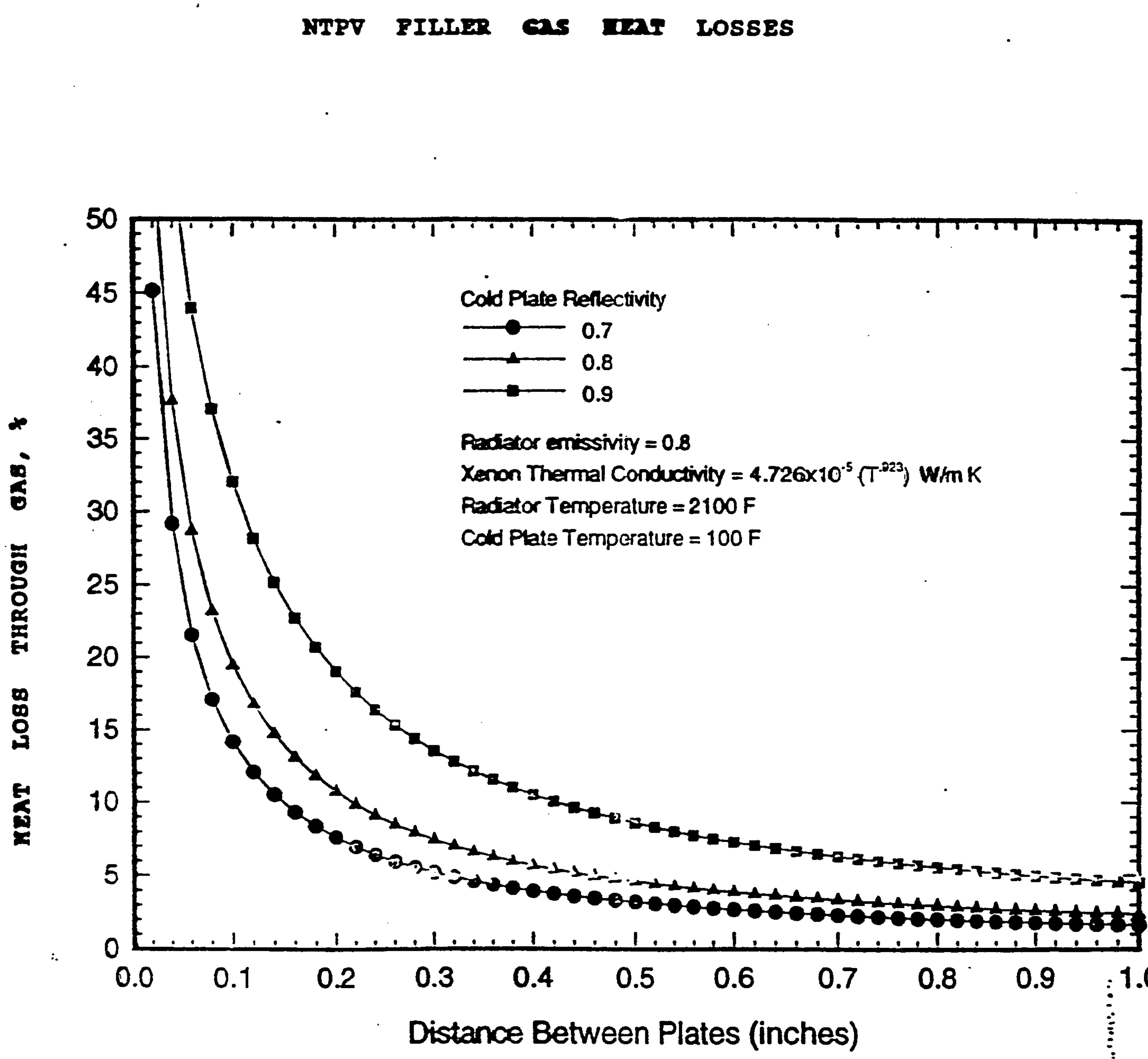


Figure 11



NTPV FILLER GAS HEAT LOSSES
Cold Plate Reflectivity
0.7
0.8
0.9
Radiator emissivity = 0.8
Xenon Thermal Conductivity = 4.726x10^-5 (T^.923) W/m K
Radiator Temperature = 2100 F
Cold Plate Temperature = 100 F
HEAT LOSS THROUGH GAS, %
Distance Between Plates (inches)
0
5
10
15
20
25
30
35
40
45
50
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

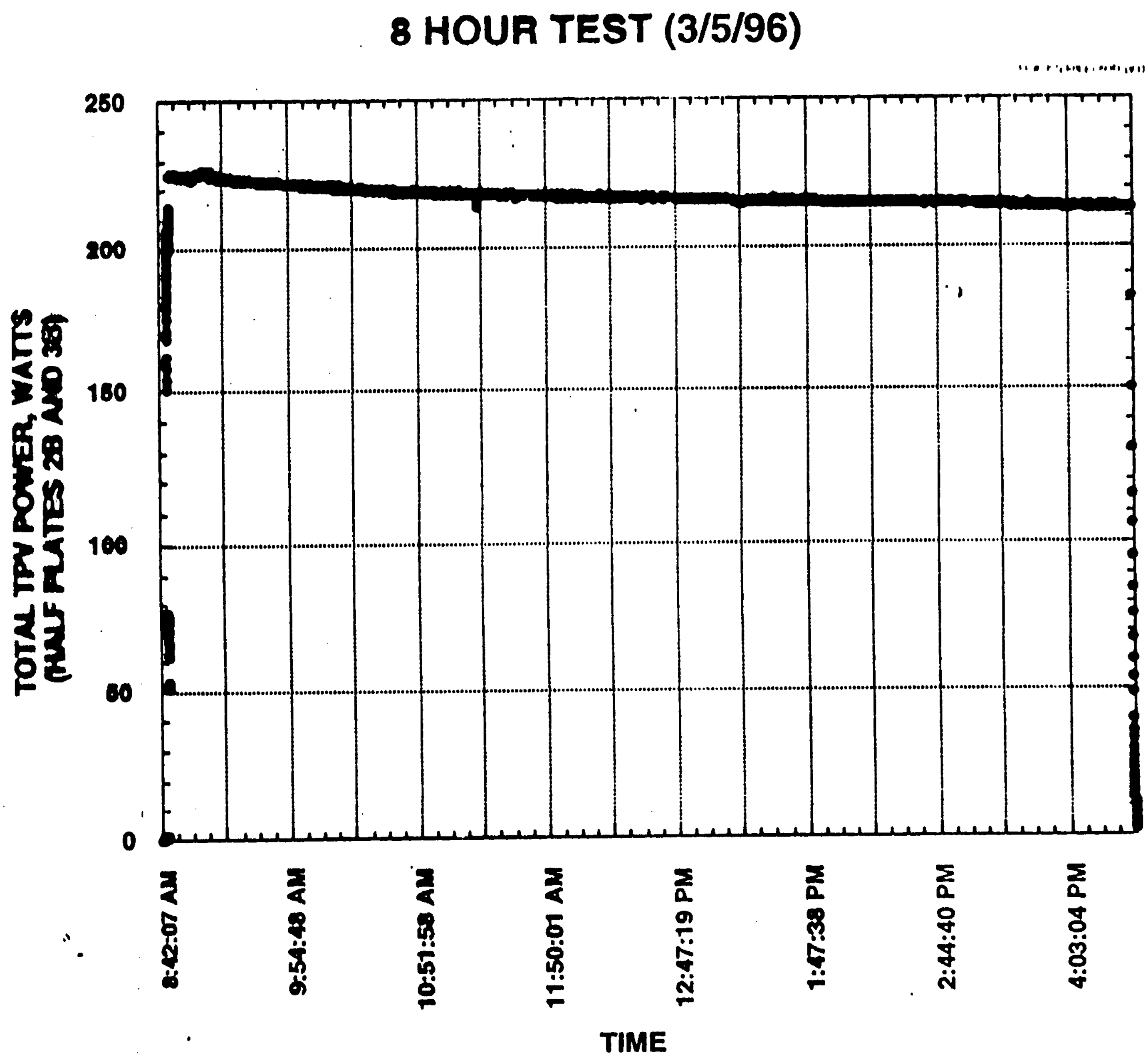
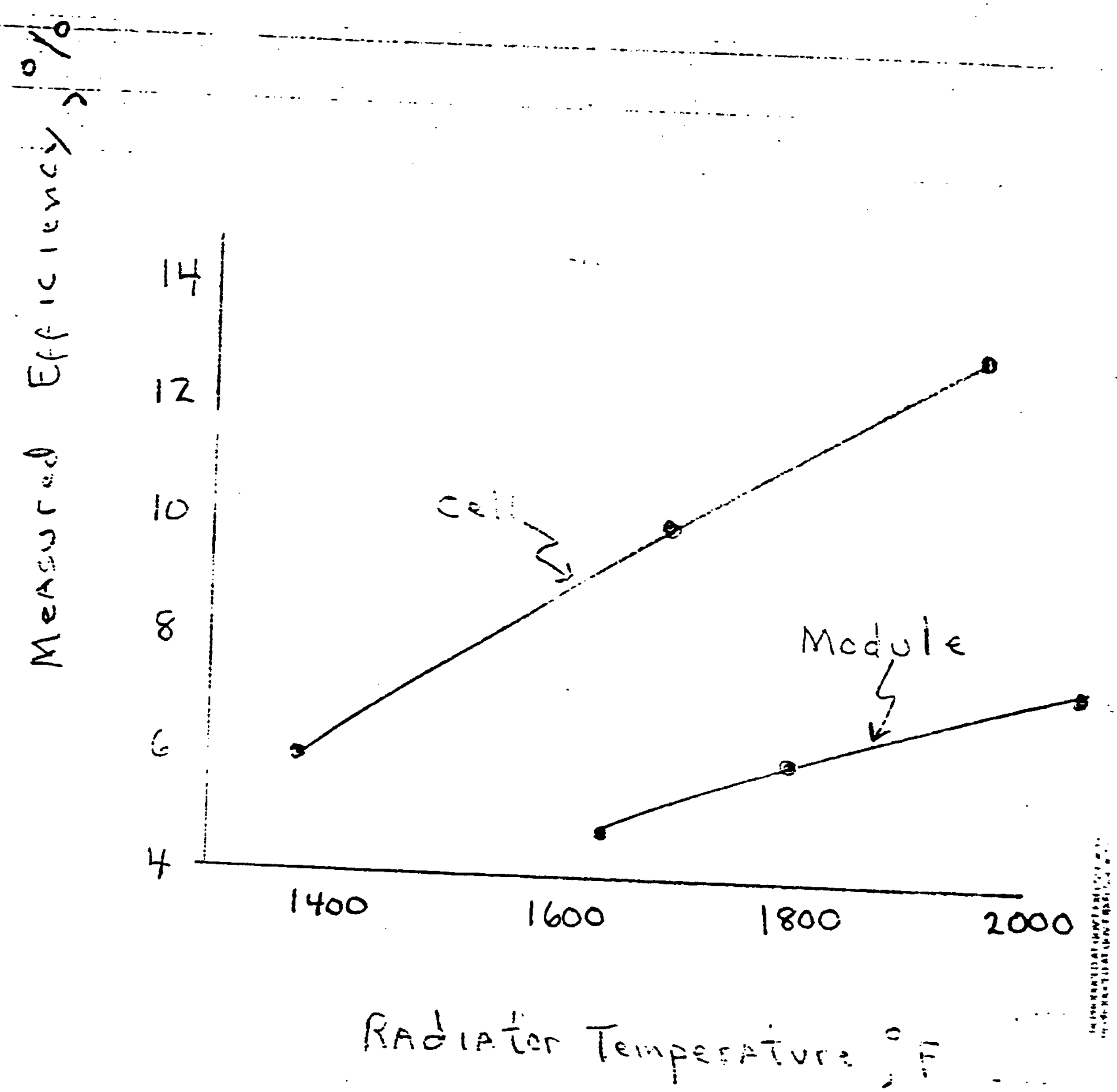


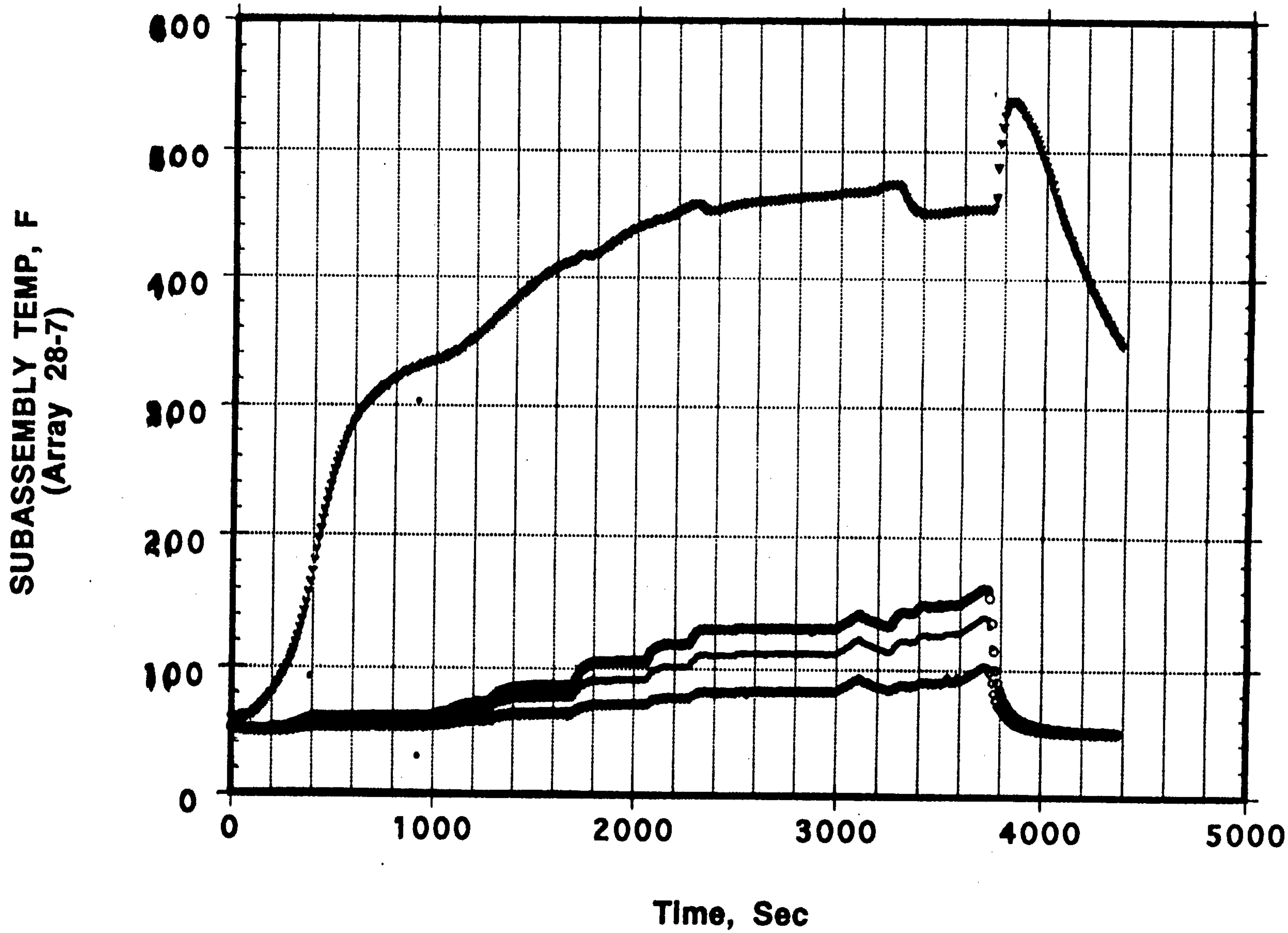
Figure 1. Graph showing TPV power (half plates 2B and 3B) degradation over the course of eight hours.

Figure 13

Comparison of Cell and Module Conversion Efficiencies



LOSS OF BONDING EXCURSION



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NASA PROGRAM IN THERMOPHOTOVOLTAIC ENERGY CONVERSION TECHNOLOGY

PRESENTED
TO
PROSPECTOR VIII WORKSHOP
BY

DENNIS J. FLOOD

DURHAM, NC
JULY 14-17, 1996

WHERE ARE WE GOING AND WHY DO WE CARE?

- NEW STARTS ARE REQUIRED TO BE

  "FASTER, BETTER, CHEAPER"

- DEEP SPACE MISSIONS ARE A SPECIAL CONCERN
  - S/C RADIOISOTOPE INVENTORY MUST BE REDUCED
  - NEW TECHNOLOGY IS MANDATED (AND REQUIRED!)

- NASA BUDGETARY CLIMATE IS "RESTRAINED" AT BEST
  - 180$K TOTAL, FY94-96 DIRECT BUDGET
  - SBIR $'s, DARPA $'S ONLY (>2.0$M, FY95-97)

- NASA IS SEEKING "REVERSE SPINOFF"

- CURRENT PROGRAMS HAVE PRIMARILY TERRESTRIAL APPLICATIONS, PROVIDE SYNERGISTIC TECHNOLOGIES
  - LOW T: RADIOISOTOPE TPV/DEEP SPACE
  - HIGH T: SOLAR TPV/EARTH ORBITING, NEAR SUN

Plasma-Sprayed Thin-Film Selective Emitter for Thermophotovoltaic Power Conversion

Contract NAS3-27829
SBIR 95-1 Phase I
Period 12/01/95 to 5/31/96

Prepared for
NASA Lewis Research Center
Power Technology Division
Cleveland, Ohio

Prepared by
Creare Inc.
Christopher J. Crowley, Principal Investigator
Patrick J. Magari, Project Engineer

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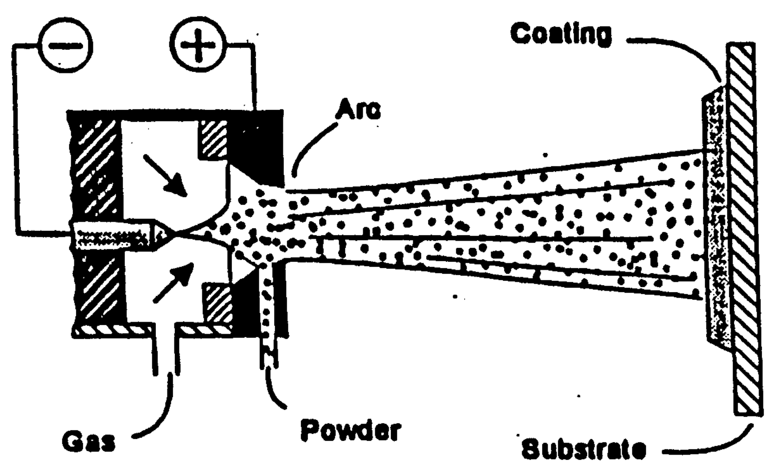


Figure 12. Plasma-Spray Process

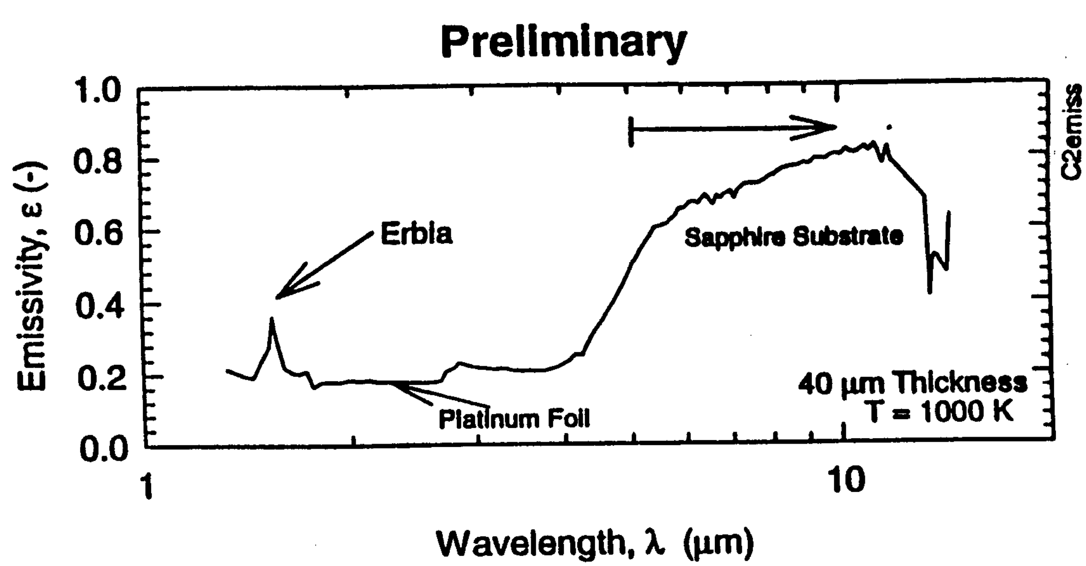


Figure 8. Wide-Range Spectral Emittance for an Erbia Plasma-Spray Coating (40 µm) on a Sapphire Substrate

PHOTOVOLTAIC BRANCH

Lewis Research Center

A Solar Thermophotovoltaic Electrical Generator for Remote Power Applications

NAS3–27779
Final Report

Contractor –
Essential Research, Inc.
2460 Fairmount Blvd.
Suite A
Cleveland, OH 44106

ESSENTIAL RESEARCH INCORPORATED

This effort is funded by the Ballistic Missile Defense Organization Small Business Innovation Research Program, and administered by the NASA Lewis Research Center.

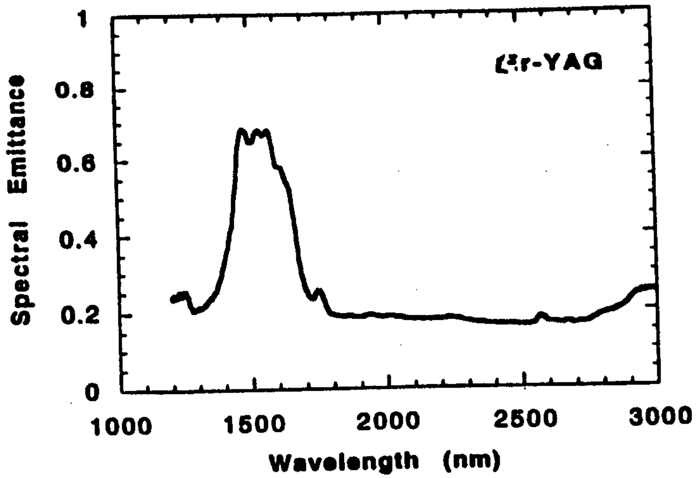


Figure 7.—Spectral emittance of a 40% Er-doped YAG selective emitter.

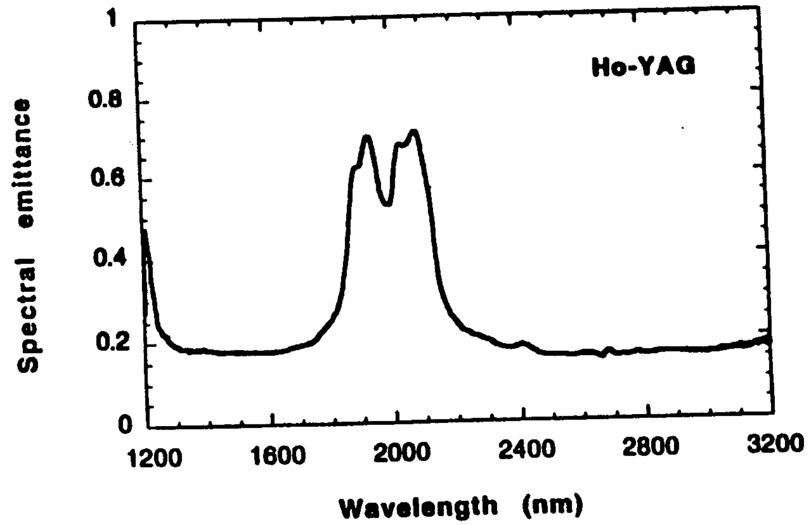


Figure 5.—Spectral emittance of a 25% Ho-doped YAG selective emitter.

Table VI.—TPV Converter output power density and efficiency data for a source temperature of 1700 K.

Emitter	Filter λc (μm)	PV Cell Eg (eV)	Pout (W/cm^2)	Efficiency (%)
Ho-YAG	2.2	0.51	0.29	11.4
Tm-Lu,YAG	2.0	0.57	0.44	16.2
Er-YAG	1.7	0.69	0.78	29.0
Blackbody	1.7	0.69	1.94	26.9

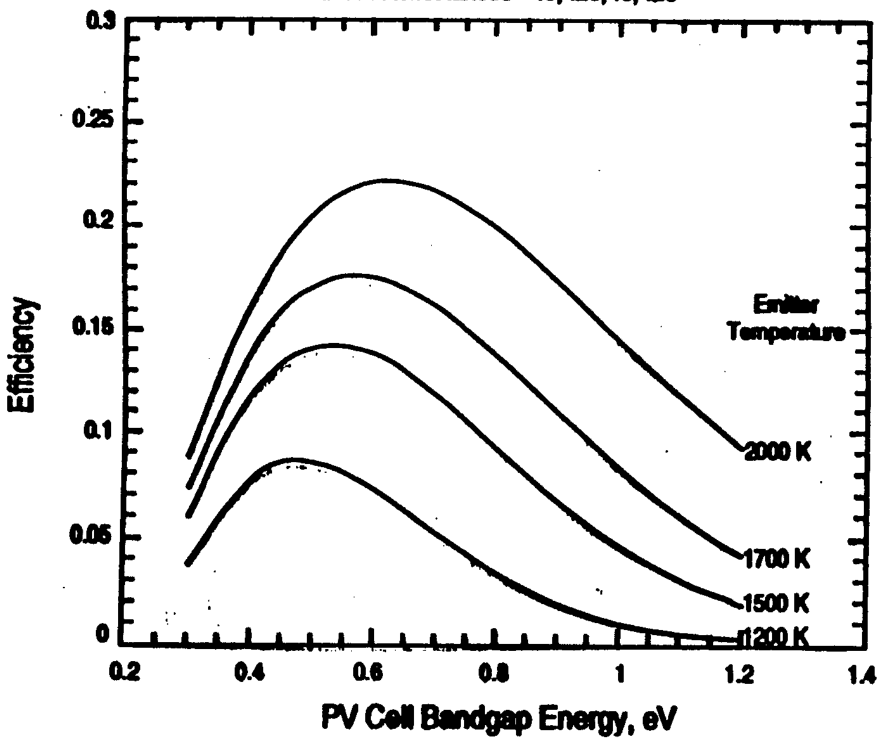
National Aeronautics and
Space Administration

Lewis Research Center

COMPUTER MODELING OF THERMOPHOTOVOLTIC SYSTEMS

POWER TECHNOLOGY DIVISION

Conversion Efficiency vs. Cell Bandgap Energy
Baseline Selective Emitter System
Band Emittances = .2, .75, .2, .75
Band Reflectances = .8, .25, .8, .25



ACCOMPLISHMENTS:

- COMPUTER CODE NEEDED TO ACCURATELY PREDICT PERFORMANCE OF THERMOPHOTOVOLTAIC (TPV) SYSTEMS
- MODEL APPLIES TO ANY SYSTEM (i.e., RTPV, STPV)
- TEMPERATURE PREDICTIONS USING CODE VALIDATED AT McDONNELL-DOUGLAS
- THE WORK HAS BEEN DESCRIBED IN SEVERAL PUBLICATIONS AND IN INVITED TALKS

MODEL WILL AID IN DESIGN OF ANY TYPE TPV SYSTEM

NREL TPV Activities and Capabilities

Timothy J. Coutts

NREL

Introduction

- Background in low-bandgap infrared-sensitive components of tandem cells
- Initially asked to perform modelling of TPV performance using these low-bandgap cells
- Involved in TPV for over four years
- Strong synergy between TPV and other NREL programs

Capabilities

- Cell design and optimization
- Semiconductor device growth by APMOVPE
- Device fabrication and diagnostics
- Device/materials characterization

Characterization Center

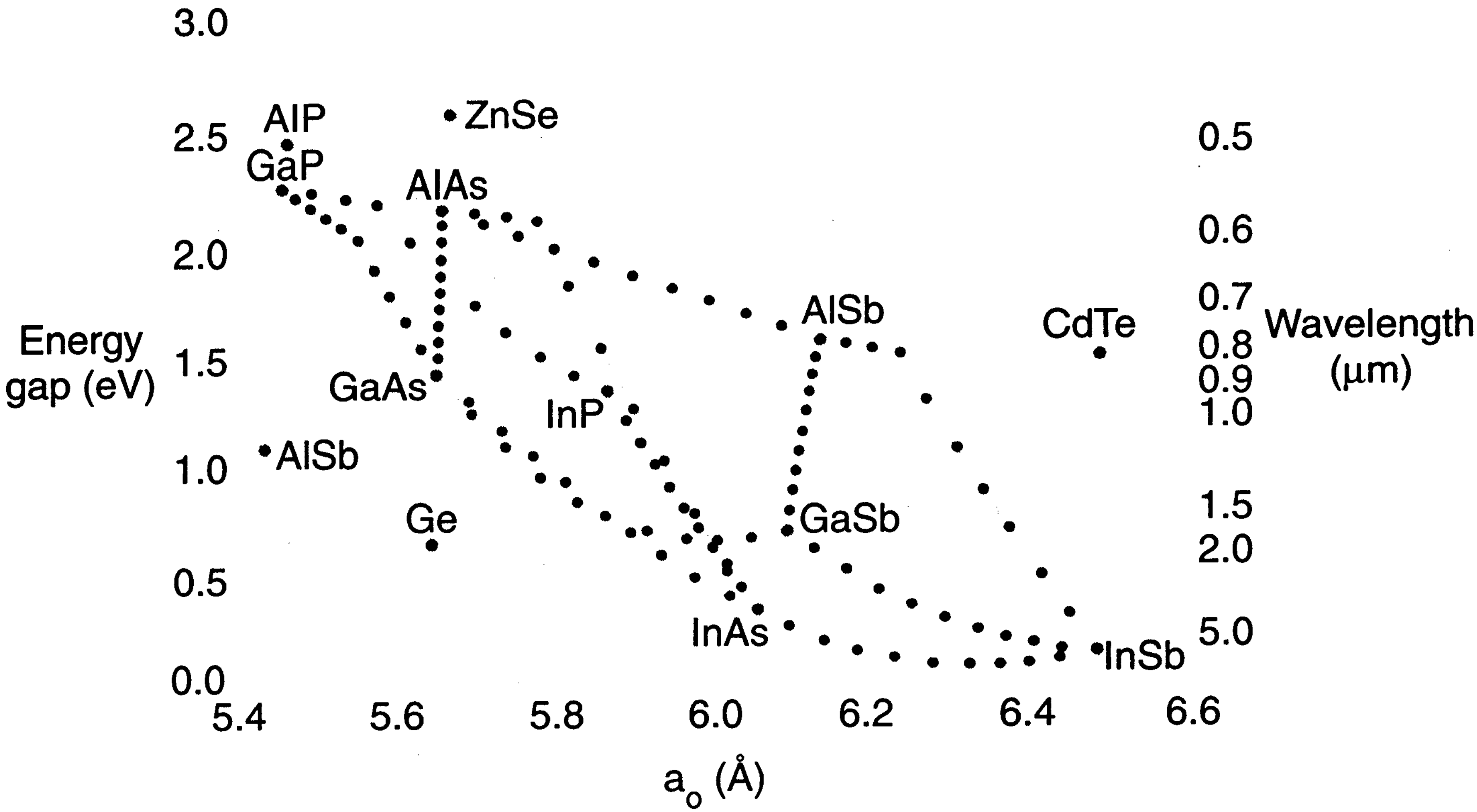
- Nano-scale characterization
- Chemical and compositional properties
- Electro-optical properties
- Structural and defect properties
- Device performance characterization

Unique Center covering materials research, device development, complete range of characterization capabilities

Projects

- Low-bandgap cells
- Interconnection techniques
- Bulk crystal growth (CAST)
- Electromigration in metallization

Lattice parameter and bandgap data for III-V compounds and alloys



Projects (contd.)

- Solar-powered TPV system
- Thin-film converters
- Plasma filters
- NREL/TPV Conference organization

3rd. NREL/TPV Conference

- Will be held 18-21 May, 1997
- Antlers Doubletree Hotel, Colorado Springs
- First announcement and Call for Papers due September 1st. 1996
- Abstracts due around November 1st.
- Advisory Group formed to help plan the Conference
- Proceedings again to be published by AIP in their Conference Series

PROSPECTOR VIII

THERMOPHOTOVOLTAICS
Sponsored by
Army Research Office
July 14-17, 1996

Second NREL Conference on Thermophotovoltaic Generation of Electricity

PORTABLE POWER SOURCES

Battery Technology

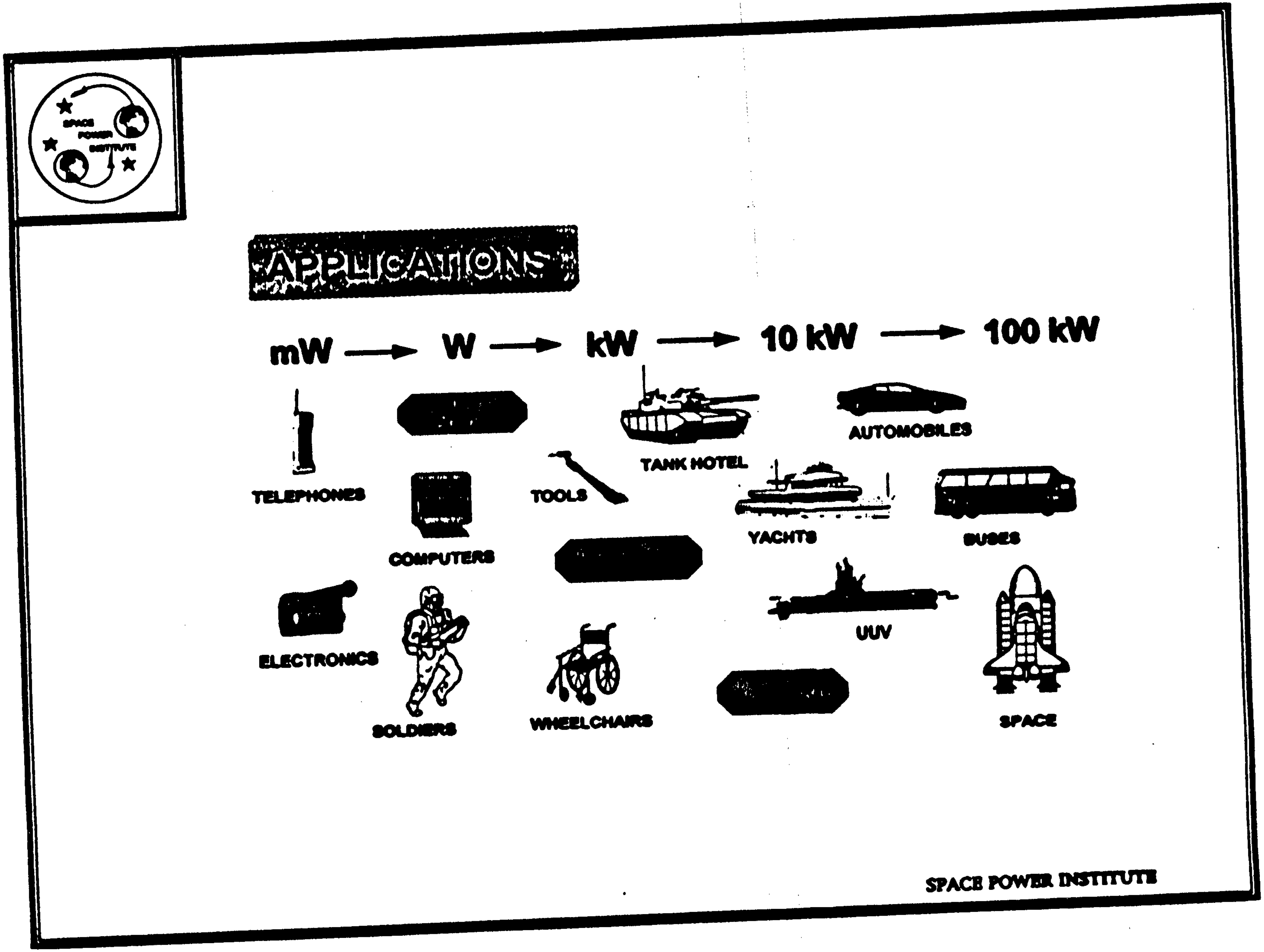
Fuel Cells
- Hydrogen PEM
- Methanol PEM

Alkali Metal Thermal To Electric Converter (AMTEC)

Motor - Generators

Thermoelectrics

SPACE POWER INSTITUTE


SPACE POWER INSTITUTE
APPLICATIONS
mW → W → kW → 10 kW → 100 kW
TELEPHONES
[redacted]
TANK HOTEL
AUTOMOBILES
COMPUTERS
TOOLS
YACHTS
BUSES
[redacted]
ELECTRONICS
SOLDIERS
WHEELCHAIRS
UUV
[redacted]
SPACE
[redacted]
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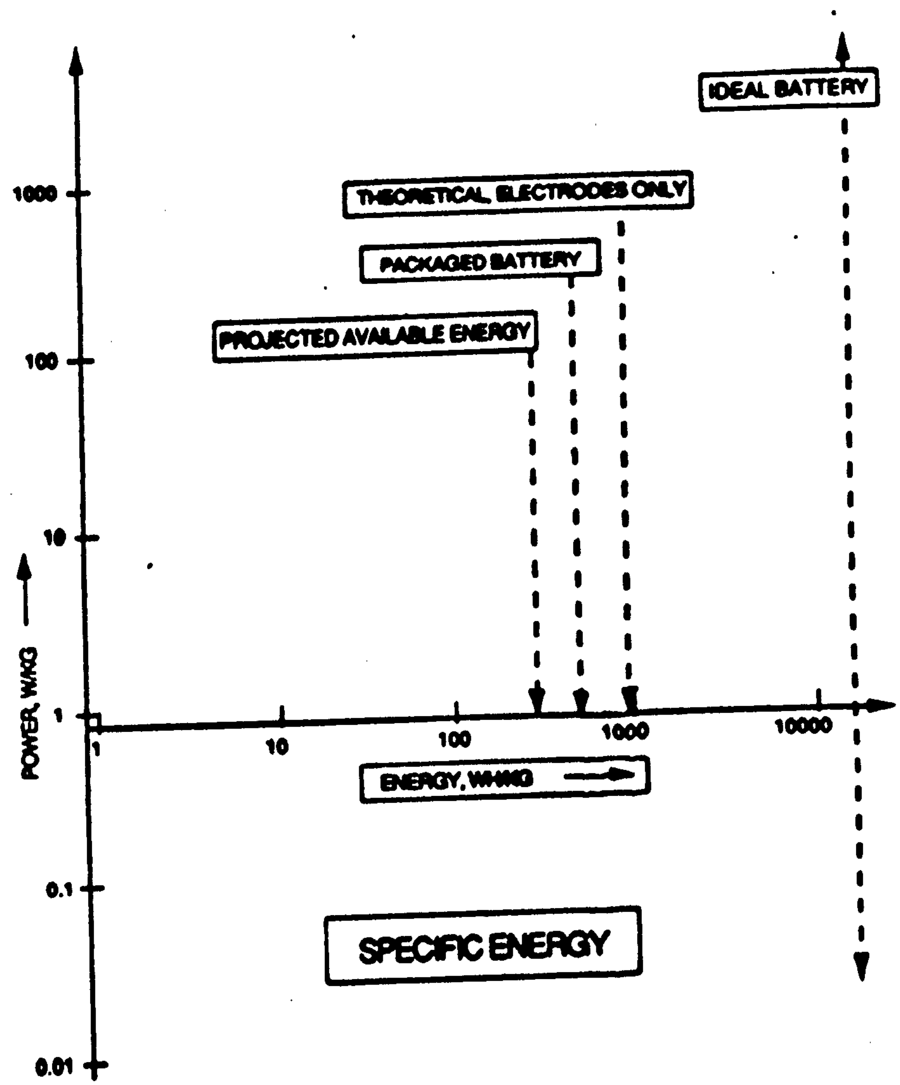

SPECIFIC ENERGY

SPACE POWER INSTITUTE

Second NREL Conference on Thermophotovoltaic Generation of Electricity

BATTERY TECHNOLOGY

ADVANTAGES

Well established manufacturing infrastructure
Reliable in established formats
Scale to small sizes
Self contained energy storage and converter

DISADVANTAGES

Safety
Limited shelf life
Limited charge-discharge cycling capability
Low power density
Minimal repair capability
Cost
Disposal

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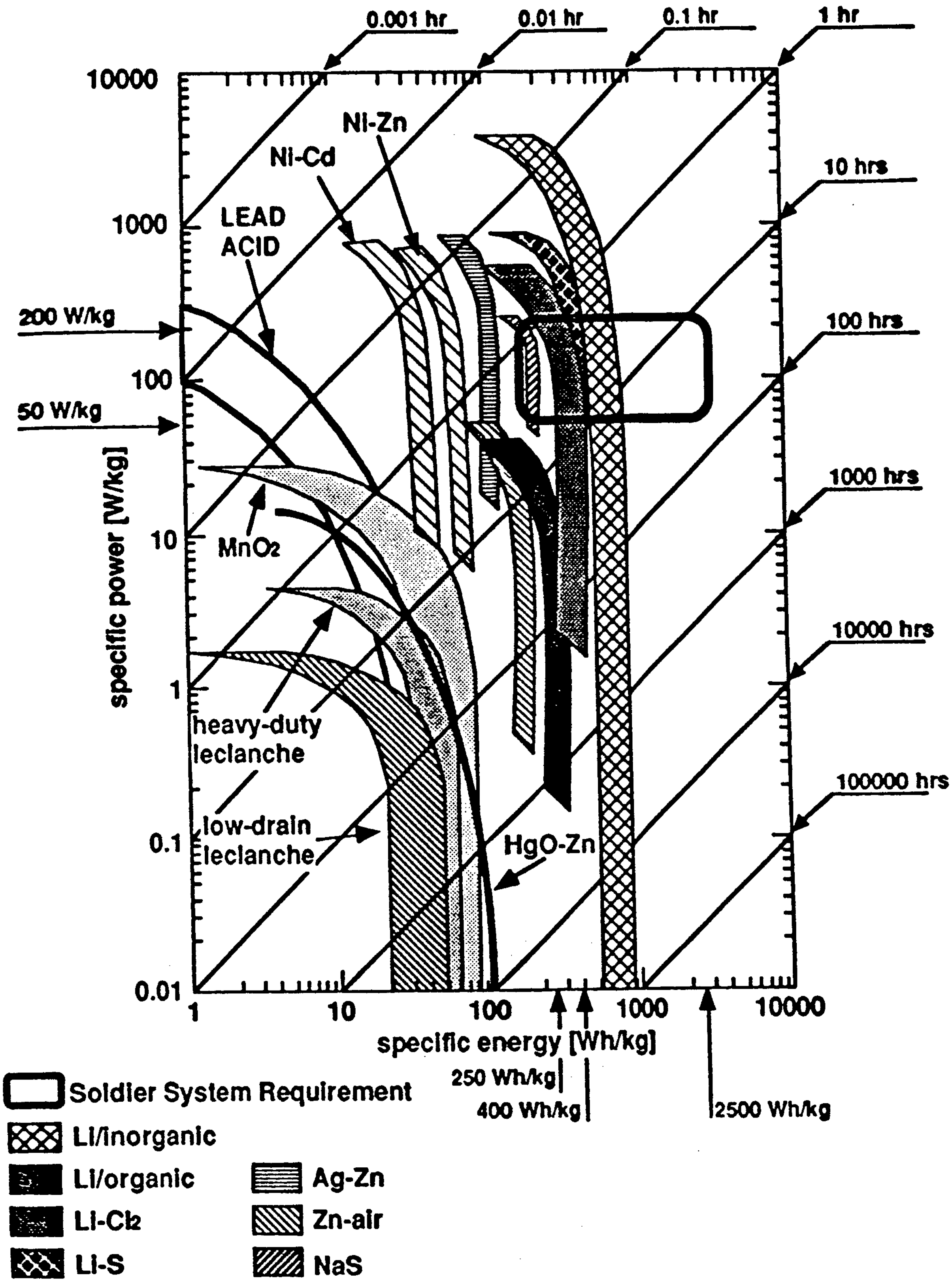

Figure 2. Ragone plot of a representative sampling of battery technologies relevant to Army needs.

Hydrogen PEM

Power level 150 W

H_2-ambient air with filtration

Forced ambient air convective cooling

Efficiency Approximately 65% at 80 ASF

Weight 3.6-4.5 kg

Volume Approximately 2.5 ltr

Lifetime >500 hrs

Power Density Approximately 50 W/kg

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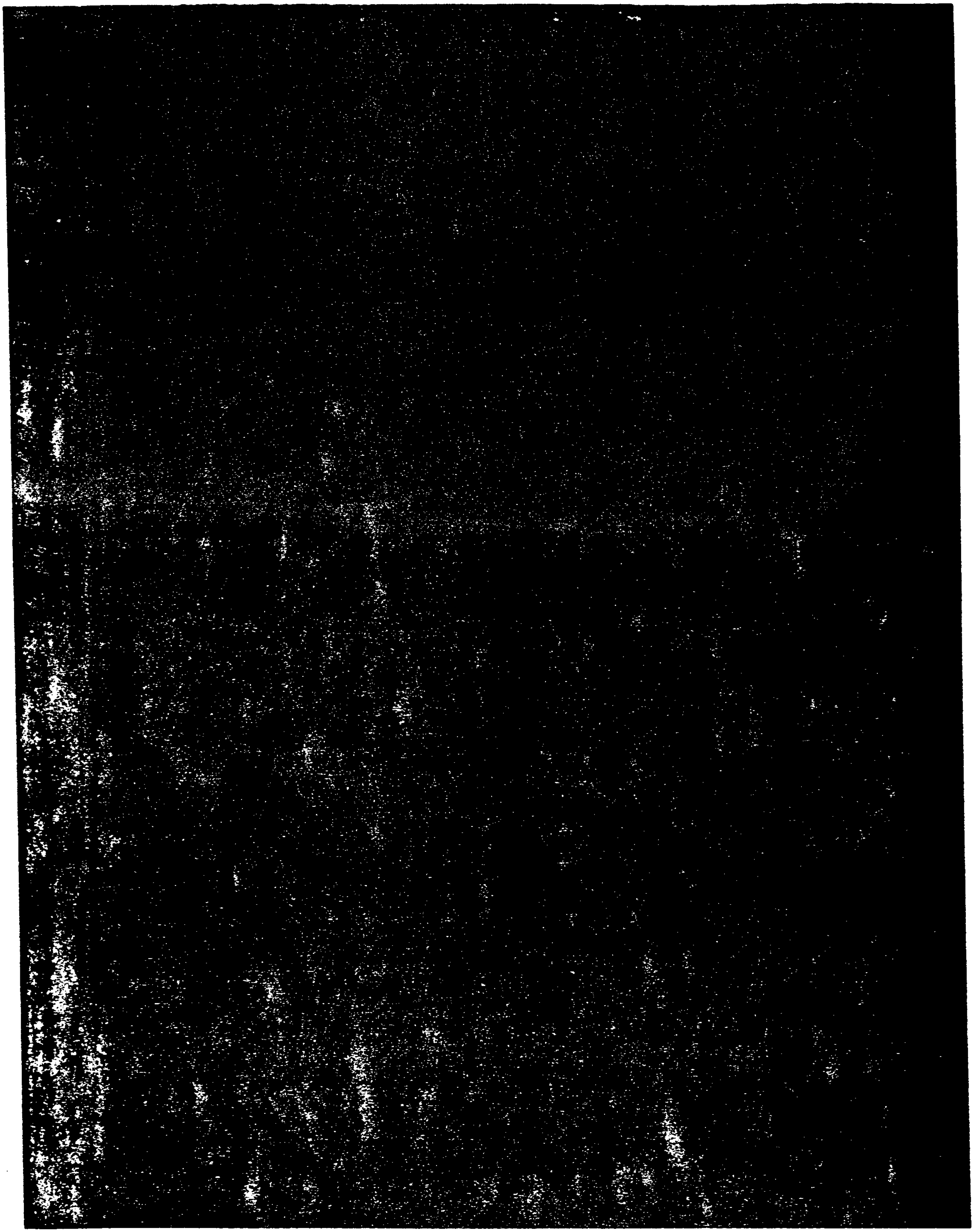
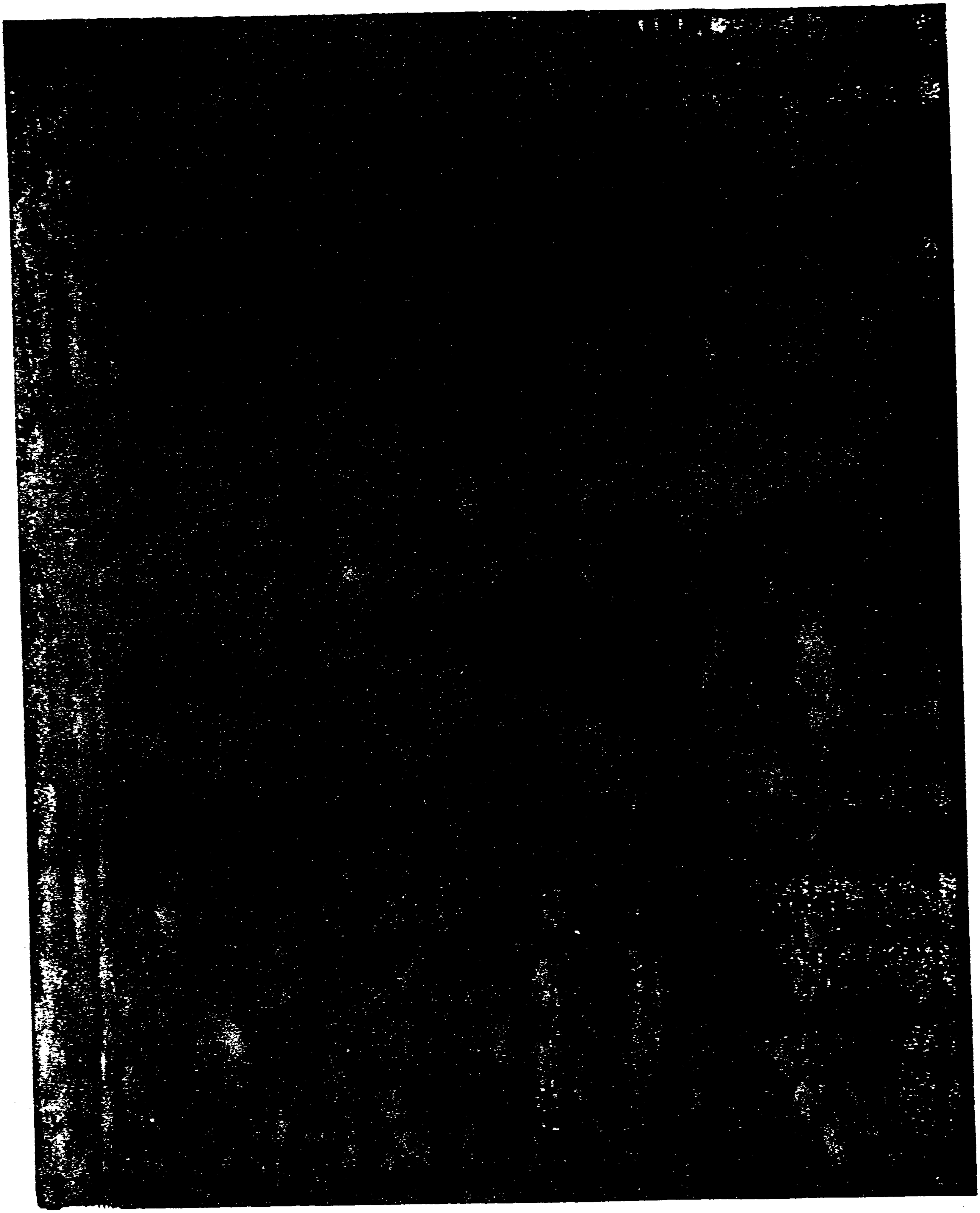
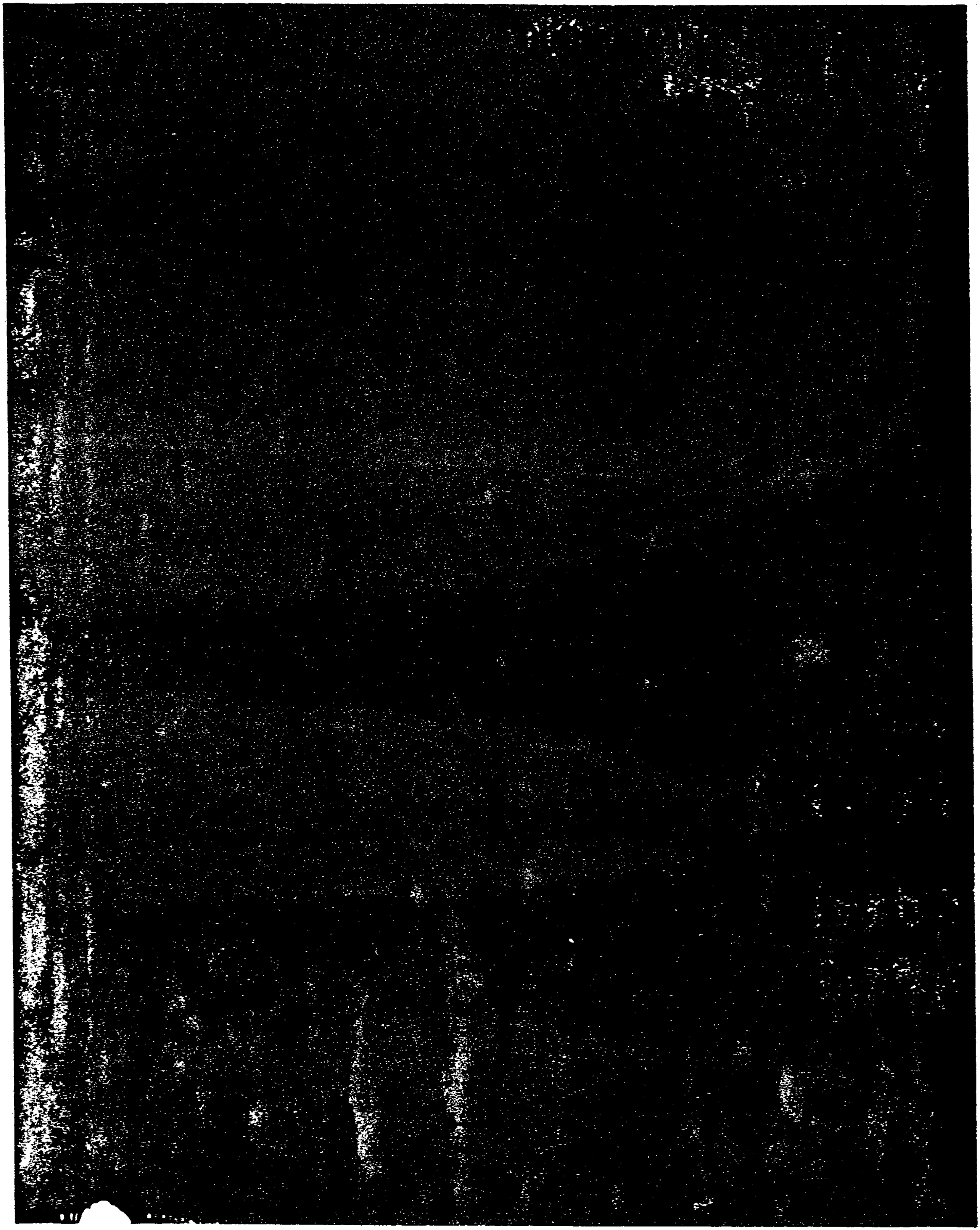




POLAROID
K476 9690 C



METHANOL PEM

Single Cell	0.33 V @800 mA/cm^2
	0.44 V @640 mA/cm^2
5-Cell Stack	0.45 V @300 mA/cm^2
Life Tests	>200 hrs continuous Tests (single cell)
	>500 hrs intermittent (single cell)
	>400 hrs @48 W (5 cell stack)
Efficiency	25-30% @ <300 mA/cm^2
Fuel Efficiency	>70% @300 mA/cm^2

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METHANOL PEM

ADVANTAGES

Same as for Hydrogen PEM
Available, abundant, easily handled fuel

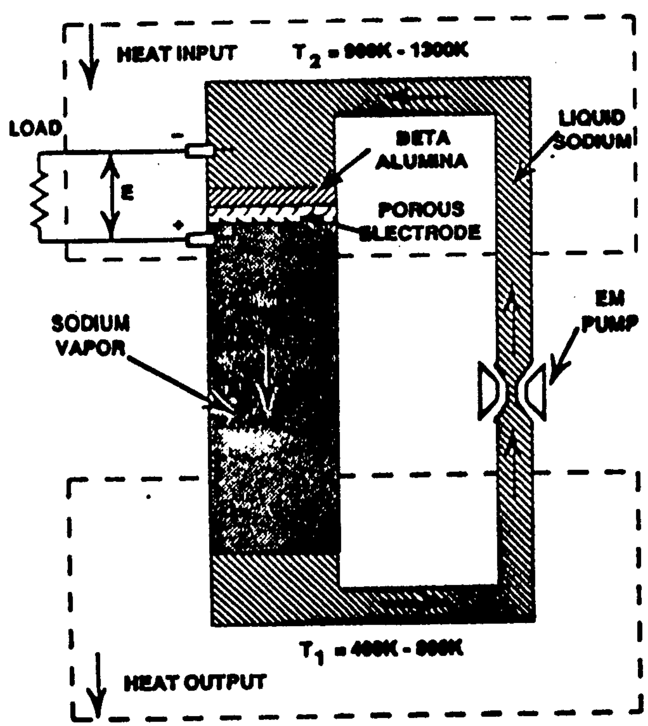
DISADVANTAGES

Immature technology
- Poor anode kinetics
- Methanol crossover
- Fuel loss
- Cathode polarization

Not mature enough to estimate cost

AMTEC

CYCLE SCHEMATIC



CHARACTERISTICS

- Capable of high efficiency (20-40 percent)
- Heat input at 900-1300 K
- Efficiency independent of size
- Converter power density > 0.5 kW/kg or 0.5 kW/liter
- Modular
- No moving parts (static system)
- Long life potential
- Uses commercially available materials

SPACE POWER INSTITUTE

ALKALI METAL THERMAL TO ELECTRIC CONVERTER (AMTEC)

Single Cell Efficiency	Approximately 20%
Life Testing	Approximately 14000 hours
Cost Studies	$300 - $500 per kwe for fully developed and mature technology
Power Density	>0.5 kW/kg

SPACE POWER INSTITUTE

Second NREL Conference on Thermophotovoltaic Generation of Electricity

AMTEC

PERCEIVED ADVANTAGES

- Long life potential
- High power density
- Few or no moving parts
- Readily adaptable to a variety of fuels
- Involves only one exotic material
- Low cost (Estimated to be $300 - $500 per kWe)

Disadvantages unclear due to state of development.

SPACE POWER INSTITUTE

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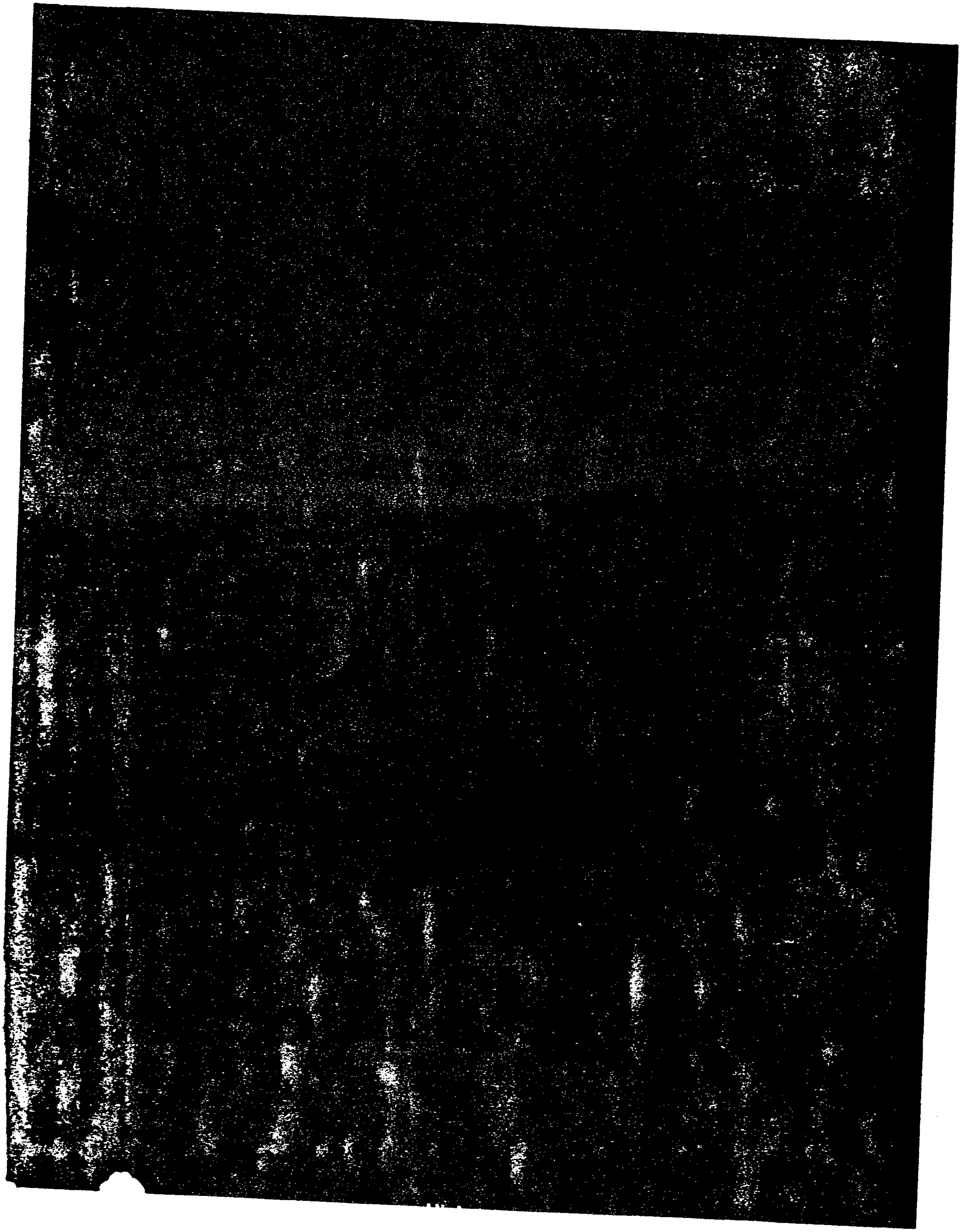
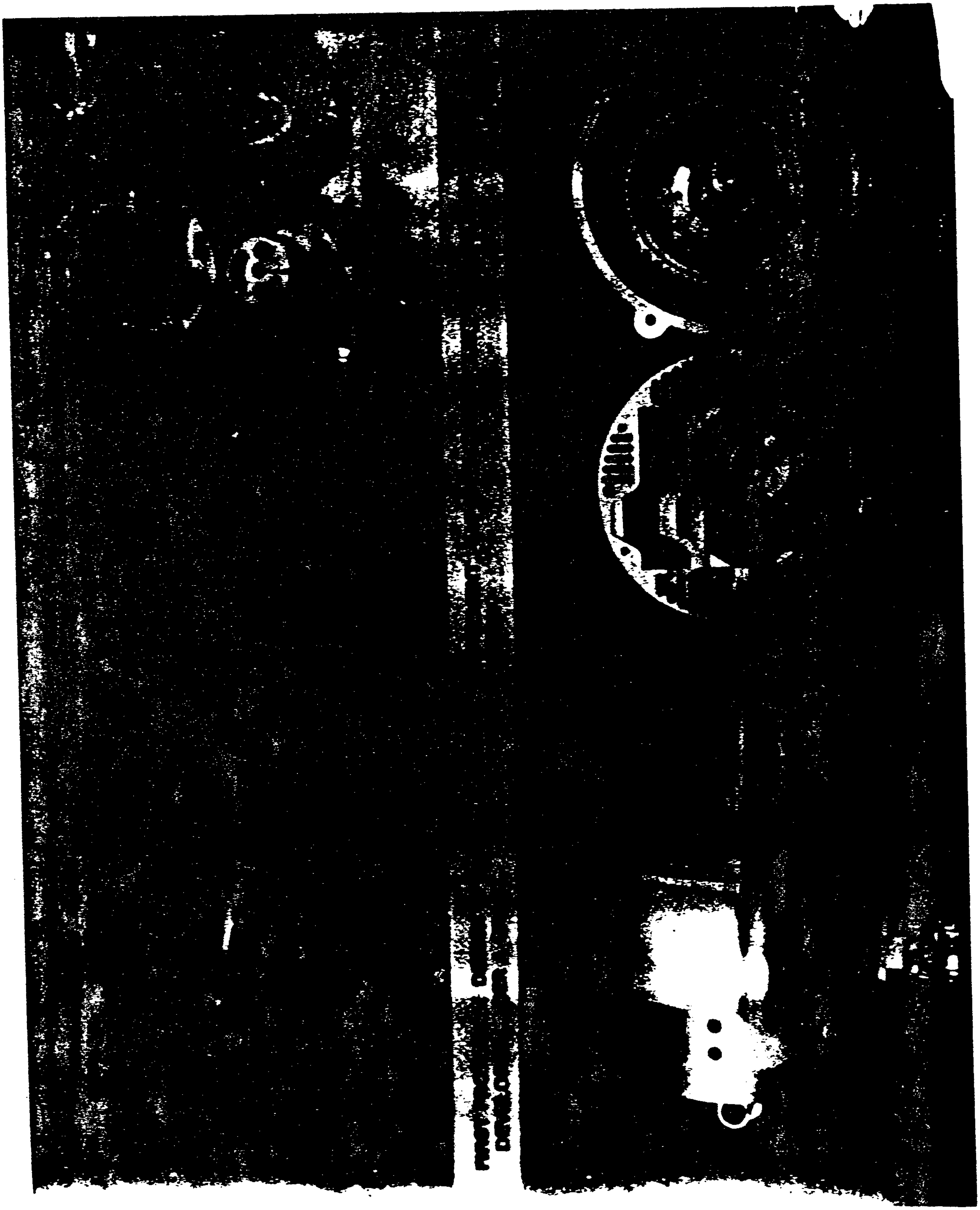
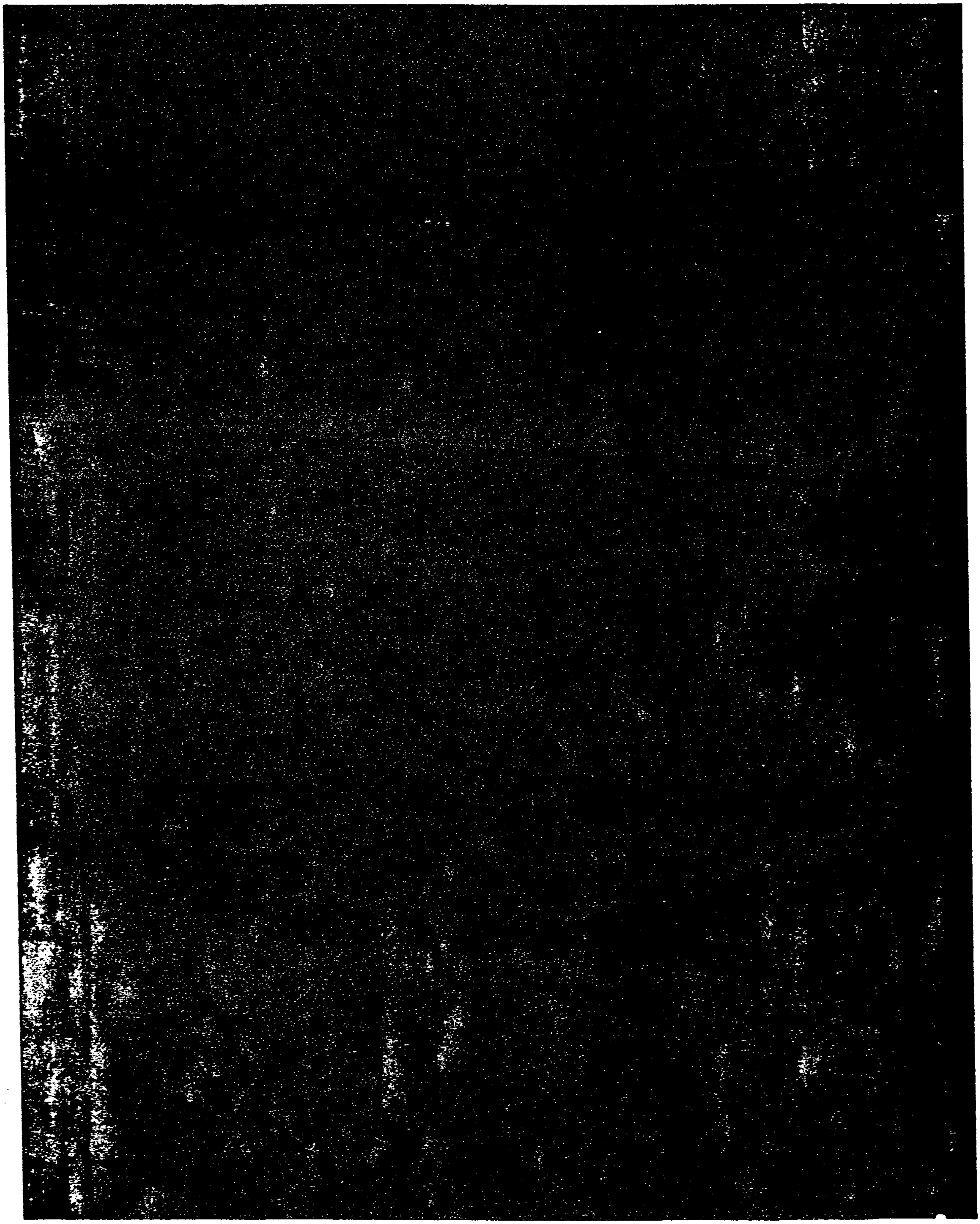
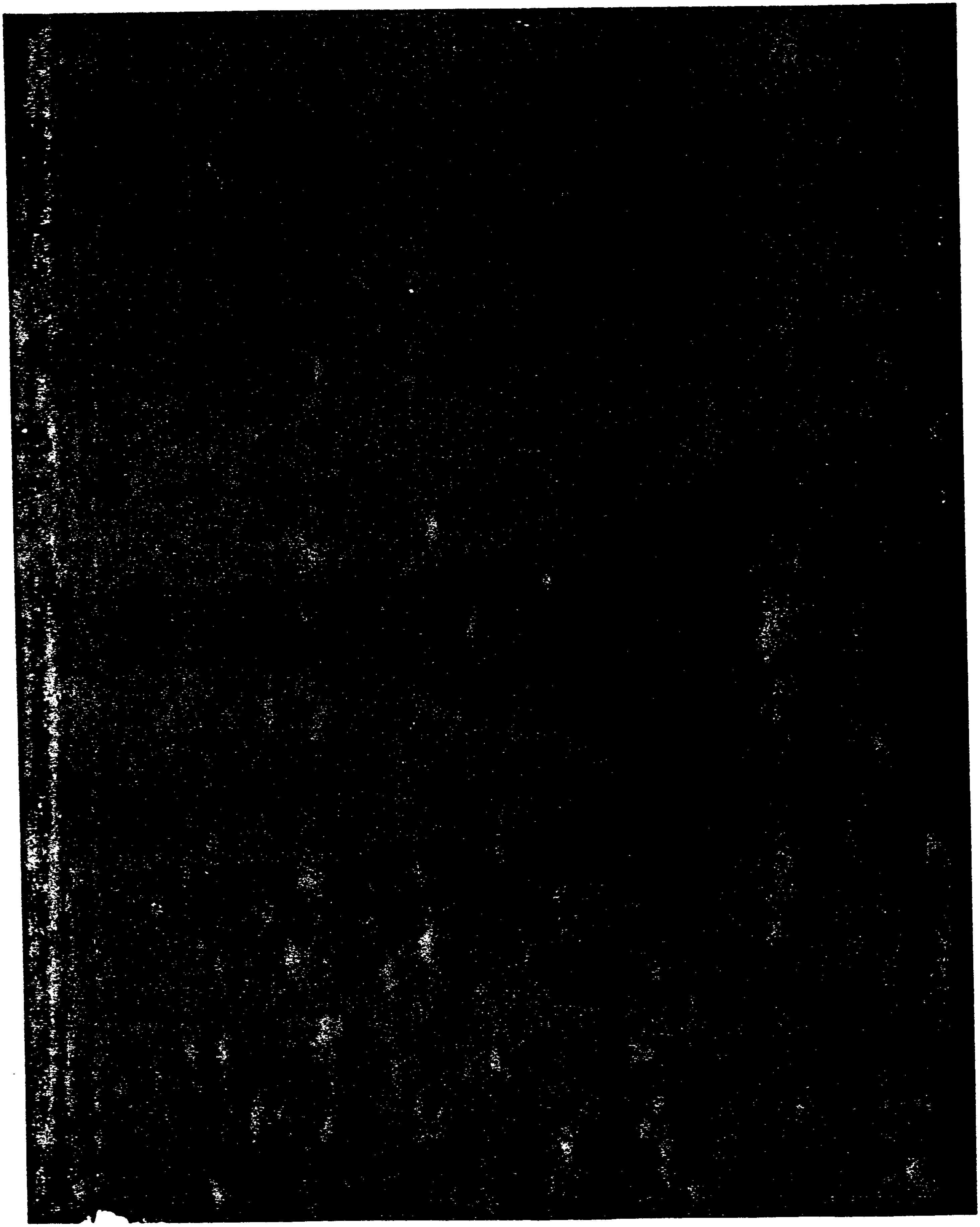






POLAROID
K473 9690 C



NORTH AMERICAN SHIPMENTS OF CONSUMER AND INDUSTRIAL ENGINES 3 TO 30 HORSEPOWER							
Product Application	1985	1986	1987	1988	1989	1990	% Growth
Agricultural							
Gasoline	[illegible]	[illegible]	[illegible]	[illegible]	10142	[illegible]	[illegible]
Diesel	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Construction							
Gasoline	56115	[illegible]	[illegible]	[illegible]	[illegible]	51266	[illegible]
Diesel	[illegible]	[illegible]	[illegible]	[illegible]	10712	[illegible]	107.3%
Gen Industrial							
Gasoline	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	67054	1.6%
Diesel	9101	7910	[illegible]	11662	[illegible]	[illegible]	13.5%
Lawn & Garden							
Gasoline	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	17.5%
Diesel	12145	[illegible]	10673	21045	[illegible]	10737	[illegible]
Marine							
Gasoline	[illegible]	61	60	[illegible]	60	67	(1.7%)
Diesel	[illegible]	6974	[illegible]	[illegible]	4201	3237	[illegible]
Material Hdlg							
Gasoline	1478	[illegible]	[illegible]	3730	[illegible]	[illegible]	[illegible]
Diesel	[illegible]	[illegible]	[illegible]	[illegible]	478	[illegible]	[illegible]
Other							
Gasoline	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Diesel	[illegible]	[illegible]	1812	[illegible]	[illegible]	5113	[illegible]
Pumps & Comp							
Gasoline	117162	[illegible]	[illegible]	[illegible]	134211	[illegible]	[illegible]
Diesel	4176	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Welders & Gen							
Gasoline	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Diesel	10171	14770	17164	[illegible]	[illegible]	[illegible]	[illegible]
Total							
Gasoline	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Diesel	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
NOTE: "Other" includes primarily exports							

Critical ingredients in the supply of diesel engines to the North American market has been the ability to provide excellent parts and technical support.

SPACE POWER INSTITUTE

POTENTIAL FOR MICRO ENGINE?

4 Stroke Cycle, Spark Ignition, Jet Fuel

Weight	2.5 lb/hp	1.5 g/w
Fuel consumption	0.5 lb/hp-hr	0.3g/w-hr
Start without aid		
Quiet	65 db (A)@ 1m ?	
Durable	1,000 hr	

SPACE POWER INSTITUTE

MOTOR-GENERATORS

ADVANTAGES

- Consumer acceptable
- Well established mature technology
- Well established manufacturing infrastructure
- Low cost

DISADVANTAGES

- Polluting
- Reliability in many formats
- Does not scale well to small sizes
- Thermal signature

THERMOELECTRICS

Power	500 W	
Voltage	24 V DC and 110 V AC	
Reliability	10,000 hrs MTBF	
Maintenance	1 hr for 5,000 hrs operation	
Noise	< 50 db at 1 m	
TEG	Lead Telluride	
Hot Junction	832 K	
Cold Junction	377 K	
Mass	<20.4 kg	
Volume	$<0.4\ m^3$	
TEG Eff.	Theoretical 9.6%	Actual 8.9%

SPACE POWER INSTITUTE

Second NREL Conference on Thermophotovoltaic Generation of Electricity

THERMOELECTRICS

ADVANTAGES

Quiet
Reliable
Established technology

DISADVANTAGES

Poor efficiency
Low power density
Cost

SPACE POWER INSTITUTE

TPV Systems State-of-the-Art

- Laboratory demonstration of the concept
- Small portable devices for “show and tell” presentations
- All demonstration devices today are less than 5% efficient
- Existing R&D efforts are in place to extend efficiency and explore technological limits

Blackbody TPV System

Advantages

- Radiator technology well advanced
- Potentially more power dense than selective emitters
- High temperature materials reasonably well characterized
- Leverage on technology of industrial drying industry

Disadvantages

- Requires advanced high temperature optical filter technology
- Requires the development of optimium Photovoltaic cell technology
- Places high demand on energy recouperators

Selective Emission TPV

Advantages

- Concentrates energy into a narrow emission band
- Limited out of band emission
- Range of selective emitters and wavelengths
- Higher efficiency
- Places less demand on recouperator
- Limited need for filtering

Disadvantages

- Radiator technology less well developed
- May require the development of appropriate cell technology
- Lower Power density than a blackbody
- High temperature materials properties less well understood

Thermophotovoltaics
Key Technologies

- Fuel Choice
- Photovoltaic Cell Technology
- Recouperators
- System Configurations

TPV Key Technology

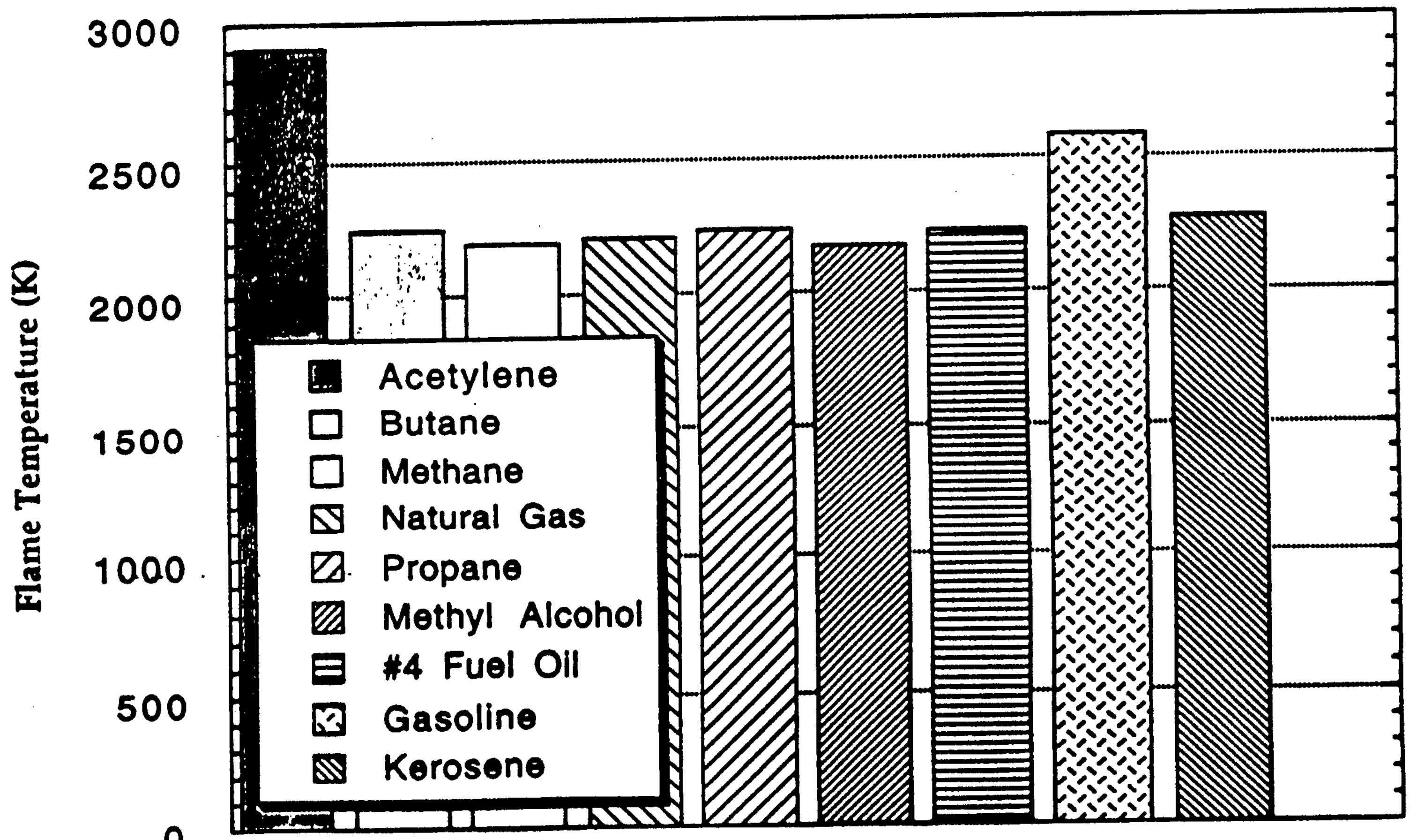
Fuel Choice

- Fuel must have high combustion Temperature
- The difference between the combustion temperature and the radiator temperature determines the amount of energy extracted from the combustion products

TPV Key Technology

Fuel Choice

Adiabatic Flame Temperatures for Select Hydrocarbon Fuels



TPV Key Technology

Photovoltaic Cells

- Cell Band gap can be optimized to photoconvert radiation from the radiator surface, both blackbody and selective emitter
- Silicon technology is well developed and proven at conversion efficiencies greater than 40%
- Bandgap in Silicon demands that emitters operate at temperatures greater than 2000 K
- InGaAS, GaAs can be bandgap tailored to match emission
- **Cell efficiency is a function of bandgap due to fundamental physics**

TPV Key Technology

Recouperator

- Mature technology for temperatures less than 1500 K
- Immature technology for temperatures greater than 2000 K
- Absolutely essential for efficient TPV system

TPV Key Technology

System Configurations

$$\eta = \eta_{TS}\,\eta_{E}\,\eta_{PV}$$

η_{TS} is the efficiency of the thermal system

η_{E} is the photoconvertable emitter efficiency

η_{PV} is the efficiency of the photovoltaic cell

$\eta_{TS} = \sim 0.9$ $\eta_{E} = \sim 0.7$ $\eta_{PV} = \sim 0.2 - 0.5$

"Best" TPV systems η = 12 - 30 %

TPV Summary Remarks

- Fundamentals of the technology are well understood
- TPV represents breakthrough technology for a variety of battlefield applications
- Challanges are to apply the key technologies to TPV systems in order to achieve an acceptable efficiency
- Numerous options are available depending on the application
- Demonstrators can be built within 2 years
- Fieldable devices can be built within 4 years with a modest committment of funds

Where should we go from here?

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TECHNOLOGY UPDATE 1

"LIQUID FUEL COMBUSTION"

Mr. Malachy McAlonan

Teledyne-Brown
Hunt Valley, Maryland 21031

BURNER SYSTEMS FOR TPV

THESIS

THERMOELECTRIC GENERATORS (TEG) AND TPV SYSTEMS ARE SUFFICIENTLY SIMILAR THAT:

BURNER TECHNOLOGY DEVELOPED FOR TEG SYSTEMS COULD BE ADAPTED FOR TPV, SAVING DEVELOPMENT TIME AND MONEY.

$MILLIONS HAVE BEEN SPENT ON BURNER SYSTEMS FOR TEG SYSTEMS AND SELF-POWERED HEATERS.

TELEDYNE BROWN ENGINEERING - Energy Systems

TEG HEAT SOURCES

- RADIOISOTOPE (alpha and beta emitters)
- LIQUID FUEL BURNERS (military and commercial fuels)
- GASEOUS FUEL BURNERS (propane and natural gas)

IN PRINCIPLE, THESE HEAT SOURCES CAN BE USED IN TPV GENERATORS.

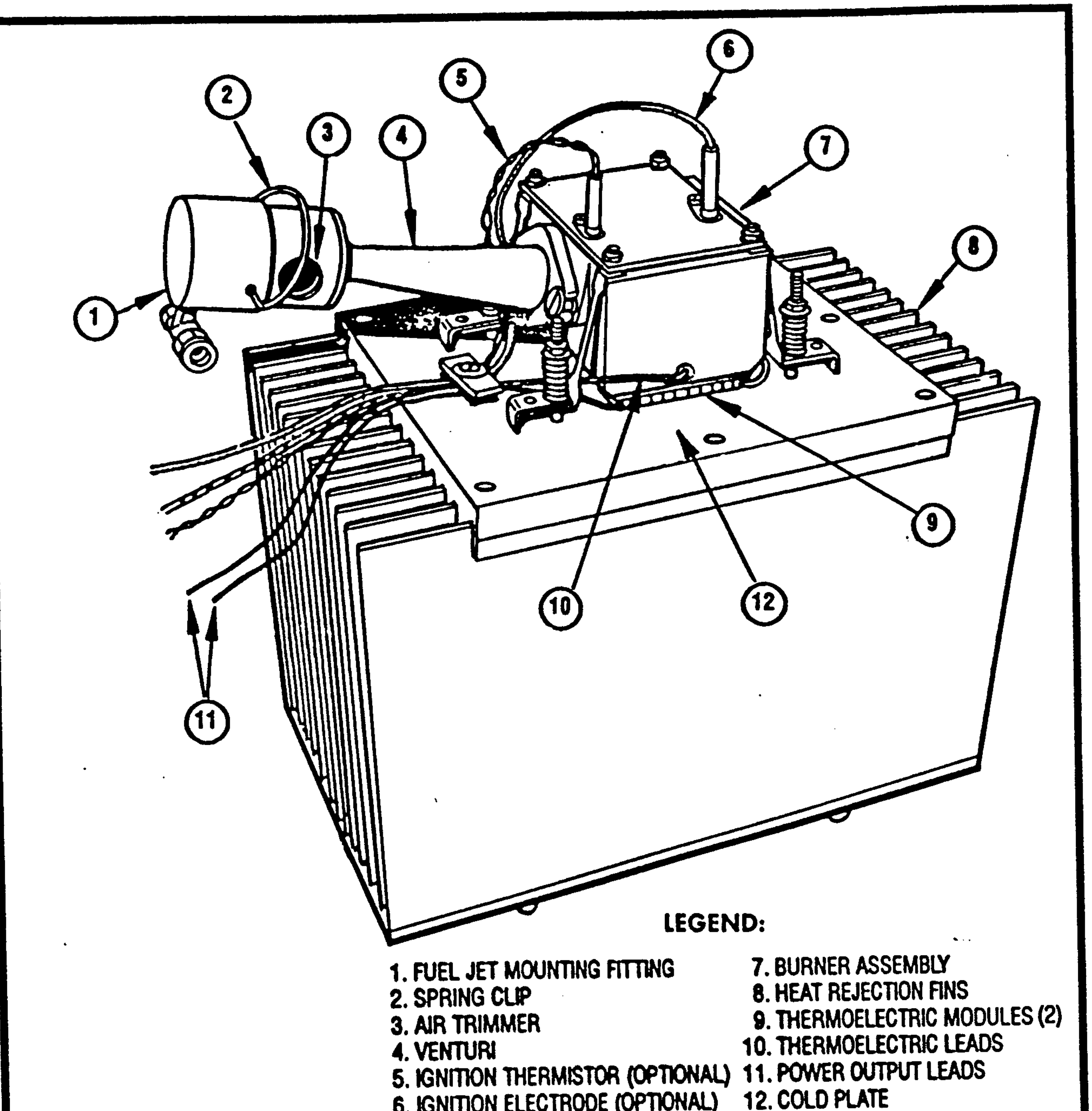


FIGURE IV-1. BURNER/FIN/MODULE (BFM) ASSEMBLY

WHY NOT VAPORIZE LIQUID FUEL AND BURN IT LIKE PROPANE ?

- OK FOR SOME LIQUID FUELS,
  e.g. gasoline, Coleman fuel, K-1 kerosine, and perhaps JP3, JP4, and even JP8.

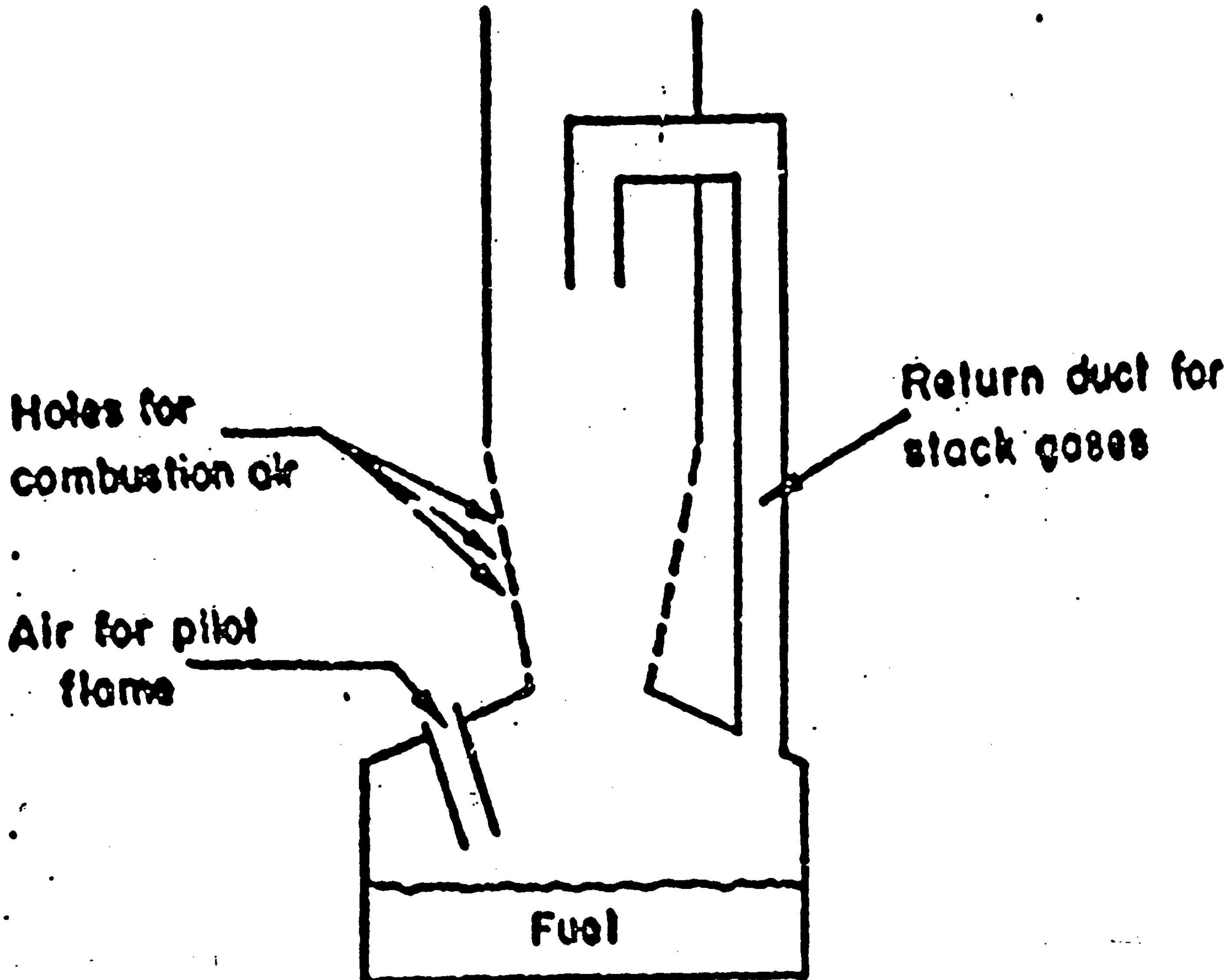
- NOT EASY WITH DF-2; CASES IN POINT:
  1. Conversion of the M-2 Cook-Stove from gasoline to diesel fuel.
  2. Conversion of a Commercial TEG from propane to diesel fuel.

  PROBLEM is carbonaceous deposits in either the vaporizer or in the venturi orifice.

- UNSUITABLE FOR TPV GENERATOR
  1. Low combustion intensity,
  2. Recuperator cannot be used with venturi aspirator because of flashback.
  3. Awkward startup.

LIQUID FUELS

FUEL	SPEC. No.	FREEZE PT&# Deg.F(max)	FLASH PT Deg.F(min)	INITIAL B.P Deg.F(max)	10"% Deg.F(max)	20"% Deg.F(max)	50"% Deg.F(max)	90"% Deg.F(max)	END PT. Deg.F(max)
JP-4	MIL-T-5624L	-72	X	#1	#1	293	374	473	518
JP-5	MIL-T-5624L	-51	140	#1	401	#1	#1	#1	554
JP-8	MIL-T-83133A	-58	100	X	401	X	X	X	572
Jet A	ASTM D1655-88	-40	100	X	400	X	X	X	572
Jet A-1	ASTM D1655-88	-53	100	X	400	X	X	X	572
Jet B	ASTM D1655-88	-58	X	X	X	293	374	473	X
Kerosine#	ASTM D3699-83	-22	100	<284>	401	X	<385>	X	572
Diesel,DFA	VV-F-800D	-60	100	X	X	X	X	550	572
Diesel,DF1	VV-F-800D	-26	100	X	X	X	X	550	626
Diesel,DF2	VV-F-800D	A	100	X	X	X	X	640/675	698
Fuel, Naval	MIL-F-16884H	30	140	X	X	X	X	675	725
Diesel,1-D	ASTM D975-89	10F>10%amb	100	X	X	X	X	550	X
Diesel,2-D	ASTM D975-89	10F>10%amb	125	X	X	X	X	640	X
Diesel,4-D	ASTM D975-89	10F>10%amb	125	X	X	X	X	X	X



THE RETURN-STACK ORCHARD HEATER

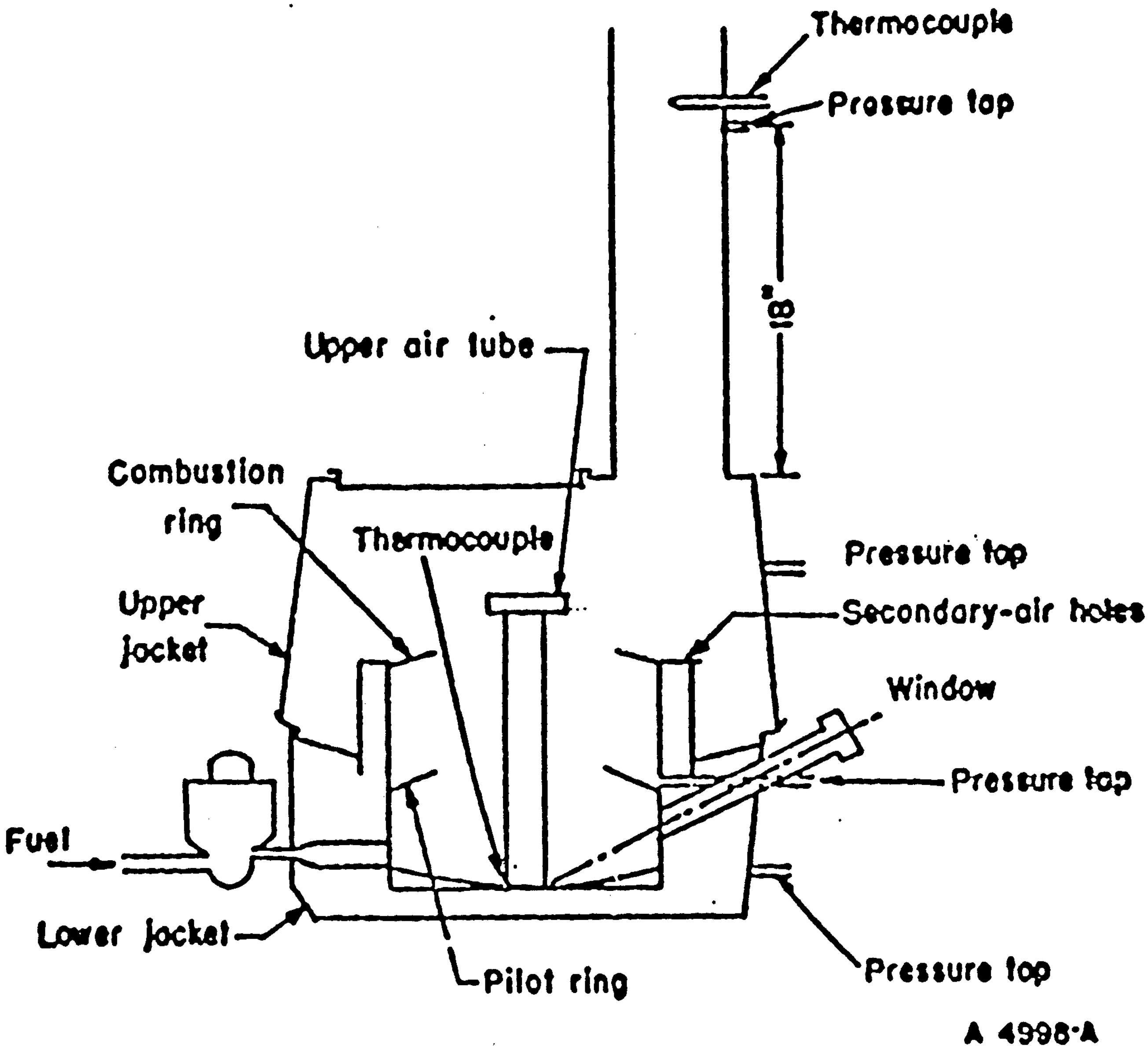


FIGURE 1. SKETCH OF THE INSTRUMENTED M-1941 TENT STOVE

BURNER FEATURES REQUIRED

FOR A PORTABLE GENERATOR

- CLEAN, STABLE COMBUSTION,
  to meet performance and maintenance requirements.
- LIGHTWEIGHT,
  implies small, compact combustor/recuperator and intense combustion.
- LOW POWER CONSUMPTION,
  burner power is a parasitic loss and must be minimized.
- EFFICIENT,
  well insulated, uses a recuperator, low excess air.
- RUGGED,
  to withstand the rigors of military field handling, transportation and environmental service conditions.
- OTHER GENERAL FEATURES:
  reliable, user friendly, acceptable time to readiness/response, signature suppressed, safe, acceptable longevity and life-cycle cost.

ATOMIZATION TECHNIQUES

1. PRESSURE NOZZLE.
2. ULTRASONIC ATOMIZER.
3. THIN OIL FILM / AIR JET.

ATOMIZATION TECHNIQUES

1. PRESSURE NOZZLE.
   The pumping power is tolerable.
   The nozzle bore size is the issue when the flow < 2Kg/Hr.
   (A 500 Watt TPV generator firing rate is nearer 0.25 Kg/Hr.)

ATOMIZATION TECHNIQUES

2. ULTRASONIC ATOMIZER.

Size, weight, power consumption attractive. Droplets size 1 to 100 μ.

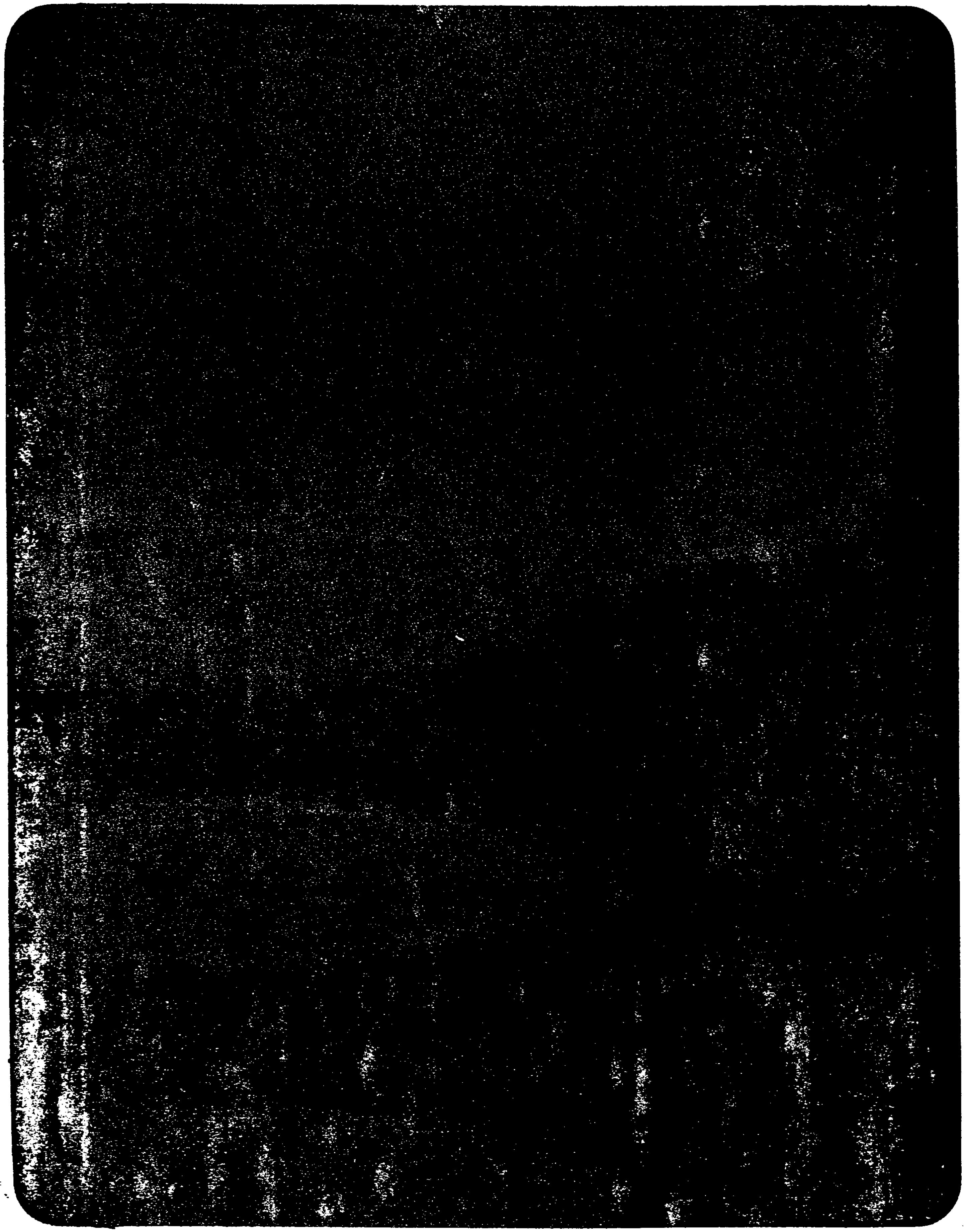
Problems:

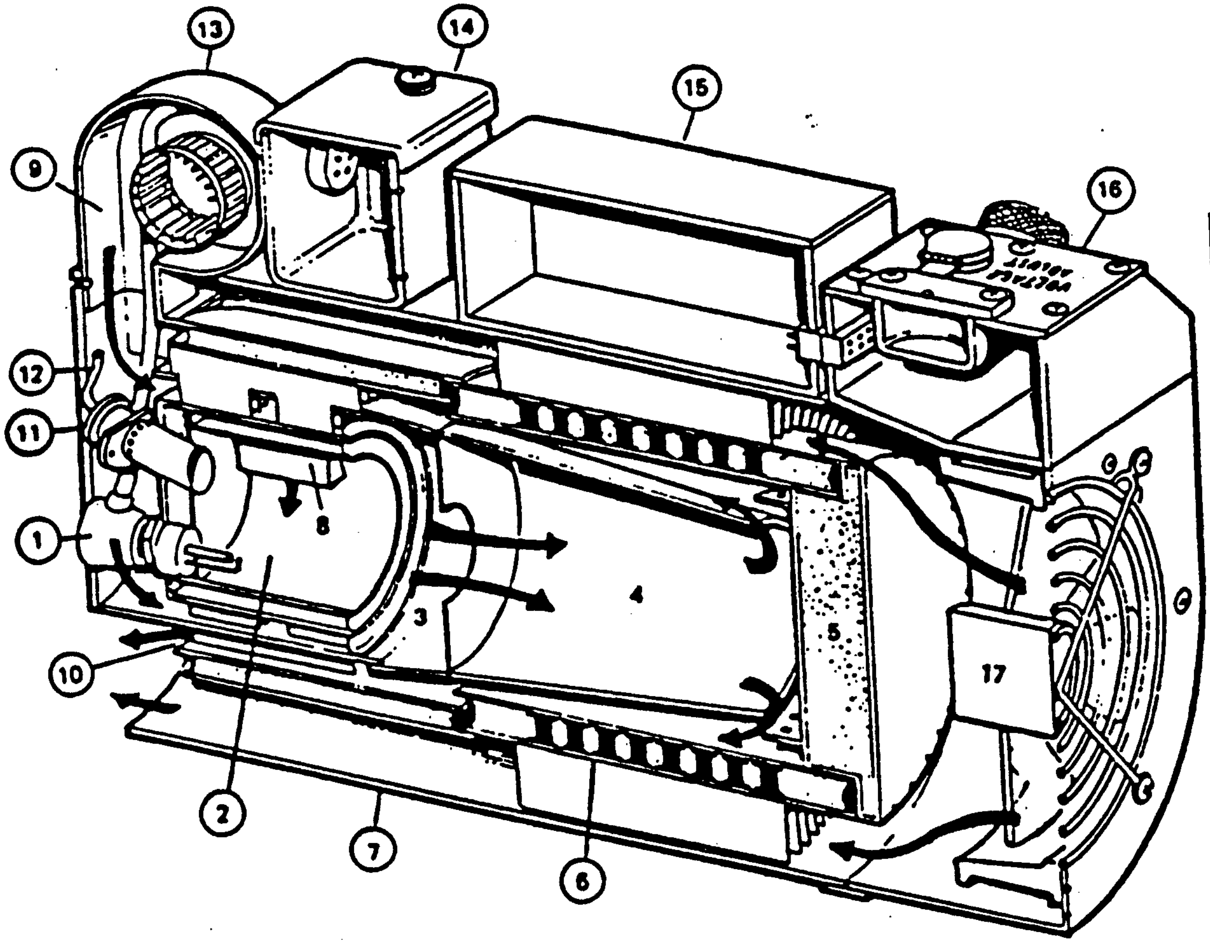
Piezo-ceramic is temperature sensitive.

Transducer resonance shifts due to dimensional changes from thermal expansion and excessive mistuning can destroy piezo-ceramic.

ATOMIZATION TECHNIQUES

3. THIN OIL FILM / AIR JET
   Excellent combustion possible thru wide range of firing rates, i.e. smoke number zero with insignificant excess air.
   Good choice for a stationary site, But the flowing oil is orientation sensitive.





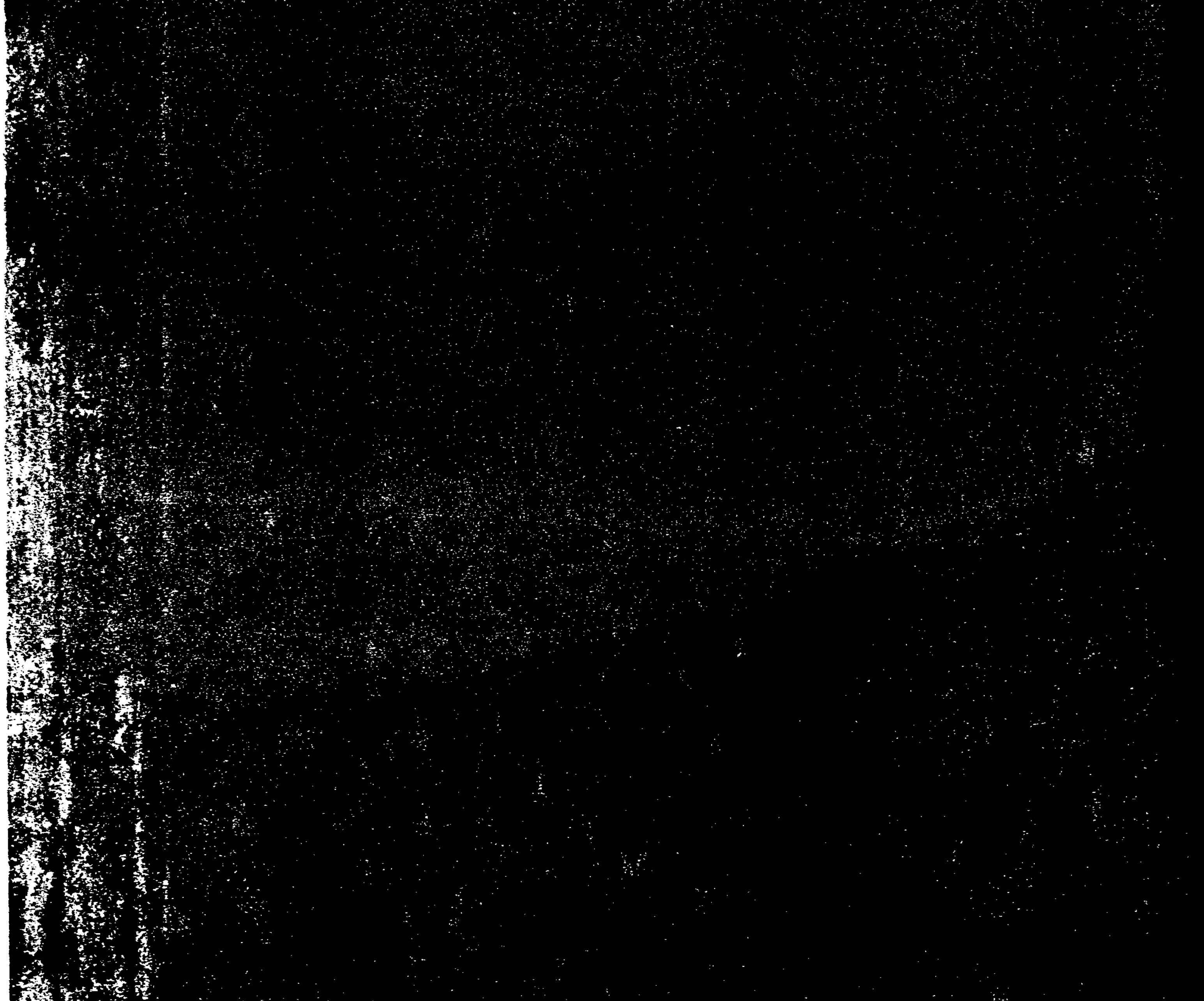
LEGEND

1. SPARK IGNITER
2. COMBUSTION CHAMBER
3. ORIFICE
4. MANTLE
5. INSULATED BULKHEAD
6. THERMOELECTRIC CONVERTER
7. OUTER SHROUD
8. ENTRY DUCT
9. REGENERATOR (COMBUSTION AIR)
10. REGENERATOR (EXHAUST)
11. FUEL ATOMIZER
12. FUEL INLET TUBE
13. COMBUSTION AIR BLOWER
14. COIL HOUSING
15. DC/DC CONVERTER MODULE
16. ELECTRONIC POWER ASSEMBLY
17. COOLING AIR FAN

← BURNER AIR FLOW PATTERN

Fig. 2 Power Module Assembly (Cutaway View)

SELF-POWERED SPACE HEATER



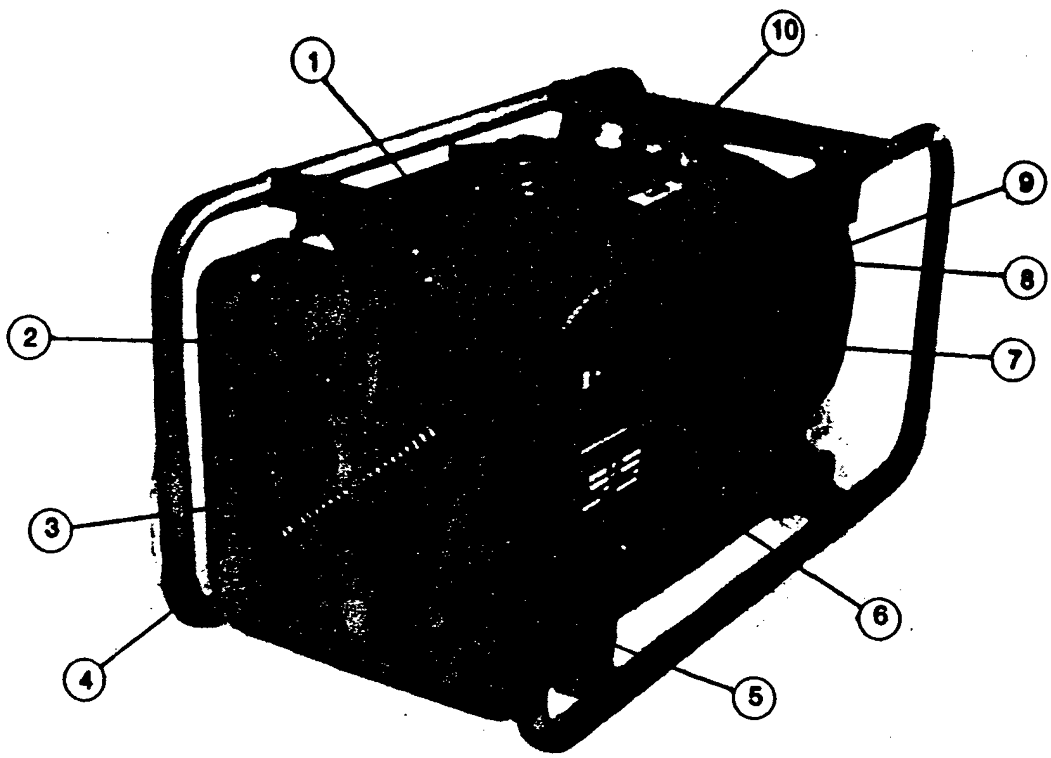
LEGEND:

1. SADDLE TYPE FUEL TANK
2. HOUSING FOR FAN, FUEL PUMP, FILTER AND ACCUMULATOR
3. AIR INLET
4. PROTECTIVE FRAME
5. SHOCK ISOLATOR
6. BATTERY HOUSING
7. MAIN HOUSING, CONTAINING BURNER, THERMOELECTRIC MODULE AND HEAT EXCHANGERS
8. ELECTRICAL COMPONENTS
9. 6 INCH DIAMETER HEATED AIR OUTLET
10. COMBUSTION EXHAUST

TELEDYNE BROWN ENGINEERING
Energy Systems

TELEDYNE
BROWN ENGINEERING
Energy Systems
10707 Gilroy Rd., Hunt Valley, MD 21031-1311
Phone: (410) 771-8600 FAX: (410) 771-8620

10,000 BTU/HR SELF-POWERED HEAT SOURCE
MODEL HDT10-1



LEGEND

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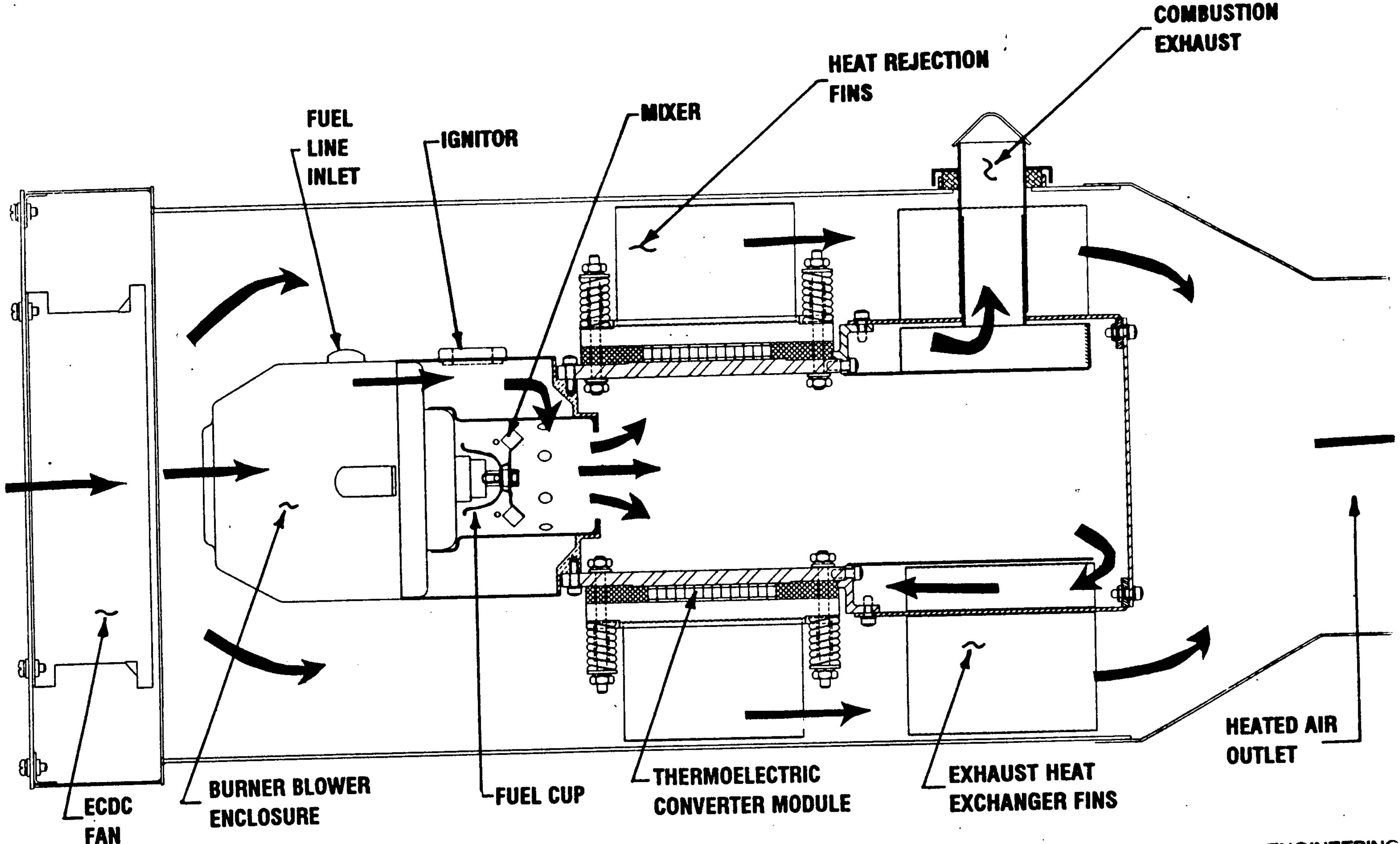
OPERATING COMPONENTS OF HEATER



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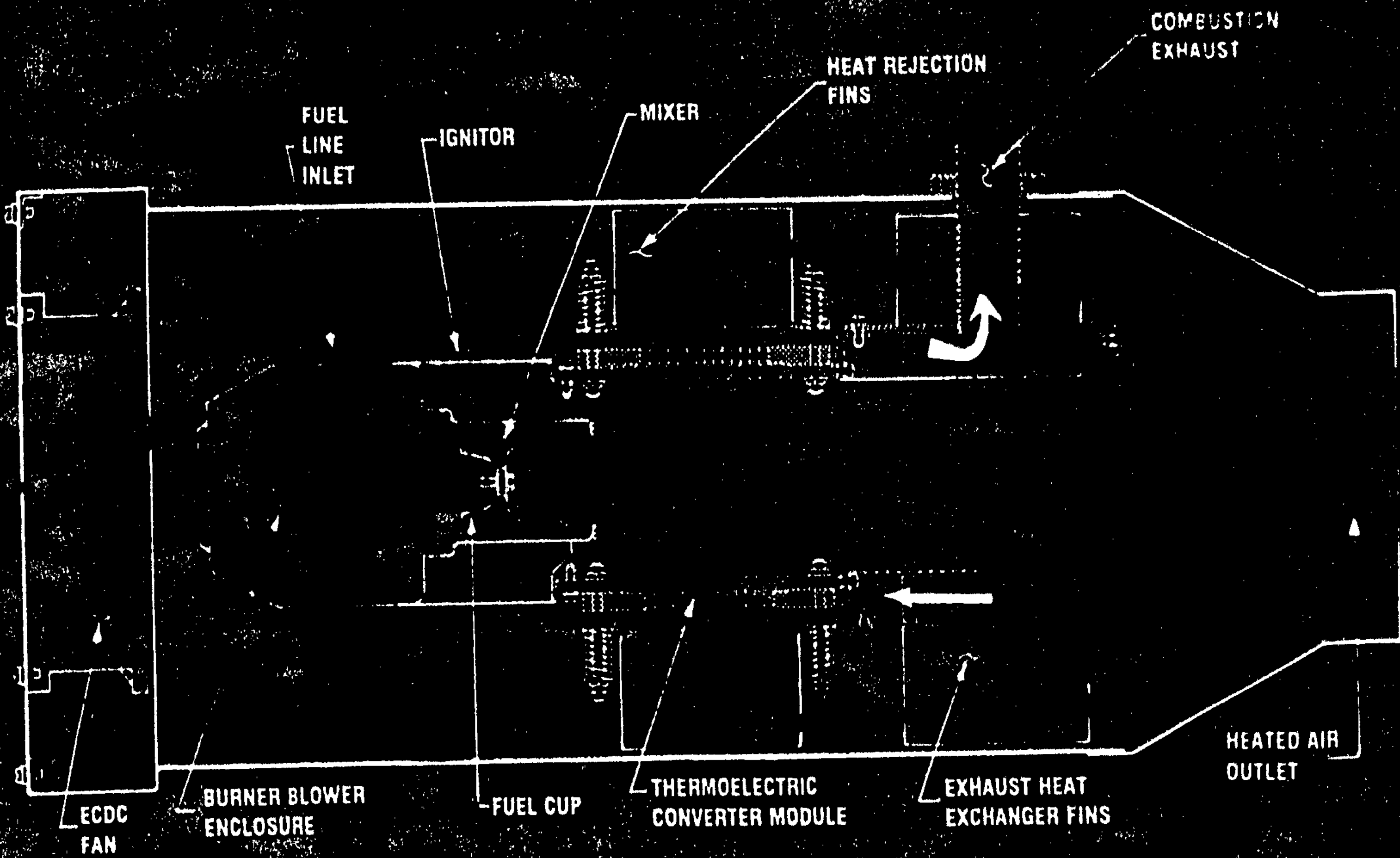
Energy Systems

HEATER OPERATION



LEGEND:

HTD CLEAN AIRFLOW

COMBUSTION FLOW PATH

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SPINNING CUP TECHNIQUE

- Hybrid enhanced vaporizer, high combustion intensity. Vigorous recirculation of gases similar to Ventres blue flame burner.

- Burns like an atomizer burner in the high air input region.

TPV BURNER CONCERNS

1. CONTROL
   - Firing rate
   - Air/Fuel ratio
   - microprocessor controller

2. UNIFORMITY OF RADIATION
   - Uniformity of heating emitter
   - Interfacing to emitter

3. MATERIALS/COMPONENTS
   - Emitter choice
   - Combustor material
   - Recuperator HEX
     if parallel flow, perhaps superalloys
     if counterflow, ceramics at hot end
   - components, e.g. ignitors etc.
   - insulation.

TELEDYNE BROWN ENGINEERING - Energy Systems

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"RECUPERATORS FOR TPV SYSTEMS"

Mr. Fred Becker

Tecogen
Waltham, MA 02254

RECUPERATORS FOR THERMOPHOTOVOLTAIC (TPV) ENERGY CONVERSION SYSTEMS

PROSPECTOR VIII WORKSHOP

Thermophotovoltaics -- An Update on DoD, Academic, and Commercial Research

July 14 - 17, 1996

Prepared By

Tecogen Division
Thermo Power Corporation
A Thermo Electron Company

AIR PREHEATER

PURPOSE:

- TO RAISE TPV SYSTEM EFFICIENCY
  - by using heat in exhaust gases from emitter to preheat combustion air
- TO REDUCE TEMPERATURE OF EXHAUST GASES
  - for personnel safety and for lower heat signature

Thermo Power
Corporation

AIR PREHEATER

DESIGN REQUIREMENTS:

- HEAT TRANFER EFFECTIVENESS
- PRESSURE DROP
- MATERIAL CAPABILITIES
  - Thermal
  - Mechanical
  - Chemical
- SIZE AND WEIGHT

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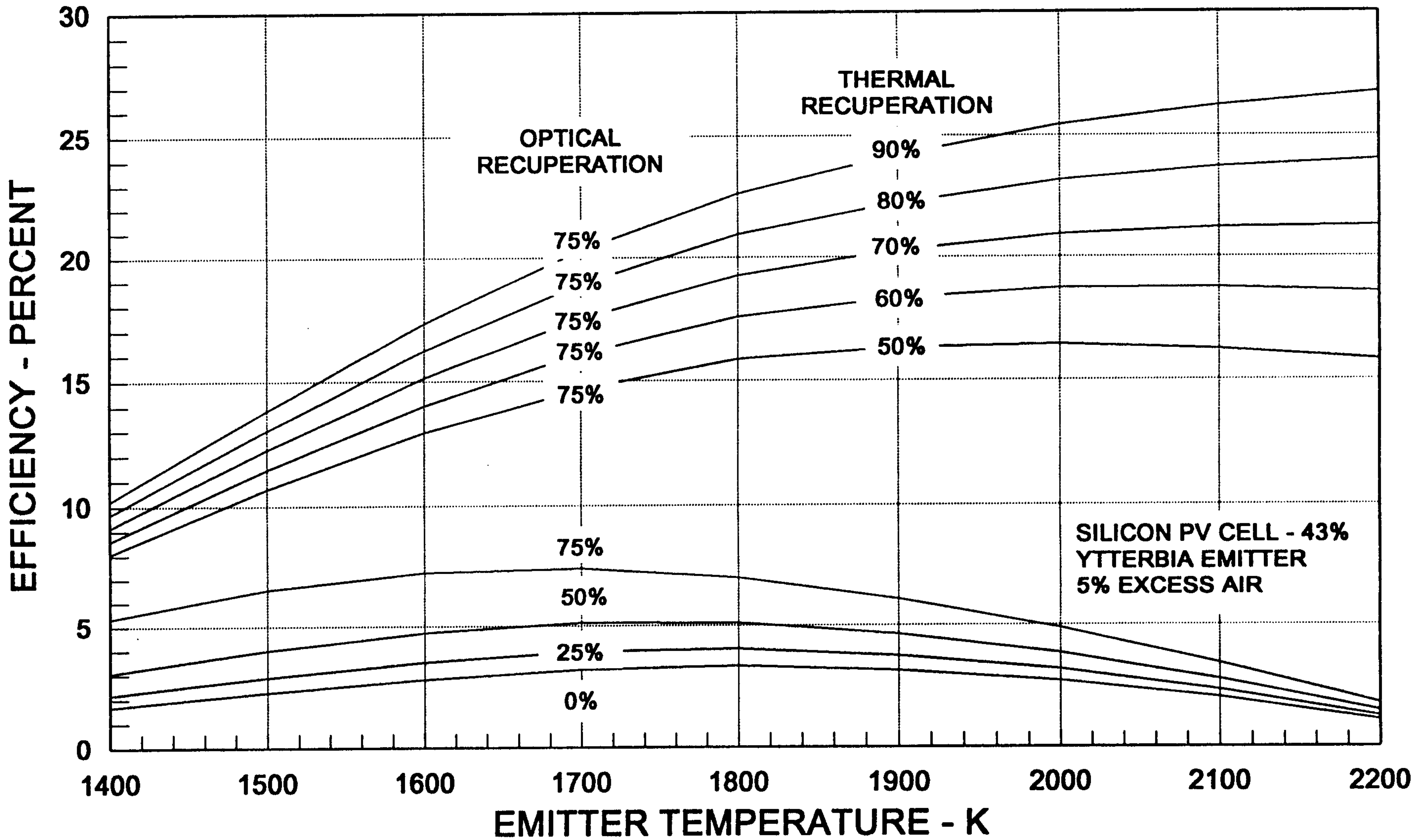
RECUPERATOR EFFECTIVENESS

DEFINITION:

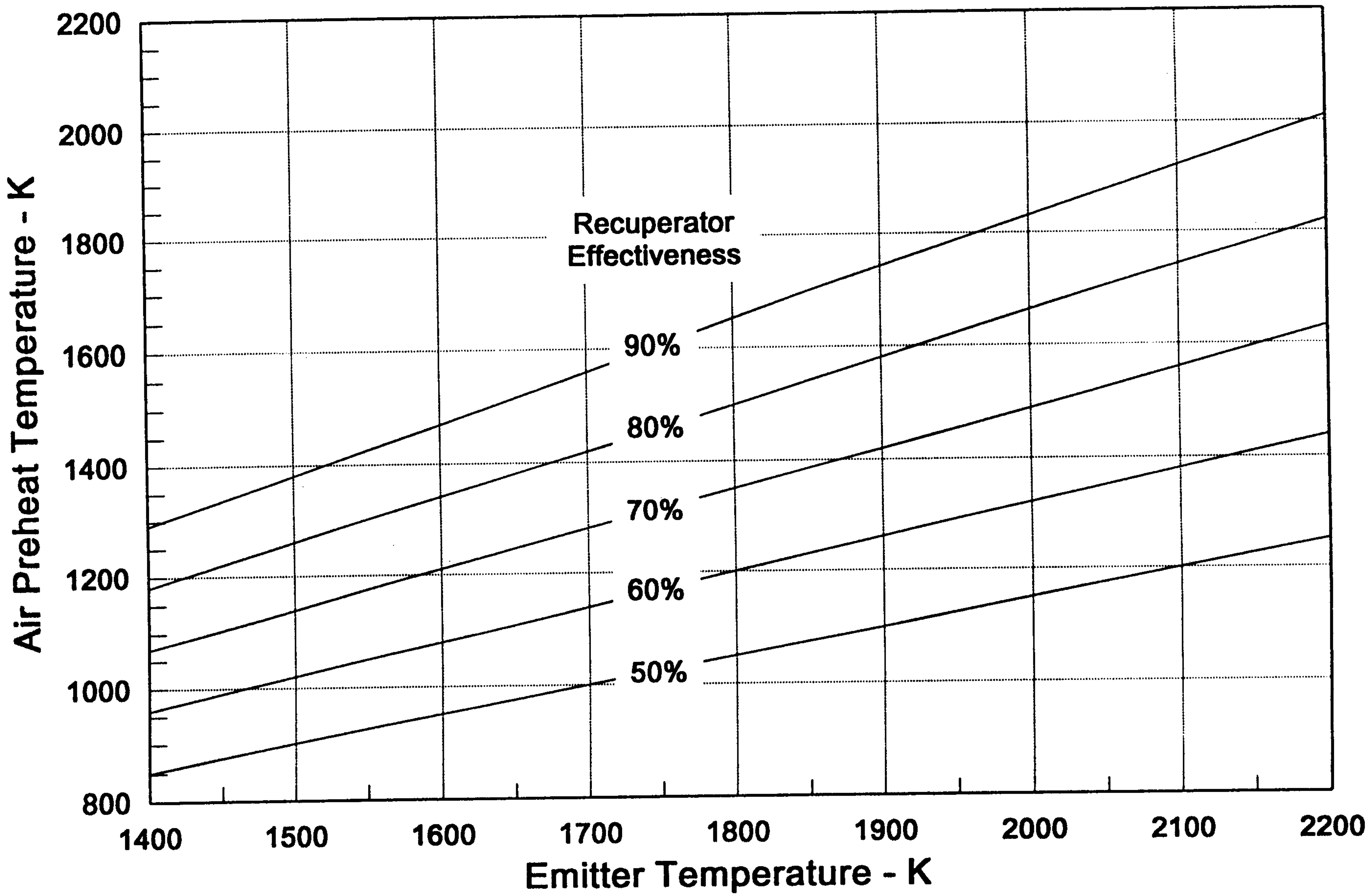
$$\frac{\textit{ACTUAL COMBUSTION AIR TEMPERATURE RISE}}{\textit{MAXIMUM POSSIBLE COMBUSTION AIR TEMPERATURE RISE}}$$

$$\frac{(T_{air\ preheat} - T_{air\ in})}{(T_{emitter\ exhaust} - T_{air\ in})}$$

TPV SYSTEM PERFORMANCE MAP



Air Preheat Temperature



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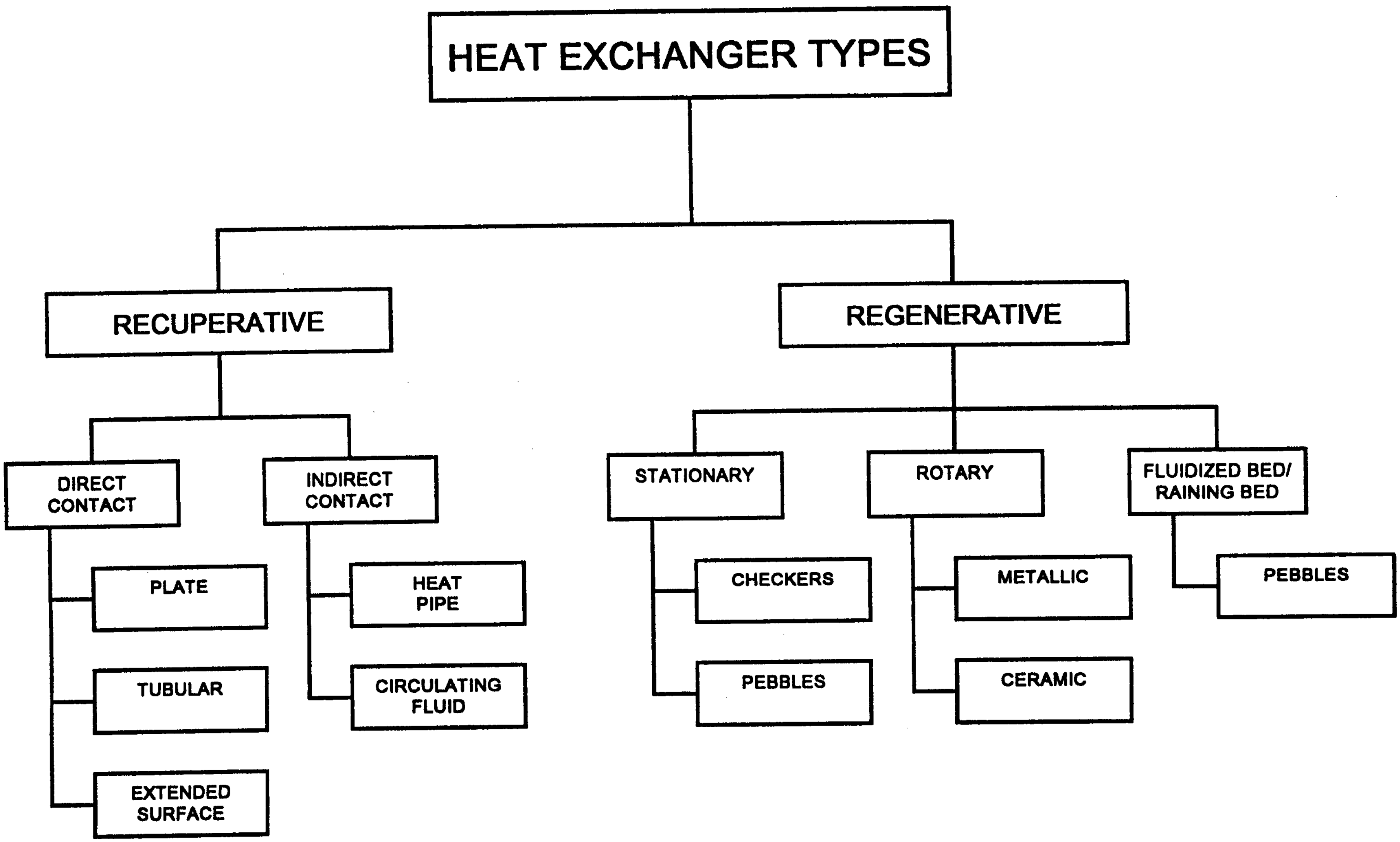
AIR PREHEATER

PRIMARY DESIGN OPTIONS:

- **RECUPERATOR (continuous flow heat exchange)**
  - **Less complex and easier to package**
- **REGENERATOR (cyclic heat storage and regeneration)**
  - **Higher temperature capability but more complex**


HEAT EXCHANGER TYPES
RECUPERATIVE
REGENERATIVE
DIRECT CONTACT
INDIRECT CONTACT
STATIONARY
ROTARY
FLUIDIZED BED/ RAINING BED
PLATE
TUBULAR
EXTENDED SURFACE
HEAT PIPE
CIRCULATING FLUID
CHECKERS
PEBBLES
METALLIC
CERAMIC
PEBBLES

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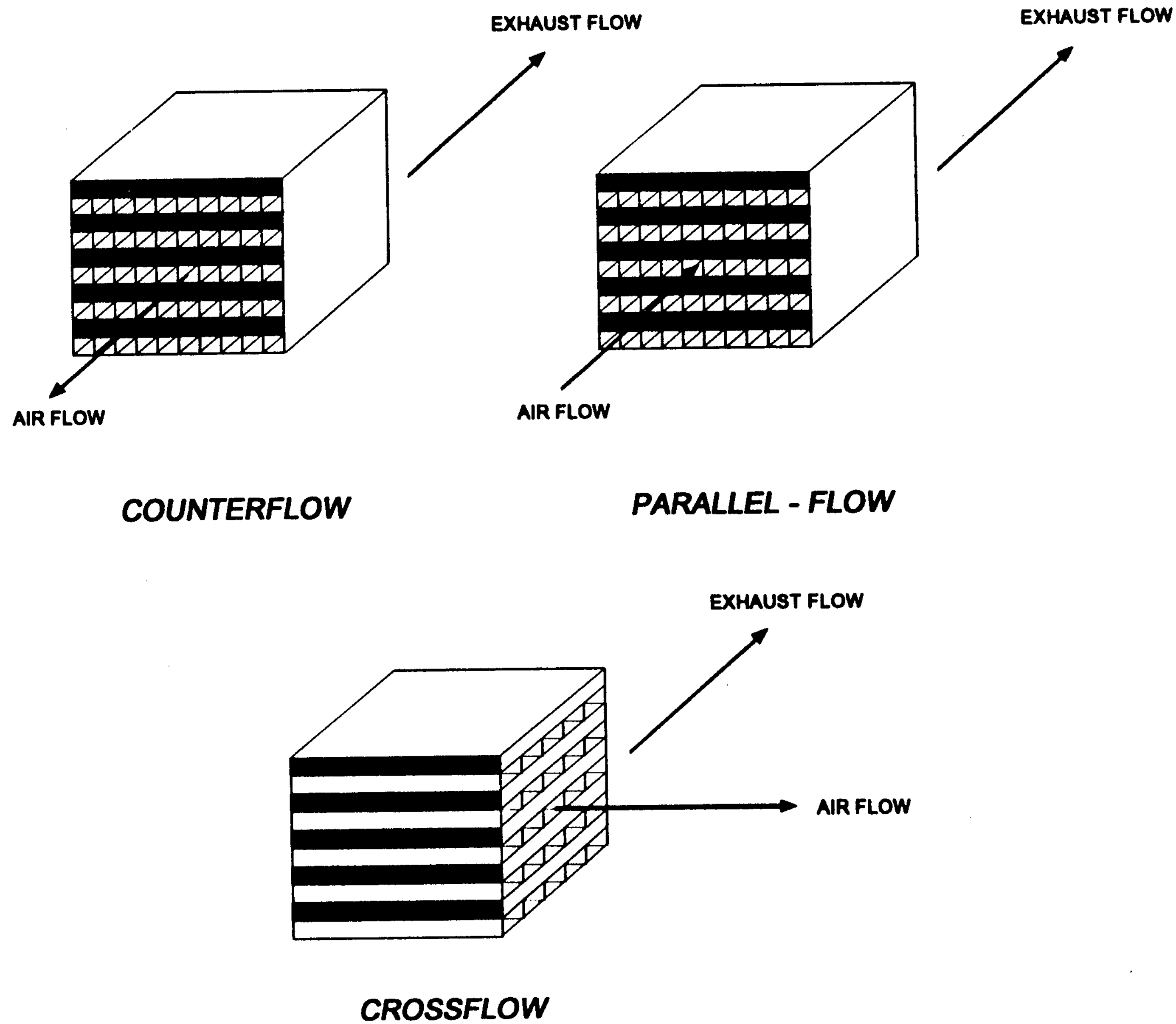
RECUPERATOR DESIGN OPTIONS

CONFIGURATIONS:

- **Counterflow**
- **Crossflow**
- **Parallel-flow**

KEY CONSIDERATIONS:

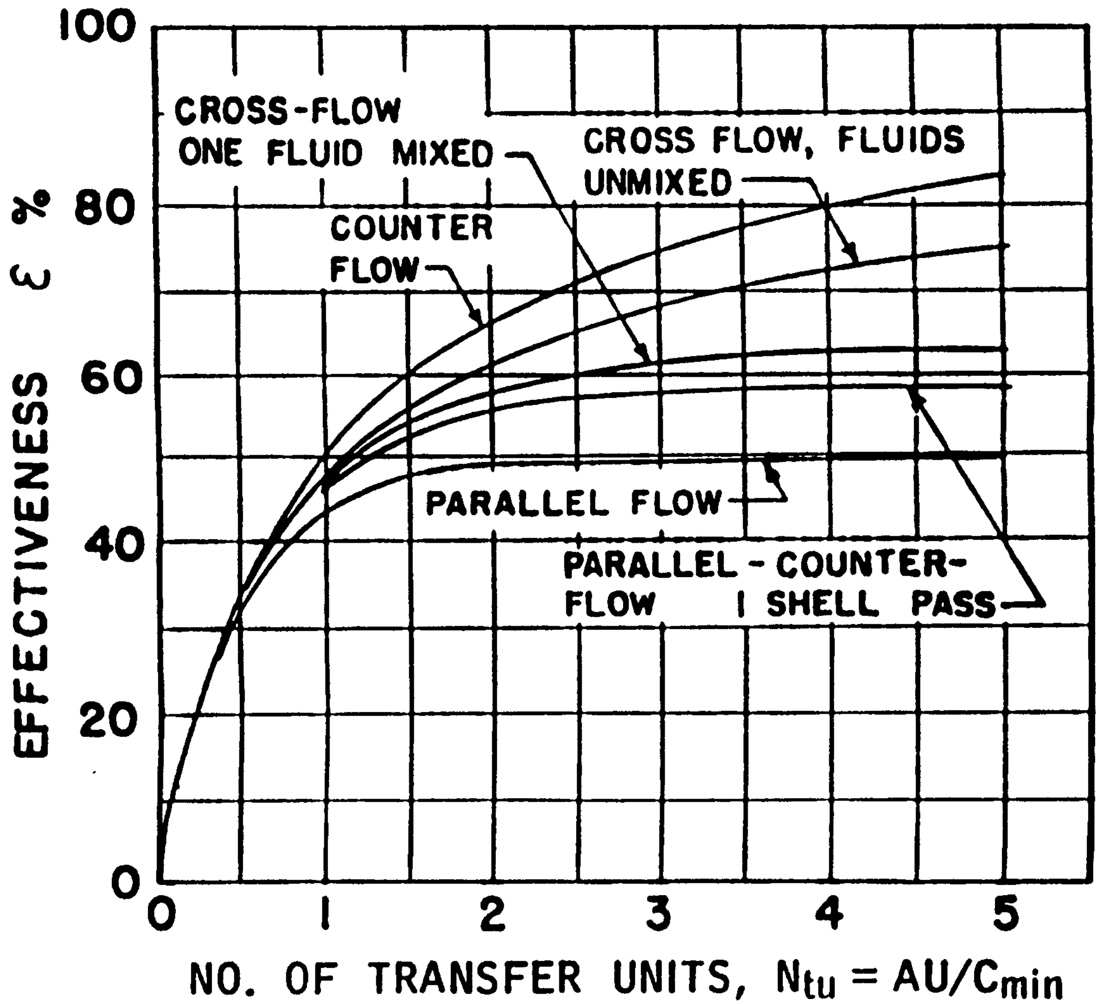
- **Effectiveness**
- **Packaging**
- **Availability**



Heat Exchanger Configurations

HEAT TRANSFER EFFECTIVENESS VS. NUMBER OF TRANSFER UNITS

Cmin/Cmax = 1



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RECUPERATOR DESIGN OPTIONS (CONT.)

TYPES:

- Primary Surfaces
  - Tube and shell
  - Plate
- Finned Surfaces
  - Finned tube and shell
  - Plate fin

KEY CONSIDERATIONS:

- Materials
- Availability
- Packaging

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RECUPERATOR DESIGN OPTIONS (CONT.)

MATERIALS:

- Metals
- Ceramics

KEY CONSIDERATIONS:

- Gas temperatures
- Material compatibility
- Thermal stress and shock properties
- Manufacturability

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RECUPERATOR HIGH TEMPERATURE MATERIAL OPTIONS

METALLIC:

TYPE	TEMPERATURE LIMIT (°C)	OXIDATION RESISTANCE
310 Stainless Steel	1000	Fair
Inconel 610	1250	Good
Hastelloy	1200	Good

RECUPERATOR HIGH TEMPERATURE MATERIAL OPTIONS

CERAMIC:

TYPE	TEMPERATURE LIMIT (°C)	THERMAL SHOCK RESISTANCE
Alumina - Al_2O_3	1850	Good
Magnesia - MgO	2100	Fair
Zirconia - ZrO_2	2300	Fair
Silica - SiO_2	1000	Excellent
Silicon Carbide - SiC	1750	Excellent
Mullite - Al_2O_3/SiO_2	1700	Good
Cordierite - $Al_2O_3/SiO_2/MgO$	1250	Excellent

Thermo Power
Corporation

RECUPERATOR DESIGN FOR HIGH AIR PREHEAT

OPTIONS SELECTED:

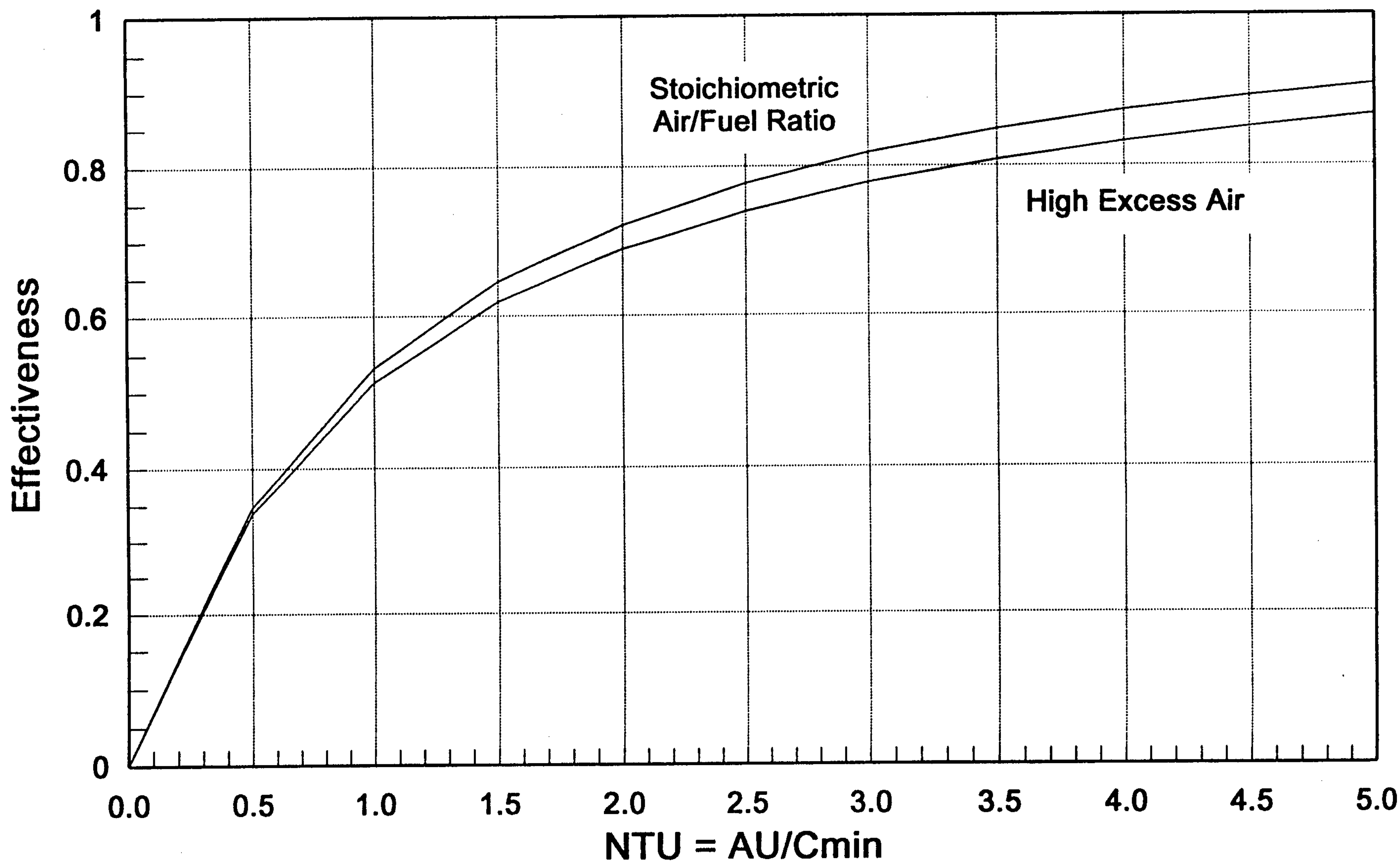
- **Configuration - Counterflow**
- **Type - Compact Plate Fin**
- **Material - Ceramic**

KEY CONSIDERATIONS:

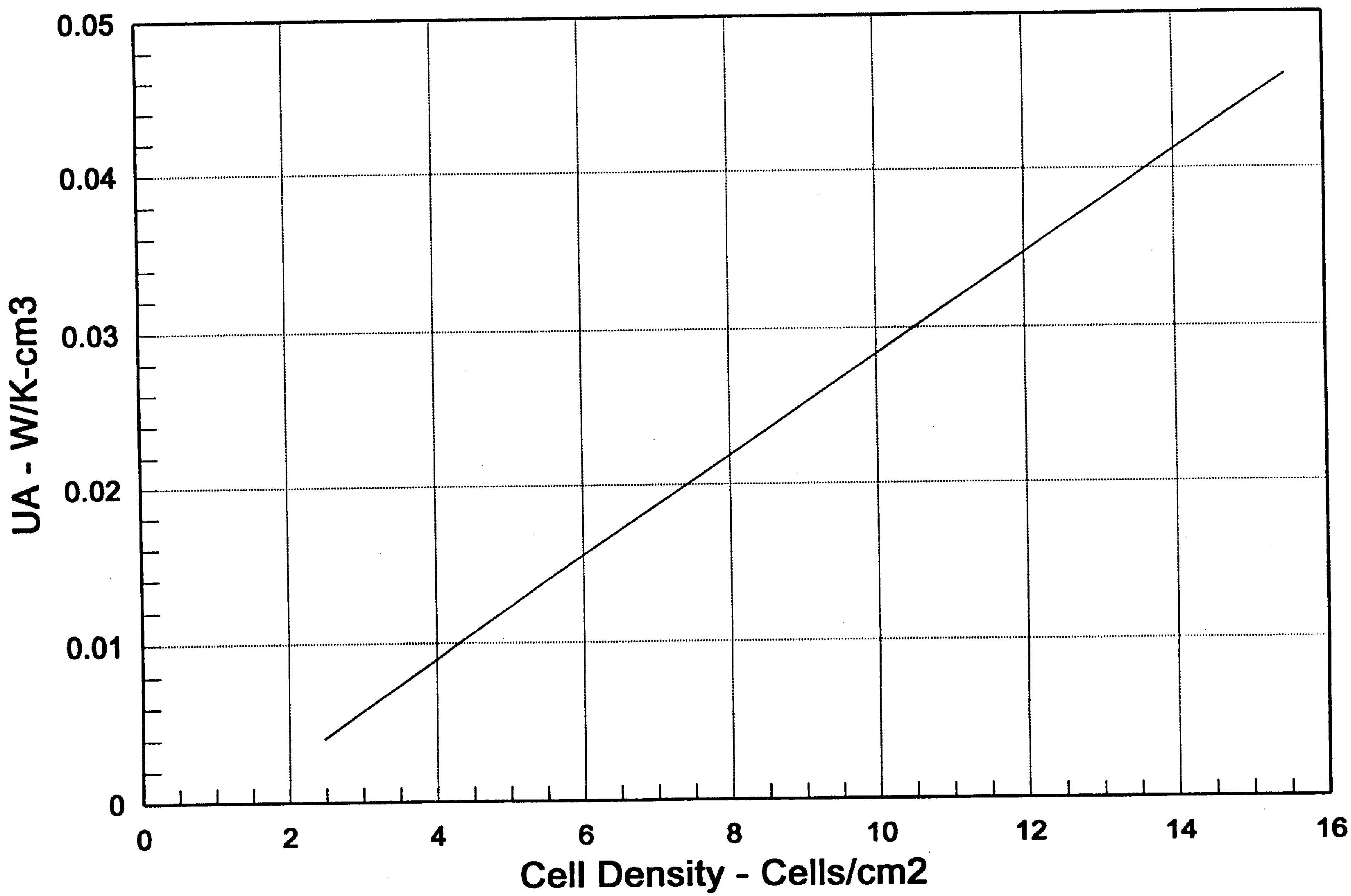
- **High Effectiveness**
- **Availability**
- **Temperature Capabilities**
- **Manufacturability**

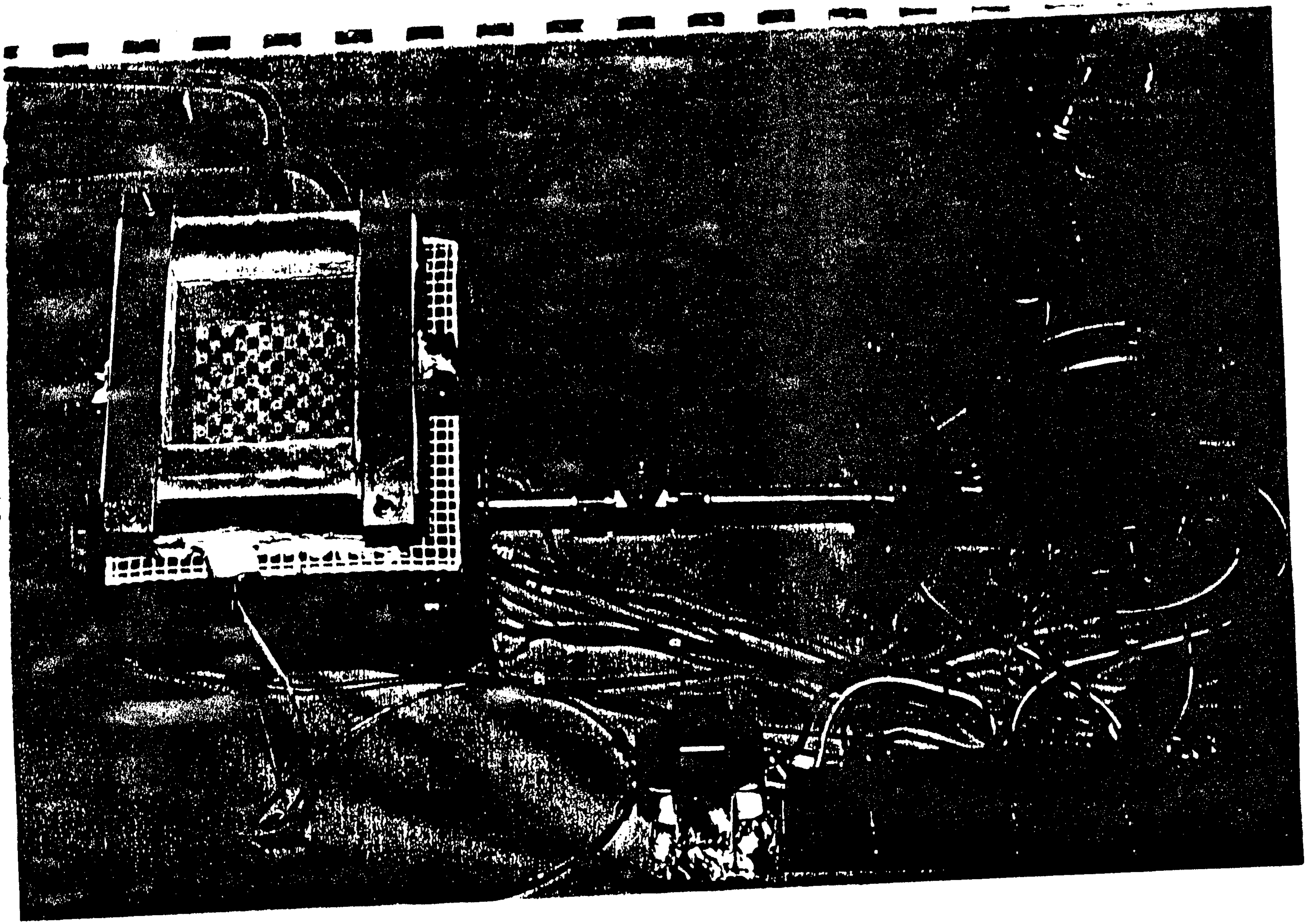
TPV Recuperator Effectiveness

For Counterflow Heat Exchanger



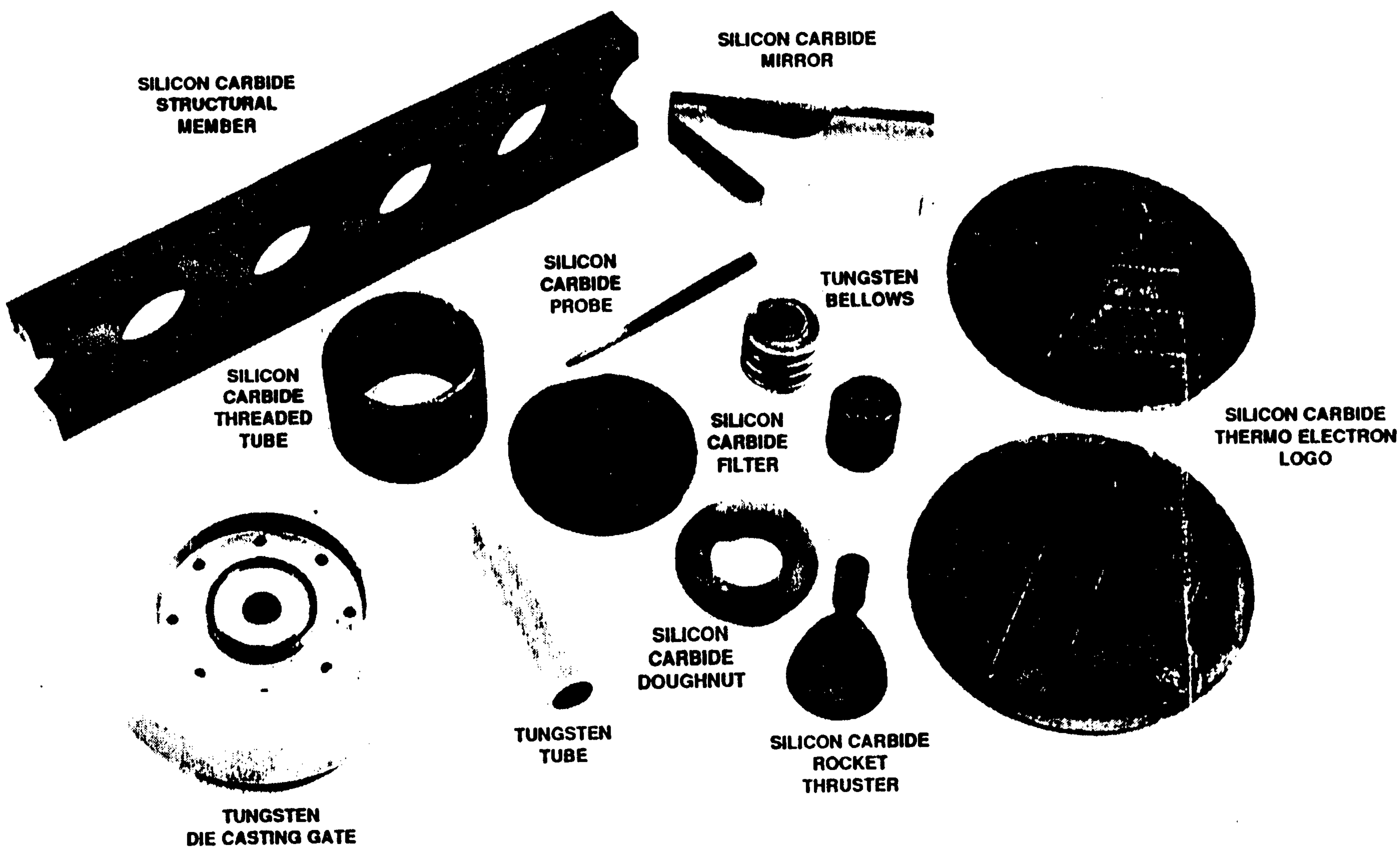
Recuperator UA vs Cell Density





HIGH TEMPERATURE CERAMIC RECUPERATOR ON TEST

COMPLEX CVC SILICON CARBIDE AND TUNGSTEN COMPONENTS



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CONCLUSIONS

- Need for High Efficiency Compact Heat Exchangers Due to Large Amount of Exhaust Gas Recuperation
- Metallic Heat Exchangers Are Practical up to 40 - 60% Effectiveness
- Ceramic Heat Exchangers Required to Achieve 90% Effectiveness and Resulting High Overall System Efficiency
- Need for Advanced Ceramic Materials to Achieve Compact Size and High Performance

"SYSTEMS ASPECTS OF TPV ENERGY CONVERSION"

Mr. Ed Doyle

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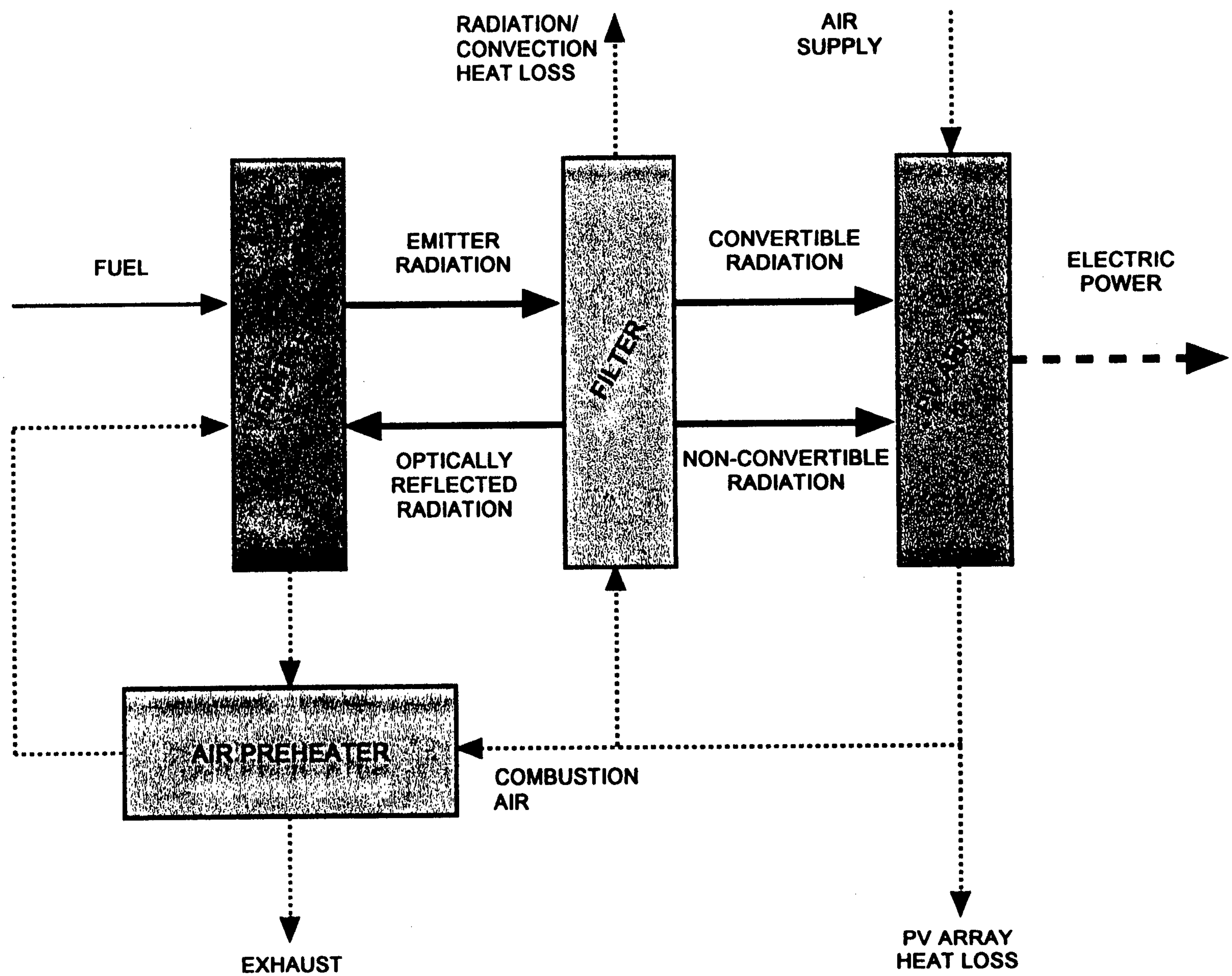
PROJECT OBJECTIVES

OBJECTIVES:

- TO DEMONSTRATE AN INTEGRATED TPV ENERGY CONVERSION SYSTEM INCORPORATING A RARE EARTH SELECTIVE EMITTER, SILICON PV CELLS, AND THERMAL AND OPTICAL RECUPERATION
- TO PREDICT ACHIEVABLE PERFORMANCE CHARACTERISTICS OF THIS TECHNOLOGY
- TO DEVELOP, CHARACTERIZE AND DELIVER A NOMINAL 500 WATT PROTOTYPE TPV POWER SUPPLY



TPV Power Source with Thermal and Optical Heat Recovery

Major Components

- Fibrous Ytterbia Emitter
  - Ideally matched to spectral response of silicon cell
  - Rapid response time
  - Planar design provides high view factor
  - Easily fabricated, thermally stress-tolerant

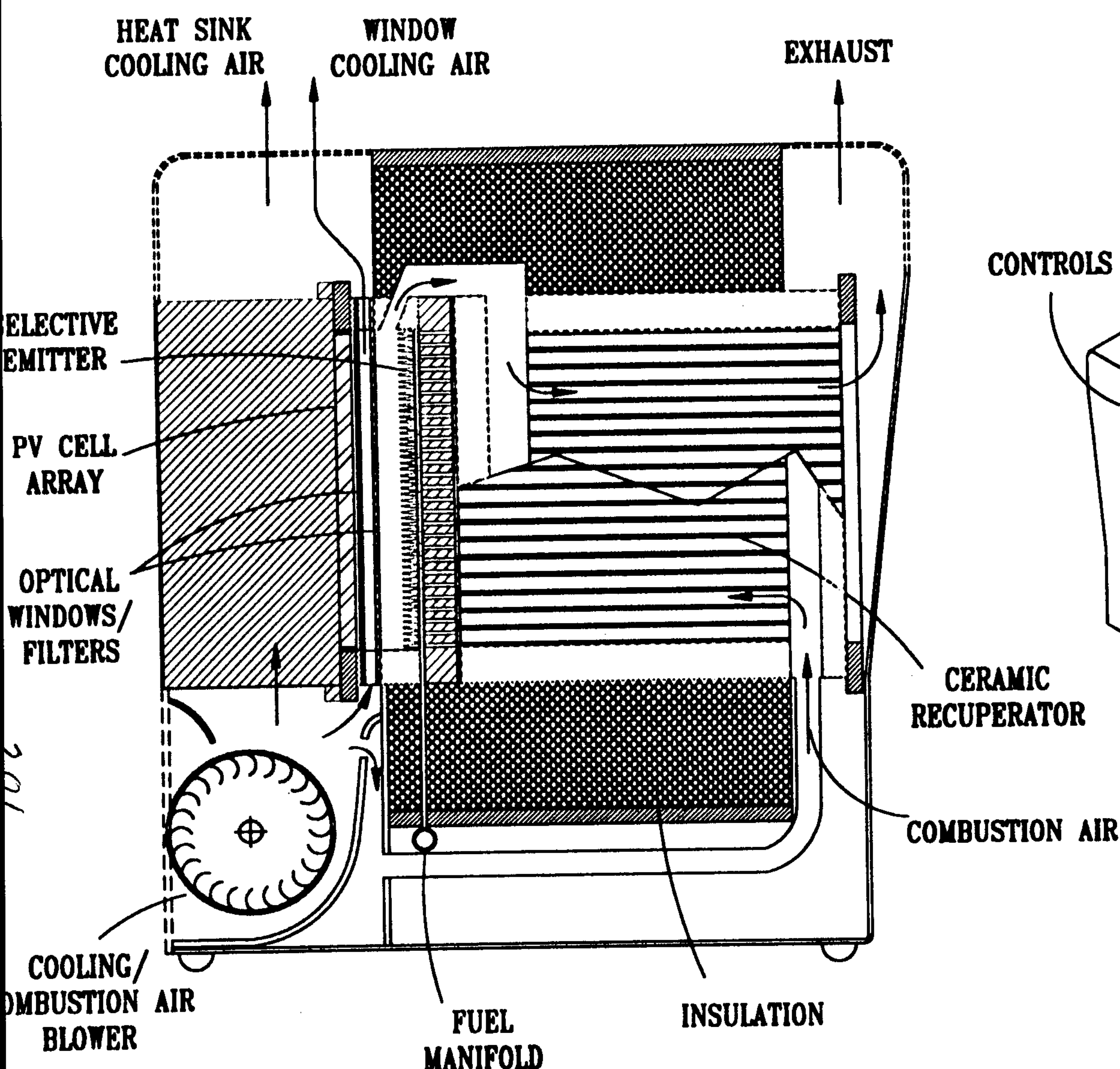
- Silicon PV Cell Array
  - Designed for 43% silicon convertible efficiency
  - 1.0 x 4.0 cm cells with inverted pyramid surface

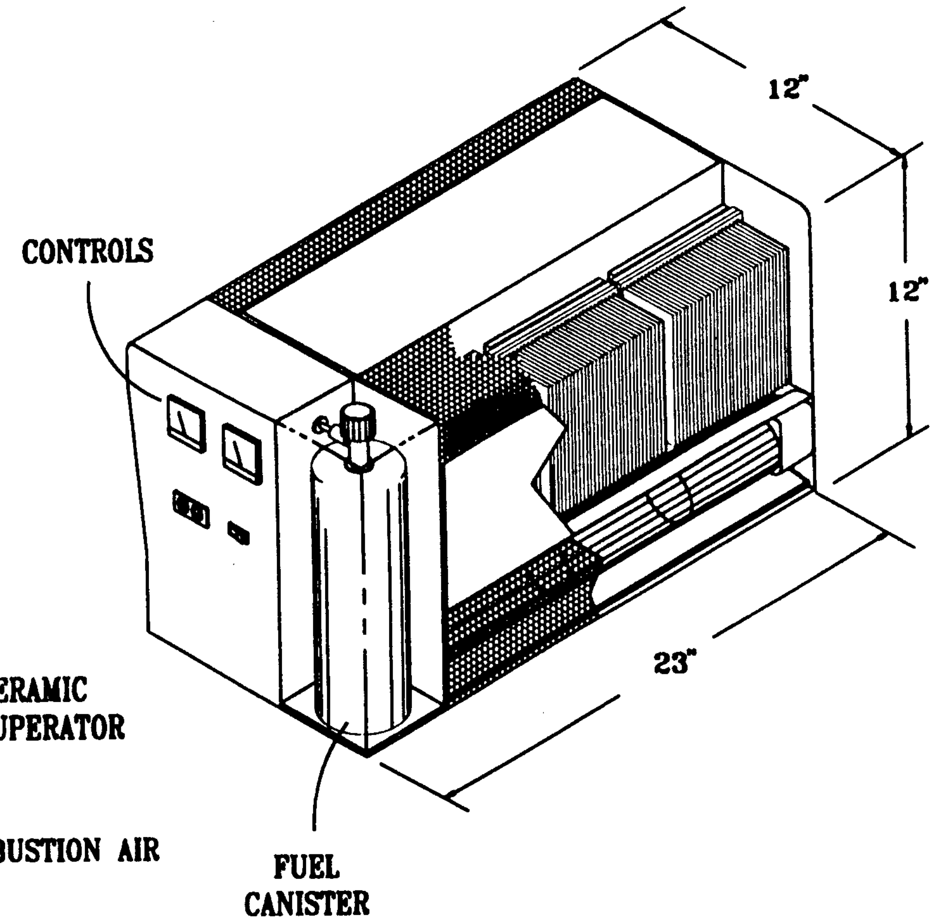
- Optical Filter/Window
  - Dual window design
  - Dielectric stack (tungsten lamp coating) on hot-window
  - Solar control film (ITO) on cold-window

- High temperature Ceramic Recuperator
  - Multi-cell design for high effectiveness
  - Close-coupled to emitter for minimum heat loss

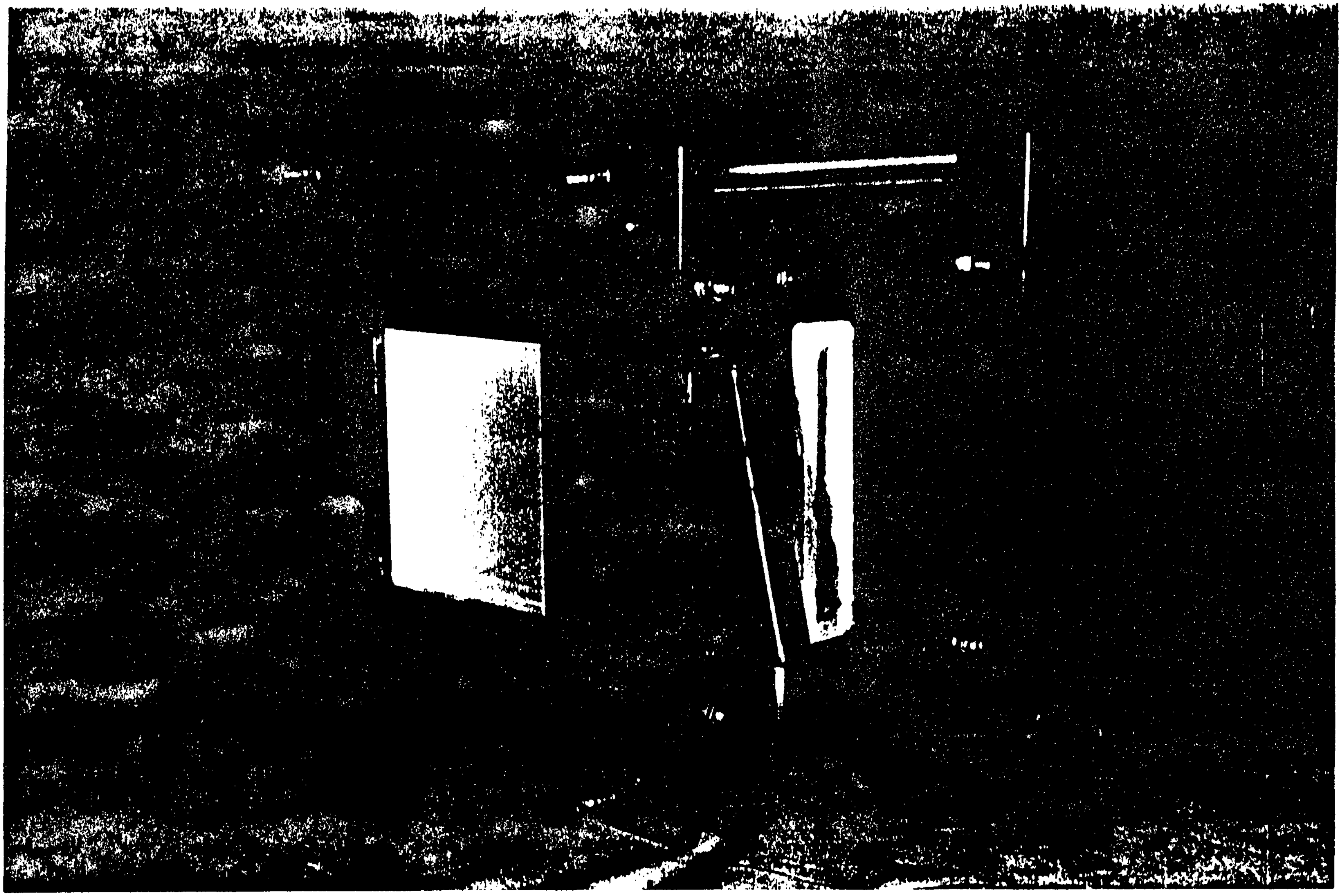
SYSTEM AND COMPONENT DEVELOPMENT AREAS

- ***OVERALL SYSTEM, SELECTIVE EMITTER, RECUPERATOR AND AUXILIARIES:***
  - THERMO POWER CORPORATION
- ***HIGH EFFICIENCY PV CELL, PV ARRAY AND HEAT SINK:***
  - TECSTAR POWER SYSTEMS INC.
- ***OPTICAL FILTER, AND EMITTER CHARACTERIZATION:***
  - ESSENTIAL RESEARCH INCORPORATED





500 WATT TPV GENERATOR



167 WATT PROTOTYPE TPV POWER SOURCE MODULE

TPV System Model

Determines Impact of Various Parameters on Performance and Size of Overall TPV System

- Takes into account the critical characteristics of the main components.
- Consists primarily of a heat transfer model of the emitter fibers, emitter substrate, and optical filter
- Accounts for both radiation and convective heat transfer.
- Also produces overall efficiency estimate for entire TPV system.

Heat Transfer Model

The radiation heat transfer model is divided into 6 bandwidth regions and the radiation heat transfer is calculated for:

- The emitter fibers
  - to the emitter substrate
  - to the optical filter
  - to the PV cells

- The emitter substrate
  - to the optical filter
  - to the PV cells

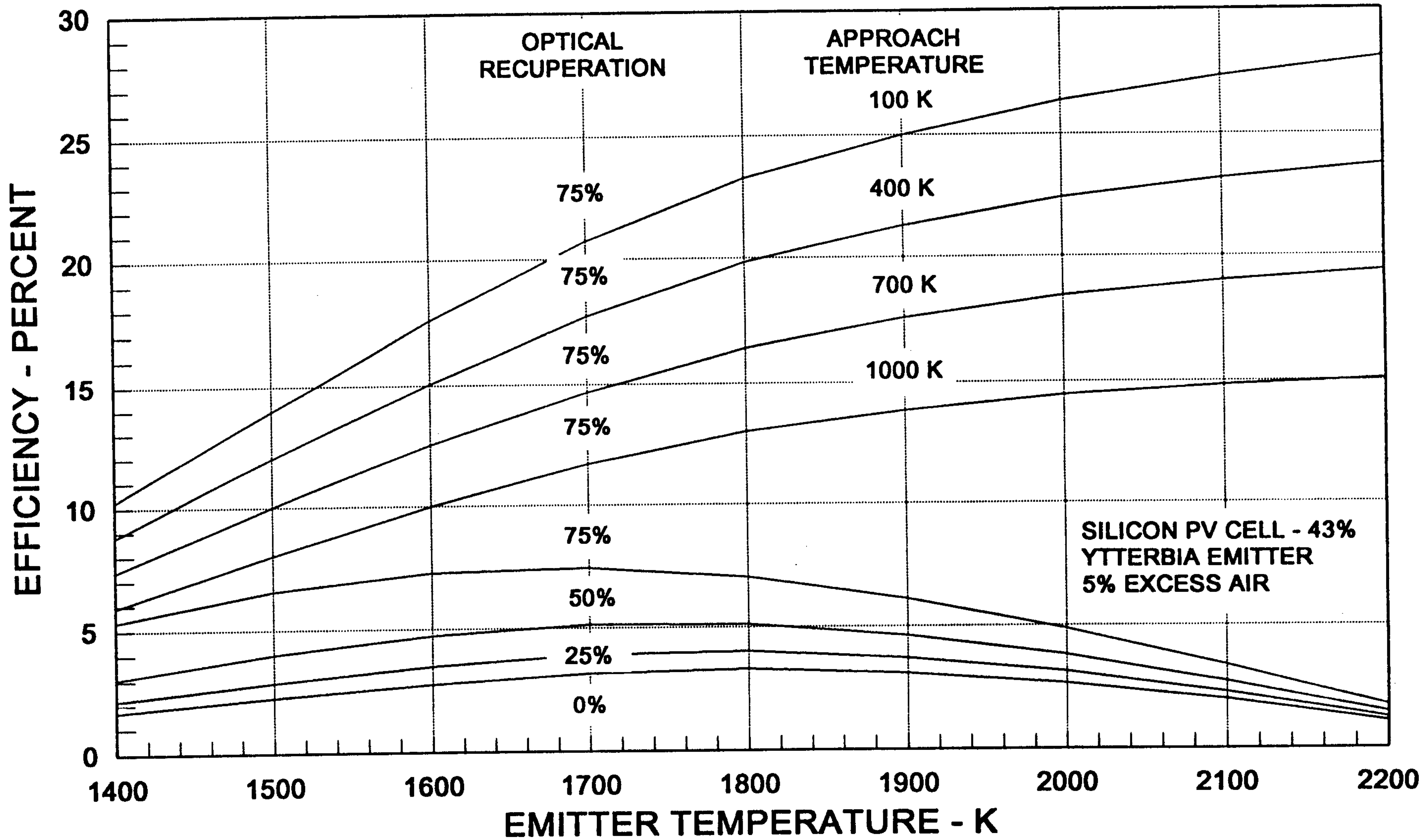
- The optical filter
  - to the PV cells

The convective heat transfer is calculated for:

- The exhaust gases
  - to the emitter substrate
  - to the optical filter

- The optical filter
  - to the cooling air

TPV SYSTEM PERFORMANCE MAP



KEY COMPONENTS AND ISSUES

SELECTIVE EMITTER AND RECUPERATOR:

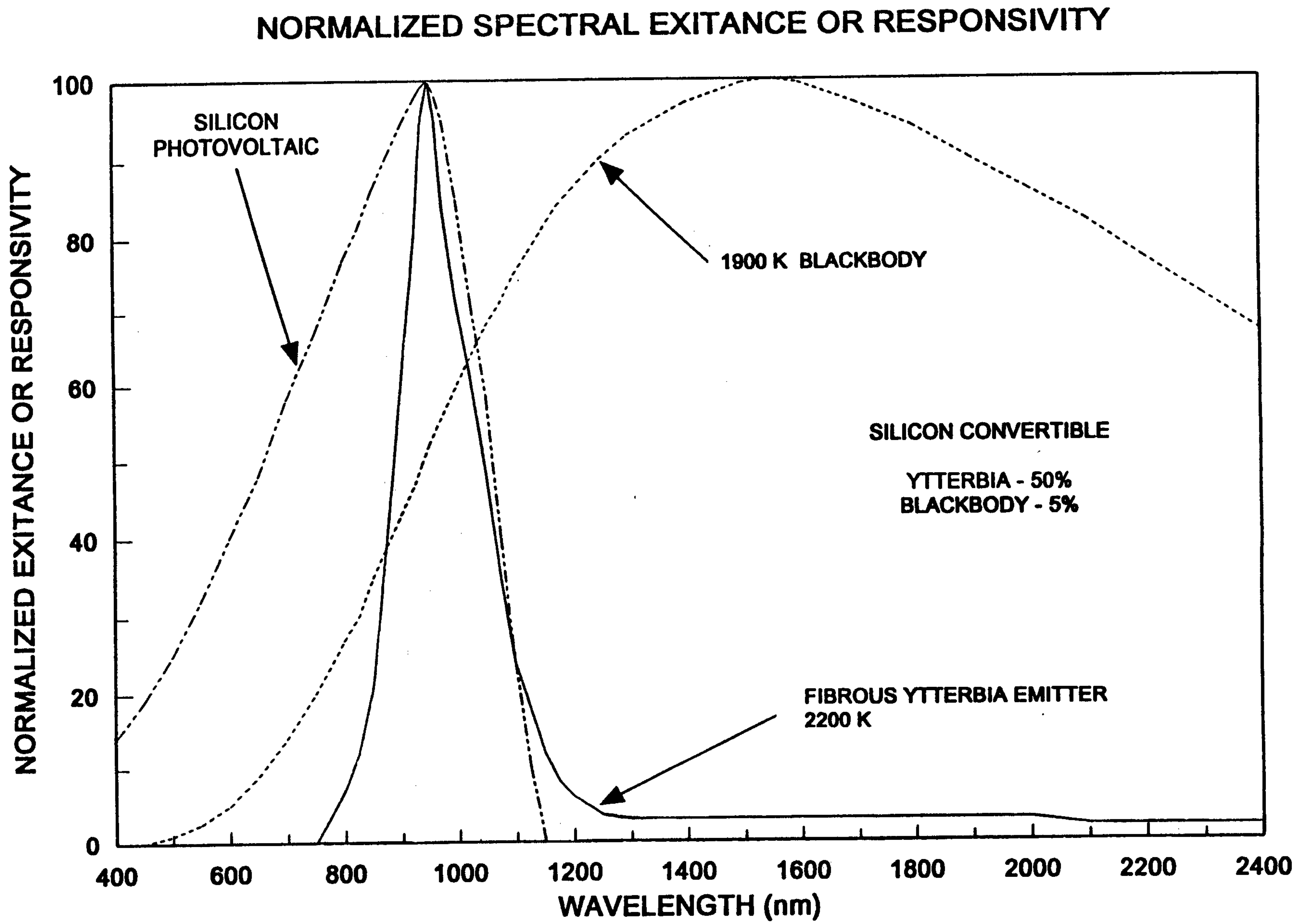
- OPERATING AT HIGH AIR PREHEAT TEMPERATURES
- MAINTAINING NARROW BAND EMITTER CHARACTERISTICS
- DELIVERING FUEL WITH HIGH AIR PREHEAT

PV CELL ARRAY:

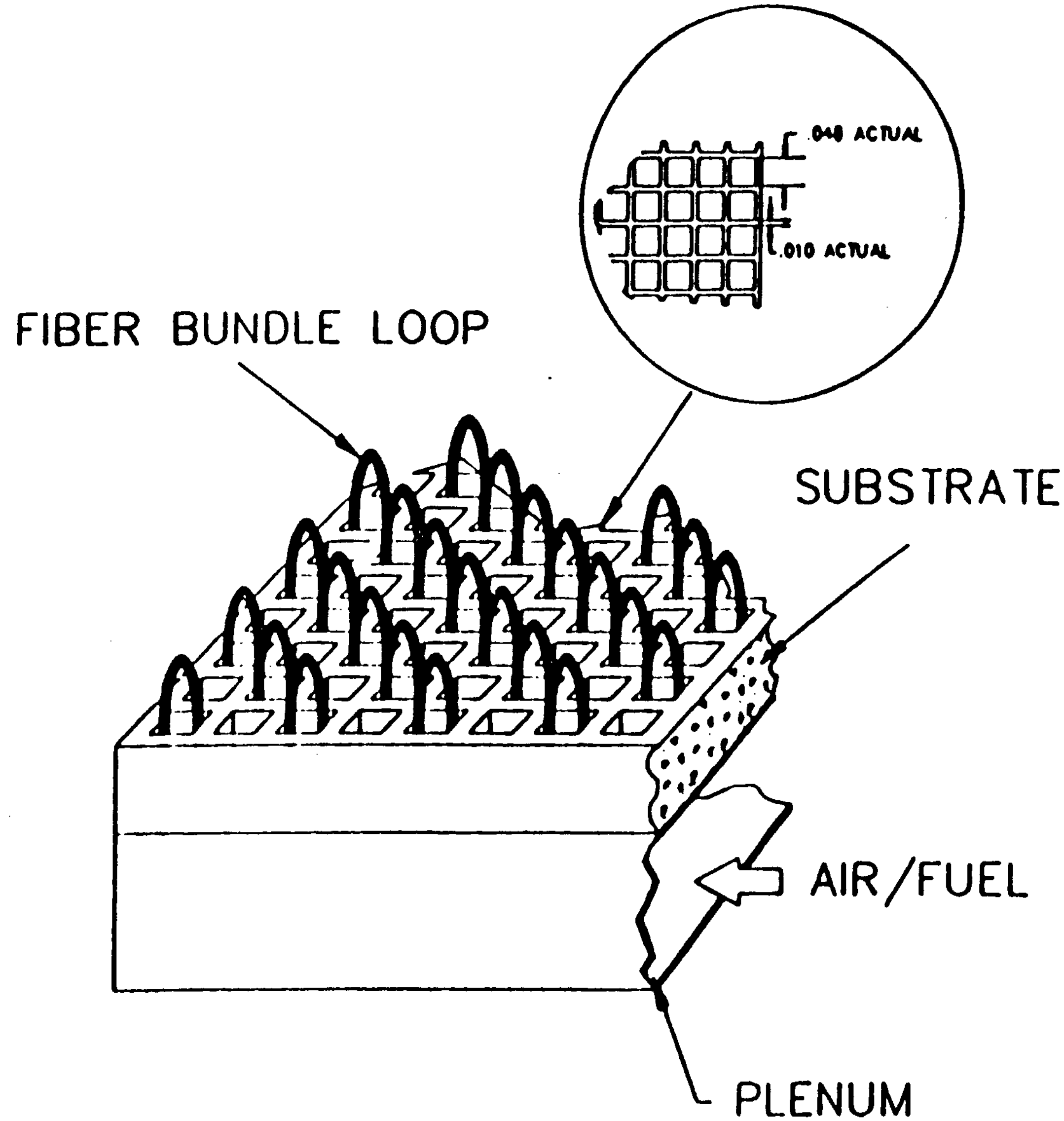
- IMPROVED MATCHING TO EMITTER FOR HIGH EFFICIENCY
- HEAT REJECTION WITHOUT PERFORMANCE DEGRADATION
- DURABLE BONDING PV CELLS TO HEAT SINK WITH HIGH THERMAL CONDUCTIVITY AND LOW ELECTRICAL RESISTANCE

OPTICAL FILTER:

- EFFICIENTLY REFLECT ONLY THE OFF-BAND RADIATION BACK TO EMITTER SYSTEM
- OPERATION IN HIGH TEMPERATURE EXHAUST GAS ENVIRONMENT



NORMALIZED SPECTRAL EXITANCE OR RESPONSIVITY
SILICON PHOTOVOLTAIC
1900 K BLACKBODY
SILICON CONVERTIBLE
YTTERBIA - 50%
BLACKBODY - 5%
FIBROUS YTTERBIA EMITTER
2200 K
NORMALIZED EXITANCE OR RESPONSIVITY
WAVELENGTH (nm)

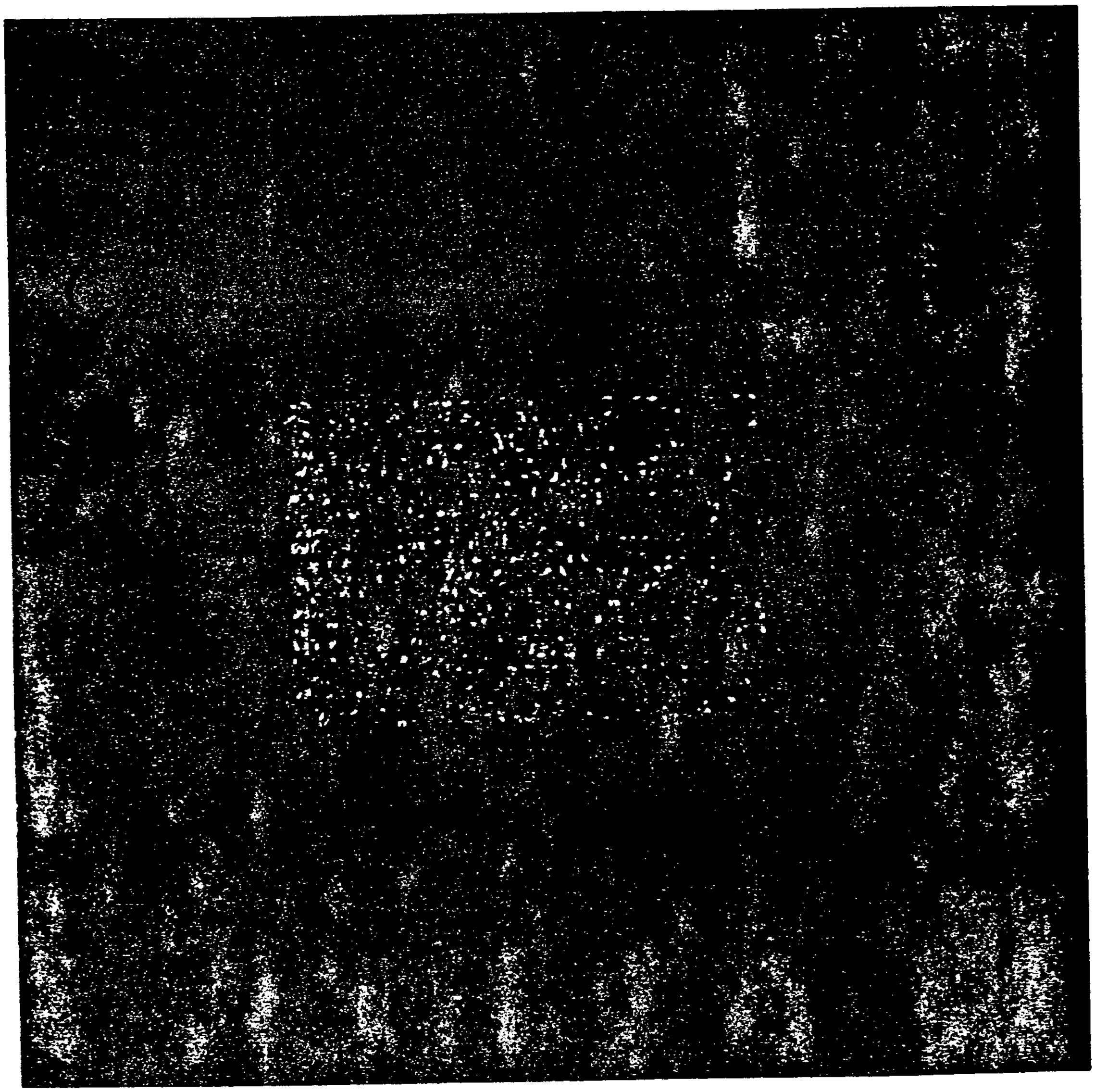


SUPPORTED CONTINUOUS FIBER SYSTEM

Fibrous Emitters

Advantages

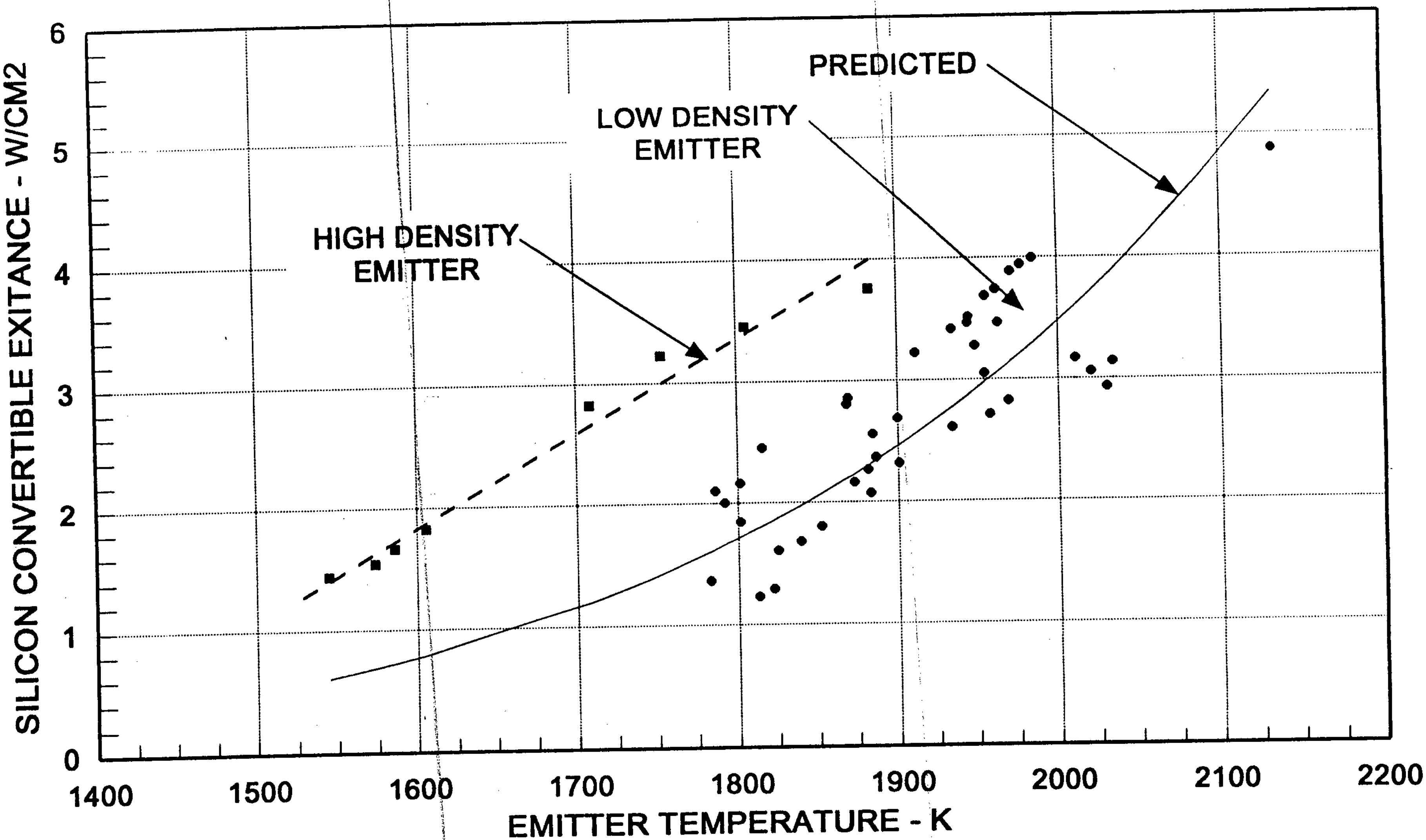
- Close Coupling to Flame
- Thermal Stress Tolerance
- Spectral Control
- Rapid Thermal Response

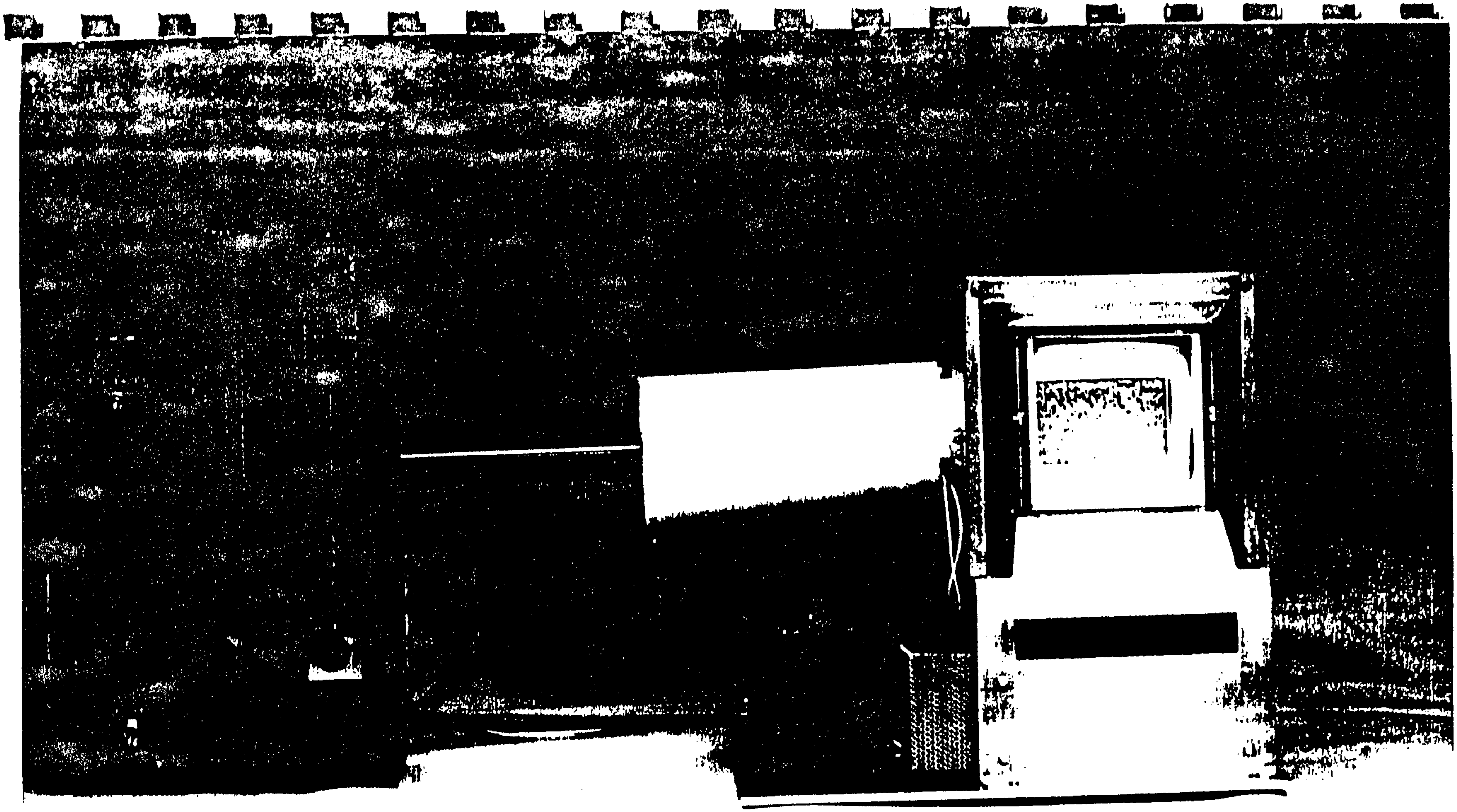


TPV EMITTER

210

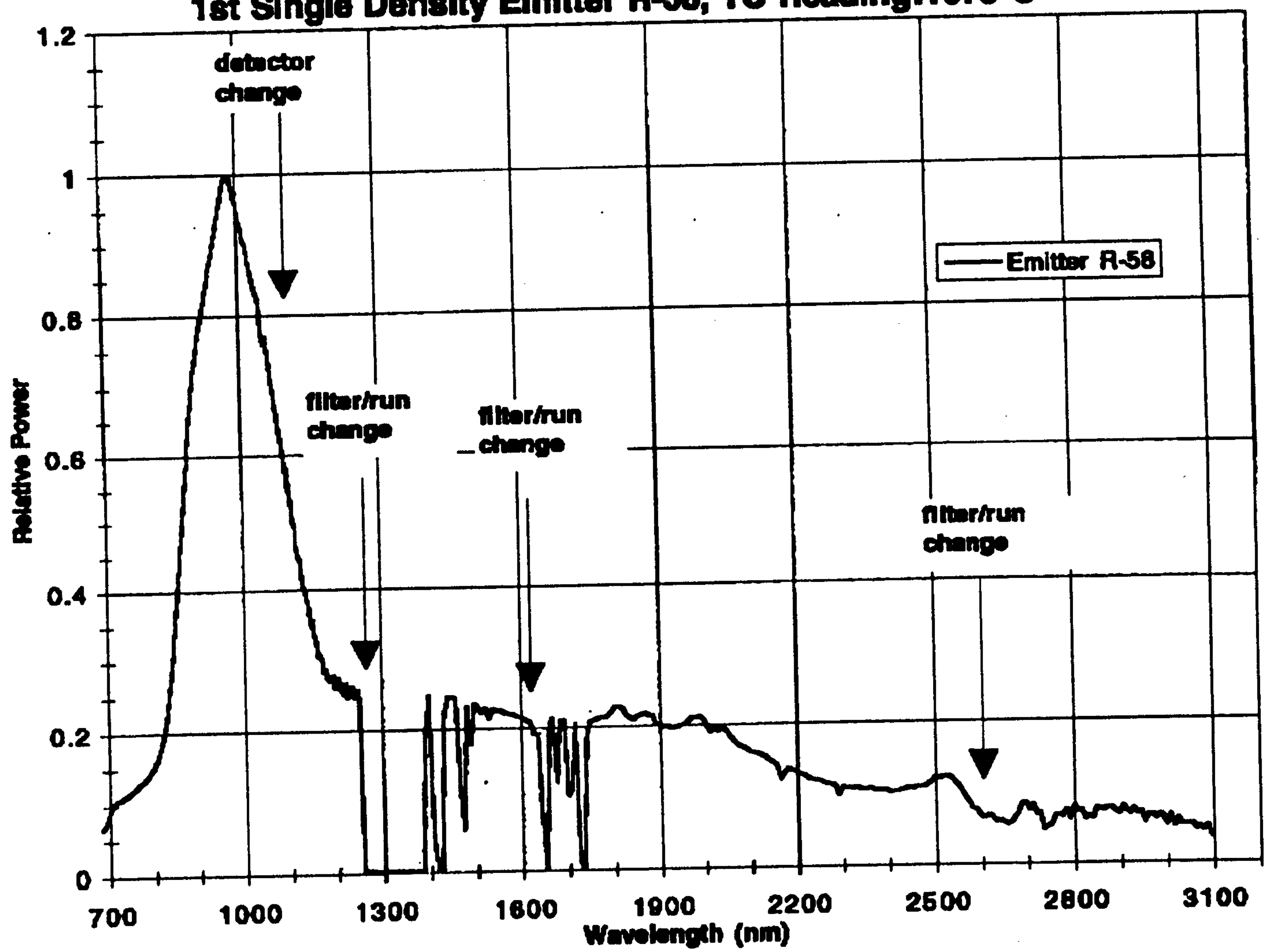
PERFORMANCE OF FIBROUS YTTERBIA EMITTERS





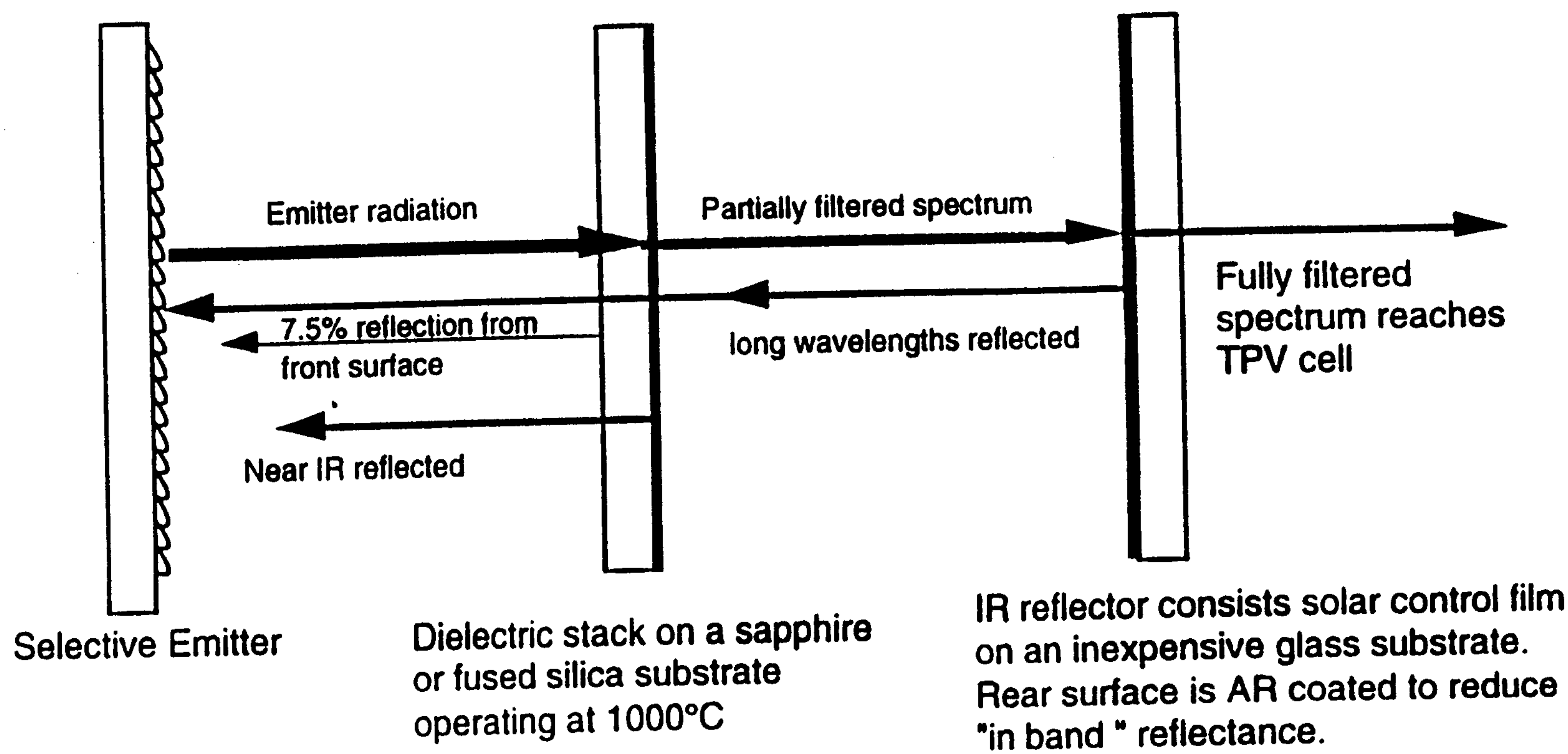
TPV EMITTER TEST STAND

1st Single Density Emitter R-58, TC Reading:1673°C

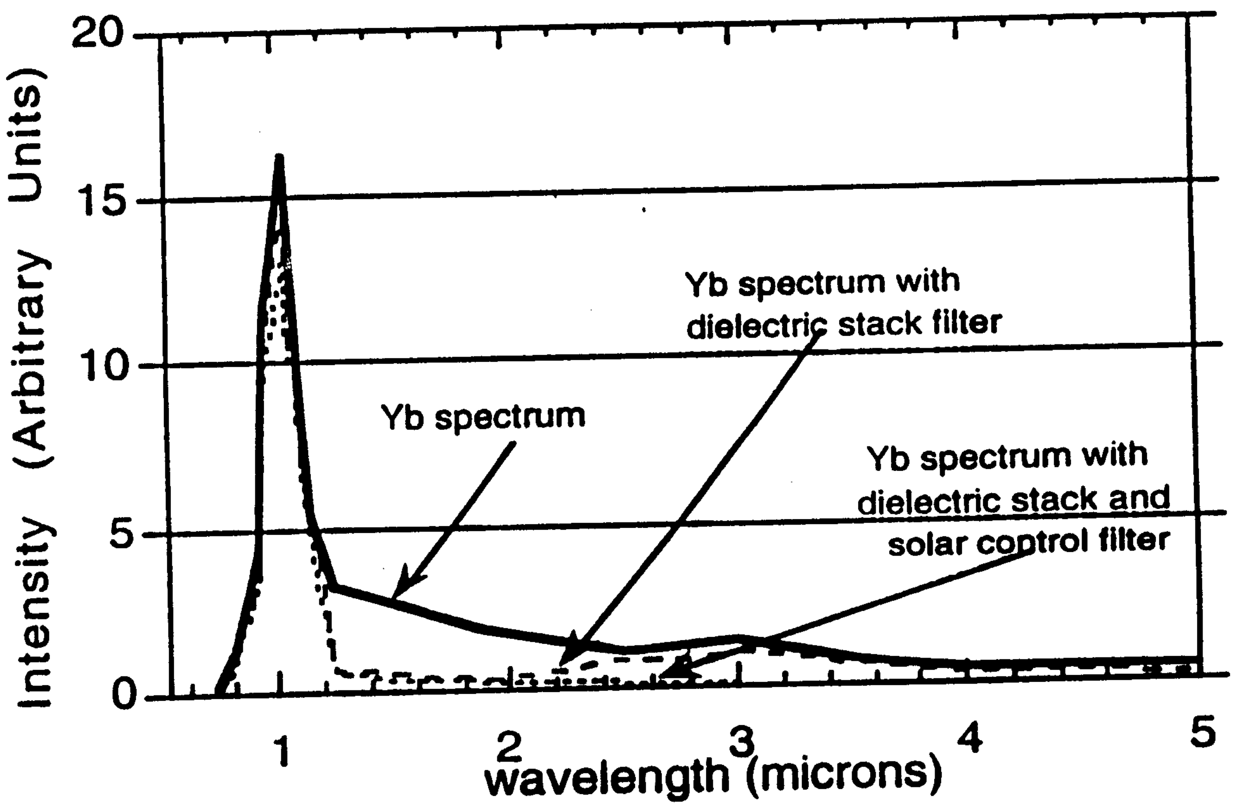


7/11/96

2/3



SCHEMATIC REPRESENTATION OF A TWO FILTER SYSTEM EMPLOYING A HIGH TEMPERATURE "TUNGSTEN LAMP" COATING AND A SOLAR CONTROL COATING ON THE SECOND ELEMENT

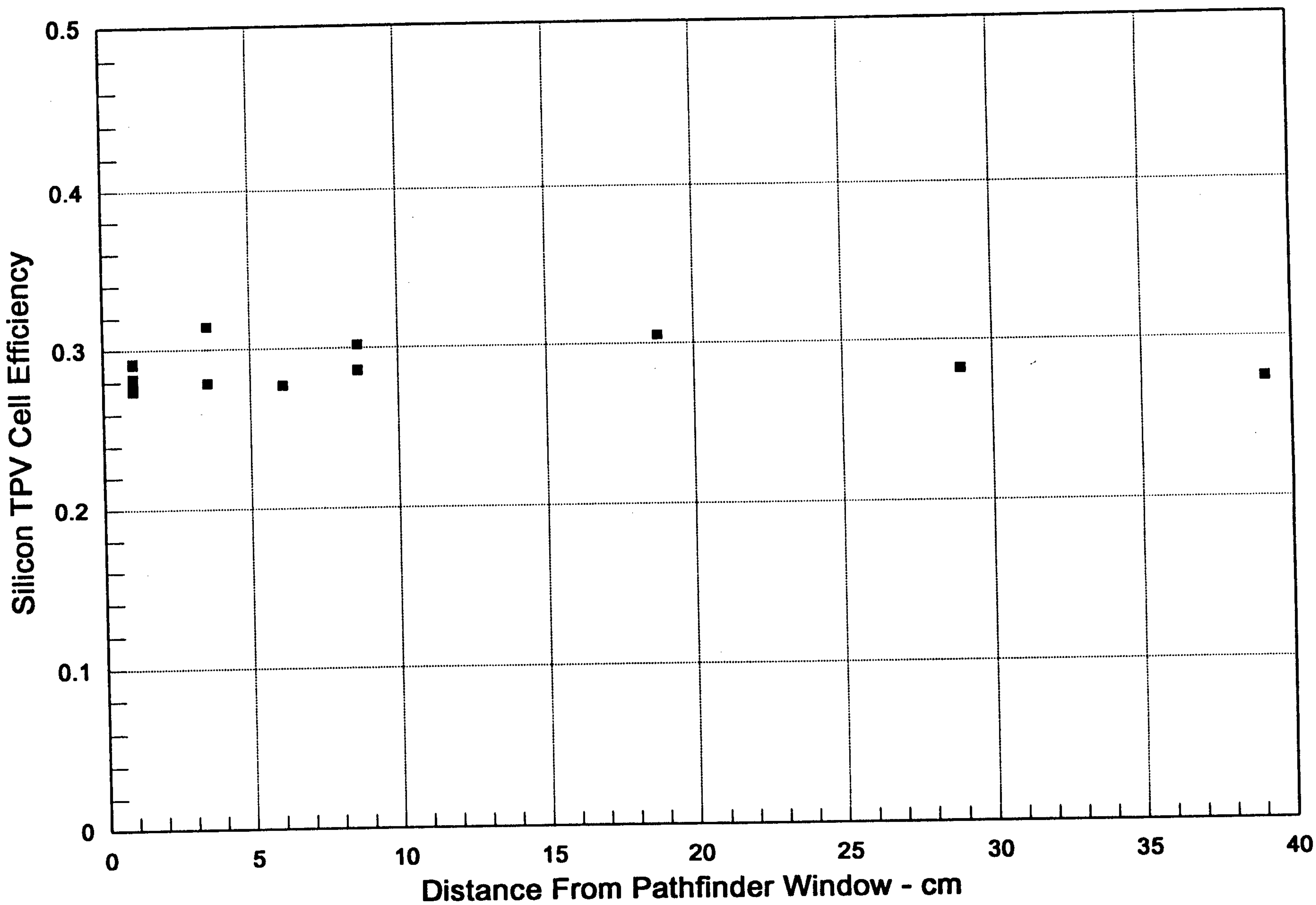


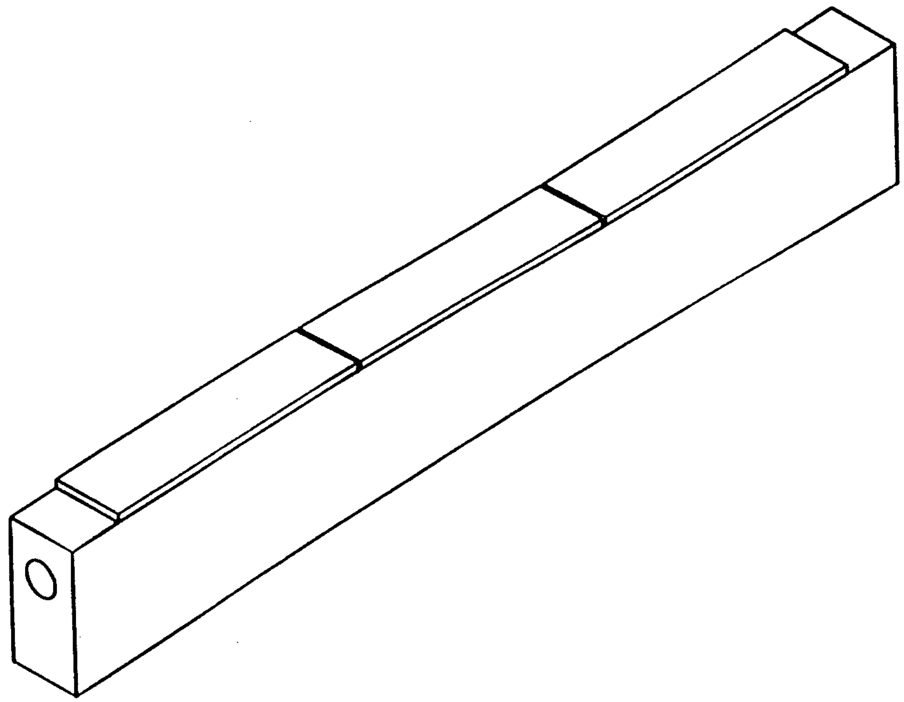
EMITTER SPECTRUM AS SEEN BY THE PV ARRAY LOOKING THROUGH A NEARLY IDEAL DIELECTRIC STACK LAMP COATING AND AN IDEAL SOLAR CONTROL FILTER

TPV Silicon Cell Array and Heat Sink

- Passivated emitter rear locally diffused (PERL) cells
- Designed to achieve 43% efficiency with the ytterbia selective emitter.
- Previously demonstrated a monochromatic efficiency of 45%
- Heat sink will be designed to reject 20 W/cm^2 with a maximum $10^{o}C$ temperature rise

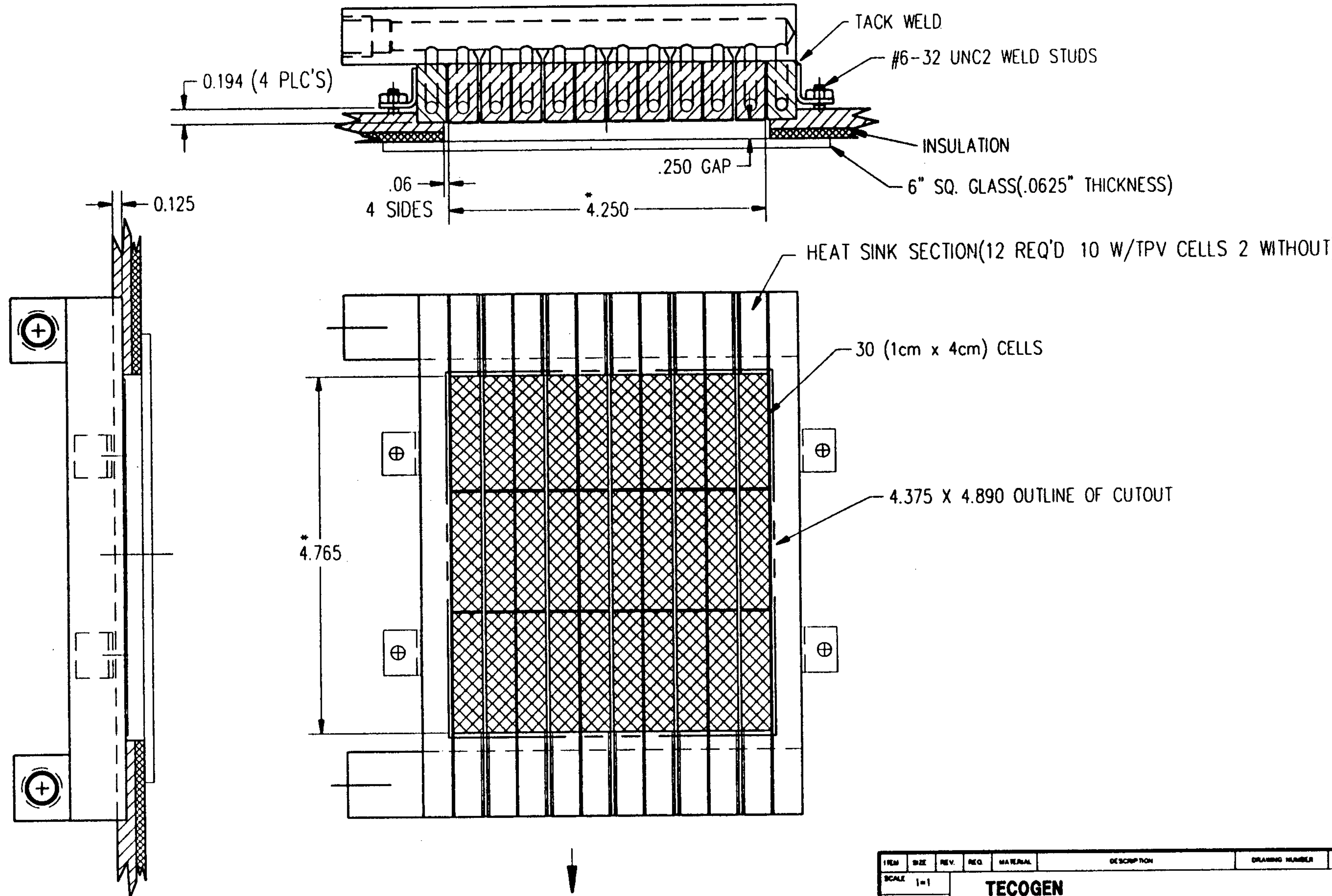
Silicon TPV Cell Performance





ONE HEATSINK SECTION WITH
THREE 1.0 cm x 4.0 cm CELLS

REV	DESCRIPTION	DATE	BY	APPR

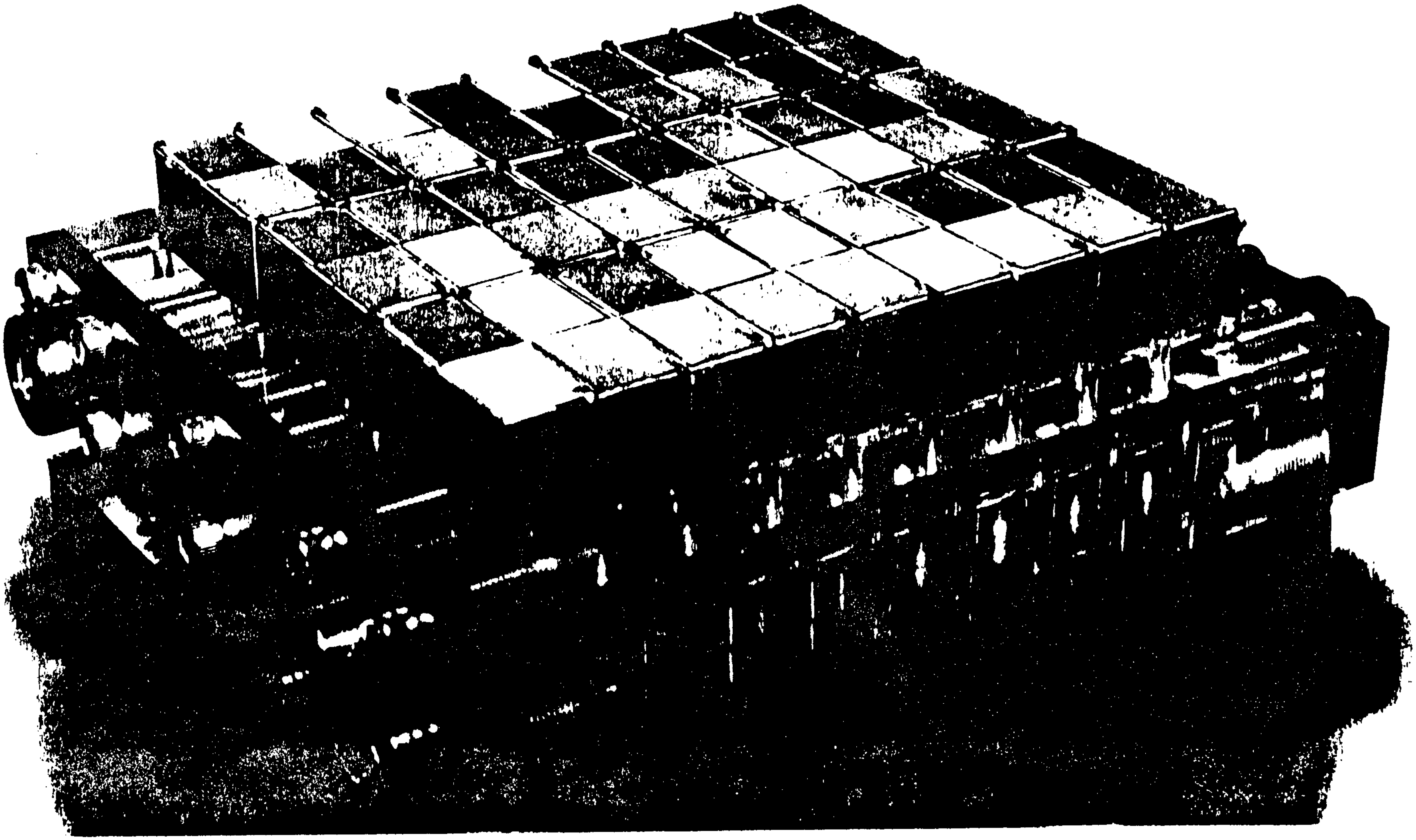


NOTES:

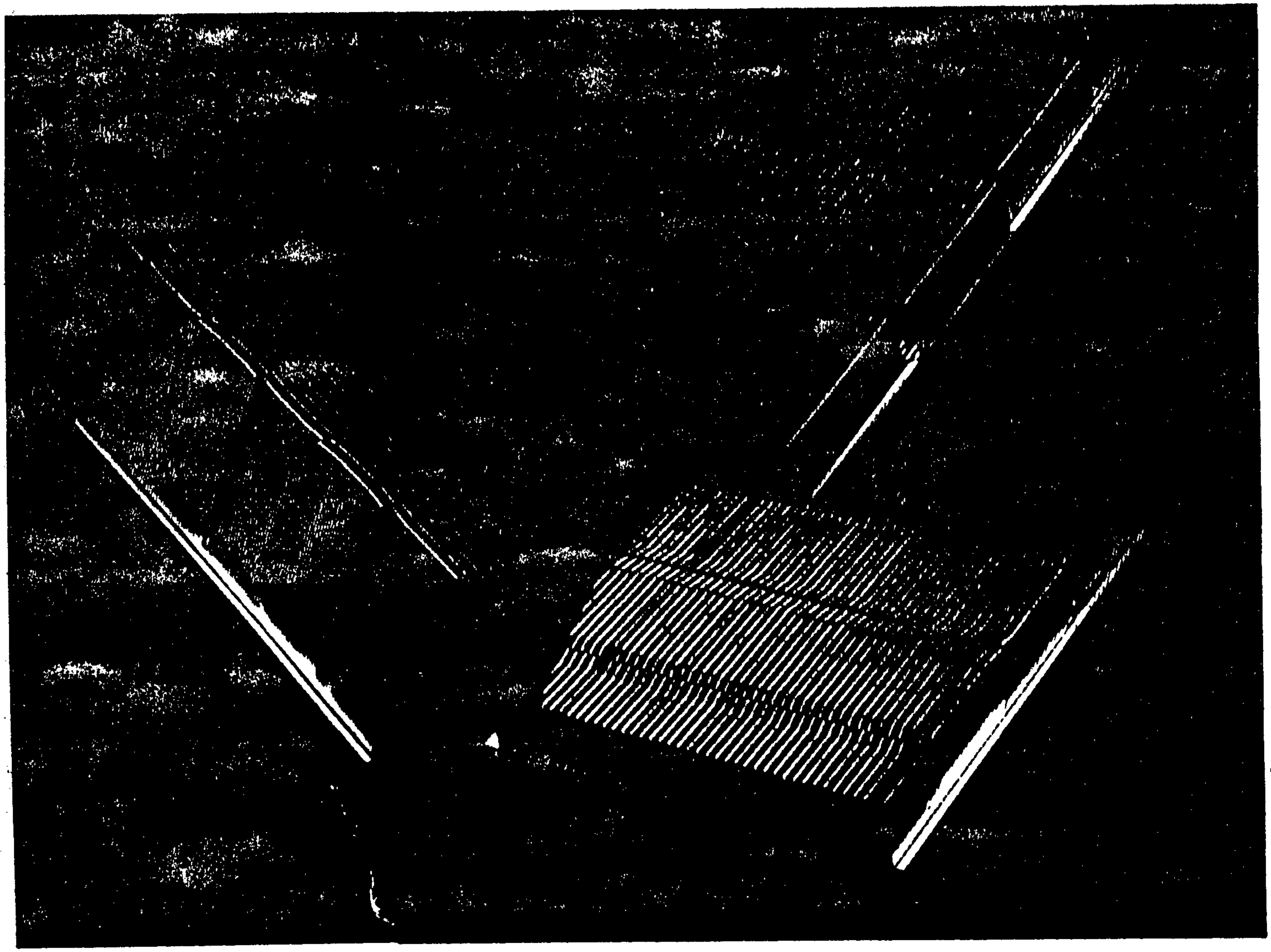
1. (*) = EFFECTIVE TPV CELL AREA.

ITEM	SIZE	REV.	REQ.	MATERIAL	DESCRIPTION	DRAWING NUMBER	REF NO

SCALE 1=1	**TECOGEN** 45 FIRST AVENUE WALTHAM,MA 02254-8995		
MATERIAL -	UNLESS OTHERWISE SPECIFIED	DRAWN M N	DATE 6-27-96
FINISH -		TITLE "TECSTAR" ARRAY WATER COOLED	
NO. REQUIRED -			
NEXT ASSEMBLY 188-28		SIZE C	DRAWING NUMBER 1MM 7M



BASELINE SILICON CELL ARRAY



AUGMENTED FIN HEAT SINKS

CONCLUSIONS

- Use of Selective Emitters Radiating to High Performance PV Cells Represents Optimal Technical Pathway for Achieving 25% Overall Thermal Efficiency
- Effective Thermal and Optical Recuperation Critical to Achieving Performance Goals
- Baseline Testing of Individual Subsystem Components Well Underway Towards Meeting Individual Target Efficiencies
- With Continued Systems Development, TPV Represents a Breakthrough Technology in the Advancement of Portable Electric Power for Military and Commerecial Markets

UPDATE ON OSC RTPV SYSTEM DESIGNS FOR POSSIBLE USE ON PLUTO EXPRESS MISSION

A. Schock
Orbital Sciences Corporation
Germantown, MD 20874

SUMMARY

- Under an OSC subcontract initiated in 1994, EDTEK has successfully achieved 94% of their projected selective-filter performance improvement, and have developed a much more economical method (Masked Ion Beam Lithography) for producing those filters.

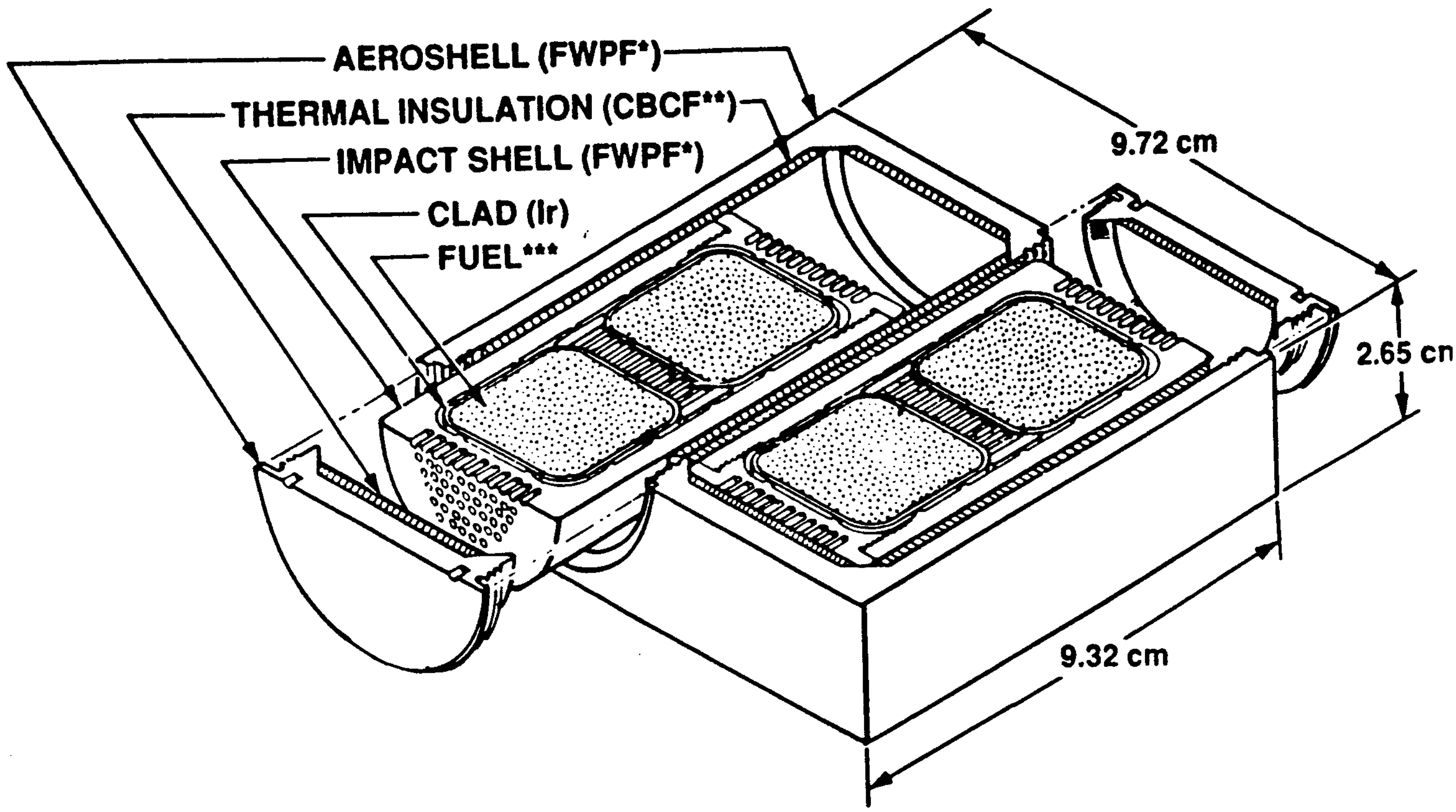
- They have successfully transferred Boeing's PV-cell technology to EDTEK, and matched their projected quantum efficiencies.

- However, their initial cell measurements, in December 1995, yielded open-circuit voltages and fill factors substantially below the theoretical values used in previous system design studies, resulting in significant system performance loss.

- More than half of that loss has been recovered as the result of subsequent cell improvements by EDTEK and system design improvements by OSC.

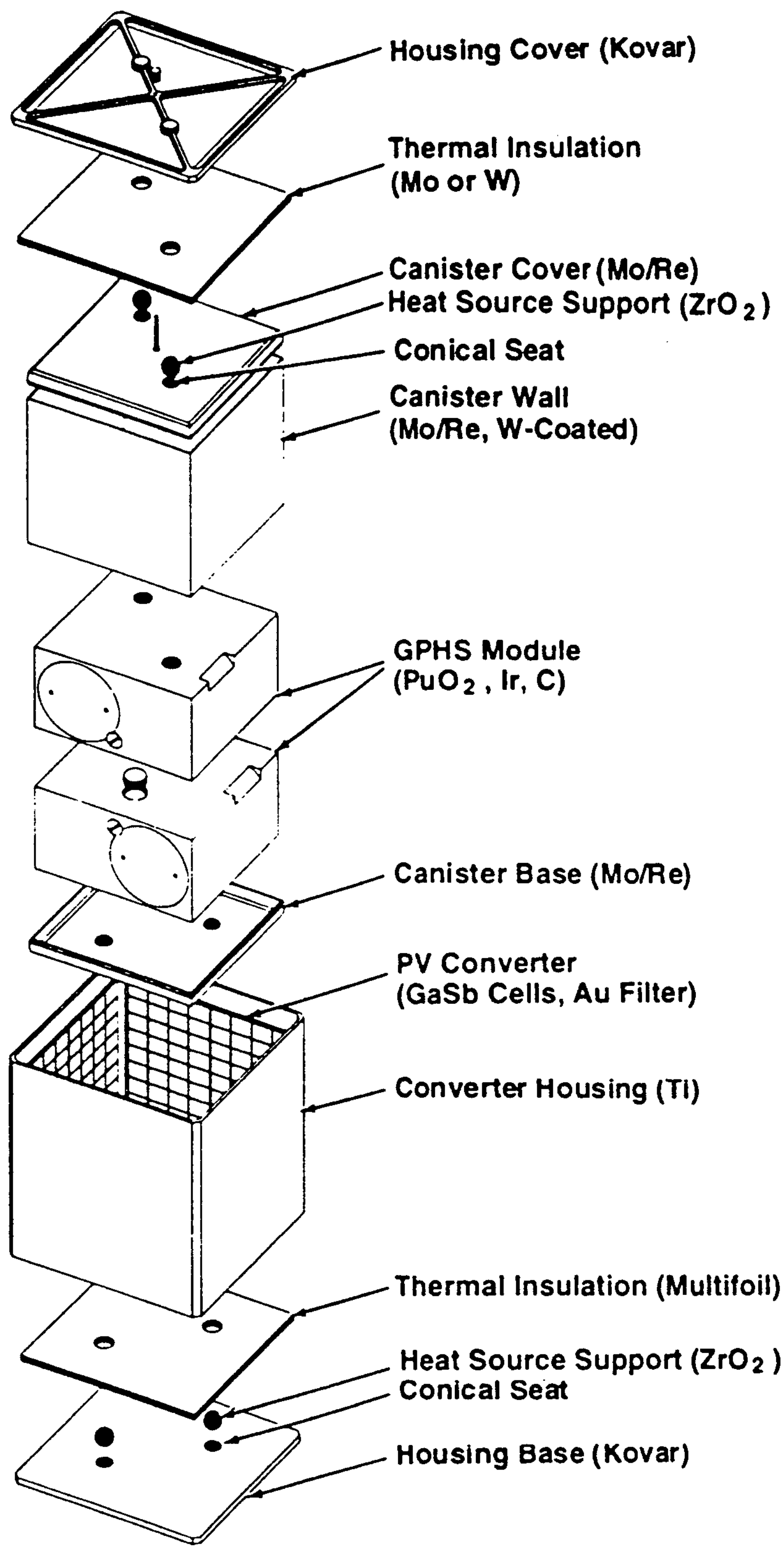
- EDTEK and Mound are awaiting release of DOE funding to initiate construction of a prototypic generator to start testing in March 1997, with the initial electrical heater to be subsequently replaced with two radioisotope heat source modules.

GPHS-GENERAL PURPOSE HEAT SOURCE MODULE (250 WATTS SECTIONED AT MID-PLANE

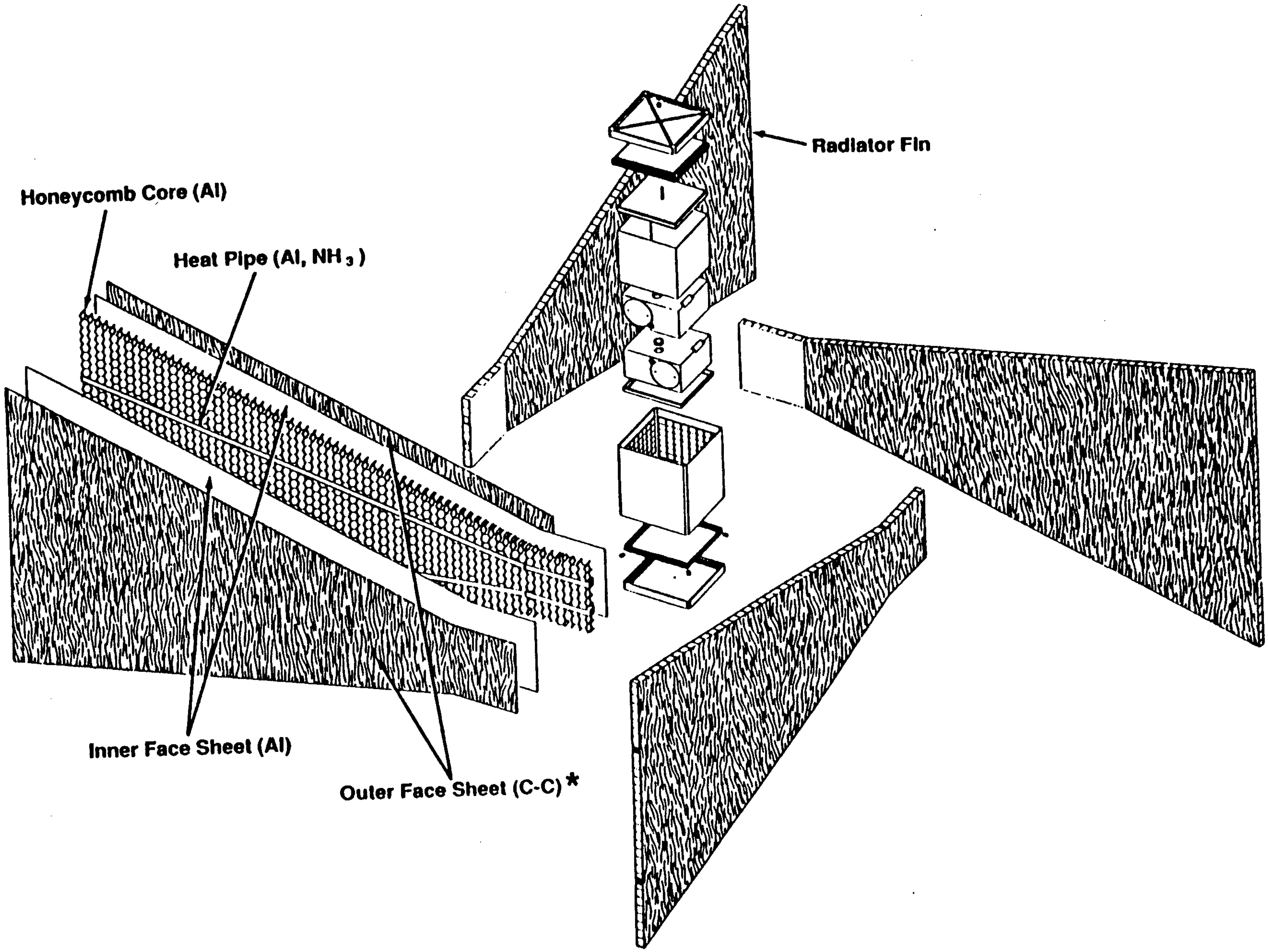


*Fine-Weave Pierced Fabric, a 90%-dense 3D carbon-carbon composite
**Carbon-Bonded Carbon Fibers, a 10%-dense high-temperature insulator
***62.5-watt $^{238}PuO_2$ pellet

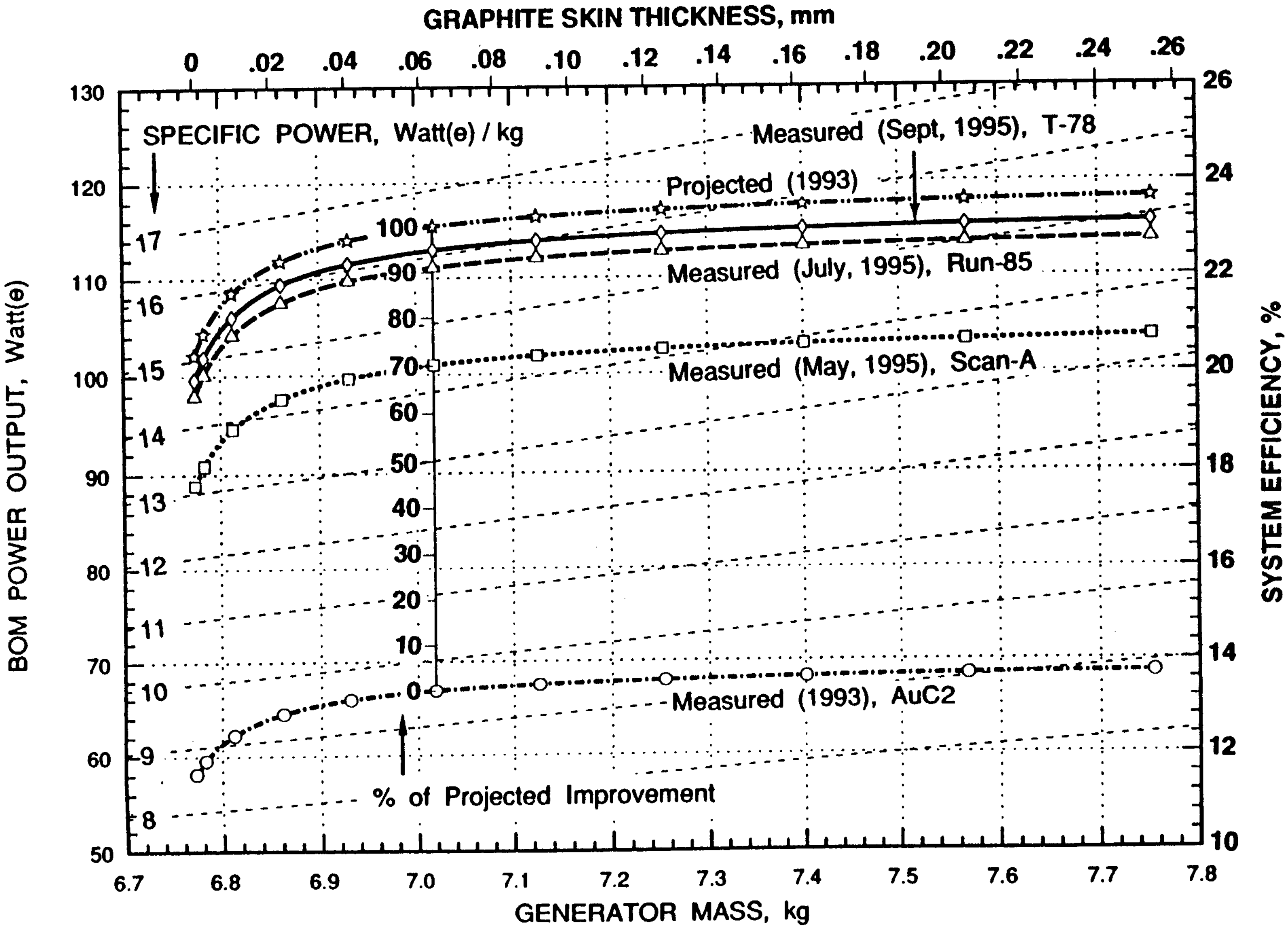
EXPLODED VIEW OF CONVERTER (1993)



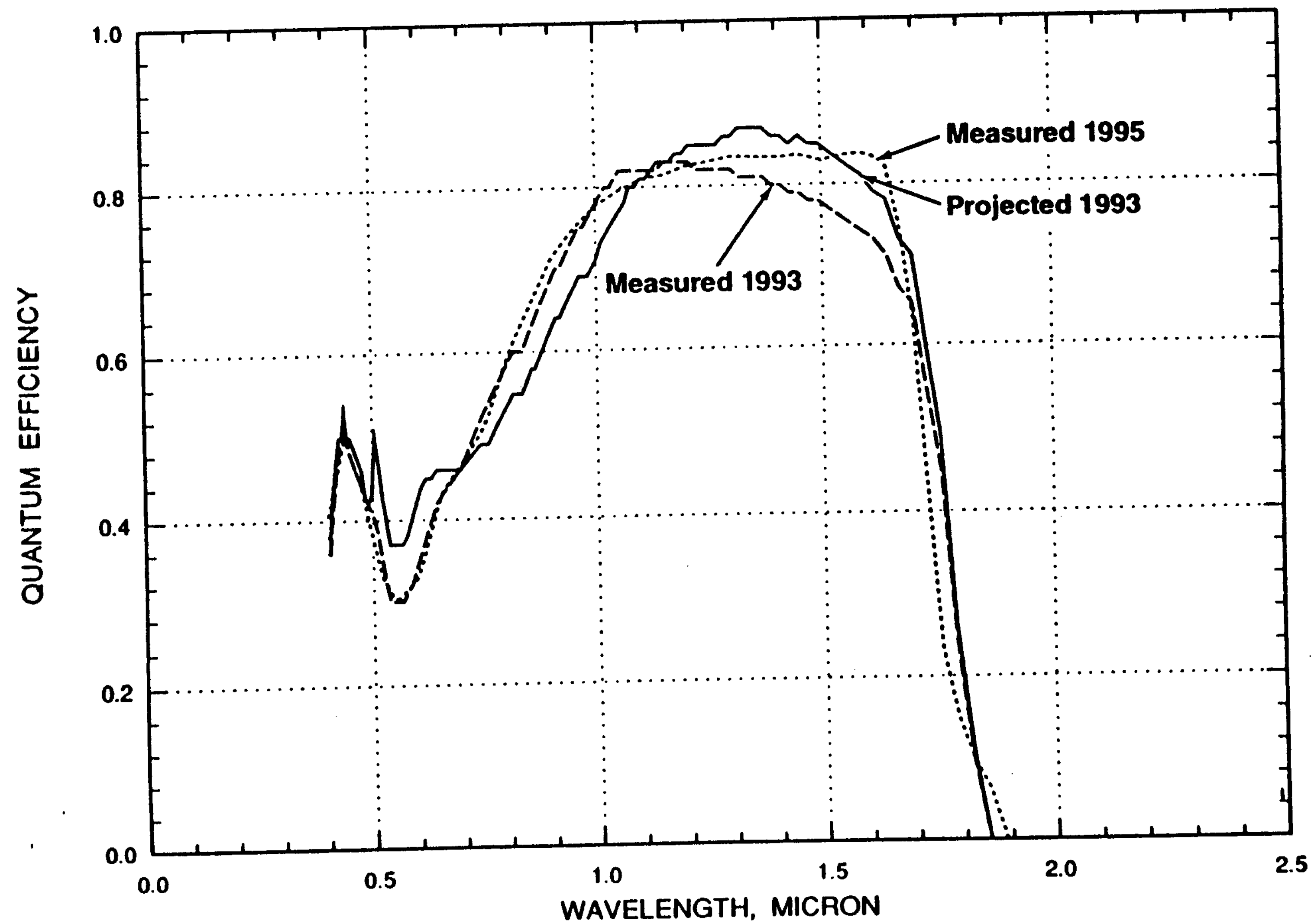
EXPLODED VIEW OF RTPV GENERATOR AND OF RADIATOR FIN



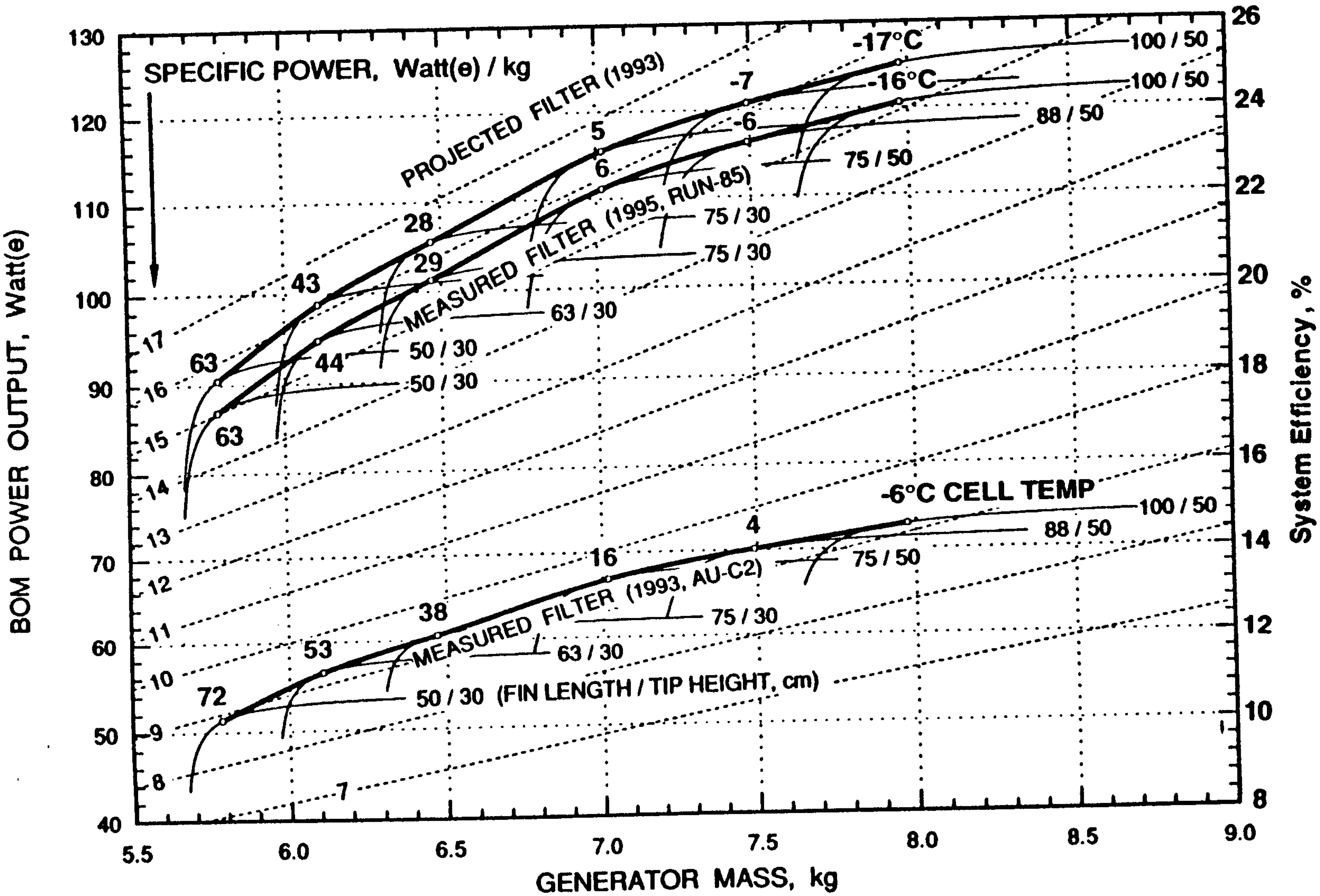
EFFECT OF FILTER IMPROVEMENTS ON SYSTEM PERFORMANCE
For Projected Cell Performance, 75 cm Fin Length, 50 cm Tip Height



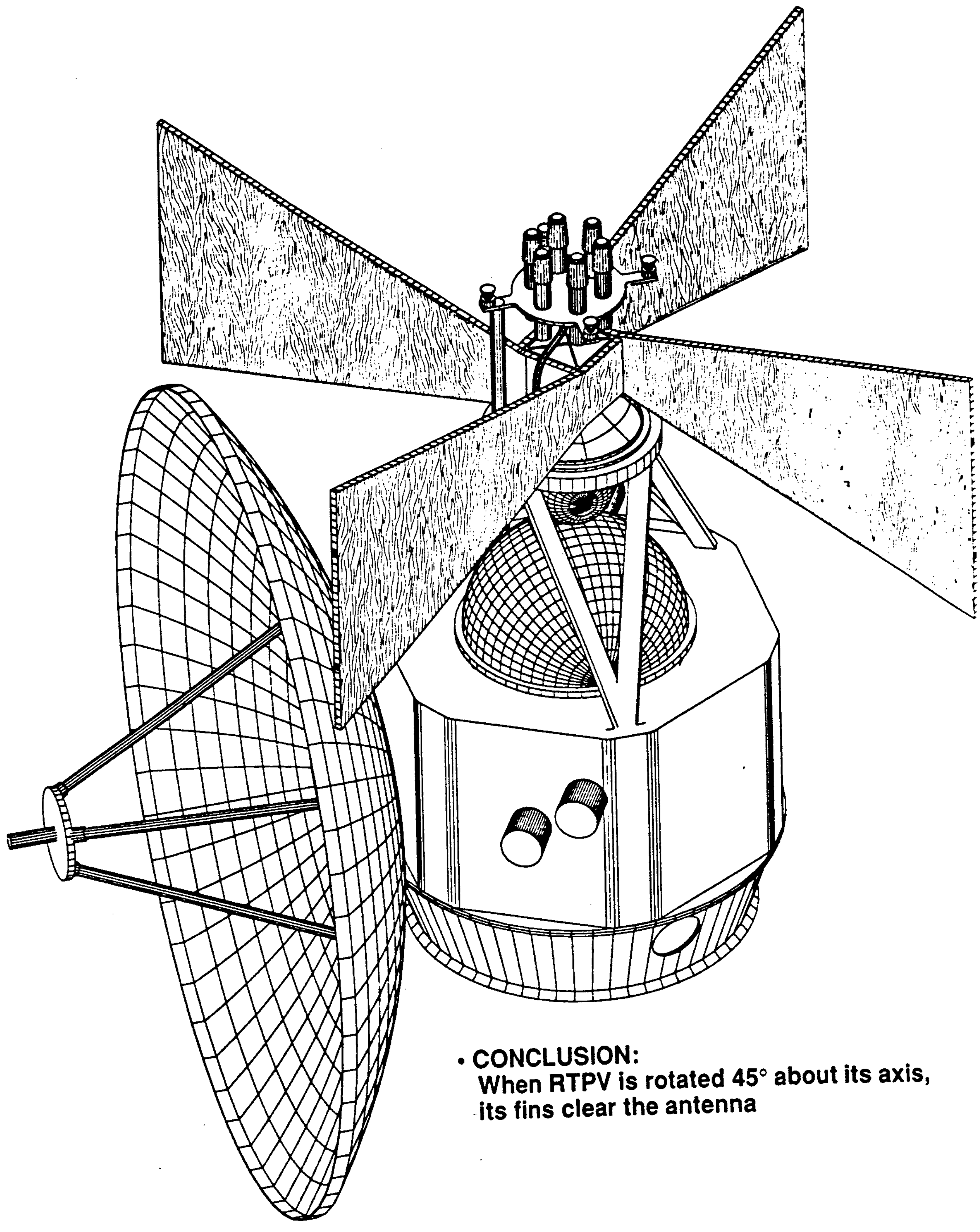
COMPARATIVE QUANTUM EFFICIENCIES OF EDTEK PV CELLS



EFFECT OF FILTER IMPROVEMENTS ON SYSTEM PERFORMANCE
For Projected Cell Performance and Various Radiator Sizes

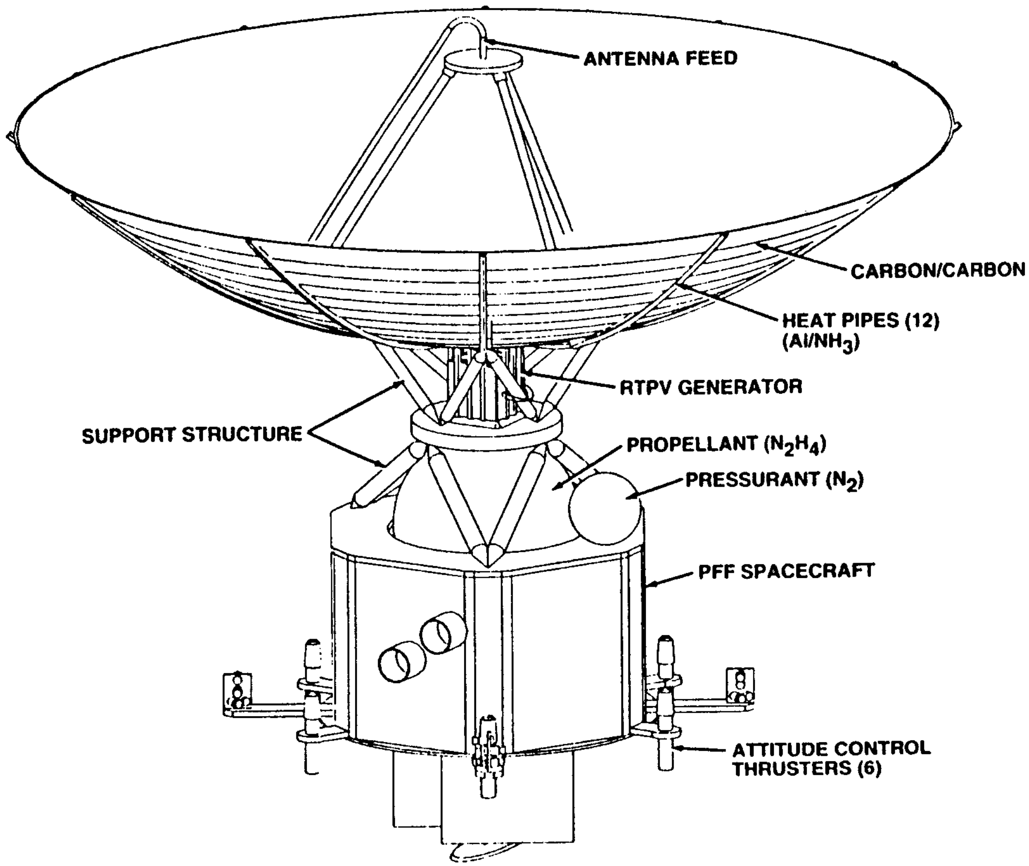


OPTIMIZED RTPV GENERATOR MOUNTED ON TOP OF PFF SPACECRAFT

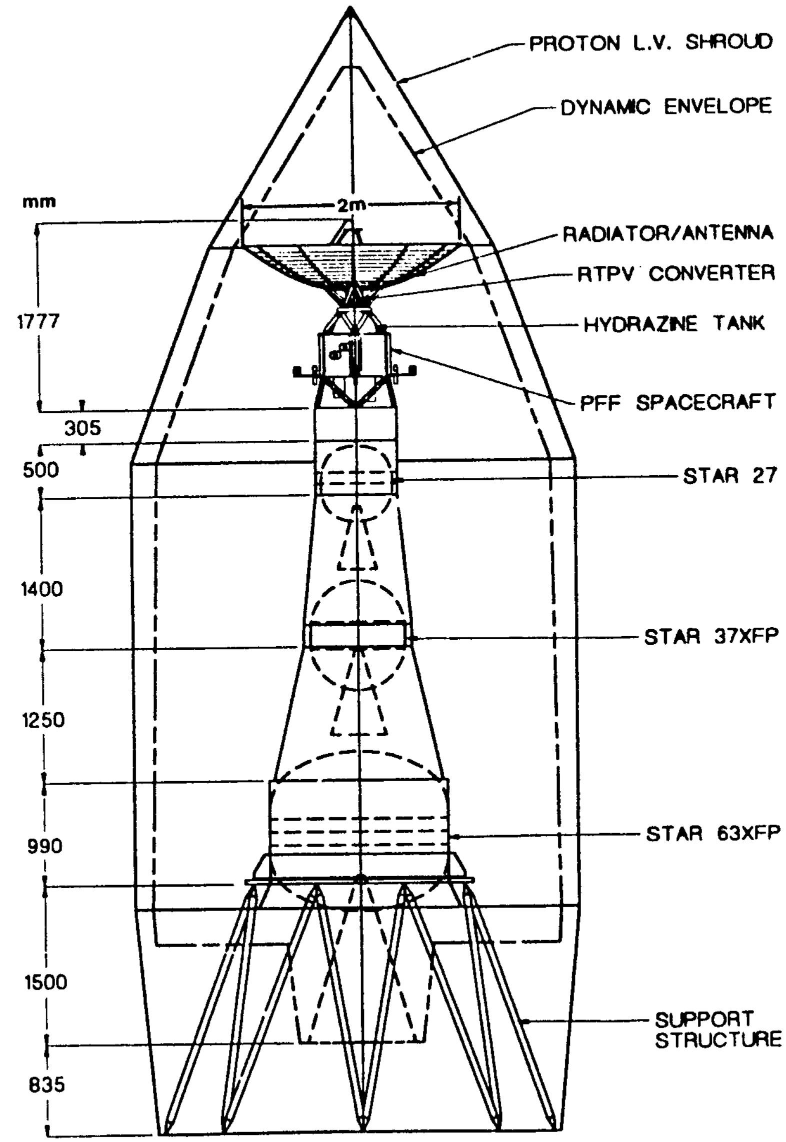


- CONCLUSION:
  When RTPV is rotated 45° about its axis, its fins clear the antenna

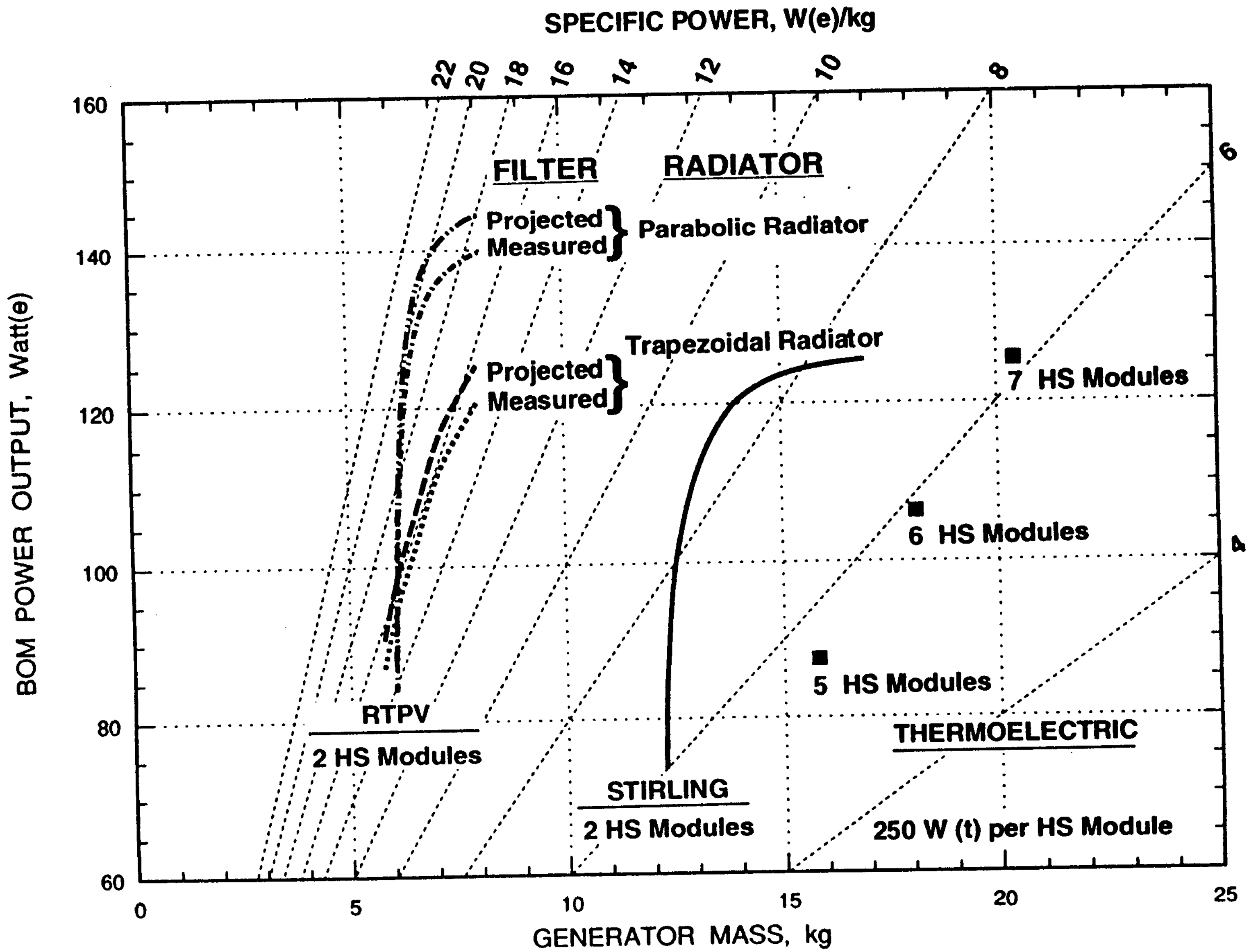
RTPV GENERATOR AND PFF SPACECRAFT WITH COMMON RADIATOR / ANTENNA



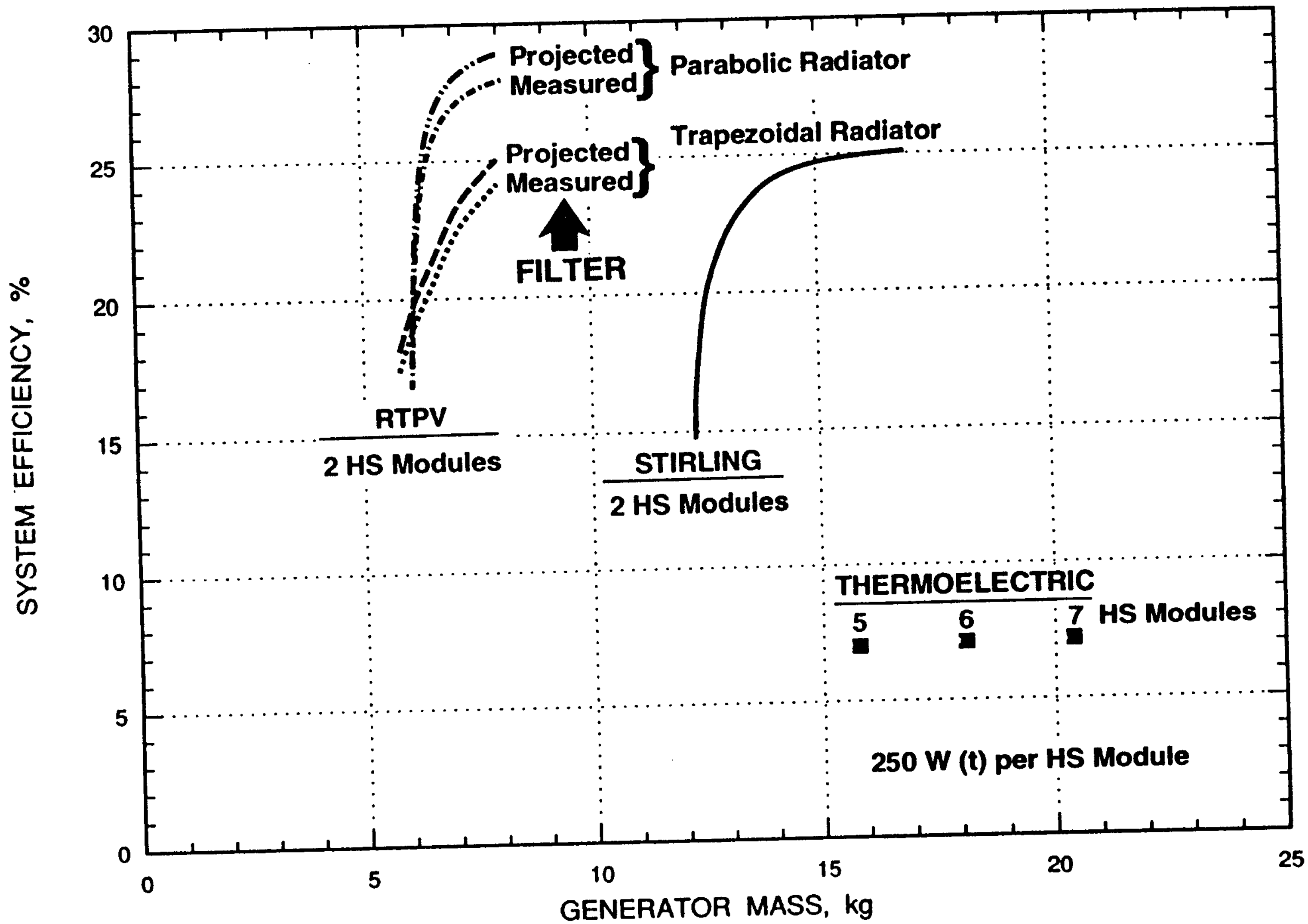
FIT OF COMBINED RADIATOR / ANTENNA IN PFF PROTON LAUNCH VEHICLE



COMPARATIVE MASS AND SPECIFIC POWER OF THREE OPTIONS



COMPARATIVE MASS AND EFFICIENCY OF THREE OPTIONS



BASIC CONVERTER EQUATIONS AND REQUIRED TEST DATA

Input Heat Flux

$$q_s = 2\pi hc^2 \int_0^\infty \frac{\lambda^{-5}[\exp(hc/\lambda kT_E) - 1]^{-1}}{\varepsilon_\lambda^{-1} + \{[\alpha\rho_\lambda + (1-\alpha)\gamma_\lambda]^{-1} - 1\}^{-1}} d\lambda$$

ε_λ — Emitter Emissivity; ρ_λ — Filter Reflectivity; γ_λ — Gold Reflectivity

Short-Circuit Current Density

$$J_{sc} = 2\pi ce \int_0^\infty \frac{\lambda^{-4}\varepsilon_\lambda Q_\lambda \tau_\lambda [\exp(hc/\lambda kT_E) - 1]^{-1}}{1 - [\alpha\rho_\lambda + (1-\alpha)\gamma_\lambda](1-\varepsilon_\lambda)} d\lambda$$

Q_λ — Cell Quantum Efficiency; τ_λ — Filter Transmissivity

Output Power Density

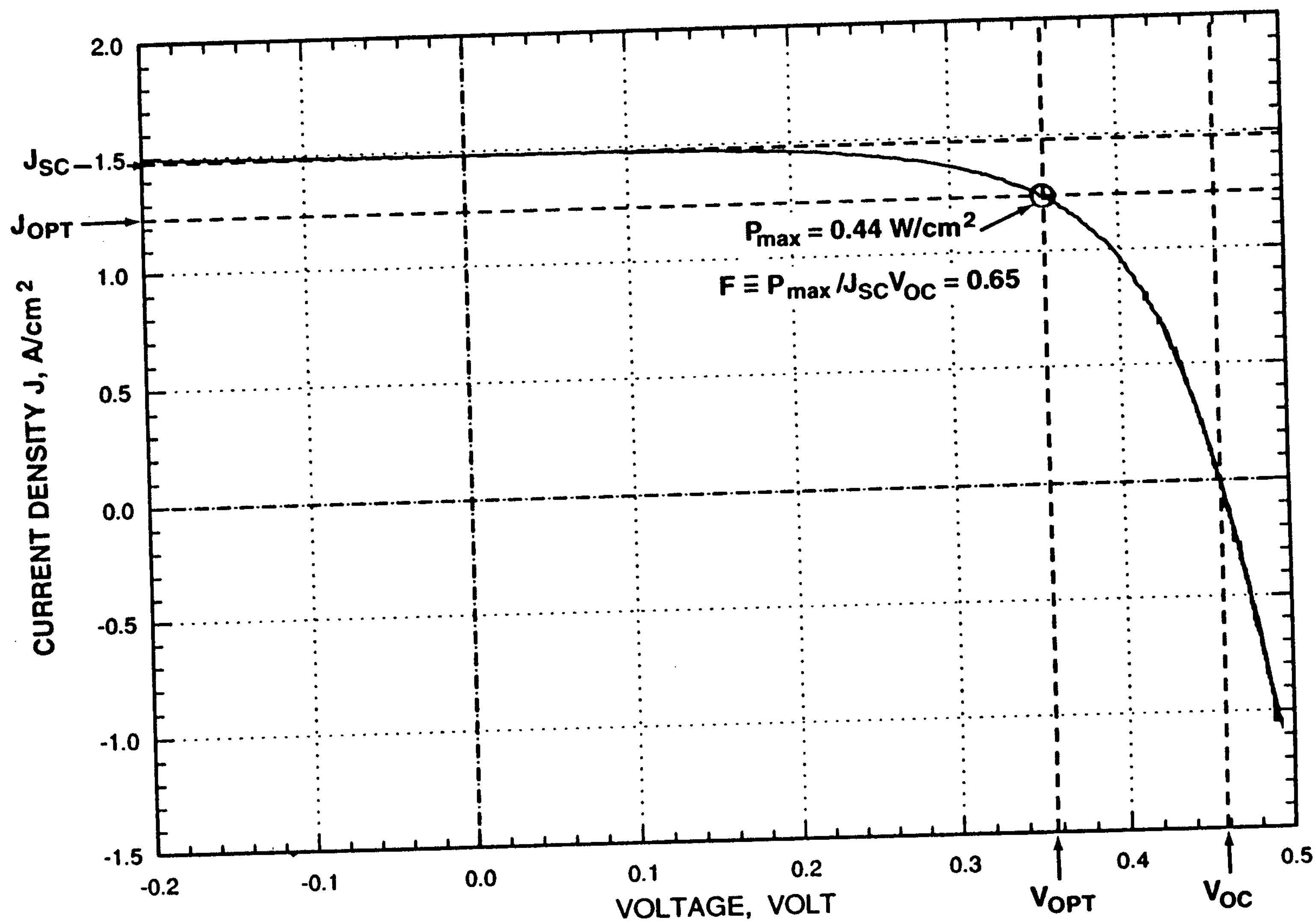
$$P_{max} = J_{sc} V_{oc}(J_{sc}, T_c)\, F(J_{sc}, T_c)$$

J_{sc} — Short-circuit current density; V_{oc} — Open-circuit cell voltage; F — Fill Factor

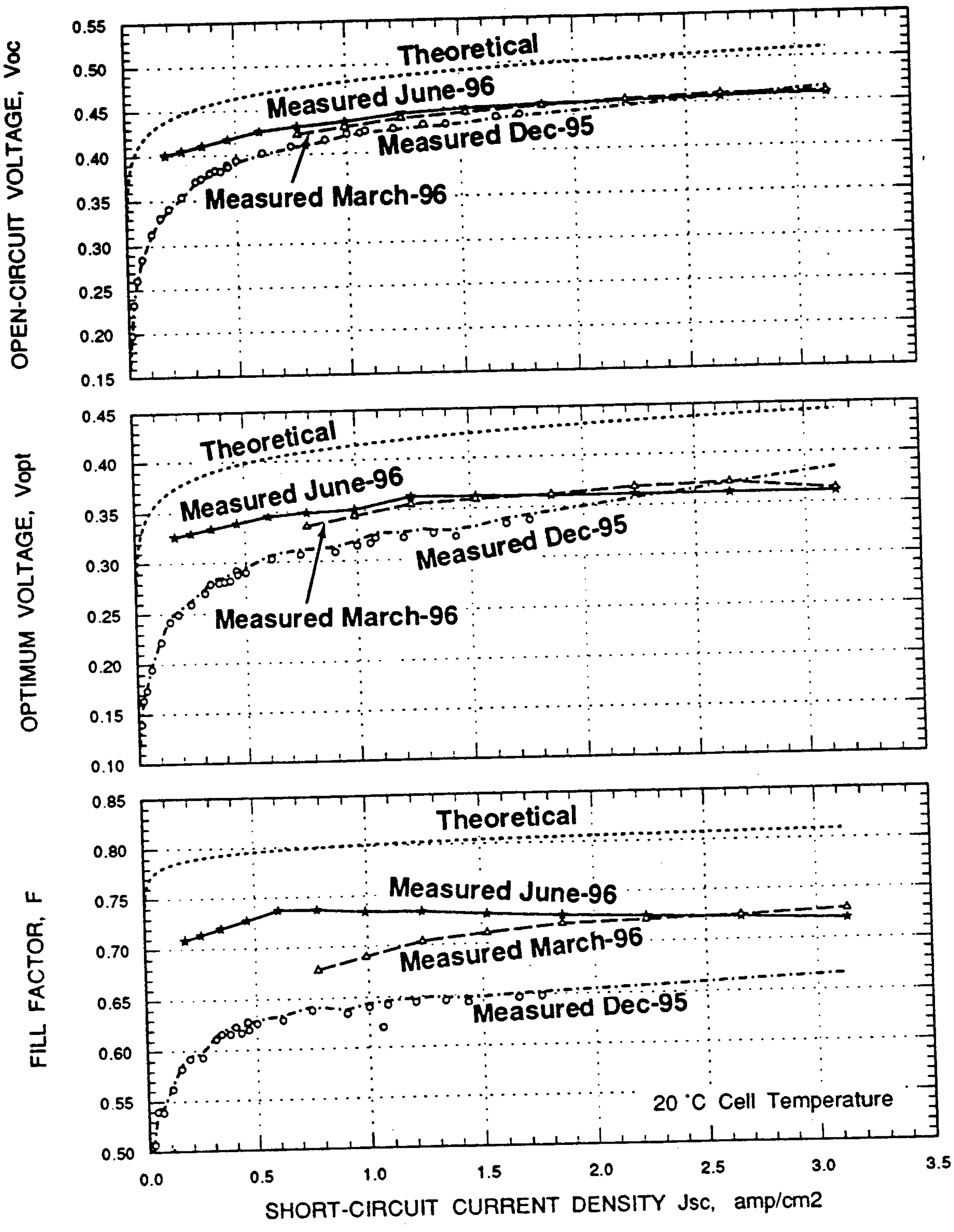
Converter Efficiency

$$\eta_{conv} = P_{max}/q_s$$

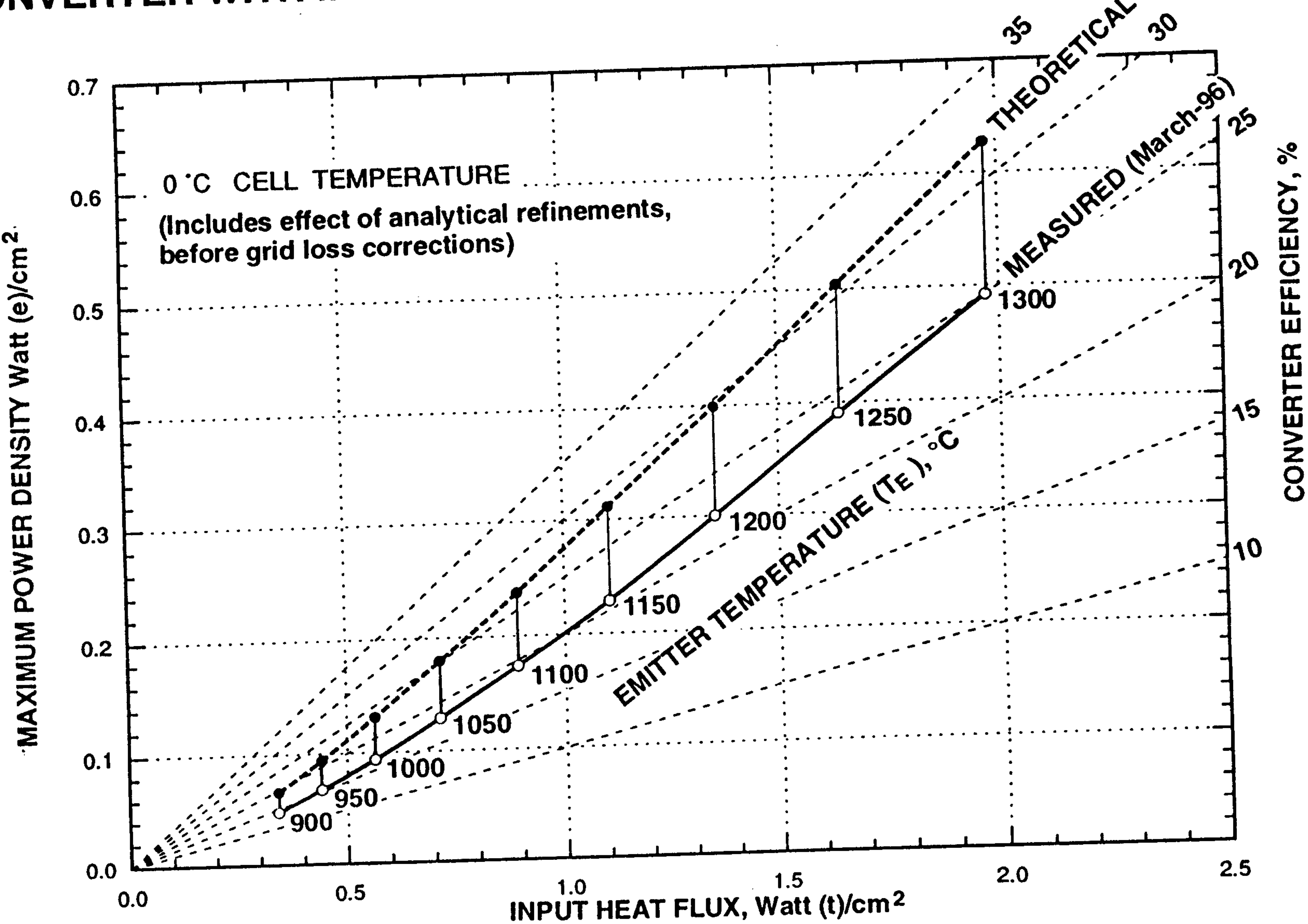
TYPICAL CURRENT-VOLTAGE CHARACTERISTIC OF EDTEK CELL
At $J_{SC} = 1.48\ A/cm^2$, $T_C = 20°C$



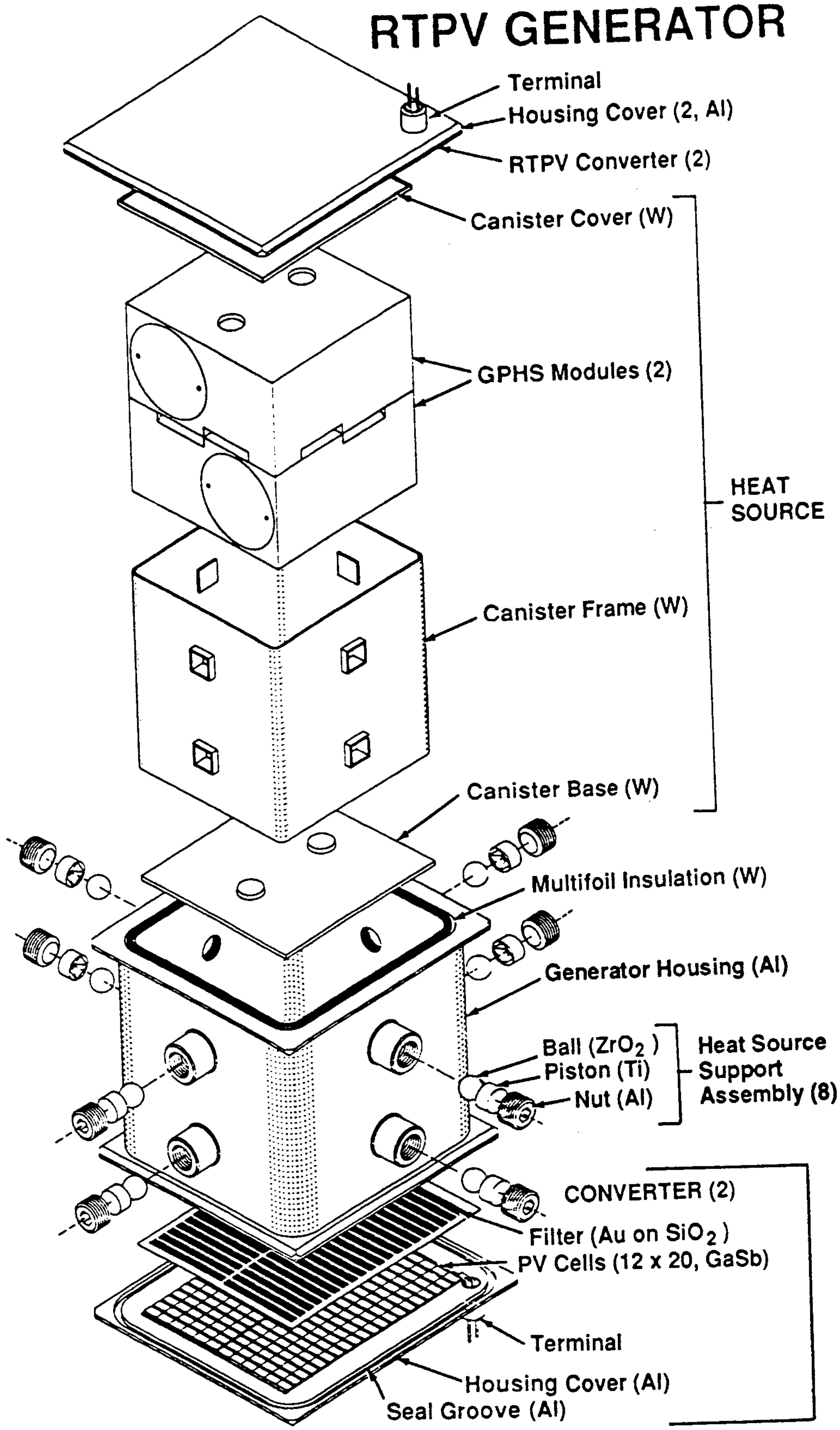
EFFECT OF J_{SC} ON THEORETICAL VERSUS MEASURED CHARACTERISTICS, AT 20°C



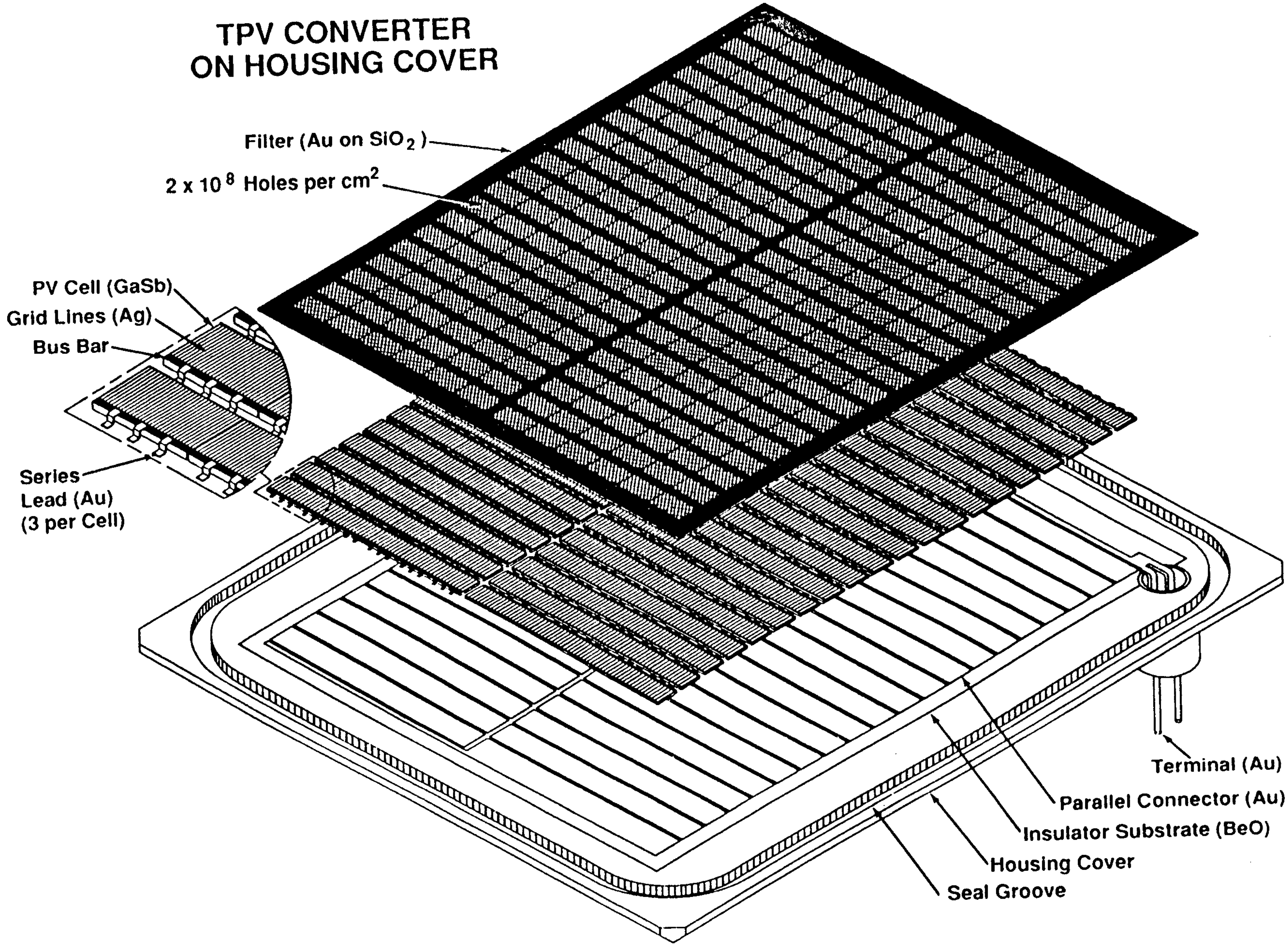
EFFECT OF MEASURED vs. THEORETICAL CELL VOLTAGES (V_{OC}, V_{OPT}, F) ON CONVERTER WITH MEASURED FILTER (T-78) AND QUANTUM EFFICIENCY



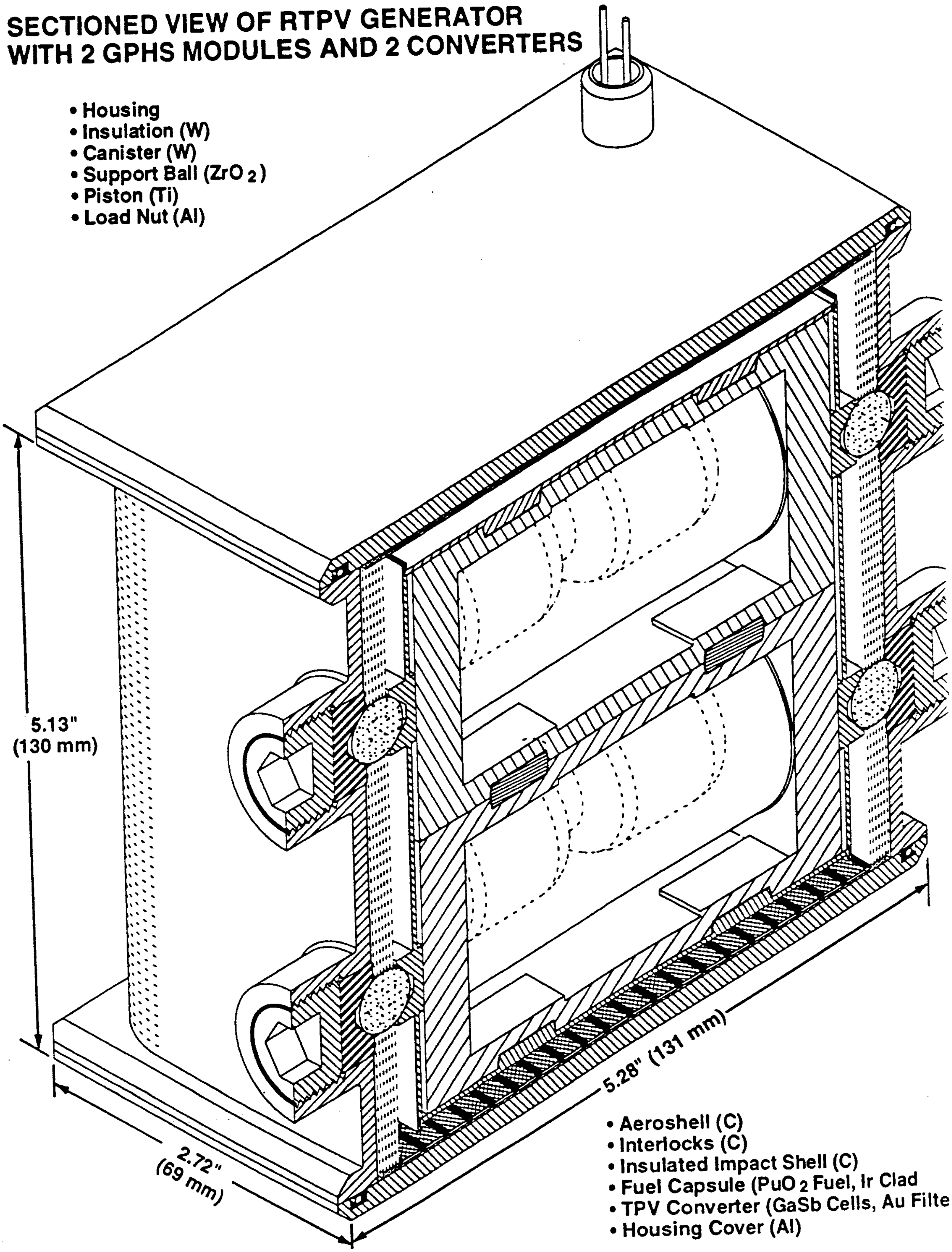
RTPV GENERATOR

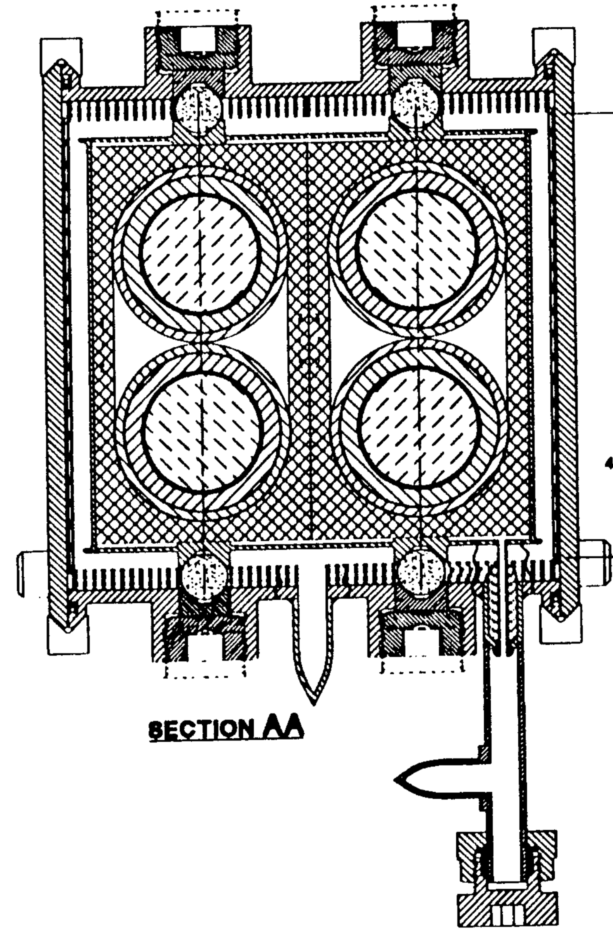


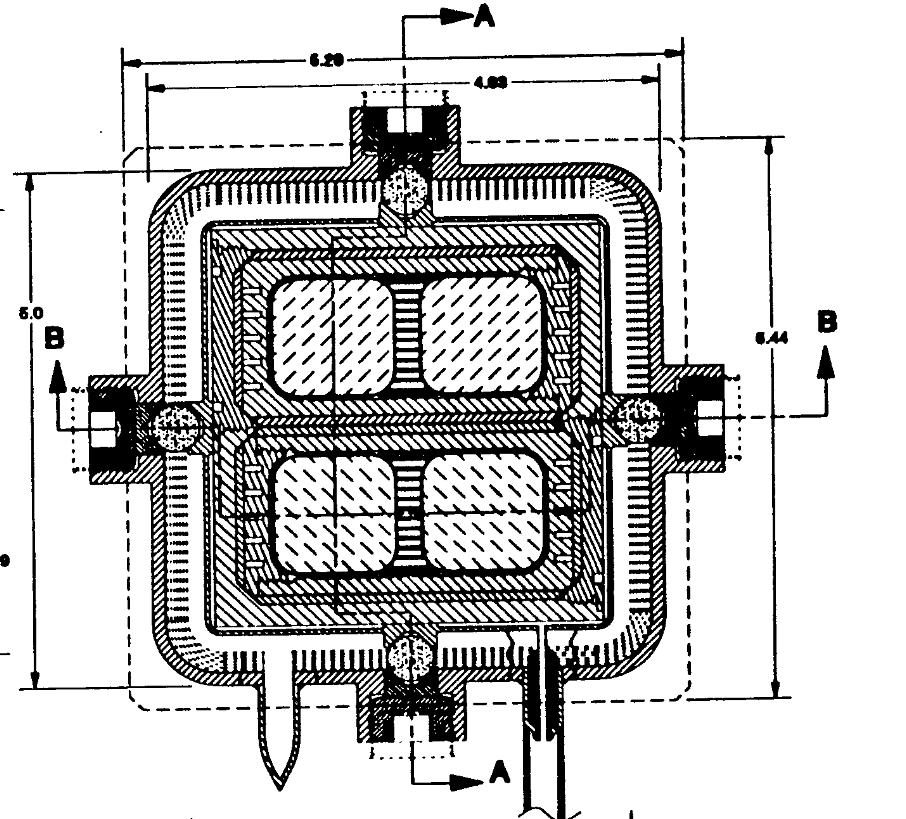
TPV CONVERTER ON HOUSING COVER

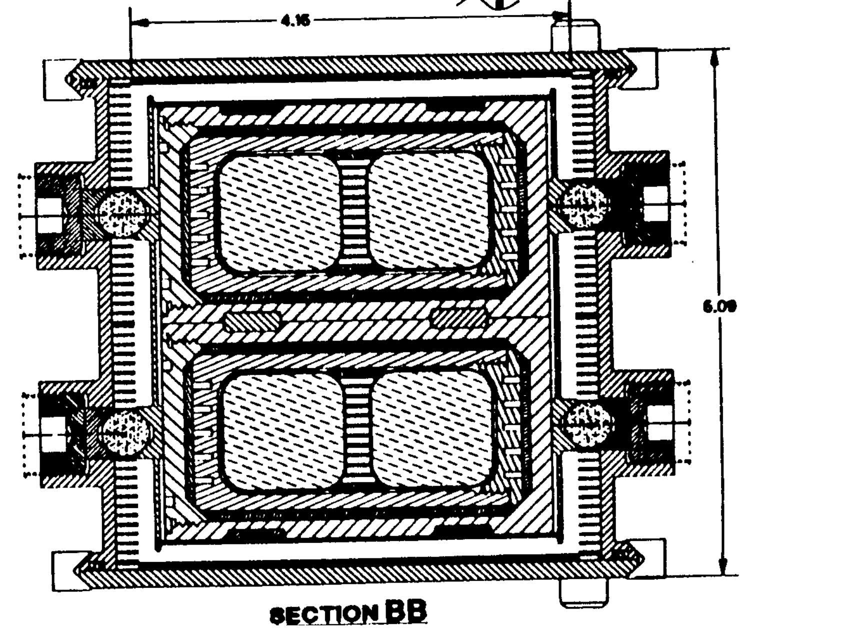


SECTIONED VIEW OF RTPV GENERATOR WITH 2 GPHS MODULES AND 2 CONVERTERS





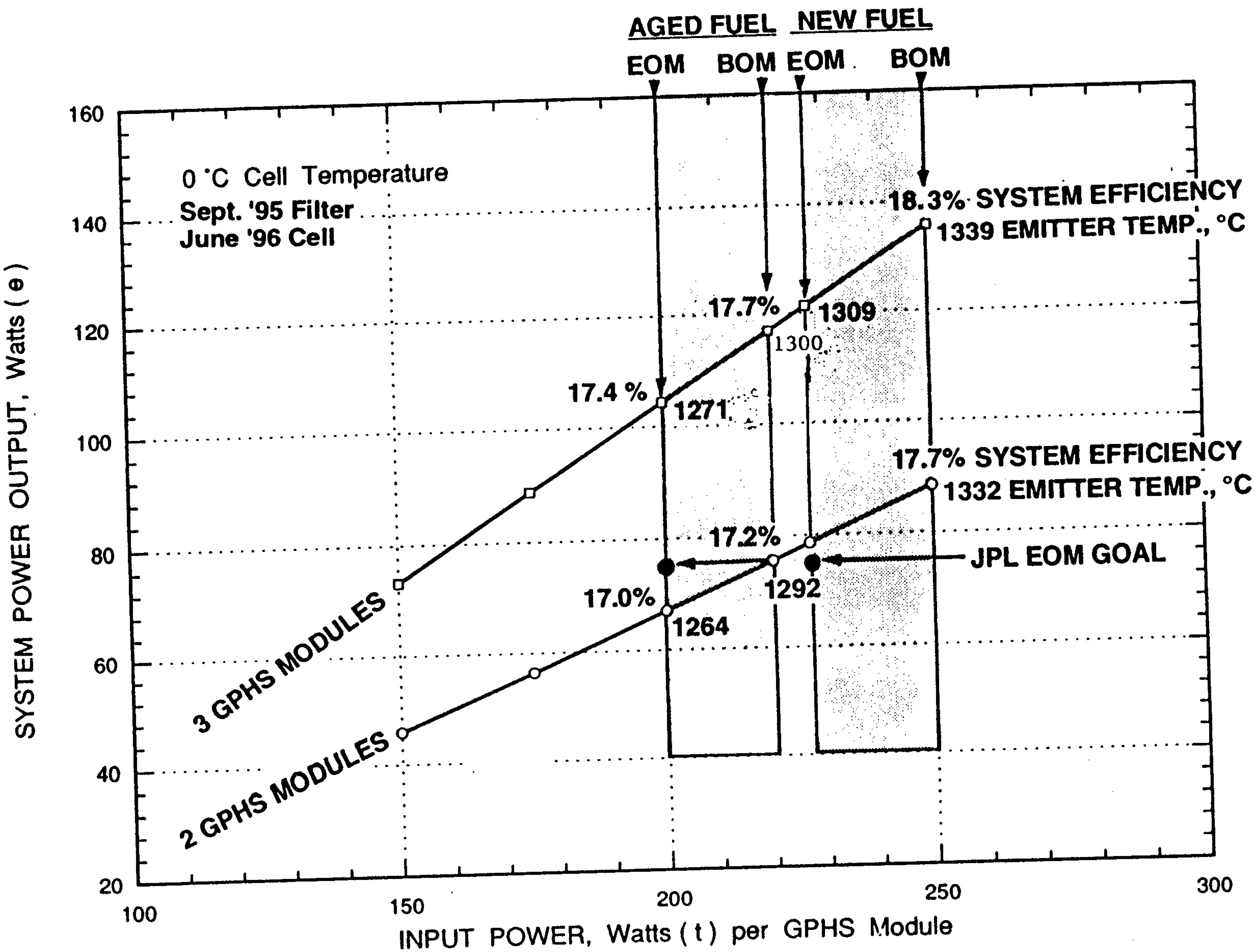




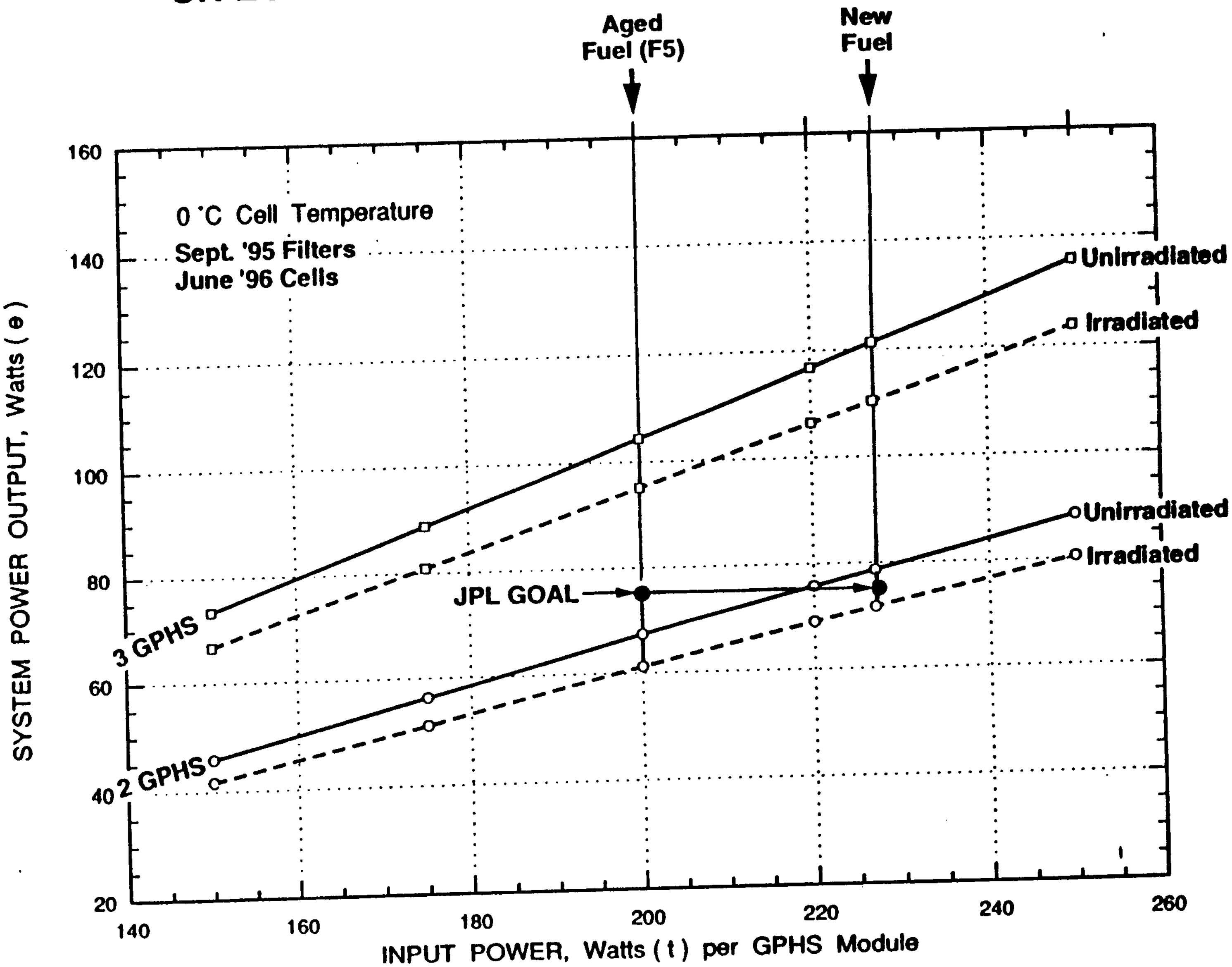
TPV GENERATOR

2 Panels & 2 GPHS

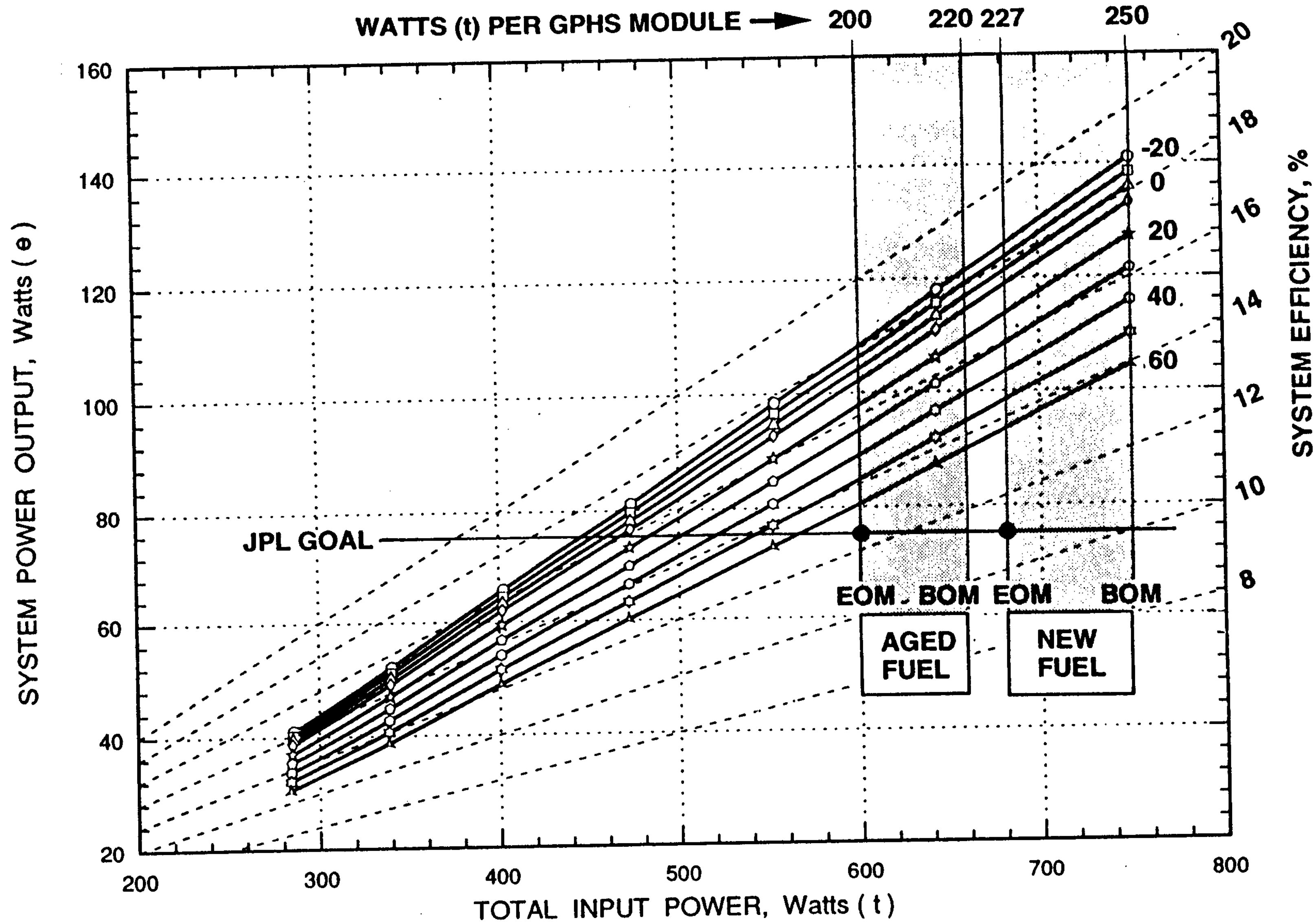
PERFORMANCE OF RTPV GENERATORS WITH 2 AND 3 GPHS MODULES



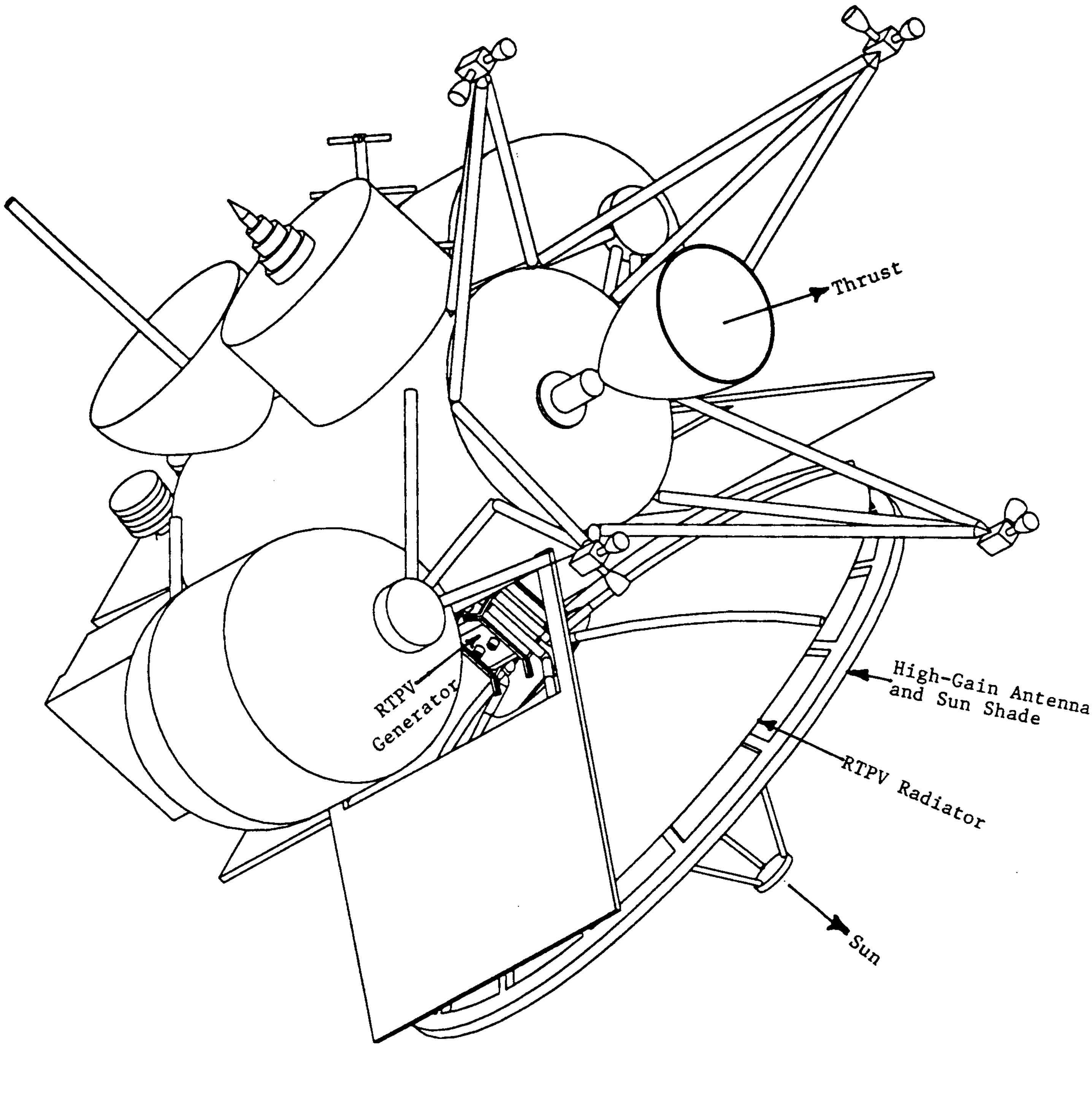
EFFECT OF NEUTRON IRRADIATION OF PV CELLS ON EOM PERFORMANCE OF RTPV GENERATOR



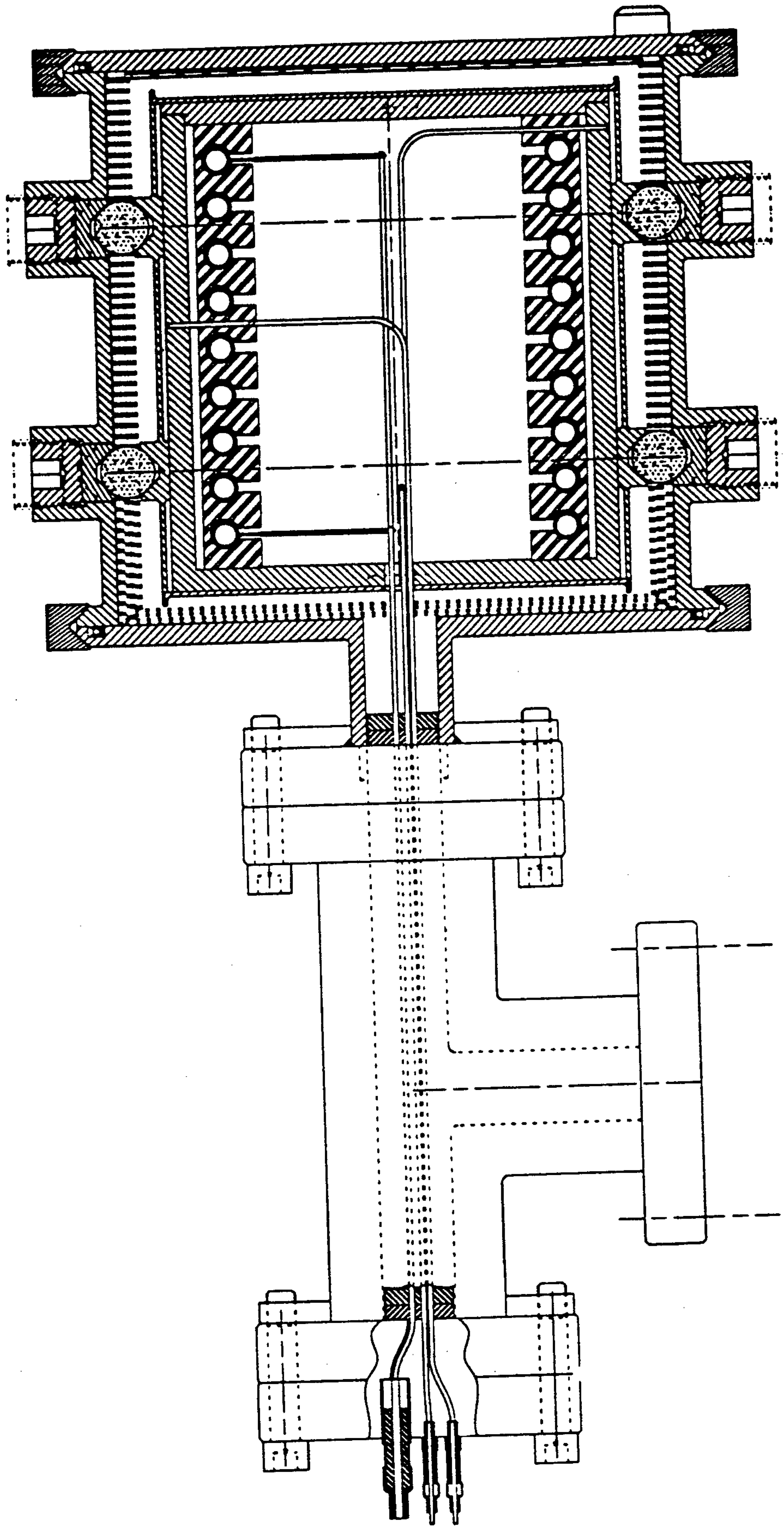
EFFECT OF CELL TEMPERATURE ON PERFORMANCE OF GENERATOR WITH 3 GPHS MODULES AND JUNE-96 CELLS



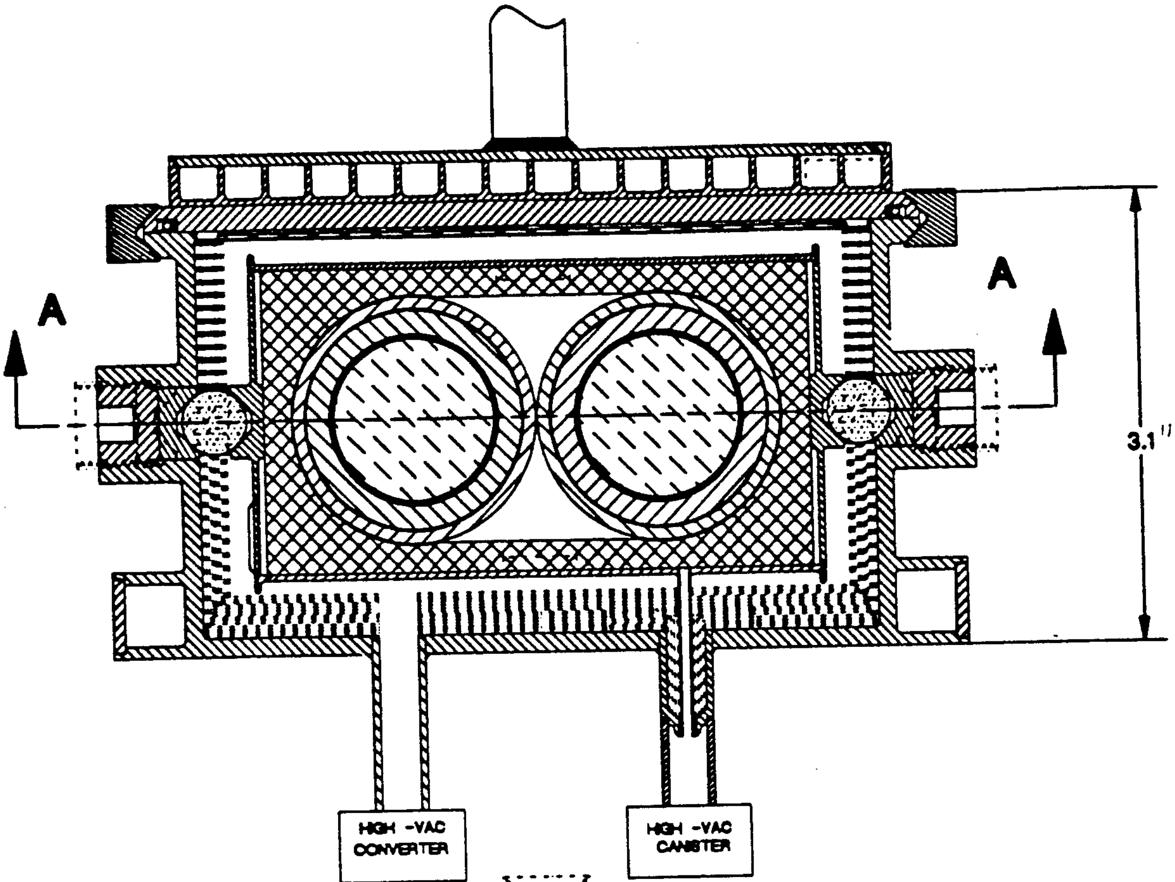
POSSIBLE SCHEME FOR INTEGRATION OF RTPV GENERATOR WITH PLUTO EXPRESS SPACECRAFT

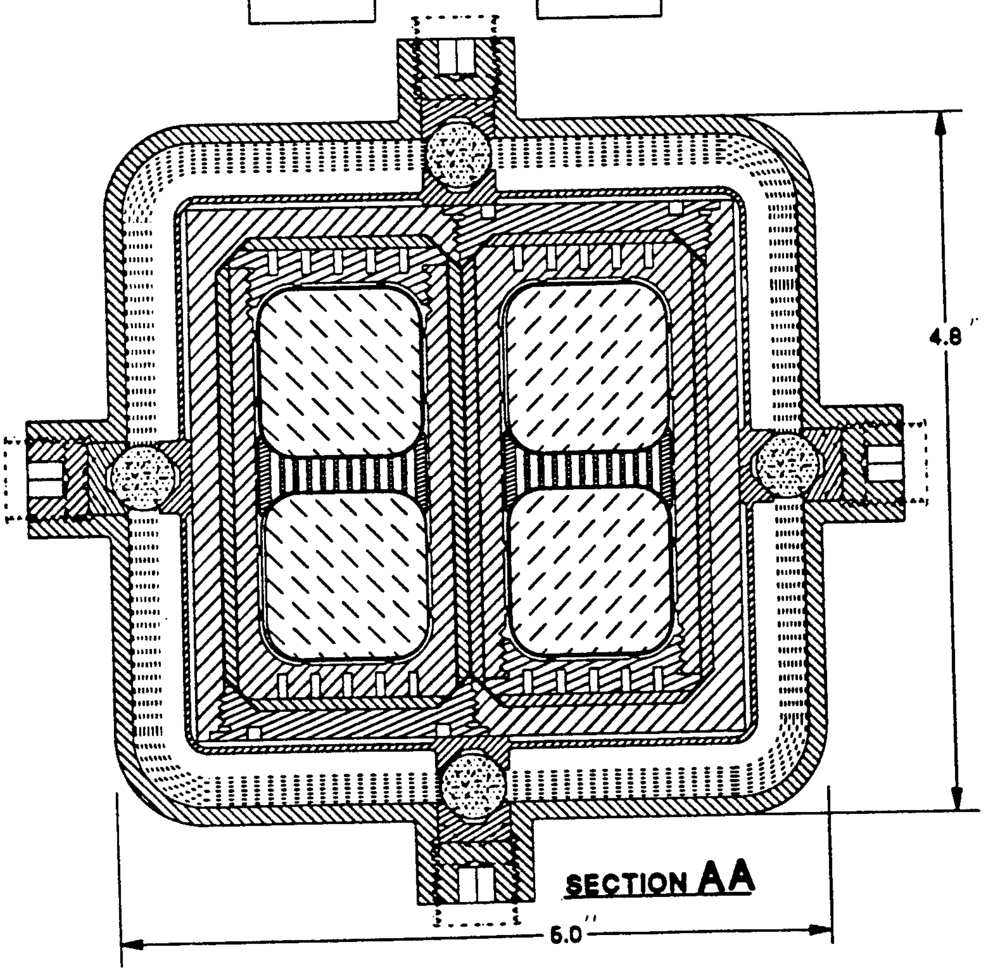


ELECTRICALLY HEATED CONVERTER TEST ASSEMBLY READY FOR BAKE-OUT AND OUTGASSING IN VACUUM BELL JAR



ISOTOPICALLY HEATED RTPV TEST ASSEMBLY





SECTION AA

JPL

THERMOPHOTOVOLTAIC RESEARCH AT THE JET PROPULSION LABORATORY

M.A. Ryan, D.R. Burger and R.L. Mueller

Jet Propulsion Laboratory
California Institute of Technology
Pasadena CA 91109

Prospector VIII, Thermophotovoltaics - An Update on DoD, Academic and Commercial Research; July 15, 1996

THERMOPHOTOVOLTAIC RESEARCH AT JPL
1991 - 1996

1. **Experimental Work: E_g 0.5 - 0.6 eV**
   Cell materials: AlInAs on InP or InGaAs substrates
   GaInAsSb on GaSb substrates

2. **Cell Modelling and Systems Studies**
   Cell performance modelling: InAs, InGaAs
   Small spacecraft systems such as Pluto Fast Flyby

3. **Cell Testing**
   Standard Operating Conditions
   Testing procedures
   Characterization

CHARACTERIZATION OF THERMOPHOTOVOLTAIC CELLS

Establish conditions and tests

(1) Establish Standard Operating Conditions (SOC)

Emission Spectrum
Use of blackbody emitter to allow reproducible emission spectra (T_{BB})

Emission Intensity
Intensity measured at cell using power meter; *e.g.* $I = 2$ W/cm²

Cell Temperature
Temperature controlled during operation; *e.g.* $T_{cell} = 20°C$

(2) Establish characterization tests

Light and dark, reverse bias, iV curves

Cell radiation sensitivity

Cell stability

CHARACTERIZATION OF THERMOPHOTOVOLTAIC CELLS

Testing

(1) Determine cell operation (light, forward bias, iV curves) under SOC

(2) Determine cell operation under varying operating conditions

e.g. iV curves at varying T_{cell} and constant T_{BB} and I

varying I and constant T_{BB} and T_{cell}

varying T_{BB} and constant I and T_{cell}

(3) Determine spectral response of cell as T_{cell} is varied

(4) Determine cell sensitivity to β, γ, and neutron radiation

Expose to radiation and repeat (1) and (3)

(5) Determine cell stability

Continuous illumination and temperature soaking, annealing and cycling

JPL

CHARACTERIZATION OF THERMOPHOTOVOLTAIC CELLS

Physical Characterization and Quality Control

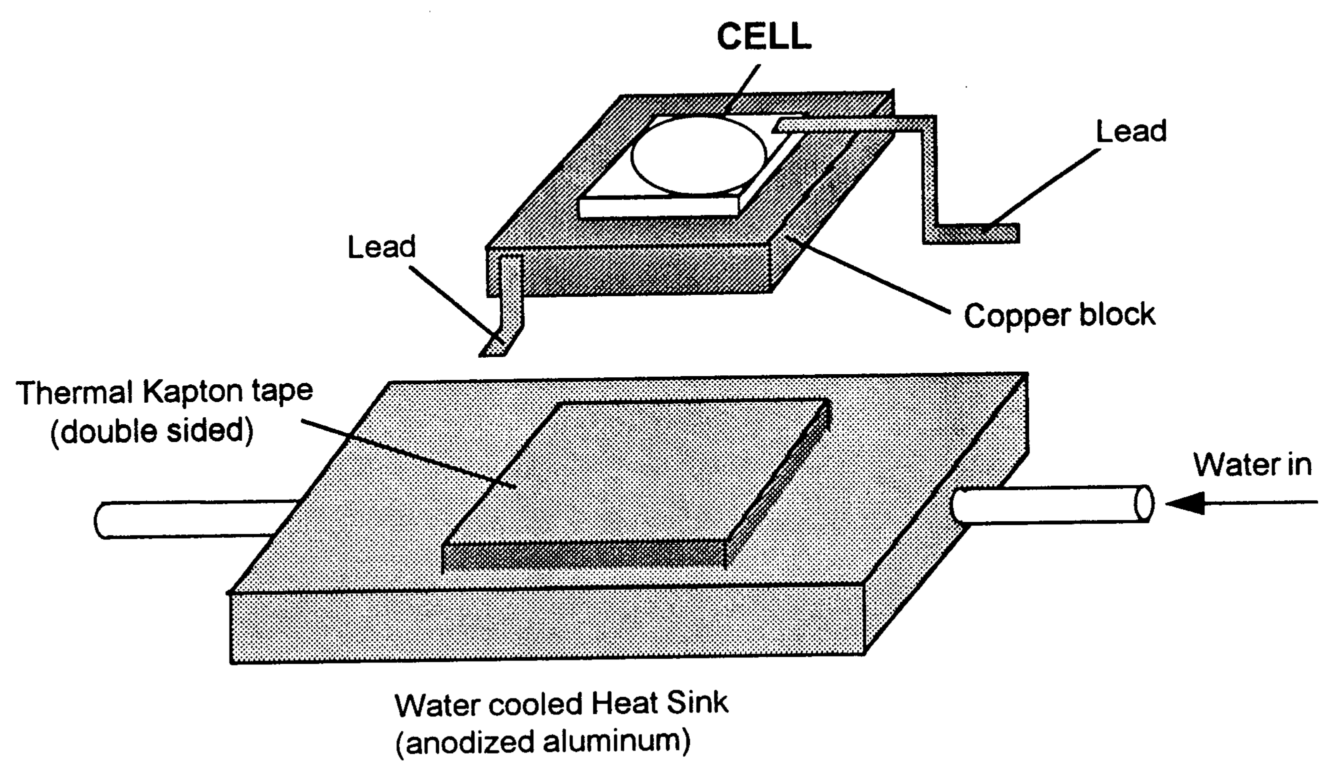
(1) Measure physical parameters:
Cell size and active area vs. shadow area, metallization pattern dimensions, metallization resistance

(2) Measure back surface reflectivity as a function of wavelength

(3) Determine processing characteristics
carrier concentration, bandgap, dark diode current at forward bias

JPL

MOUNTING FOR THERMOPHOTOVOLTAIC CELL TESTING



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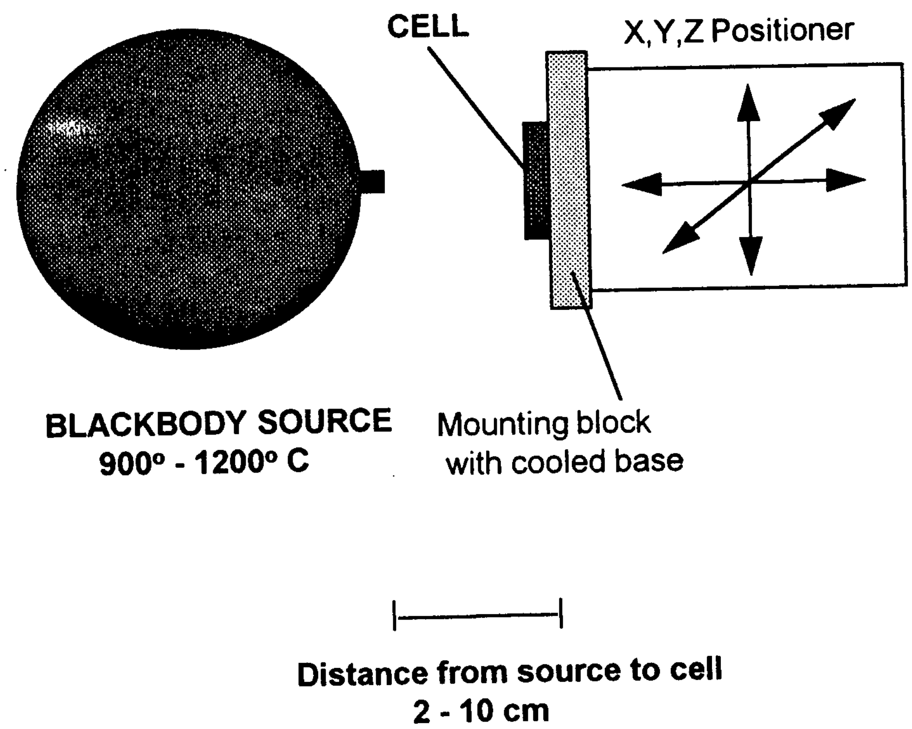
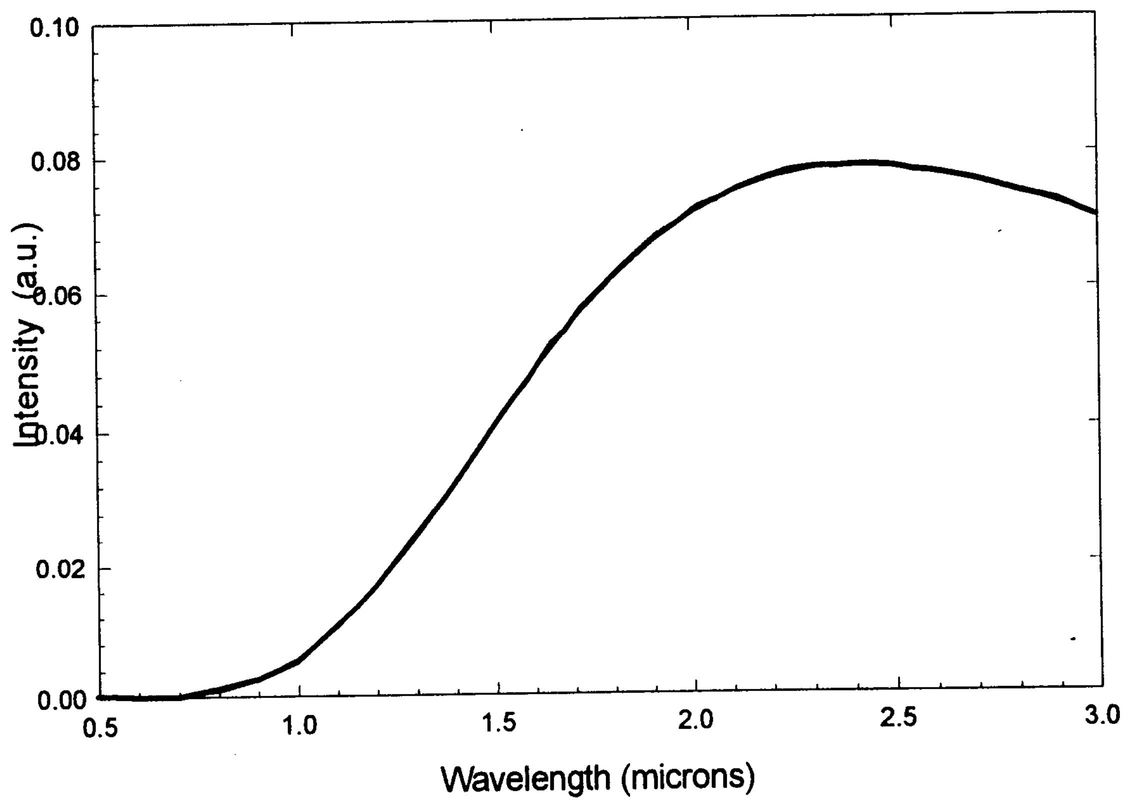
SET-UP FOR BLACKBODY IRRADIATION



ELECTRIC POWER SYSTEMS SECTION

JPL

BLACKBODY SPECTRUM



CHARACTERIZATION OF THERMOPHOTOVOLTAIC ARRAYS

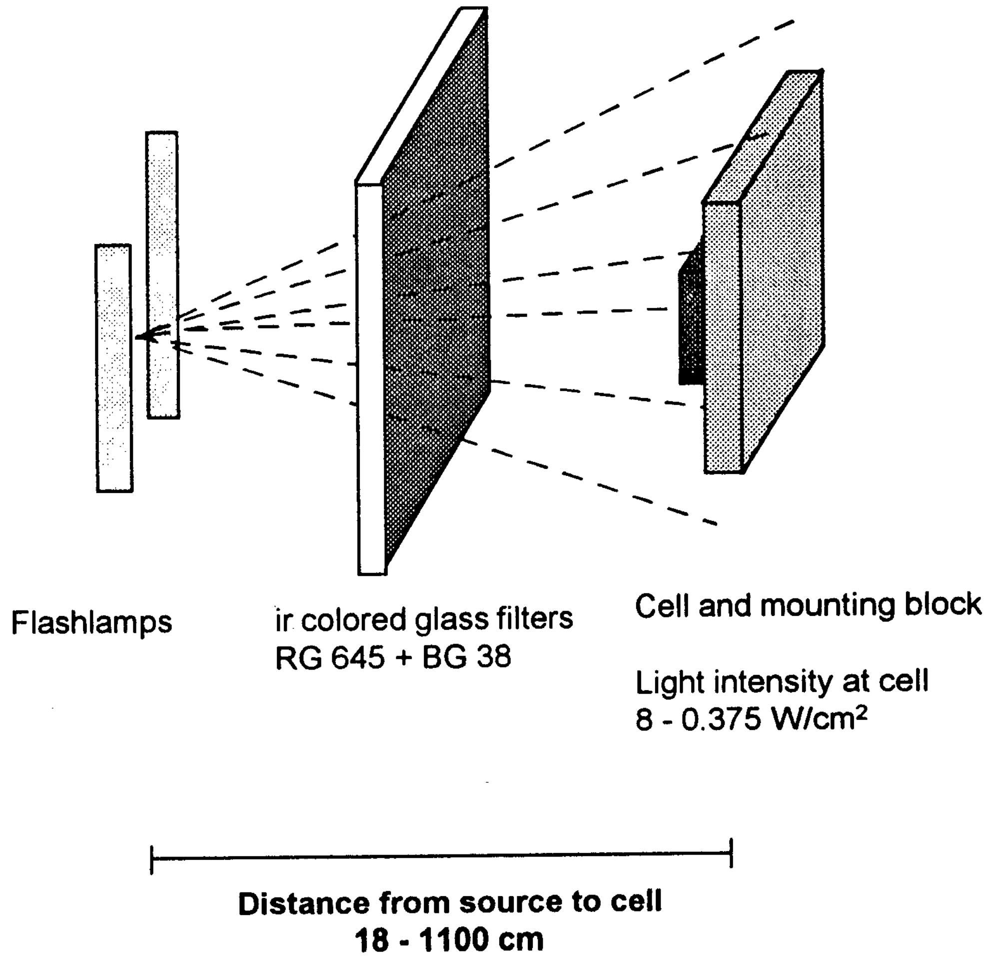
Test and characterize under conditions established for cells

Radiation source must irradiate array uniformly at power levels established for cell testing

Large Area Pulsed Solar Simulator (LAPSS) provides sufficient radiation

- 1.5 msec pulse is filter using optical colored glass filters to mimic black body spectrum
- iV curve is taken during 1.5 msec pulse (points at 15 μsec intervals)

SET-UP FOR LAPSS IRRADIATION



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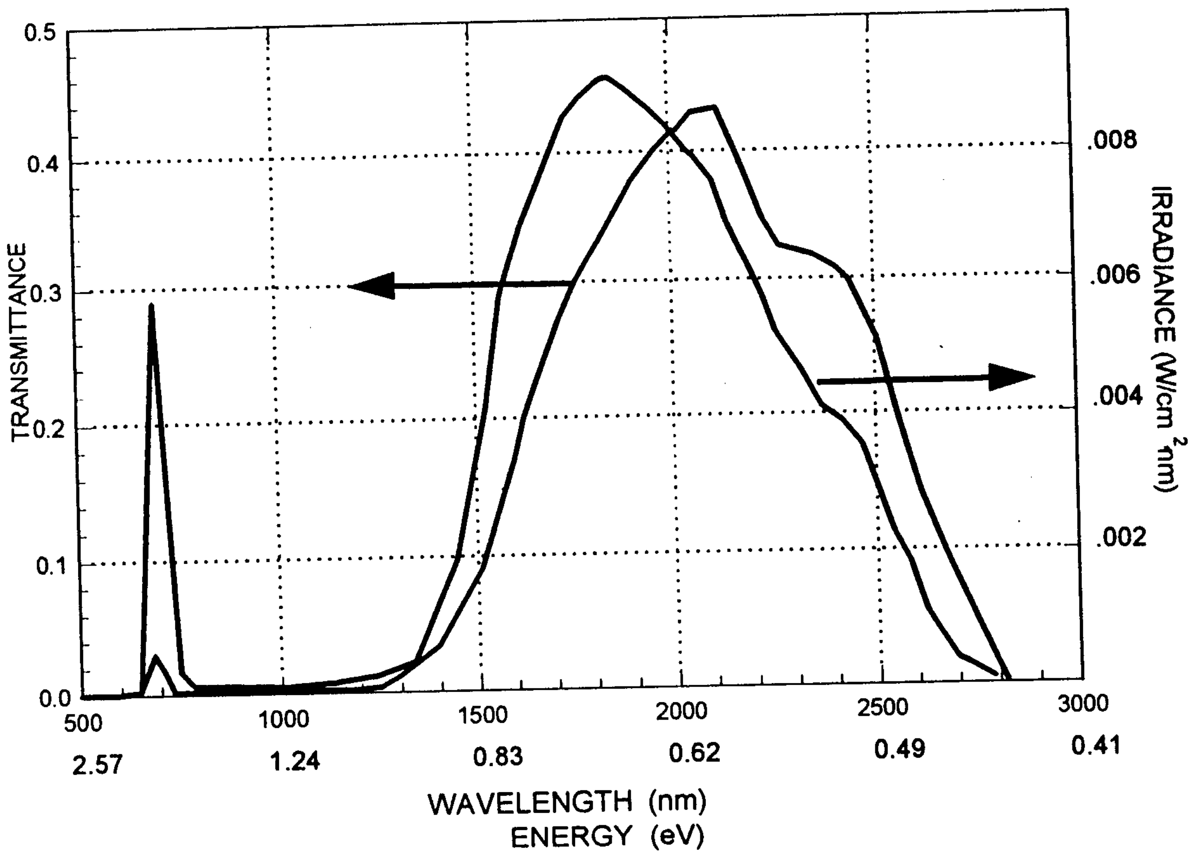
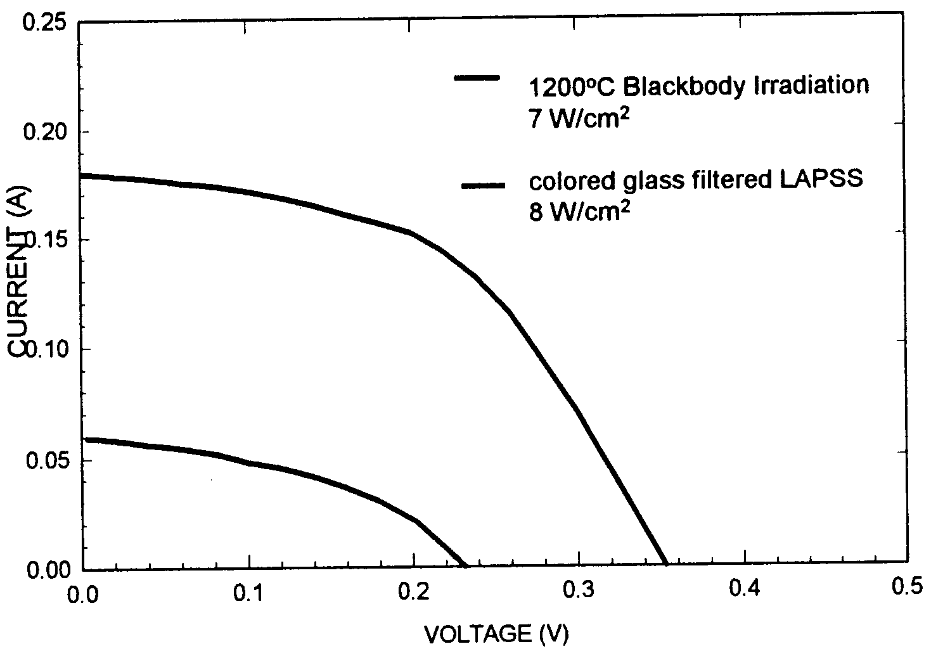
FILTER TRANSMITTANCE IN LAPSS SET-UP

RG 645 & BG 38 filters to select infrared radiation



COMPARISON OF BLACKBODY AND LAPSS IRRADIATION
InGaAs Cell Response



	Blackbody	LAPSS
I_{sc} (A)	0.725	0.2237
V_{oc} (V)	0.2355	0.3414
P_{max} (W)	0.0066	0.0388
F.F.	0.385	0.509

CONCLUSIONS

Test and characterization conditions established for cells

Arrays tested using Large Area Pulsed Solar Simulator (LAPSS)

Equipment for testing is in place; Si TPV cell testing beginning

Experimental work in cell materials stopped for now

Systems studies ongoing for small missions

Cell and systems modelling capabilities strong

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MONOLITHICALLY INTERCONNECTED InGaAs TPV MODULE DEVELOPMENT

David M. Wilt, Navid S. Fatemi*, Phillip P. Jenkins*, Richard W. Hoffman, Jr*.,
Donald L. Chubb, Geoffrey A. Landis●, Raj K. Jain#

NASA Lewis Research Center, Cleveland Ohio
*Essential Research, Inc., Cleveland Ohio
●Ohio Aerospace Institute, Cleveland, Ohio
#NASA Lewis Research Center (NRC), Cleveland Ohio

This paper describes the status of development of an Indium Gallium Arsenide (InGaAs) Monolithically-Interconnected Module (MIM) for thermophotovoltaic (TPV) energy conversion applications. The MIM structure features series interconnected InGaAs sub-cells on an insulating indium phosphide (InP) substrate, with a rear-surface infrared (IR) reflector. Motivations for developing the MIM structure include: reduced resistive losses, higher output power density, improved thermal coupling and ultimately higher system efficiency. An optical model has been developed, free carrier absorption coefficients have been measured and a prototype MIM device has demonstrated output power densities of over 1.2 W/cm^2. A rear surface IR reflector has been developed with ~98% reflectance in the sub-bandgap (> 1.7 μm) region.

Many TPV cell researchers have focused their efforts toward conventional photovoltaic device designs. Use of these devices in a TPV system necessitates the use of front surface spectral control elements such as filters or selective emitters. With this approach there is a natural trade-off between output power density and system efficiency. If no front surface spectral controls are used, the output power density is maximized and the system efficiency is minimized. In order to improve system efficiency, filters are added to recycle non-convertible photons. Unfortunately, transmission losses or emittance losses associated with filters and selective emitters reduces the output power density.

A different approach involves the use of rear-surface spectral controls. In this approach, there is no filtration between the cell and the emitter (graybody or selective). The active regions of the cell absorb usable photons and transmit the remainder. An IR reflector on the rear surface of the cell reflects the unused photons back to the emitter for recycling. This approach side steps the power vs. efficiency trade-off. The MIM cell consists of series-connected InGaAs devices on a common, semi-insulating InP substrate. The rear surface of the InP substrate acts as an infrared (IR) mirror, reflecting photons back toward the front surface of the cell.

The MIM design offers several advantages. Firstly, small series-connected cells provide high voltages and low currents, reducing I^2R losses. In addition, the small size of the sub-cells allows an array to be comprised of series/parallel strings rather than a single series-connected string of large cells. This should improve the reliability of the TPV module since the failure of a single cell would not debilitate the entire array. Secondly, the design maximizes output power density since losses associated with front-surface spectral controls are eliminated. Thirdly, the rear surface of the device is not electrically active, therefore the cell may be directly bonded to the substrate/heat sink without concern for electrical isolation. This greatly simplifies the array design and improves the thermal control of the cells. Lastly, photons which are weakly absorbed have the possibility of multiple passes through the cell structure. This feature is particularly important for lattice-mismatched devices, where poor minority carrier diffusion length can be partially offset by making the cell thin, allowing the carrier generation to occur closer to the p/n junction.

An optical model was developed to calculate the long-wavelength reflectance of the MIM design. The model takes into account multiple reflections and passes within the MIM device, including reflection from both the contact surface and the grid/semiconductor interface, plus free carrier absorption in the cell layers.

In order to calculate the free carrier absorption (FCA) of the MIM structure, InGaAs layers with several different doping densities were deposited on semi-insulating InP. Absorption measurements were made and mean absorption values were determined for wavelengths greater than the bandgap of InGaAs (0.74 eV).

An interesting feature of the absorption measurements is the increase in optical bandgap for the n^{++} material. We believe that the shift in the optical bandgap between the n^{++} and the undoped material is attributable to a Burstein-Moss shift caused by degeneracy of the heavily doped (N_d=2e19 cm^{-3}) material. This phenomena is very advantageous for the MIM cell design and will be discussed below.

A p/n cell configuration was chosen for several reasons. Firstly, the free carrier absorption for n type InGaAs is significantly lower (3.5x) than for p type. Thus the p/n configuration minimizes the aeral density of holes, making it optimum in terms of optical recuperation. Secondly, the MIM design requires a thick rear conductor layer to conduct current laterally, the length of the device, to reach the back contact. The p/n configuration takes advantage of the 25x higher electron mobility for n-type InGaAs in this conductor layer, reducing the resistive losses.

Finally, the shift in the optical bandgap of the n^{++} conductor-layer material, noted earlier, may allow the use of a thin base region. Bandedge photons which are not absorbed in the base region are able to pass through the n^{++} layer without being absorbed. These photons will reflect off the rear reflector and have a second chance of being absorbed in the base region. This characteristic should allow the use of higher base doping levels to achieve higher voltages, without sacrificing long-wavelength photoresponse. Additionally, the bandedge photoresponse of lattice-mismatched devices should benefit since the carriers will be generated closer to the junction.

A baseline cell design was developed for illumination under a 1700°K blackbody ($\varepsilon = 1$) with a viewfactor of 0.9. These conditions were chosen to match the highest temperature blackbody we could simulate in our laboratory. In addition, it was decided to begin developing the MIM cell using lattice-matched (0.74eV) material to simplify development. This material is a better match to the 1700°K spectrum than the low bandgap, lattice-mismatched material which is NASA's primary interest. Using the spectral response from a previously developed n/p InGaAs device, an Isc of 8.5 A/cm^2 was calculated and used for the resistive loss analysis.

The baseline structure consists of eight (8) sub-cells, each 10mm wide x 1.25mm long. An interconnect width of 270µm is included for each sub-cell. The sub-cell length was chosen to minimize the I^2R losses in the n^{++} conductor layer. Emitter grid designs with 150µm and 100µm finger spacing were produced to accommodate various emitter thicknesses and doping levels while maintaining low series resistance. The emitter is passivated with a thin p^+ InP window layer. This material is removed from beneath the grid to allow the use of a single non-alloyed ohmic contact material (AuGe) for both the n and p type InGaAs material. Maximum resistive power losses were set at 0.1 W/cm^2. or approximately 3%, for both the emitter and the conductor.

MIM prototype structures were grown in a low pressure Organo-Metallic Vapor Phase Epitaxy (OMVPE). The prototype structure was not optimized for electrical and optical performance. A detailed analysis of the trade-off between series resistance, grid shadowing, and free carrier absorption must be done in context of the characteristics of the TPV system. These characteristics include factors such as the efficiency of the reflected photons to be reabsorbed by the emitter, etc.

An IR reflector was deposited on the rear surface of the prototype device and reflectivity measurements were taken prior to complete cell fabrication. The data indicates a IR reflectance of 79% without an AR coating. Adding the grid will increase the reflectance to ~83% and the addition of a properly designed AR coating could increase it even further.

The high intensity illumination I-V data was taken using a flash lamp and a fresnel lens. The I-V characteristics are indicative of an array of series interconnected cells under non-uniform illumination. We are currently examining our measurement equipment to improve the uniformity of illumination. Even though the cells were nonuniformly illuminated, this data represents a significant increase in performance of our MIM devices. Previous devices showed high series losses, which were attributed to the sub-cell interconnects.

The external quantum efficiency characteristics of the MIM prototype (without an AR coating) shows a small improvement in the long wavelength response when the IR reflector is added, although the absolute response is low. The prototype device was not produced from perfectly lattice matched material. We have modified our OMVPE facilities and are in the process of optimizing our material.

In conclusion, we have begun the development of a monolithically interconnected cell which incorporates a rear surface IR reflector. The MIM cell design has many potential advantages for TPV applications, namely: low resistive losses, high output voltages, increased reliability, improved and simplified thermal management, increased output power density, simplified TPV system design (no need for a selective emitter or spectrum shaping filters) and a reduced dependence on minority carrier lifetime.

The p/n cell configuration takes advantage of the reduced FCA in the n type material as well as the shift in optical bandgap which occurs for the heavily doped n^{++} layers. This shift in bandgap allows the use of incomplete absorption in the base region and a rear reflector as a method of increasing the optical thickness of the cell. This will benefit the bandedge response, particularly for lattice mismatched material which is limited by poor minority carrier diffusion length.

Prototype devices have been produced with encouraging results. Additional efforts in improving the bulk material properties and optimizing the cell design and fabrication process should quickly yield improved cells. The long-term goal is to reduce the area required for each sub-cell interconnect. This will allow the use of a larger number of smaller sub-cells, requiring thinner n^{++} conductor layers, reducing the associated FCA losses, thus increasing the long wavelength reflectivity.

Calculations indicate that the MIM cell, under a 1700°K blackbody with a viewfactor of 0.9, would produce 3.4 W/cm^2 of electrical power (assuming an efficiency of 35%). 11.3 W/cm^2 of thermal energy would need to be dissipated to maintain the cell operating temperature. Of that amount, 43% is due to FCA of the non-convertable IR. In addition, 24 W/cm^2 of energy would be reflected from the MIM device and returned to the emitter for recycling.

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Lewis Research Center

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Monolithically Interconnected InGaAs TPV Module Development

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Prospector VIII: TPV
July 15, 1996

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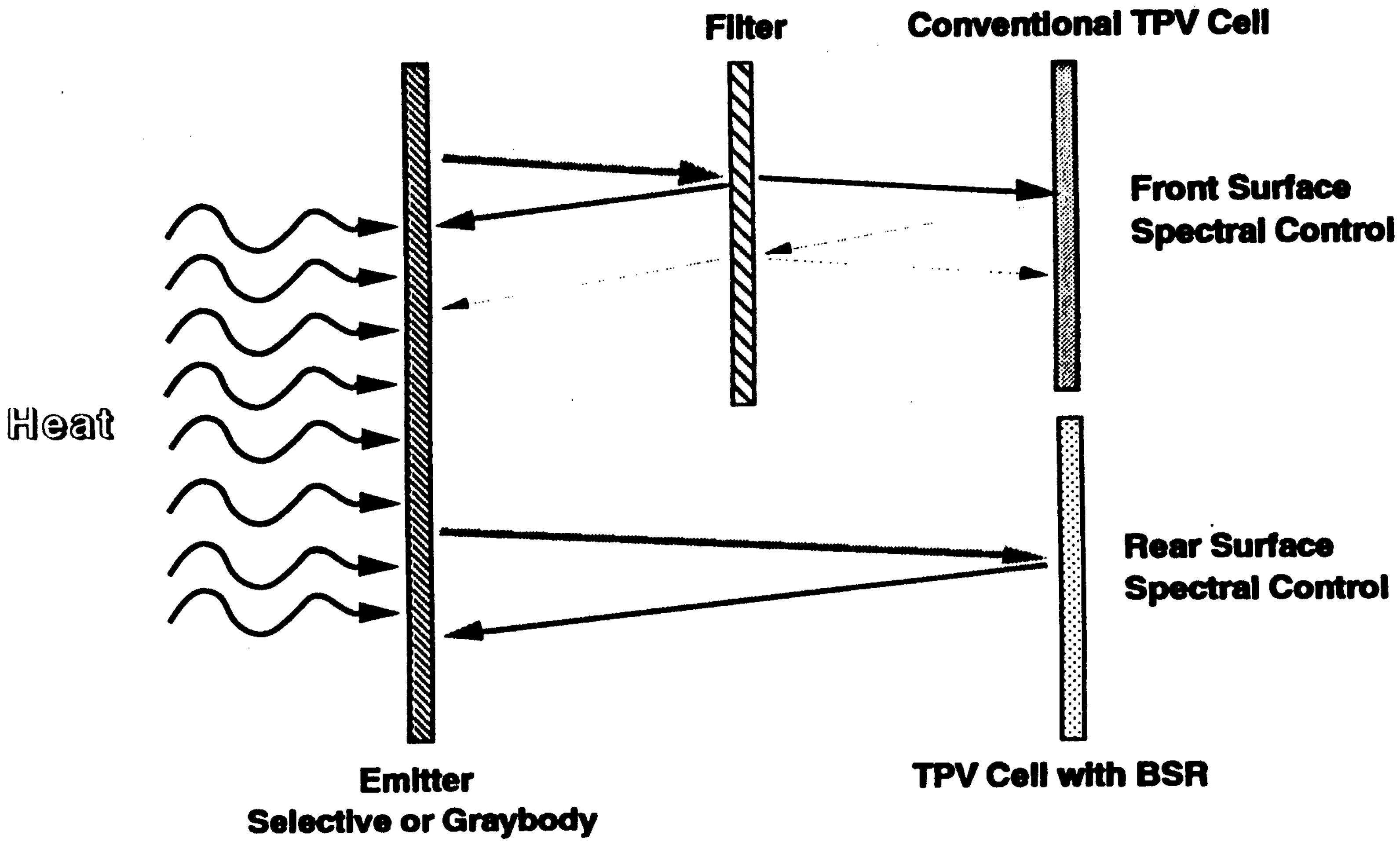
Thermophotovoltaic Systems Approaches



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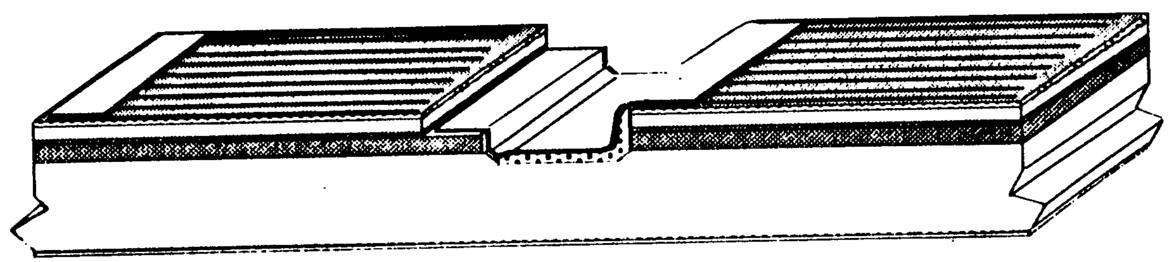
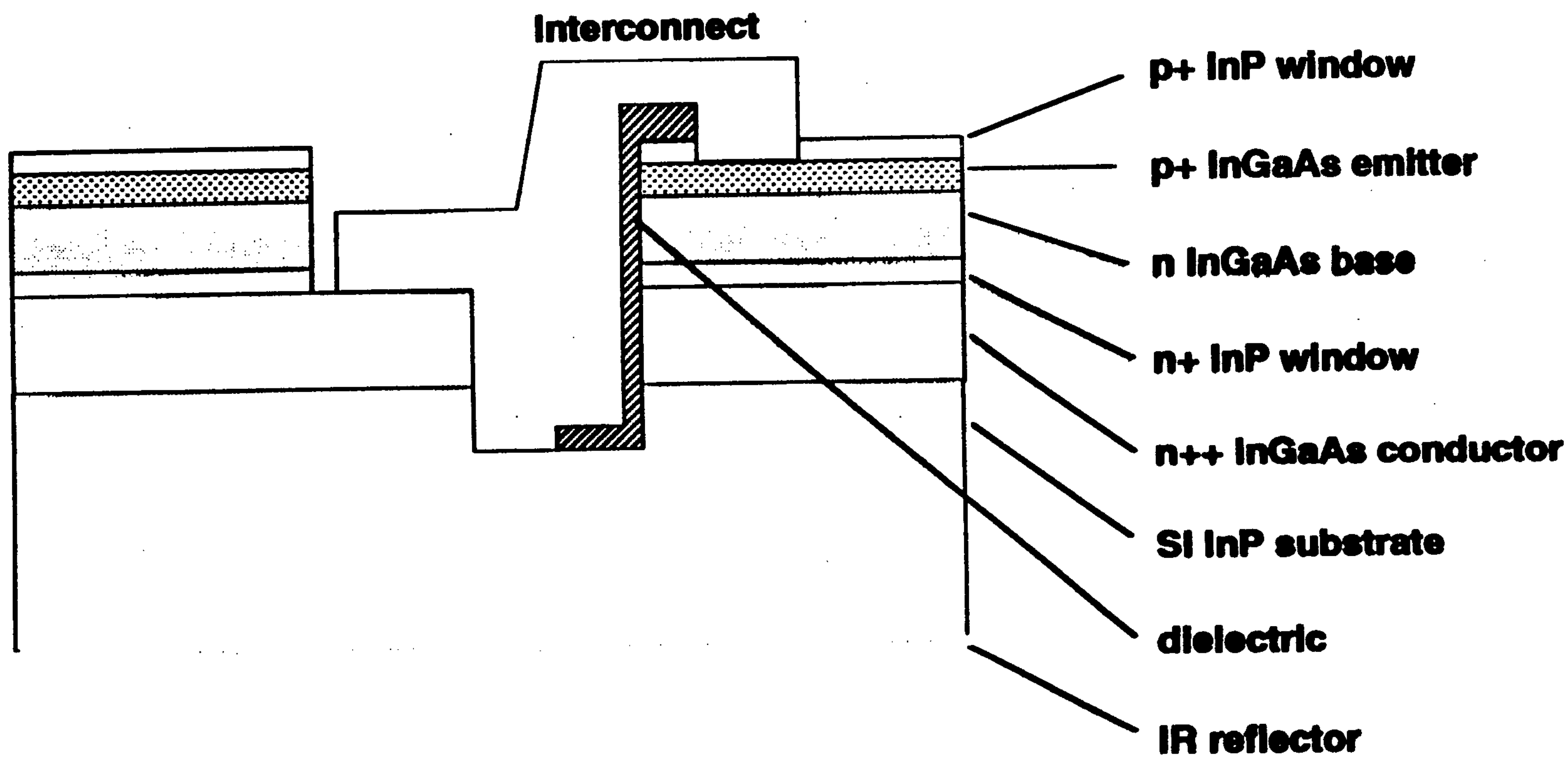
MIM TPV Cell Structure



Advantages:

- Lower resistive losses
- High output voltage
- Increased reliability
- Improved and simplified thermal management
- Higher output power density
- Simplified TPV system design
- Reduced dependence on minority carrier lifetime

Cross-Sectional View of MIM TPV Cell Structure



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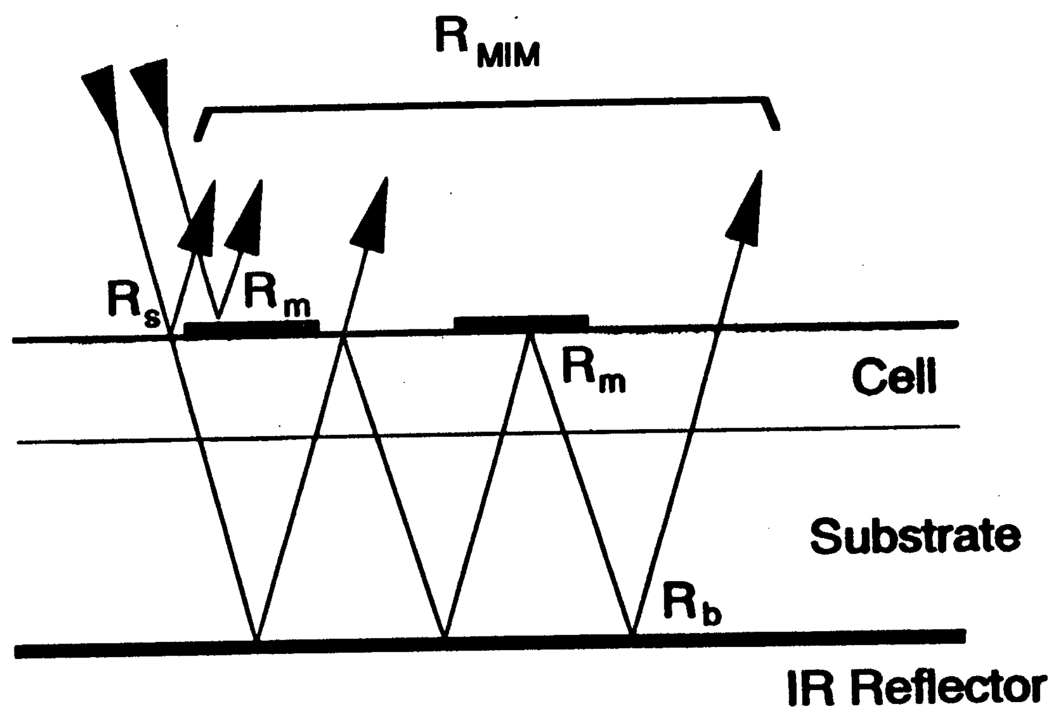
MIM Optical Model

$$R_f = FR_m + (1-F)\,R_s$$

$$R_{MIM} = \frac{\tau_d^2\,R_b^2(1-R_s)^2(1-F)^2}{1-\tau_d^2 R_f R_b} + R_f$$

$$\tau_d = e^{-\alpha d} = 1 - a = \text{Transmission}$$

F = Fractional Grid Coverage



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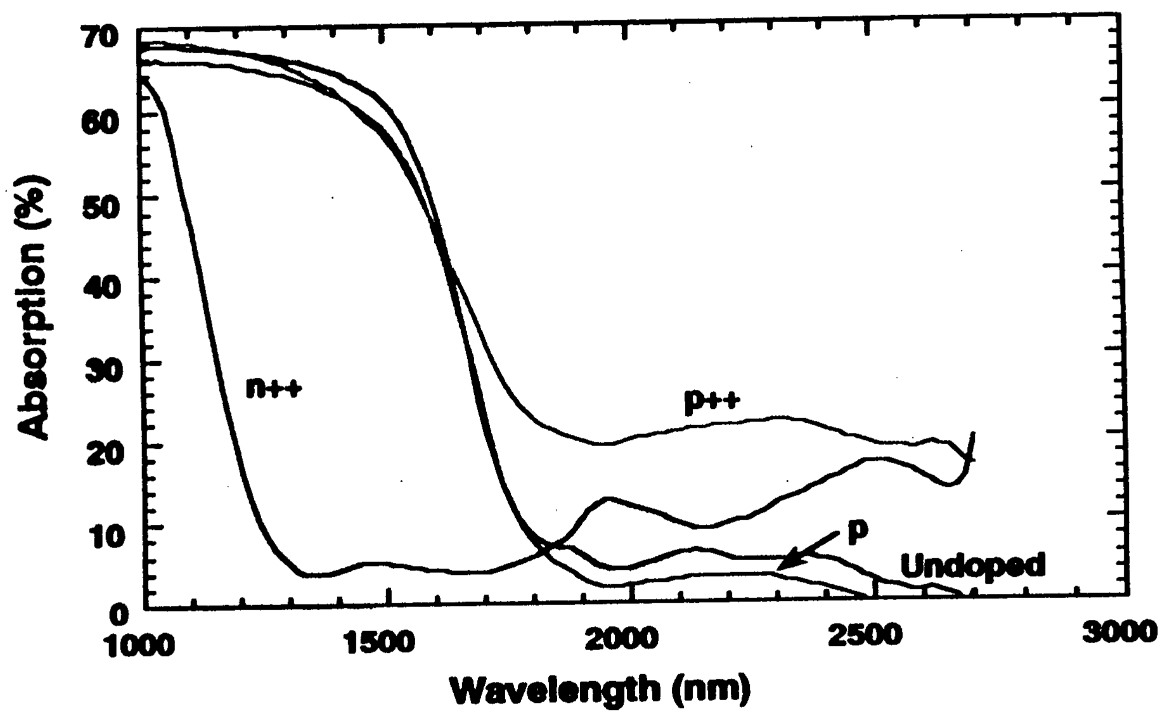
Free Carrier Absorption Measurements of InGaAs



p-type InGaAs has 3.5x higher free carrier absorbtion than n-type.

Highly doped n-type InGaAs shows a shift in optical bandgap.

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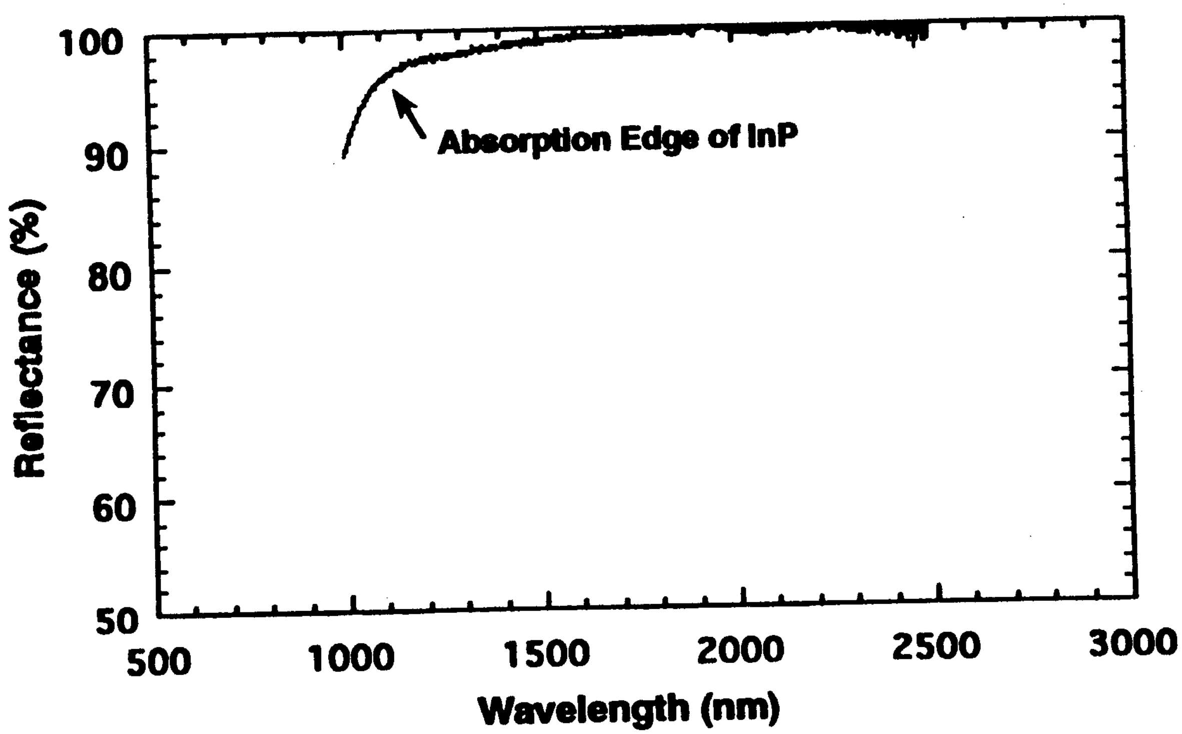
Measured Reflectance of IR Reflector Through Semi-Insulating InP Substrate



IR reflector reflectance of >95%

Semi-Insulating InP substrate is transparent.

MIM Cell Design Environment

Illumination Source:

- **1700°K blackbody emitter**
- **Viewfactor = 0.9**
- **Total radiant input to cell = 39.3 W/cm^2**
- **Radiant input to cell (E > Eg) = 11.1 W/cm^2**

Assume best n/p cell spectral response

- **Isc = 8.5 A/cm^2**

This Isc value used to model MIM resistive power loss

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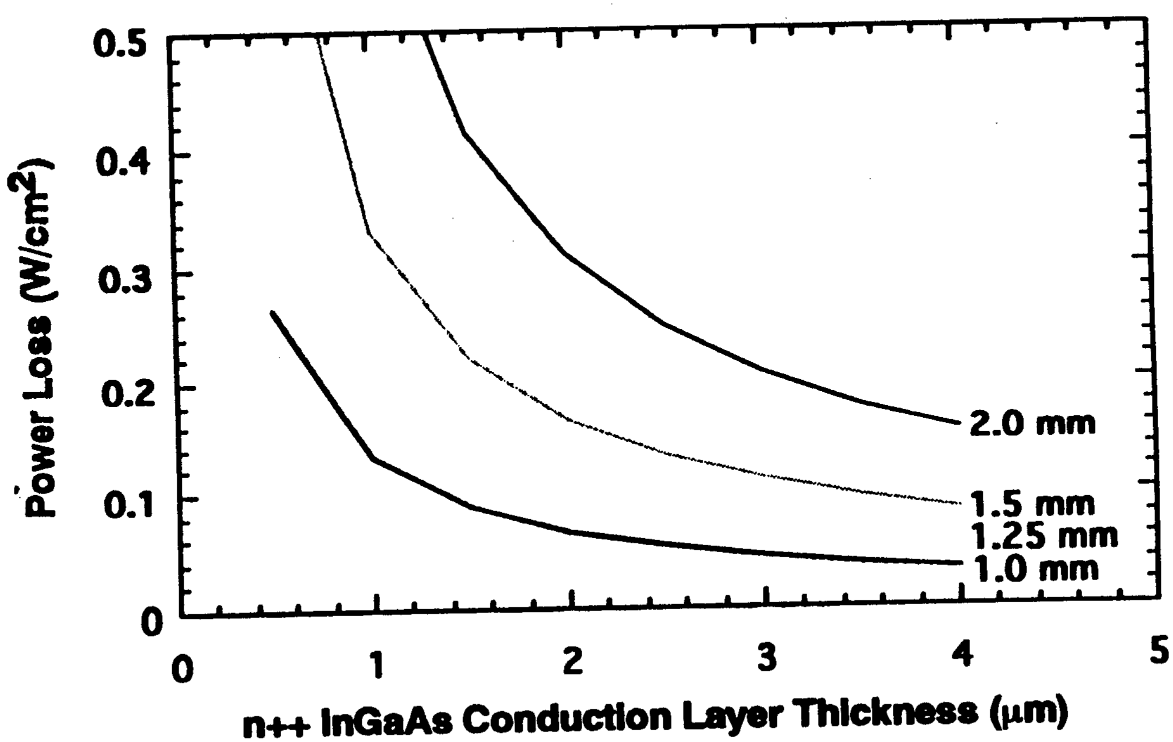
Resistive Power Loss in n++ Conduction Layer vs. Sub-Cell Length and Conductor Thickness



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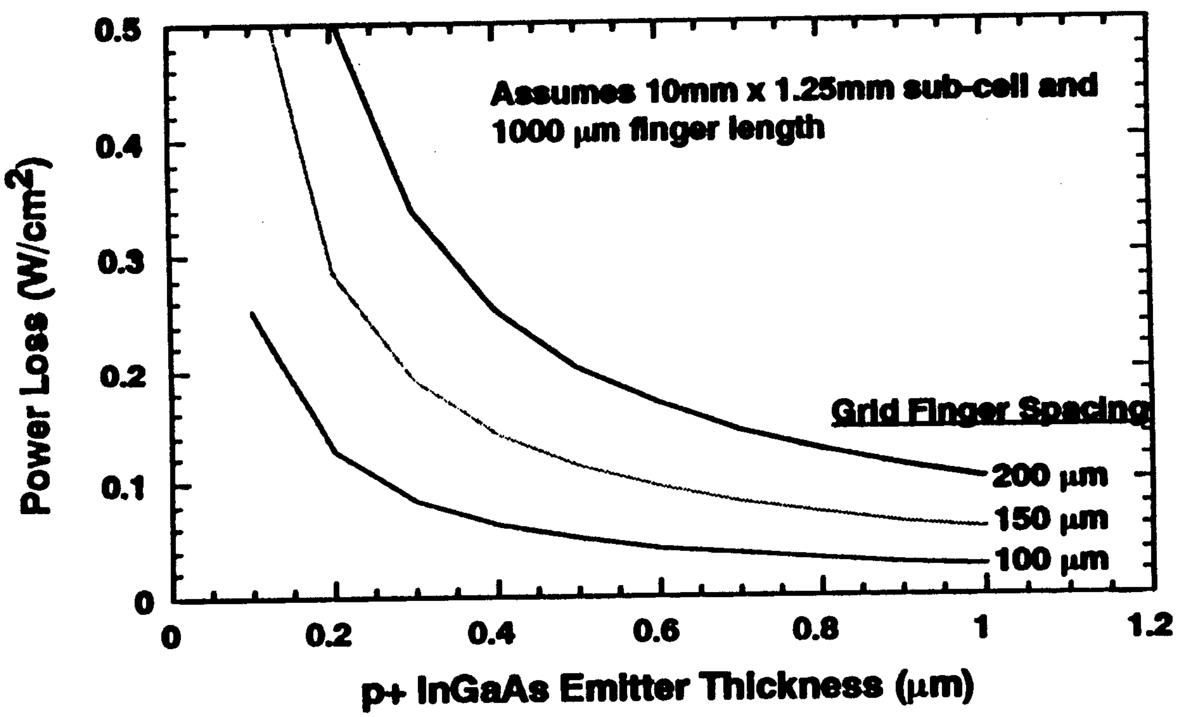
Resistive Power Loss in p+ Emitter vs. Grid Finger Spacing and Emitter Thickness



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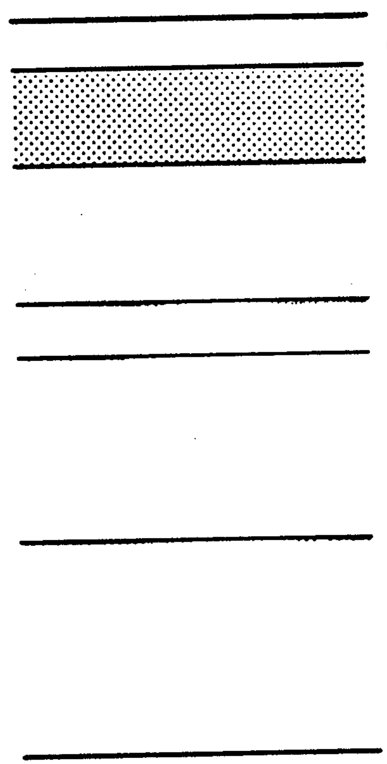
Power Technology Division

Prototype MIM InGaAs Device Structure



0.1μm p=2e18 InP

0.3μm p=1e19 InGaAs

1.8μm n=3e17 InGaAs

0.1μm n=2e18 InP

2.7μm n=2e19 InGaAs

SI InP Substrate

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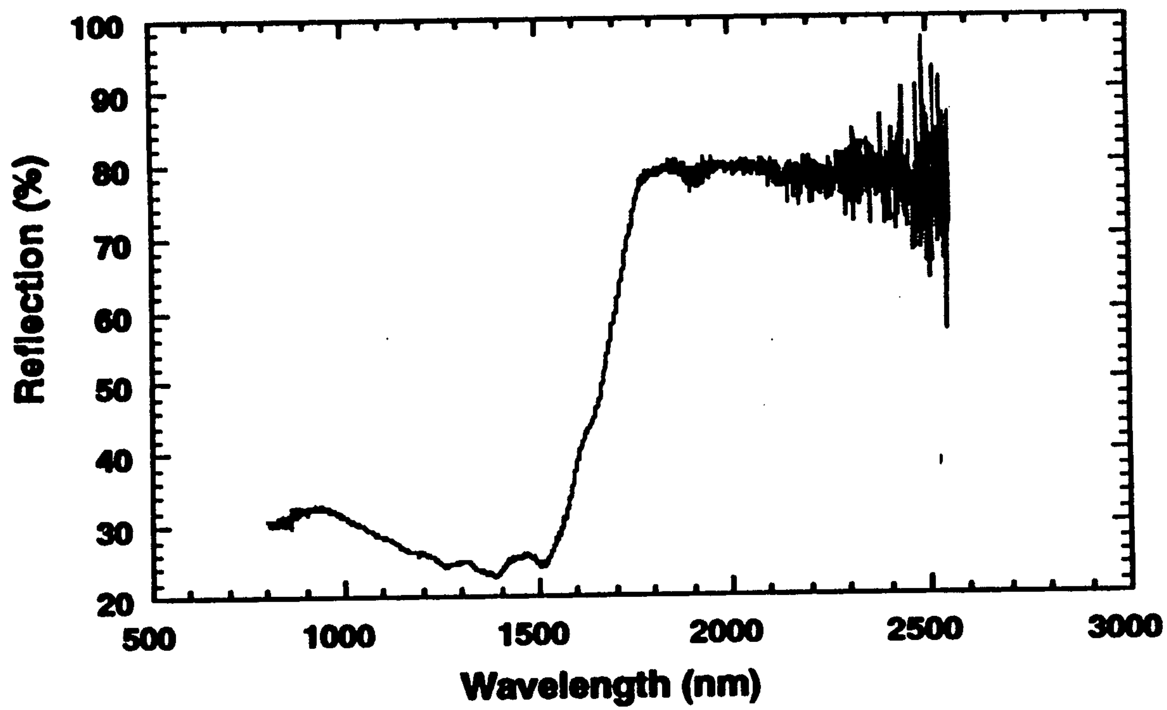
Measured spectral reflectance from a MIM cell without contact metallization



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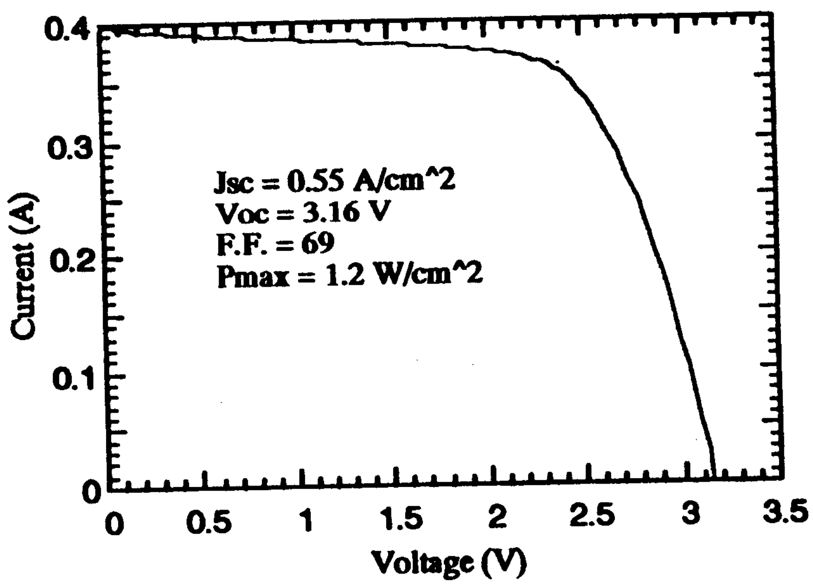
Prototype MIM InGaAs Device I-V Characteristic



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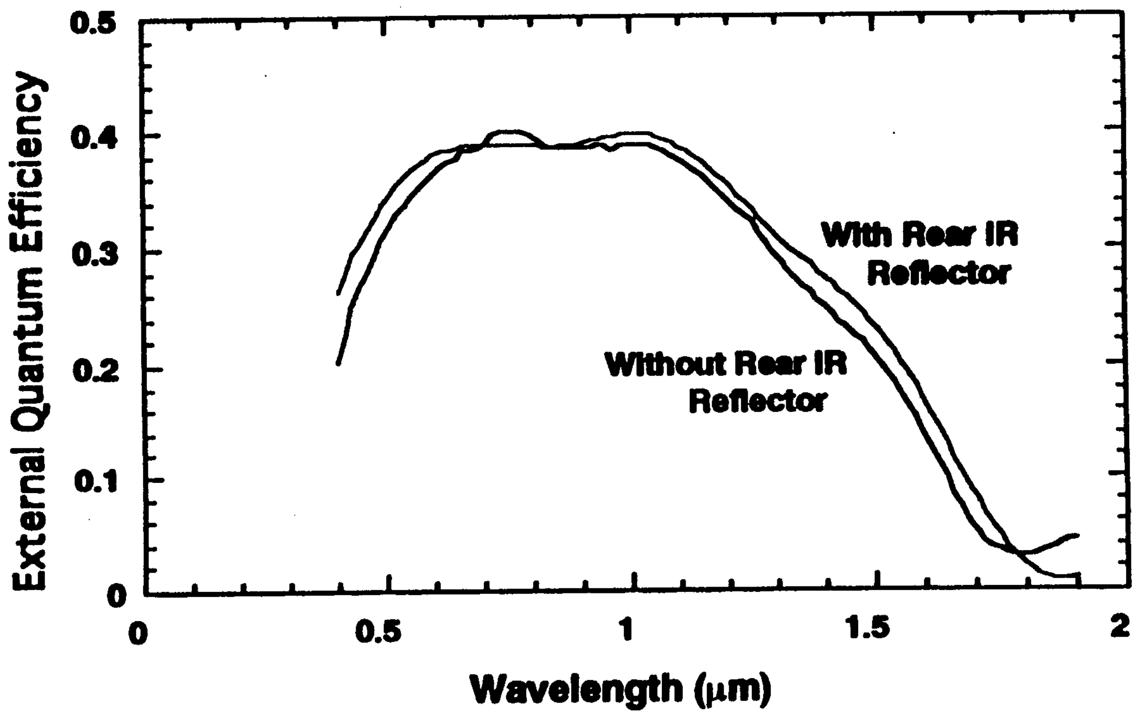
External Quantum Efficiency Measurements of MIM Cell (without an AR coating)



Conclusions

An optical model has been developed which predicts high IR reflectance from the MIM design even with moderate free carrier absorption.

An increase in the optical bandgap of heavily doped n-type InGaAs has been observed. (Burstein-Moss shift)

Free carrier absorption for n-type and p-type InGaAs has been measured.

A prototype MIM InGaAs device has been demonstrated withencouraging results.

The advantages of the MIM design include:

- Reduced resistive losses
- Increased output power density
- Improved and simplifed thermal management
- Increased system reliability
- Simplified system design

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EDTEK Inc.

Enhancement of Line Emitter Spectra Using IR Bandpass Filters

Presented

To The

Auburn University/Army Research Office

Prospector VIII Workshop

In Raleigh-Durham, North Carolina
by:

W. E.d Horne

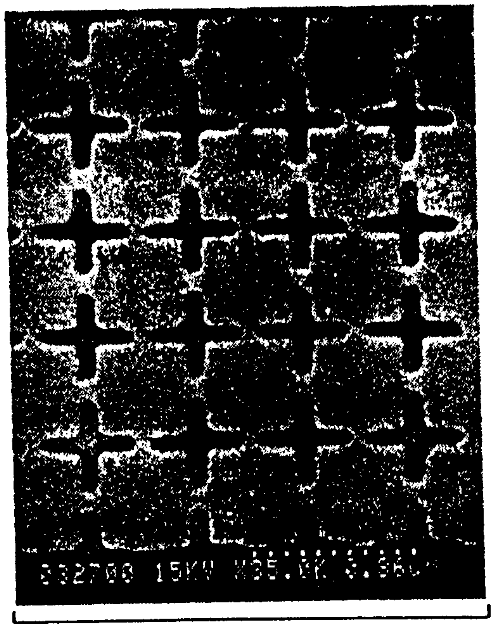
EDTEK, Inc.
7082 South 220th St.
Kent, WA 98032
(206) 395 8084

July 15, 1996

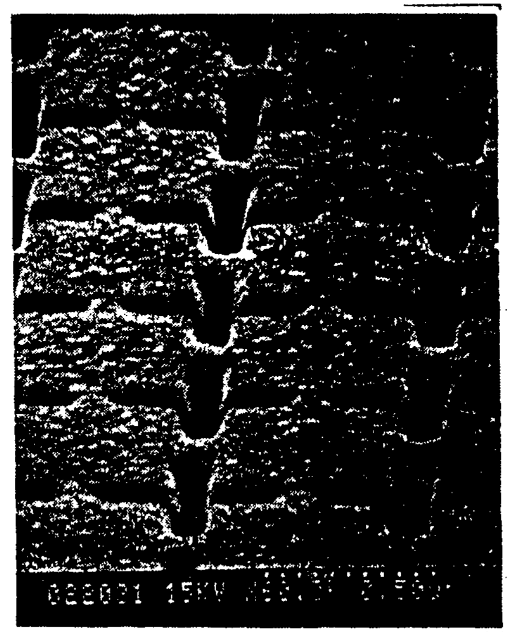
ABSTRACT

There is a wide market for compact, lightweight, quiet, and efficient power systems in both the civilian and military sectors. Thermophotovoltaic (TPV) power sources are potential candidates to fill this market in the future. Recent advances in the development of efficient rare earth composite line emitters presents an opportunity to boost the conversion efficiencyof such TPV systems. These line emitters can be enhanced significantly by a novel IR bandpass filter developed by EDTEK, Inc. When modeled with the measured characteristics of EDTEK's low-bandgap gallium antimonide (GaSb) photovoltaic (PV) cells the efficiency of an Auburn University unfiltered line emitter/cell response is more than doubled by filtering the line emitter spectrum. EDTEK has deployed a pilot production capability for both the GaSb cells and the IR bandpass filters. This presentation summarizes the status of our development of the filter production capability. We plan to commercialize modular cel/filter systems for sale both in our own products and to other TPV system manufacturers.

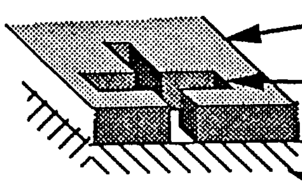
IR BandPass Filter for TPV Application



Gold IR Bandpass Filter

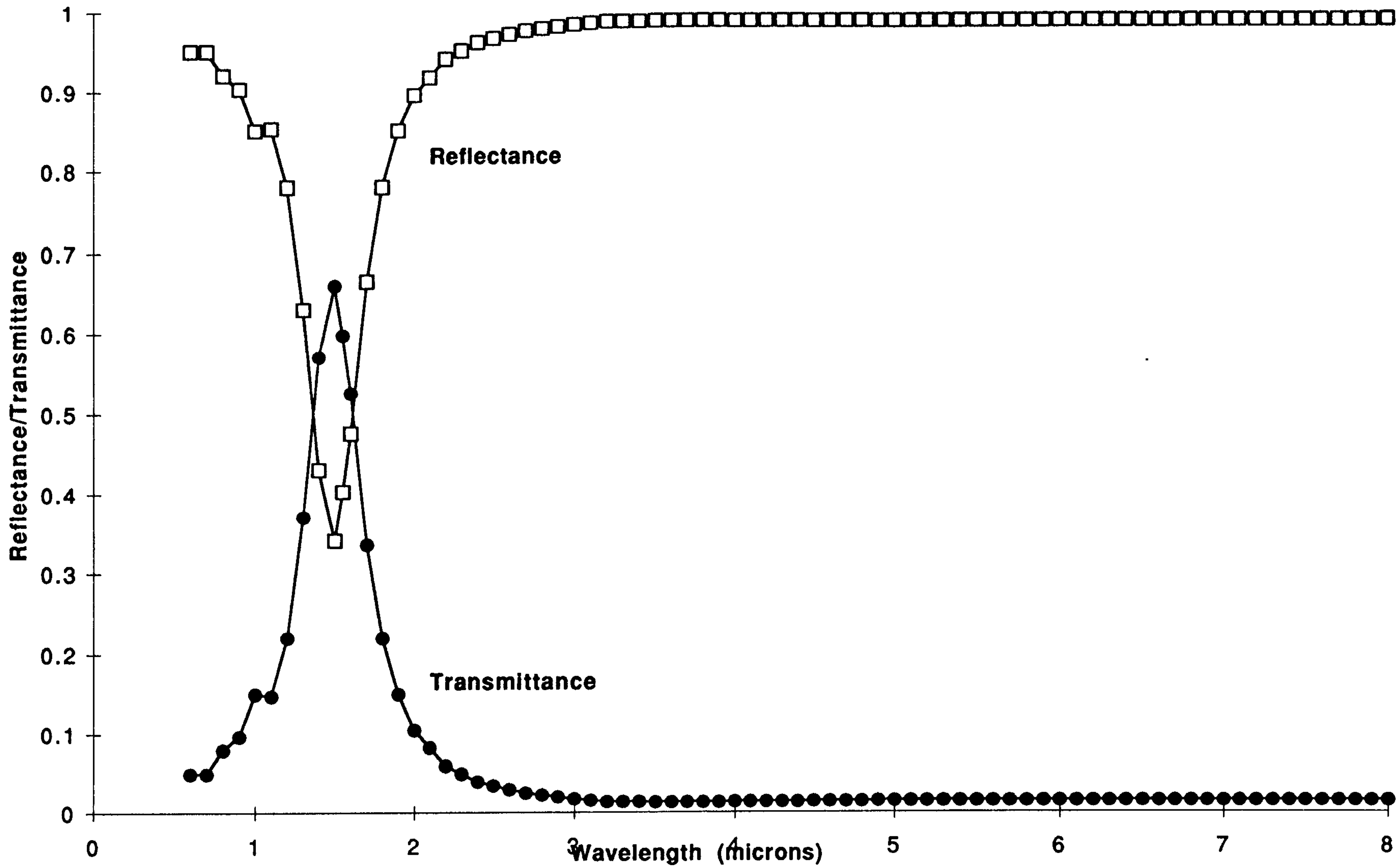


Oblique View of Gold IR Bandpass Filter



EDTEK Proprietary

EDTEK Filter Characteristic



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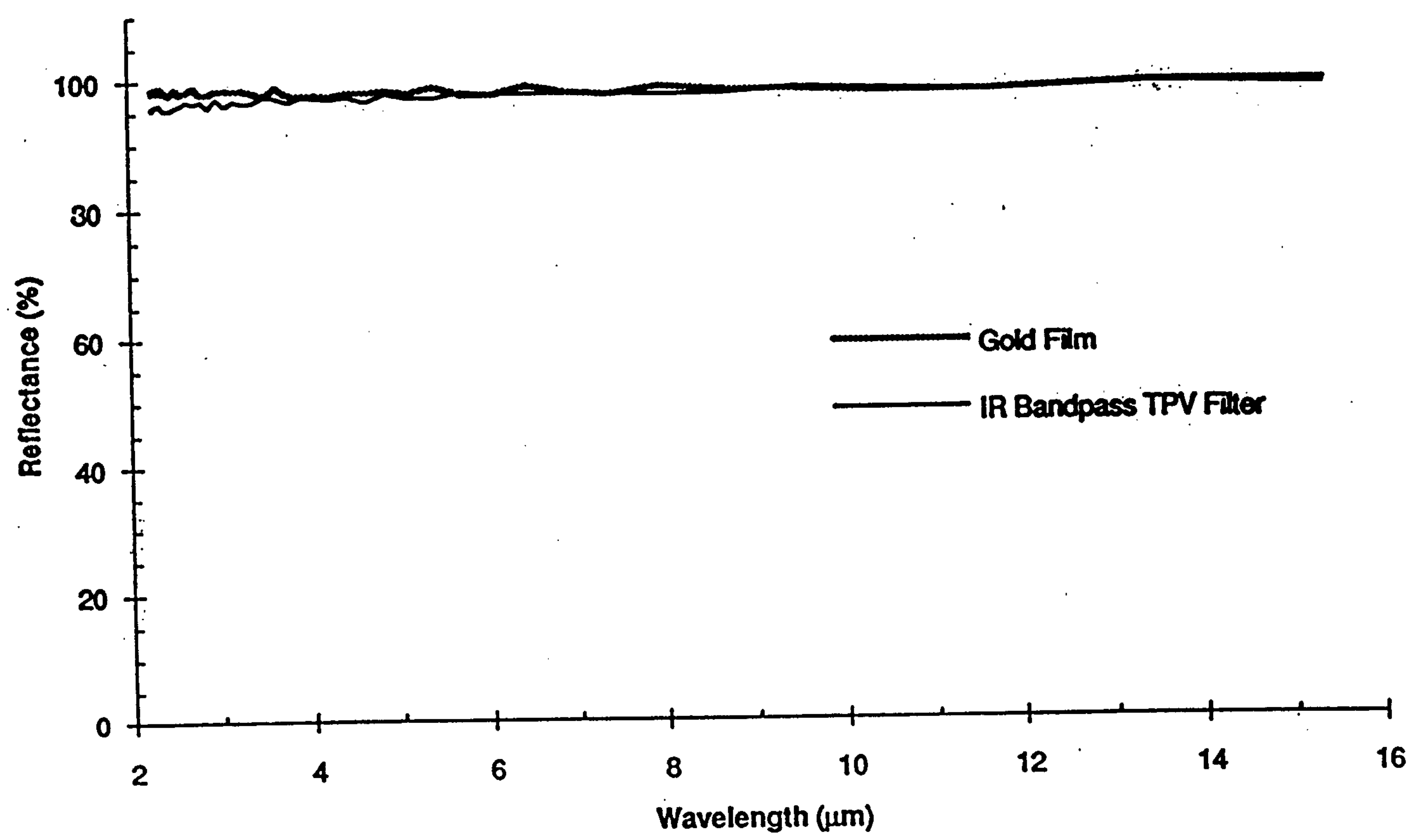
EDTEK Inc
Energetics Development

LONG WAVELENGTH FILTER REFLECTANCE



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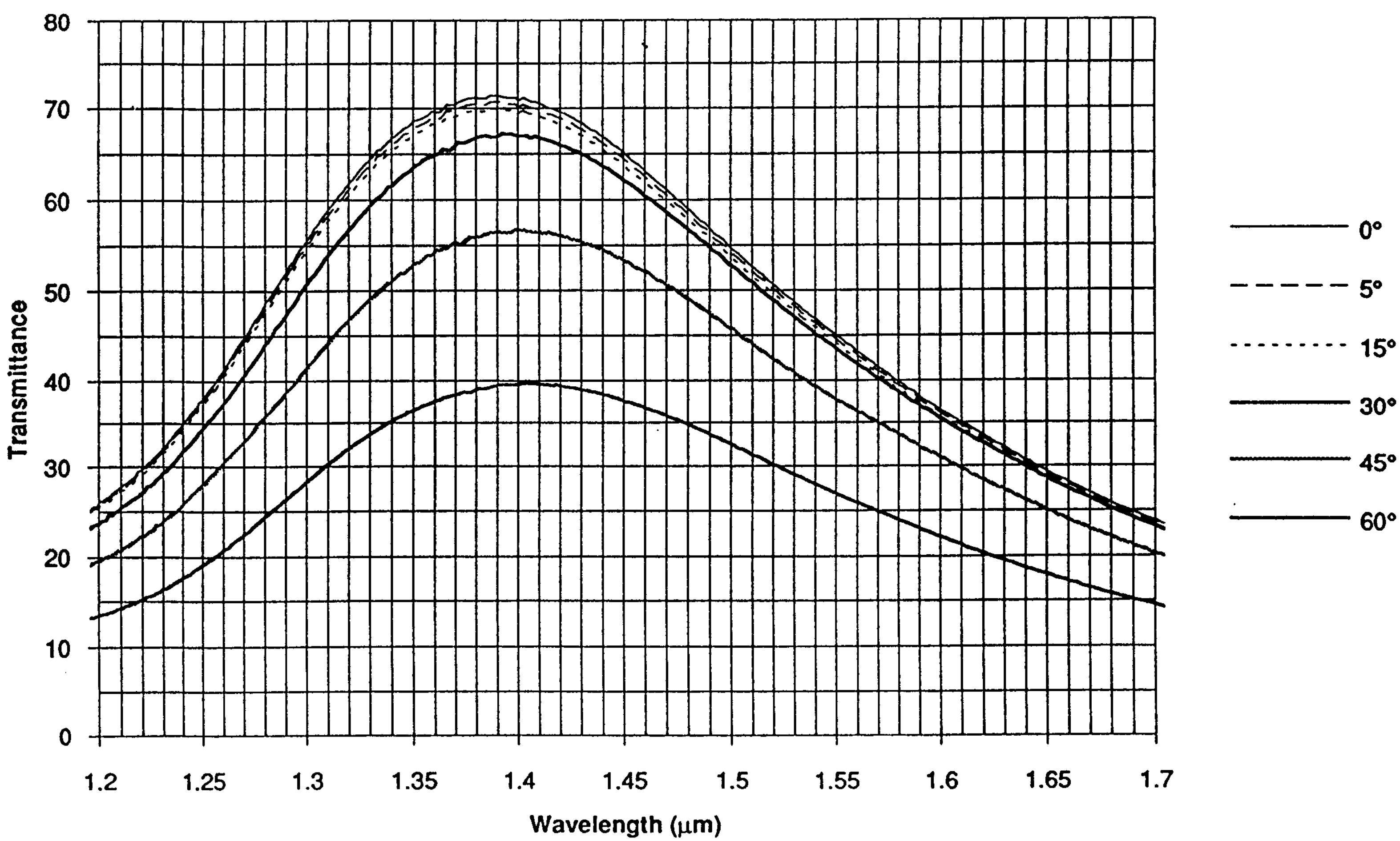
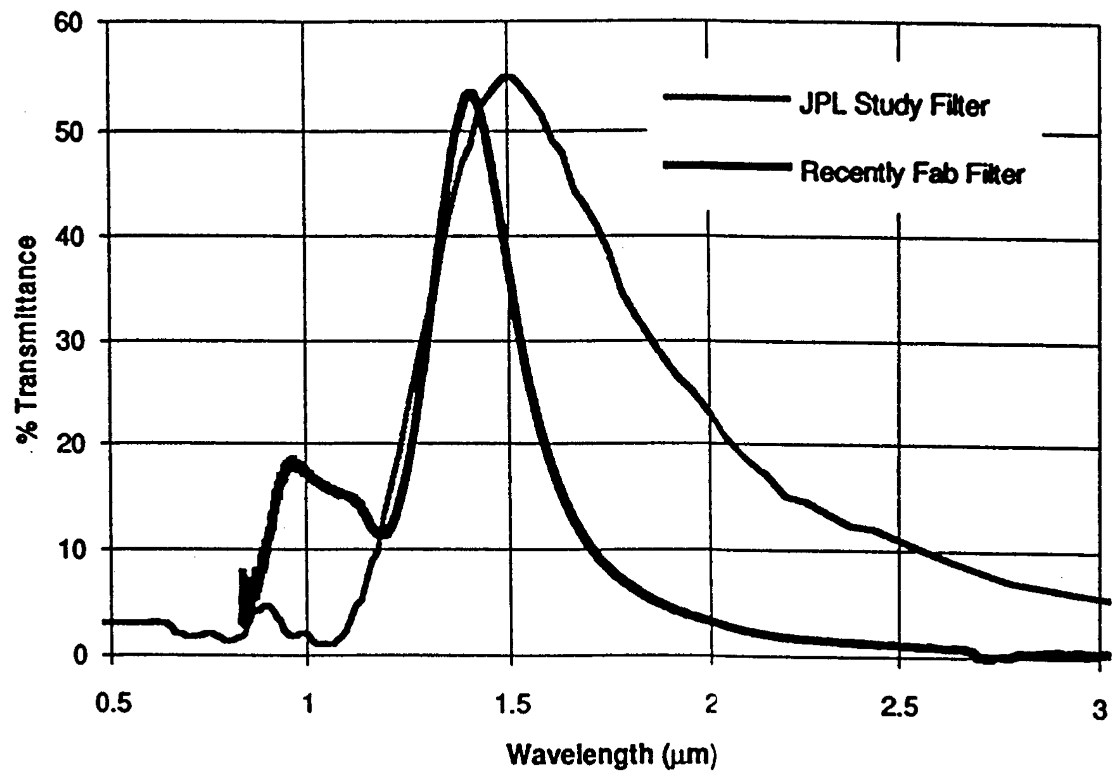
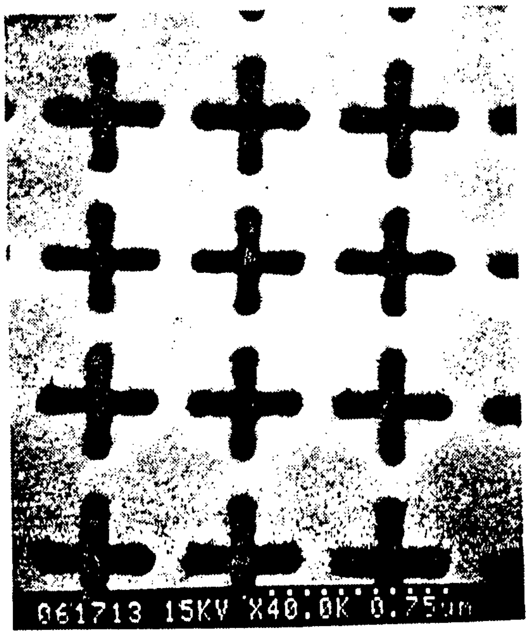
TPV BANDPASS FILTER TRANSMITTANCE VERSUS ANGLE OF INCIDENCE



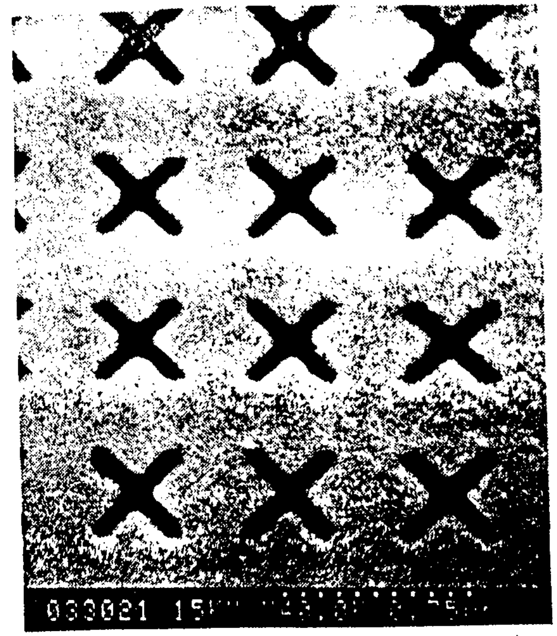
COMPARISON OF EARLY TPV FILTER TRANSMITTANCE WITH RECENT IMPROVED FILTER TRANSMITTANCE



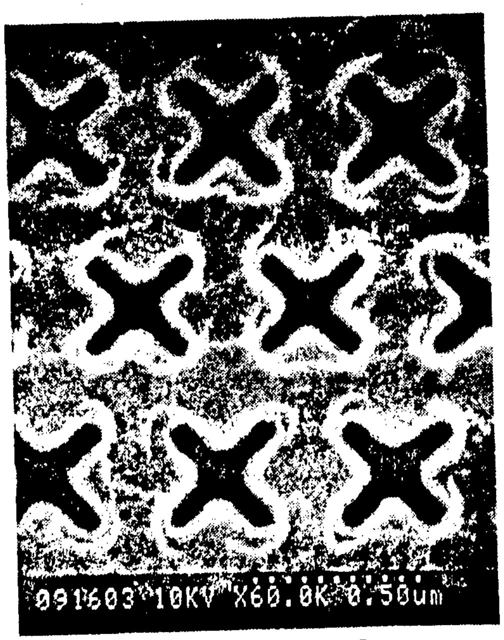
Survey of Fabricated Filter Patterns



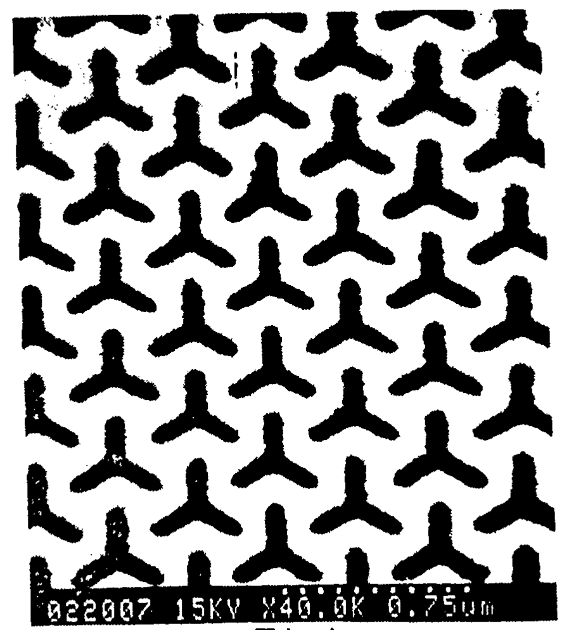
Square Cross Dipoles



Rotated Crosses (FaceCentered)

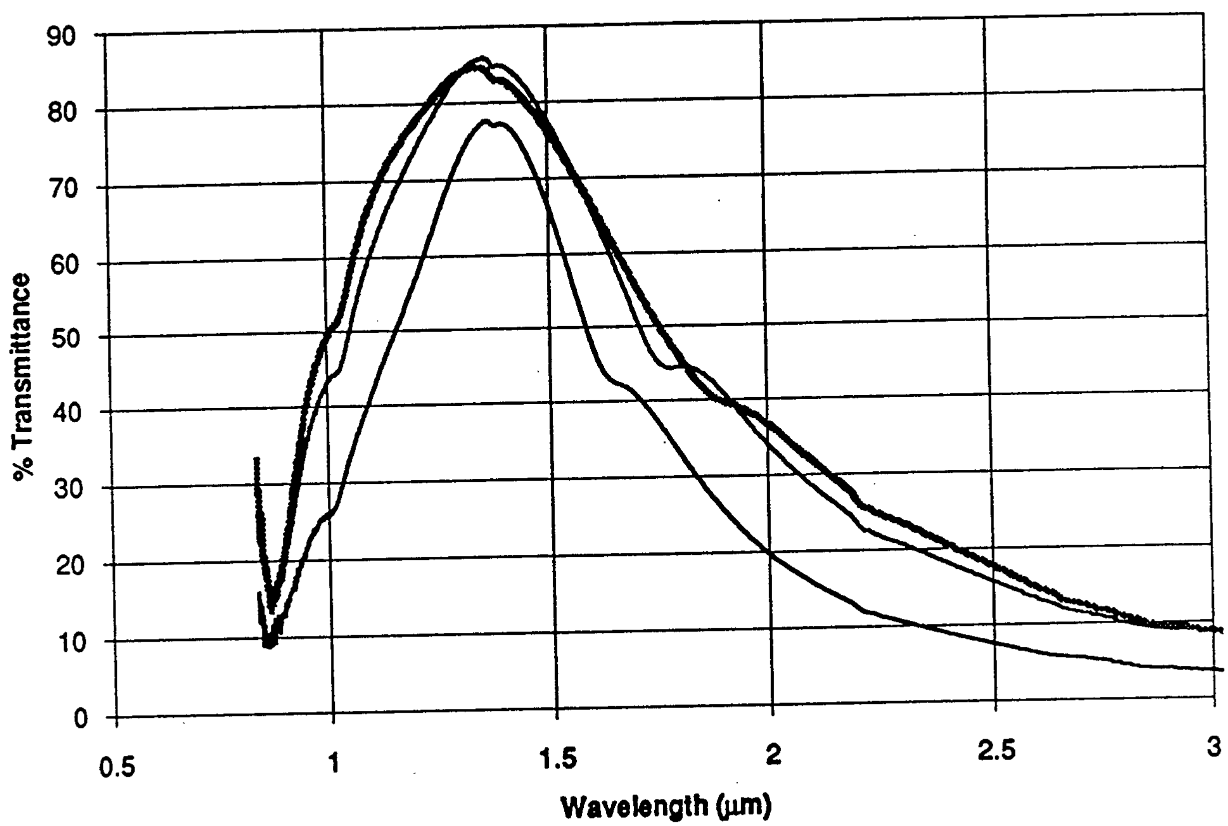


Staggered Rotated Cross

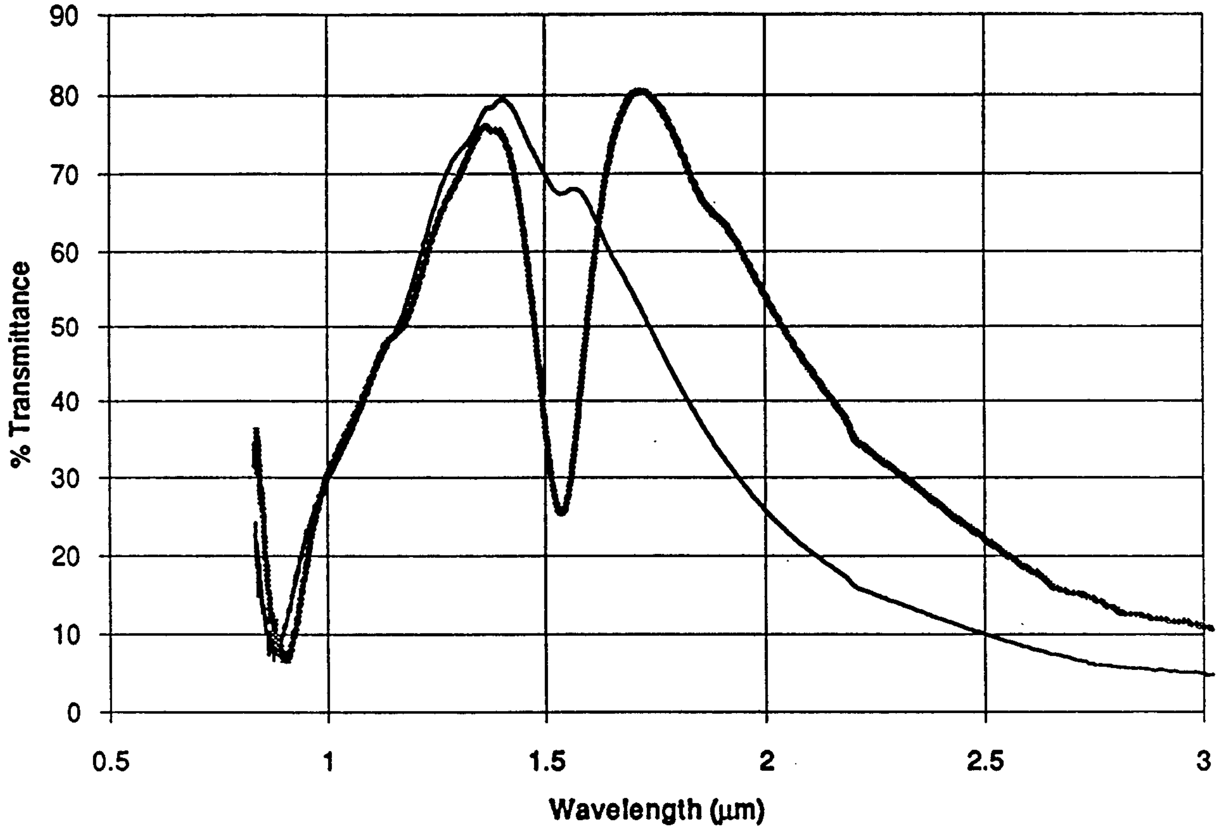


Tripole

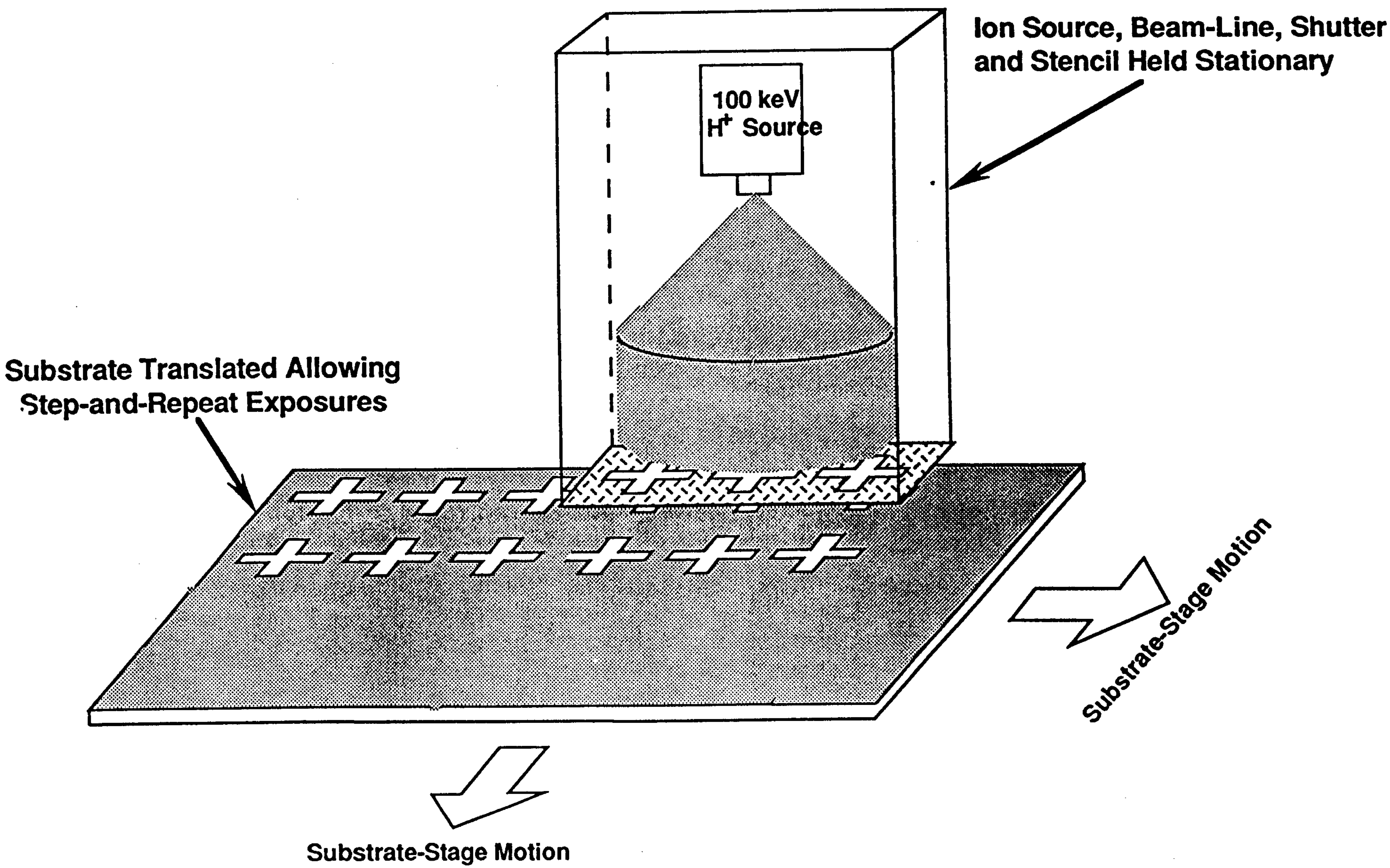
Transmission Profiles of other Filter Patterns



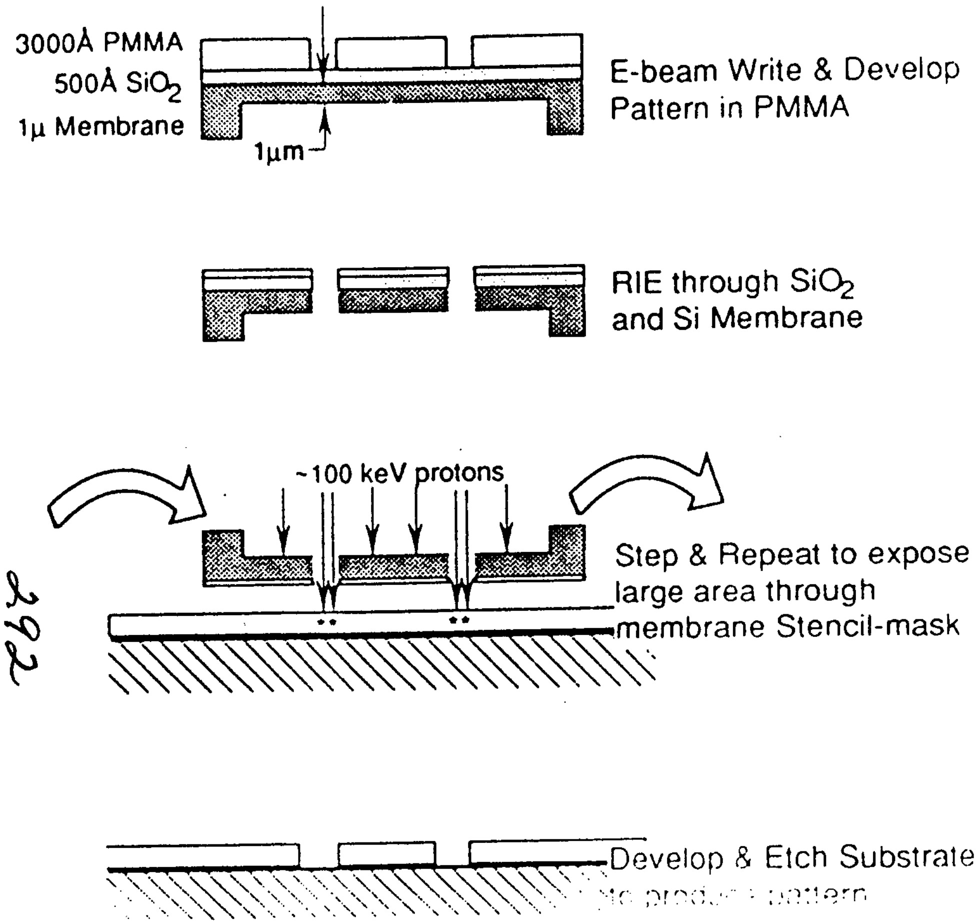
Transmission Profiles of other Filter Patterns



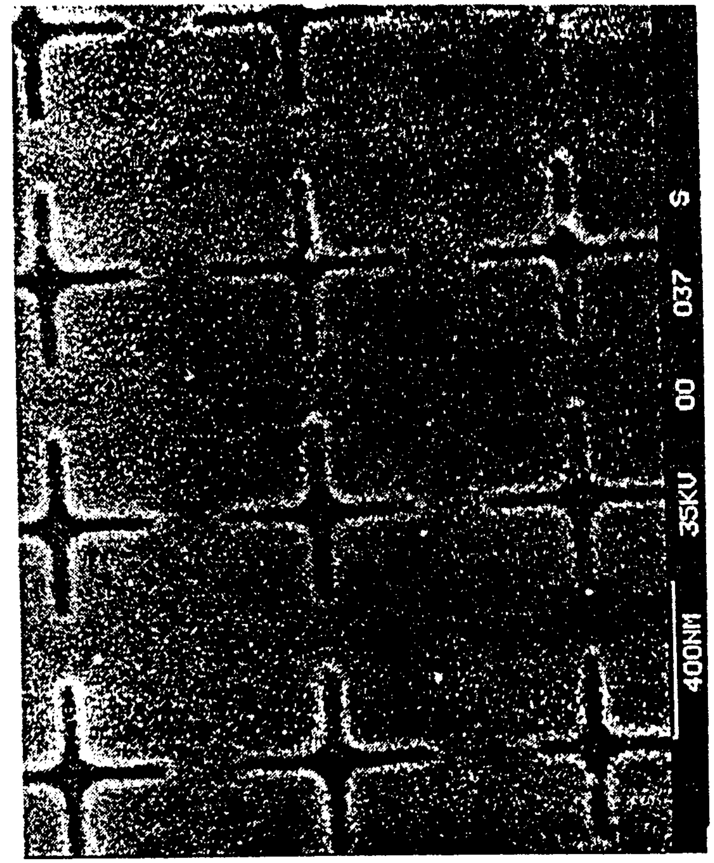
Masked Ion Beam Lithography



Production of Filters Using Masked Ion Beam Lithography (MIBL)



MIBL Process

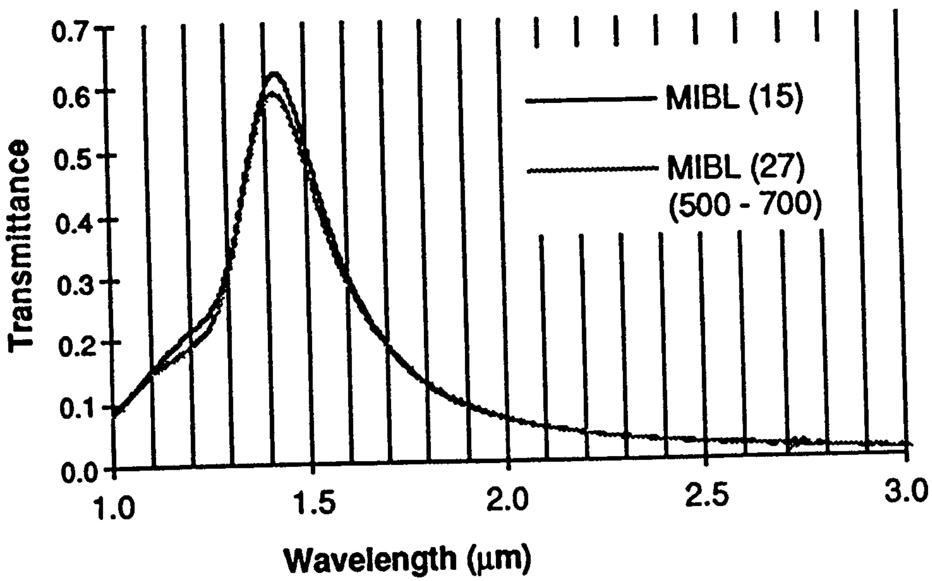


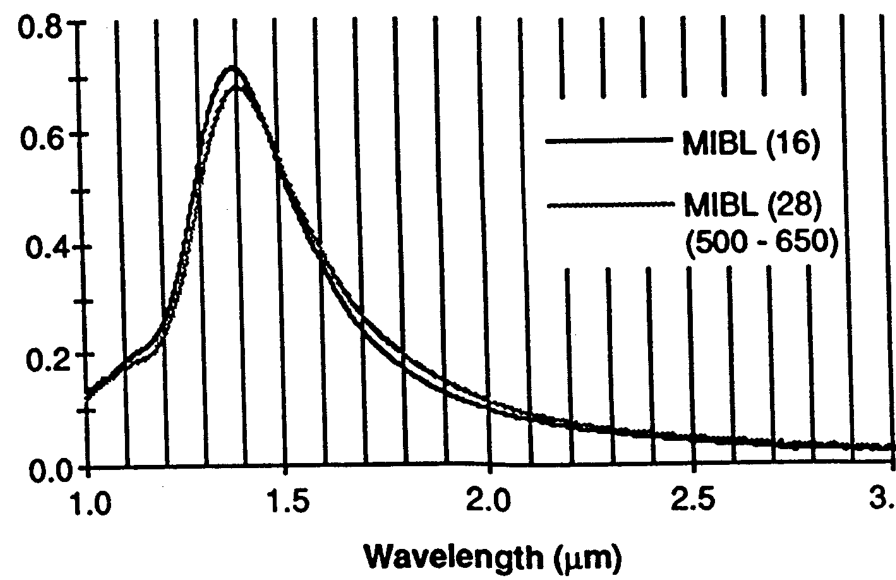
1μ thick Si membrane w/ filter pattern etched through

E-beam lithography ... preliminary etching: NNF ... hing and ... U of Houston

EDTEK Inc
Energetics Development

REPEATABILITY OF MIBL FILTER FABRICATION





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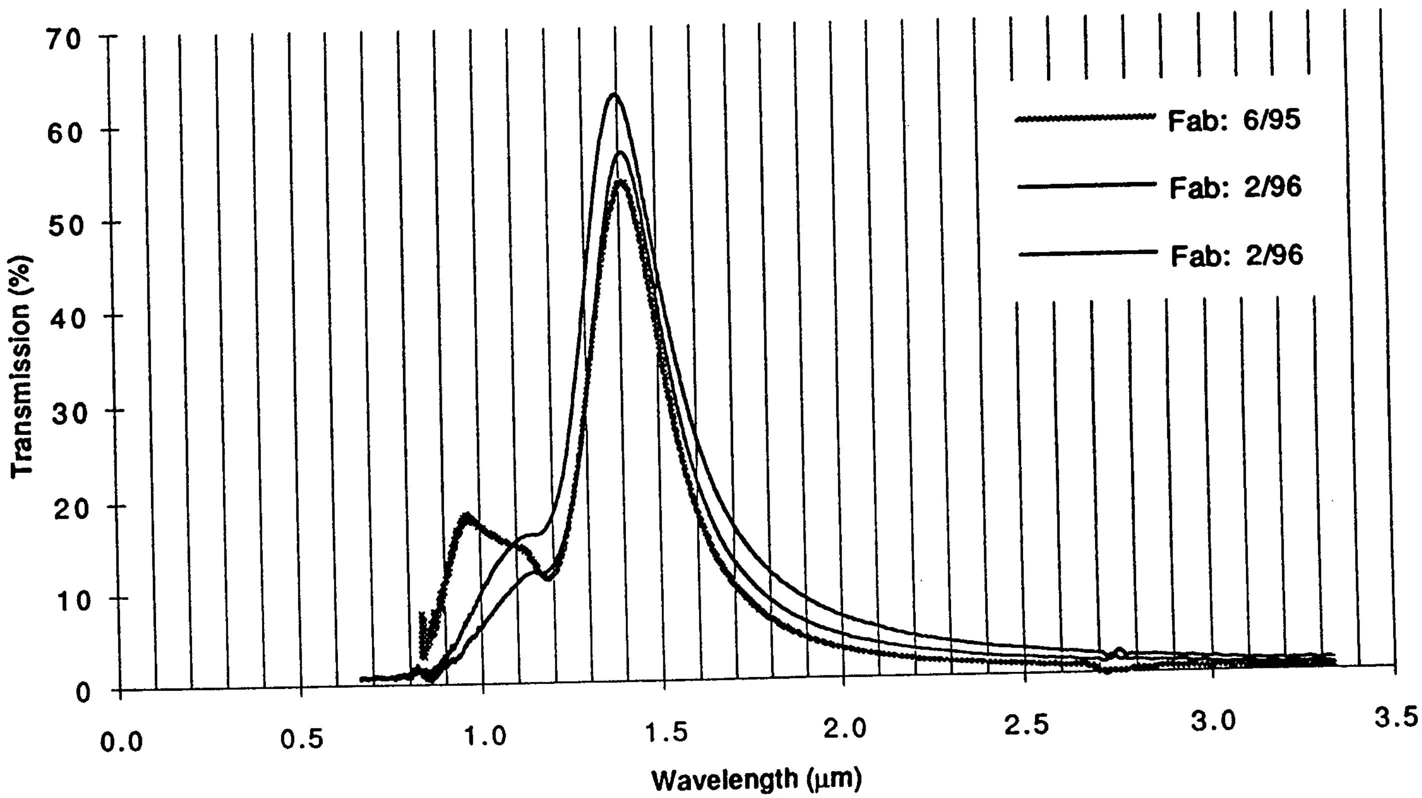
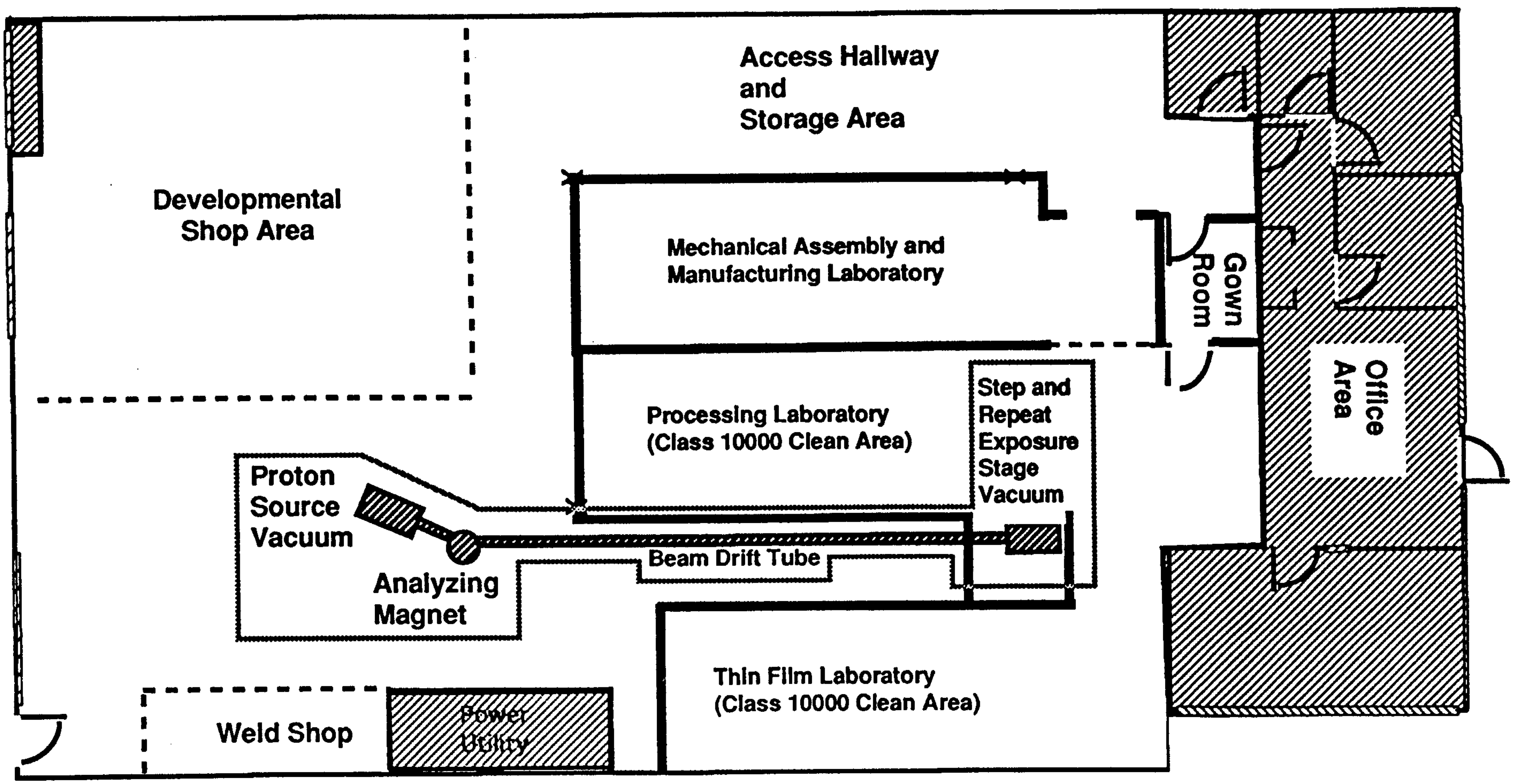
Energetics Development

Comparison of Filters Fabricated to Identical High Performance Specifications 8 Months Apart



EDTEK Inc
Energetics Development

LAYOUT OF MIBL EQUIPMENT IN EDTEK FACILITY

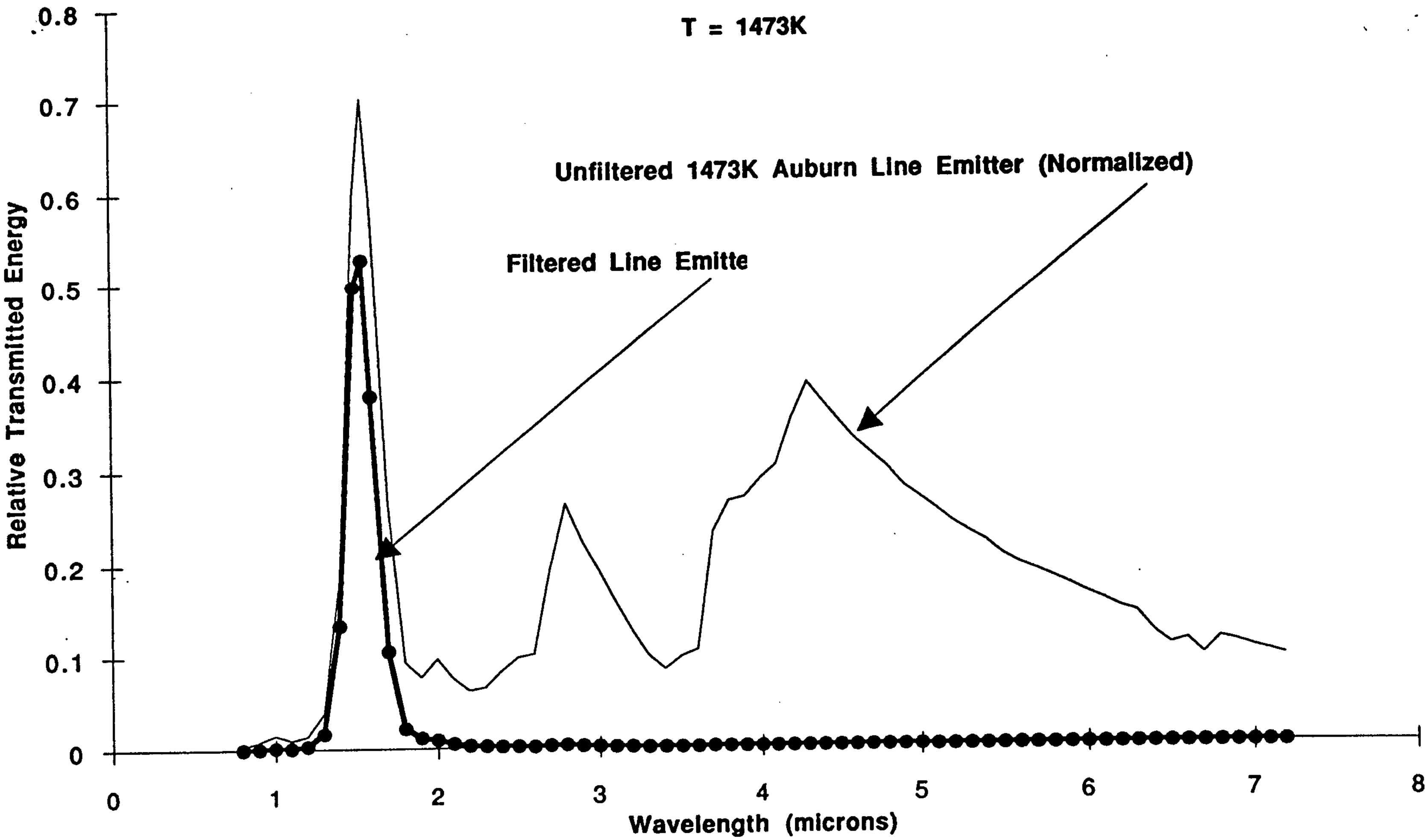


EDTEK Inc.

AUBURN LINE EMITTER vs EDTEK FILTERED LINE EMITTER T = 1473K

GaSb PV cell Efficiency (Line Emitter only) = 17.61%

GaSb PV cell Efficiency (With Filtered Line Emitter) = 39.98%



ADVANTAGES OF EDTEK FILTERED AUBURN LINE EMITTER

1) HIGHER CELL/FILTER EFFICIENCY

2) REDUCED SYSTEM LOSSES RESULT IN EVEN GREATER IMPROVEMENTS IN OVERALL EFFICIENCY

3) REDUCED LOSSES PERMITS OPERATING AT EFFICIENT EMITTER TEMPERATURE WITH LESS ENERGY INPUT TO SYSTEM

4) REDUCED HEAT LOAD RELIEVES THERMAL CONTROL PROBLEM WITH PV CELLS

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TECHNOLOGY UPDATE 2

Rare Earth Selective Emitters

Donald L. Chubb
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Cleveland, Ohio 44135

An efficient, durable selective emitter makes possible efficient thermophotovoltaic(TPV) energy conversion. The rare earths such as erbium,Er, holmuim,Ho, and ytterbium,Yb, are excellent candidates for an efficient selective emitter. At solid state densities, the emission of the rare earths is characterized by a single high emittance emission band with much lower emittance outside this emission band. It is the unique atomic structure of the rare earths that allows this band emission, rather than the usual grey body behavior at solid state densities.

Two types of rare earth selective emitters are currently receiving the most research interest; fibrous and thin film emitters. Fibrous rare earth oxides(R_2O_3) have been shown to have good radiative efficiency. Also, thin films of rare earth doped ceramics such as yttrium aluminum garnet(Yag) have also shown to have excellent emissive properties for a selective emitter.

This paper discusses the emissive properties of these rare earth selective emitters. Spectral emittance results for Er-Yag and radiative efficiency results for Ho-Yag are presented and the significant characteristics of rare earth selective emitters is discussed.

Rare Earth Selective Emitters

BY
Donald L. Chubb
NASA Lewis Research Center

LANTHANIDE SERIES

…HANIDE …RIES

Ce	58	140.12	3468	CERIUM	6.66	795
Pr	59	140.907	3512	PRASEODYMIUM	6.782	935
Nd	60	144.24	3027	NEODYMIUM	7.004	1024
Pm	61	147	2460	PROMETHIUM	7.22	1168
Sm	62	150.35	1791	SAMARIUM	7.536	1072
Eu	63	151.96	1597	EUROPIUM	5.259	826
Gd	64	157.25	3266	GADOLINIUM	7.895	1312
Tb	65	158.924	3123	TERBIUM	8.272	1356
Dy	66	162.50	2600	DYSPROSIUM	8.536	1407
Ho	67	164.930	2600	HOLMIUM	8.803	1461
Er	68	167.26	2900	ERBIUM	9.051	1497
Tm	69	168.934	1947	THULIUM	9.332	1545
Yb	70	173.04	1194	YTTERBIUM	6.977	824
Lu	71	174.97	3327	LUTETIUM	9.842	1652

- Doubly or Tribly Charged Rare Earth in a Crystal Has Desired Characteristics

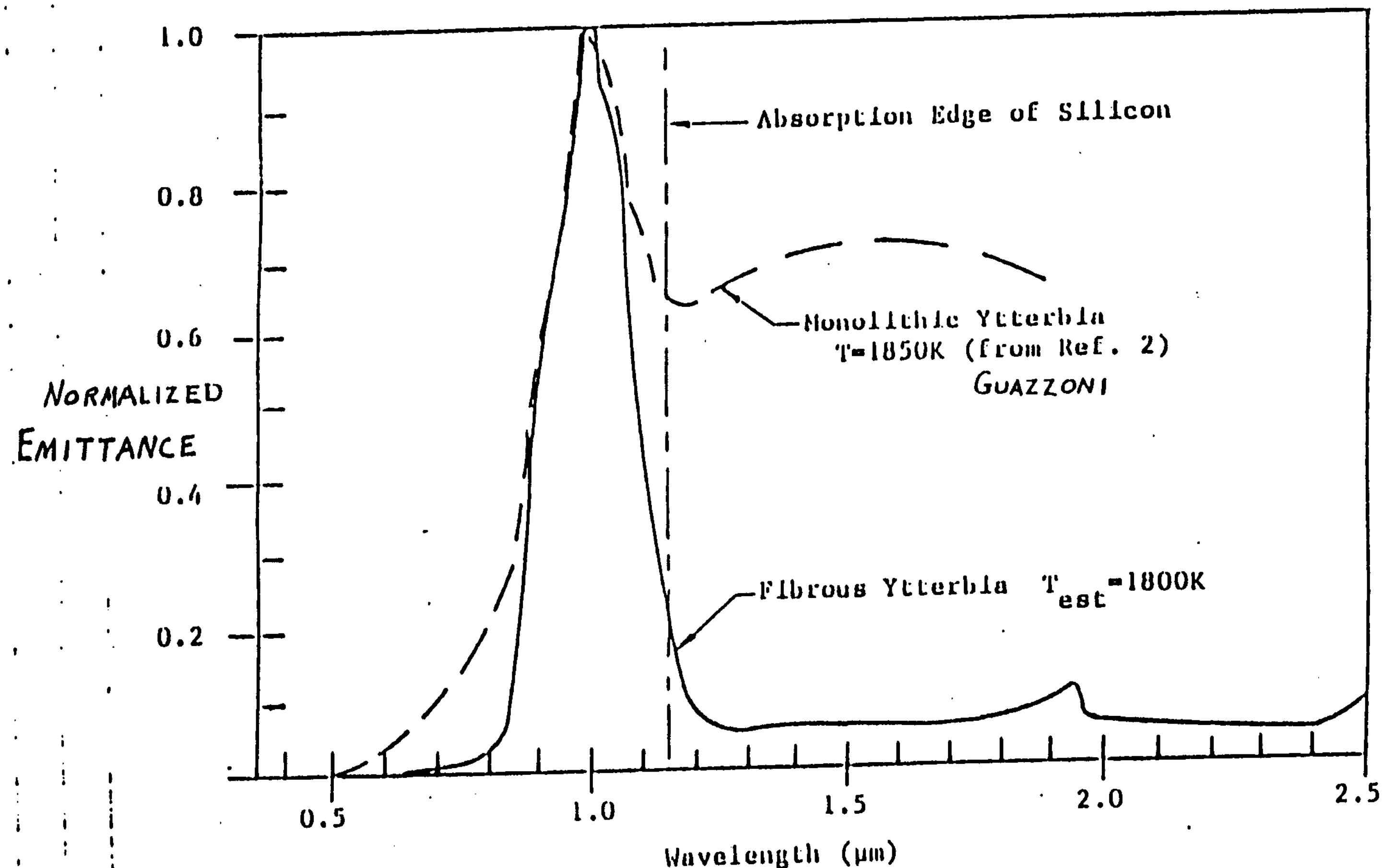
-Electron Structure for X^{+++}

$$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 5s^2 5p^6 4f^N$$

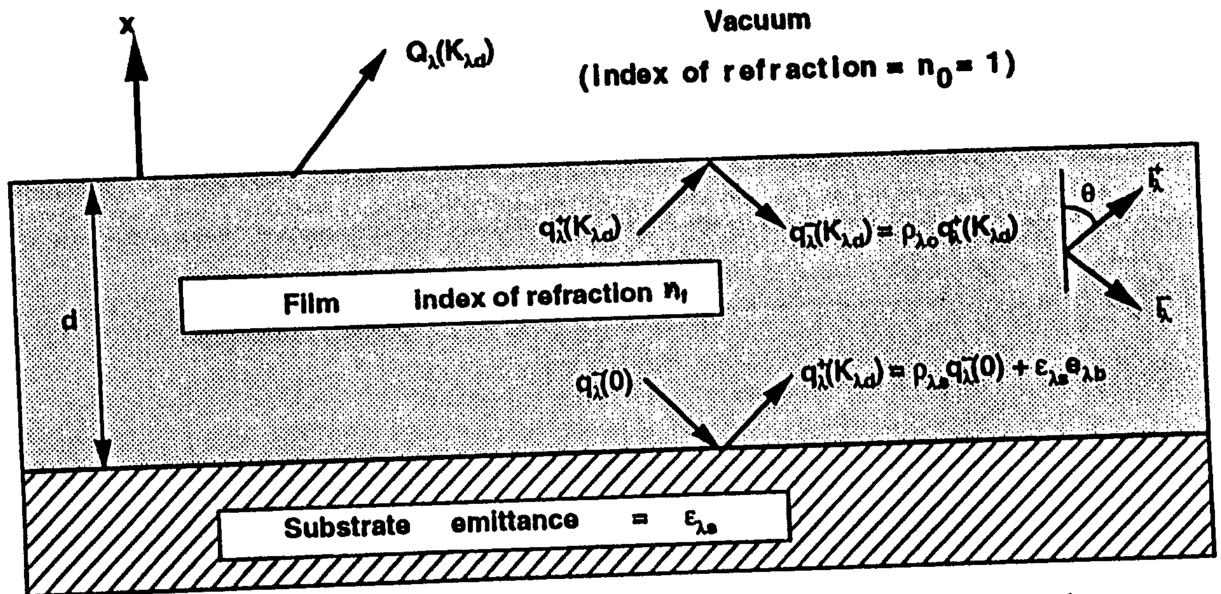
N=1 for Cerium, N=13 for Ytterbium & Lutetium

-4f valence electrons shielded by 5s & 5p electrons

COMPARISON OF NELSON & GUAZZONI EMITTERS



SCHEMATIC OF EMITTING FILM



$\rho_{\lambda s}$ = reflectivity of film-substrate interface

$\rho_{\lambda o}$ = reflectivity of film-vacuum interface

$K_{\lambda d} = \alpha_\lambda d$ – opticaldepth of film

$e_{\lambda b}$ = black body emissive power

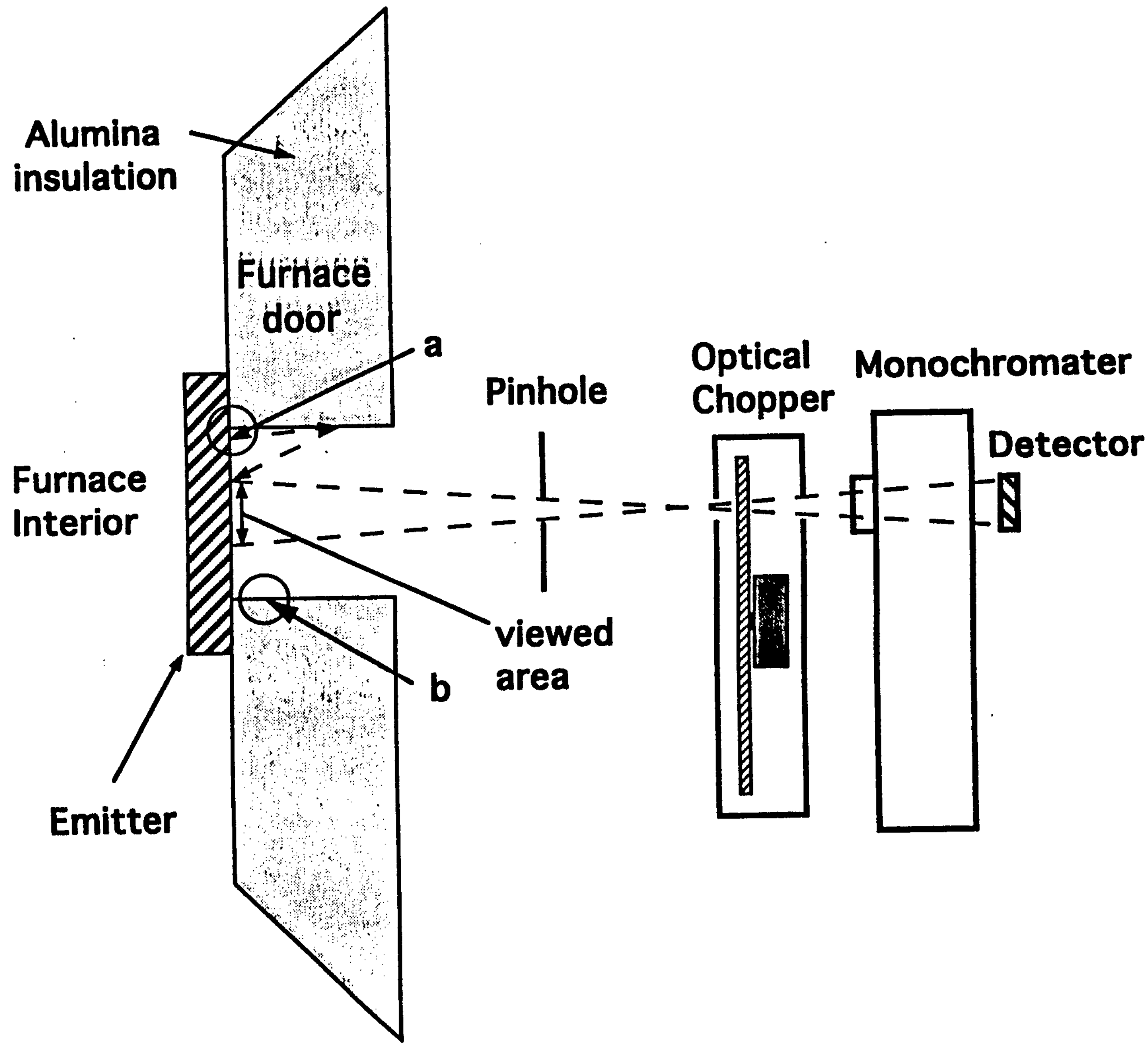
$\varepsilon_{\lambda s}$ = spectral emittance of substrate

α_λ = extinctioncoefficient

For $\rho_{\lambda o} = 0$ $(n_f = 1)$,

$$\epsilon_\lambda = \frac{Q_\lambda(K_{\lambda d})}{e_{\lambda b}} \approx 1 - \exp\left(-\frac{3}{2}K_{\lambda d}\right) + \epsilon_{\lambda s}\exp\left(-\frac{3}{2}K_{\lambda d}\right)$$

EXPERIMENT FOR MEASURING SPECTRAL EMITTANCE

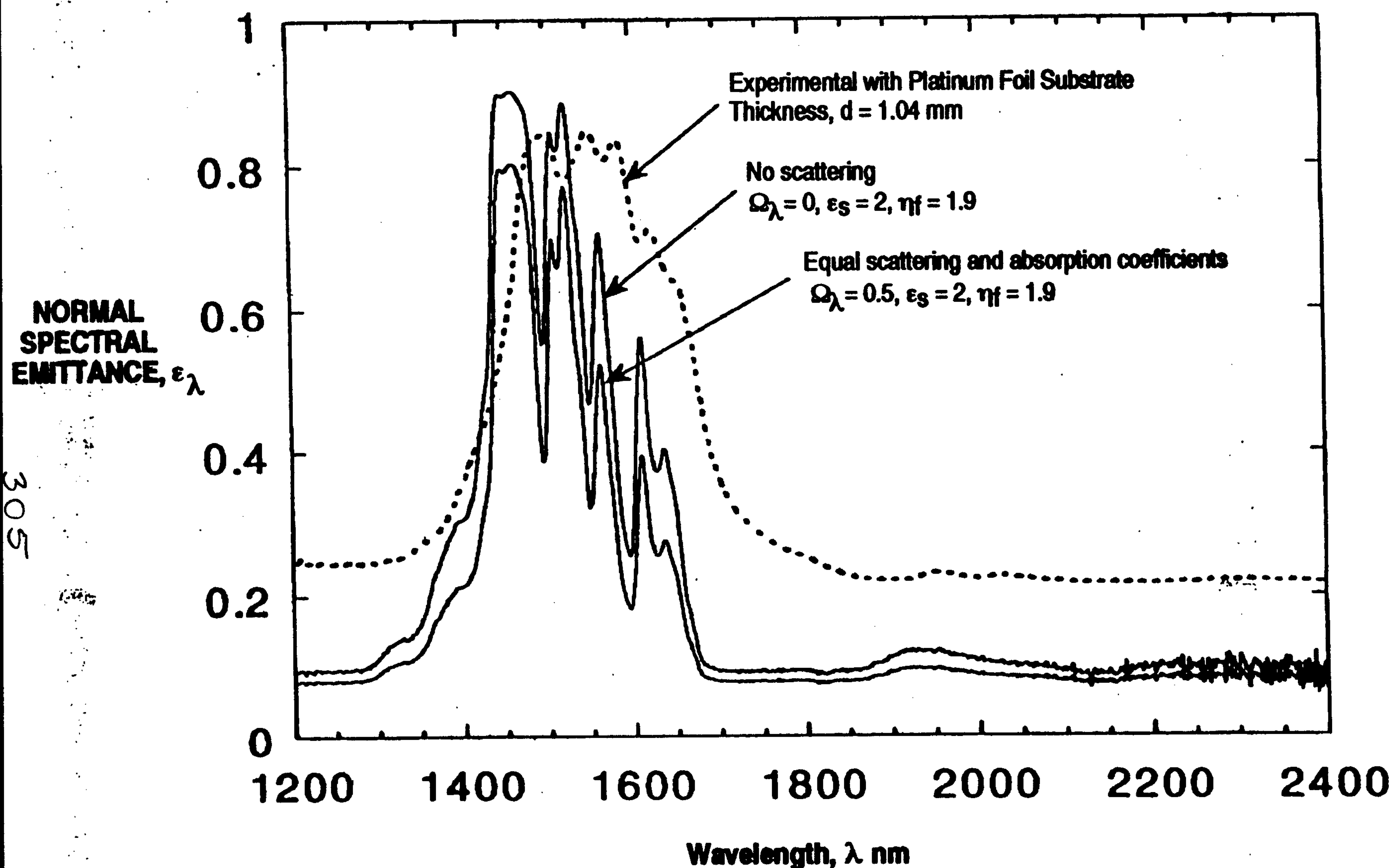


National Aeronautics and Space Administration

Lewis Research Center

POWER TECHNOLOGY DIVISION

THEORETICAL AND EXPERIMENTAL SPECTRAL EMITTANCE FOR E_R (40%) -YAG AT T_E I_{AVG} = 1500 K



National Aeronautics and Space Administration

Lewis Research Center

POWER TECHNOLOGY DIVISION

RARE EARTH-YAG SELECTIVE EMITTER EFFICIENCY

EMITTER EFFICIENCY,

$$\eta_E = \frac{\text{POWER IN EMISSION BAND}}{\text{TOTAL POWER EMITTED}}$$

RARE EARTH-YAG ε_λ CAN BE APPROXIMATED BY 4 BAND MODEL; $\varepsilon_u, \varepsilon_b, \varepsilon_\ell, \varepsilon_c$

$$\eta_E = \left[1 + \frac{\varepsilon_\ell(K_\ell)}{\varepsilon_b(K_b)} f\left(\frac{1}{\lambda_\ell T_E}, \frac{1}{\lambda_u T_E}\right) + \frac{\varepsilon_u(K_u)}{\varepsilon_b(K_b)} g\left(\frac{1}{\lambda_\ell T_E}, \frac{1}{\lambda_u T_E}\right) + \frac{\varepsilon_c(K_c)}{\varepsilon_b(K_b)} h\left(\frac{1}{\lambda_\ell T_E}, \frac{1}{\lambda_u T_E}, \frac{1}{\lambda_c T_E}\right)\right]^{-1}$$

$(K_\lambda) = \alpha_\lambda d$ - OPTICAL DEPTH α_λ - EXTINCTION COEFF. d = FILM THICKNESS

T_E = EMITTER TEMP.

EMITTANCE OPTICAL DEPTH DEPENDENCE,

$$\varepsilon_\lambda \sim 1 - \exp[-3/2\, K_\lambda]$$

THEREFORE,

- FOR FIXED T_E THERE IS OPTIMUM d FOR MAXIMUM η_E

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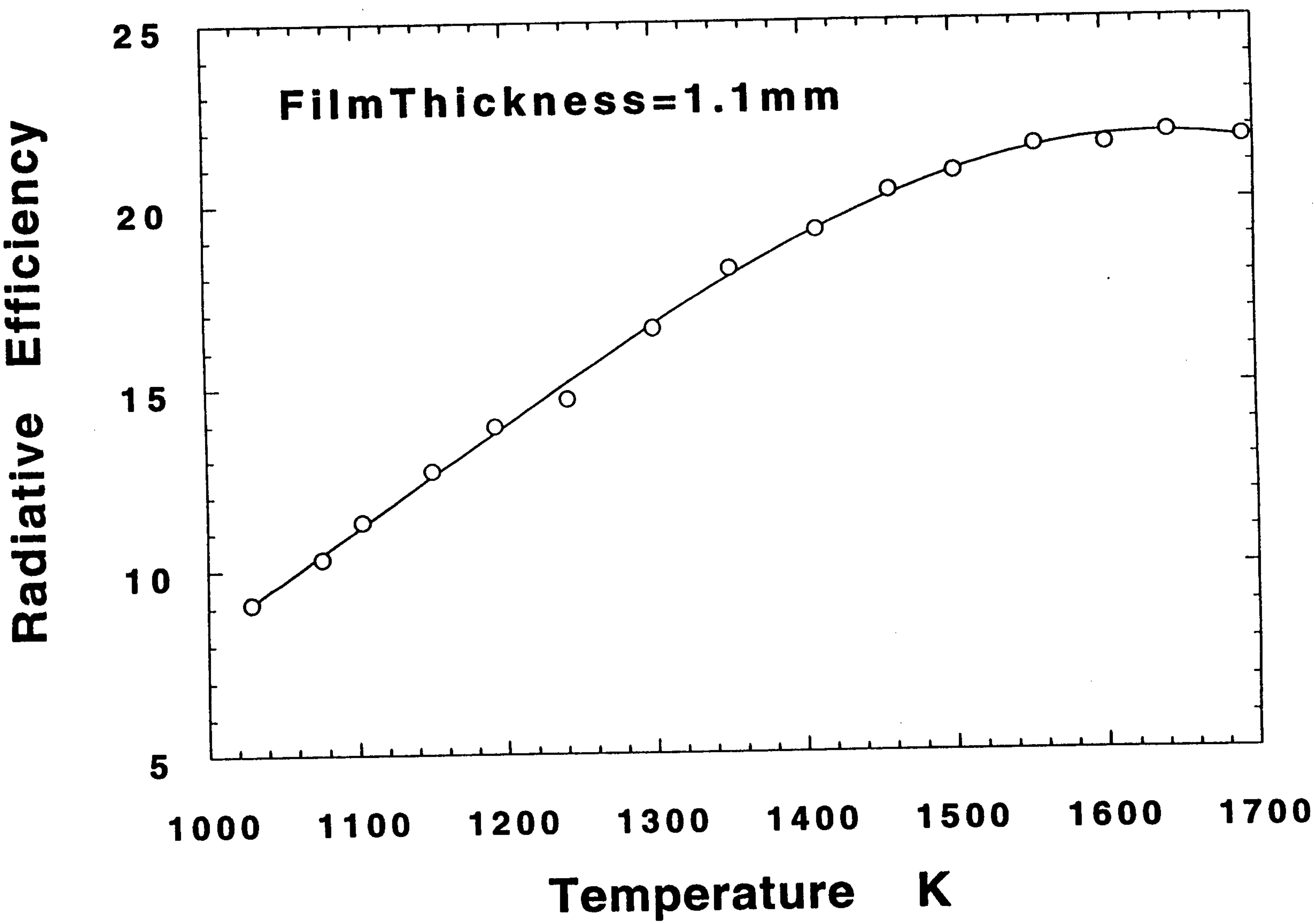
Efficiency of Ho(25%)-Yag Selective Emitter



Rare Earth Selective Emitter Characteristics

1) Single high emittance(>.7) emission band in IR with greatly reduced emittance outside emission band

2) For fixed emitter temperature there is an optimum characteristic dimension for maximum efficiency

3) For fixed characteristic dimension there is an optimum emitter temperature for maximum efficiency

4) Must maintain low substrate emittance to attain high efficiency

Rare Earth Selective Emitter Research

Fibrous Emitters (pure rare earth oxide, R_2O_3)

1) Tecogen - Waltham, MA
2) Auburn Space Power Institute - Auburn, AL
3) Quantum Group - San Diego, CA

Thin Film Emitters

1) NASA Lewis - Cleveland, OH (Rare earth doped ceramic)
2) Essential Research - Cleveland, OH (Rare earth doped ceramic)
3) Creare - Hanover, NH (R_2O_3)
4) Auburn Space Power Institute (R_2O_3 + alumina or silica)

Other

1) University of Massachusetts - Lowell, MA (porous R_2O_3 + alumina)

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STATUS OF TPV RESEARCH AT SPACE POWER INSTITUTE

Peter Adair

Space Power Institute is currently performing research on a thermophotovoltaic system to provide power to a soldier in the battlefield. The research is sponsored by the Army Research Office. The main issues that are being studied are emitter and burner issues. We are continuously looking to improve the strength of the composite emitters that were developed at Auburn University and quantify these improvements. We also have looked at how the emitter temperature affects the radiant output. We have defined our selective efficiency as the radiation centered between 1 and 2 μm in wavelength and determined that the efficiency of erbia increases with increasing temperature and reaches a plateau of around 29% after 1850K. Similarly, we looked at using erbia and thulia in the same composite emitter to increase the selective efficiency. We varied the ratio of the constituents and determined that as much as 42% selective efficiency can be attained. This particular emitter can be used to increase the photovoltaic cell electrical output power density while still maintaining a relatively high conversion efficiency. It should be noted however that only the radiation above the bandgap can be photoconverted. We have also investigated the radiant power to electrical power conversion efficiency of the composite emitters illuminating InGaAs photovoltaic cells. The cells were obtained under a cooperative agreement with NASA Lewis Research Center. We investigated three different cells with bandgaps of 0.75, 0.66, and 0.60 eV. We achieved a conversion efficiency of 16% with the 0.75 eV cell when illuminated by an erbia emitter. Conversion efficiencies of 8.4 and 5.7% were achieved with the 0.66 and 0.6 eV cells respectively, when illuminated by an erbia/thulia composite emitter.

Space Power is in the process of fabricating a prototype TPV system and developing a model for predicting TPV system performance. We investigated several different composite emitter geometries that could be used in the burner system for the TPV prototype. A cylindrical type system will be used to illuminate 100 cm^2 of lattice-matched 0.75 eV InGaAs photovoltaic cells. The photovoltaic cells were purchased from the Research Triangle Institute. The prototype will consist of a diffusion type burner with air and propane as the inlet fuels which will in turn heat a composite emitter. The radiant output of the composite emitter has to be uniform as both a function of height and azimuthal angle around the emitter. The emitter must also have a large radiating surface in a small volume. We found that a spoke shaped emitter satisfies these criteria.

PROSPECTOR VIII: TPV - UPDATE OF DOD, ACADEMIC, COMMERCIAL RESEARCH
JULY 14-17, 1996

SPACE
POWER
INSTITUTE

STATUS OF TPV RESEARCH AT SPACE POWER INSTITUTE

Peter Adair

Auburn University

Primary Goal of Research

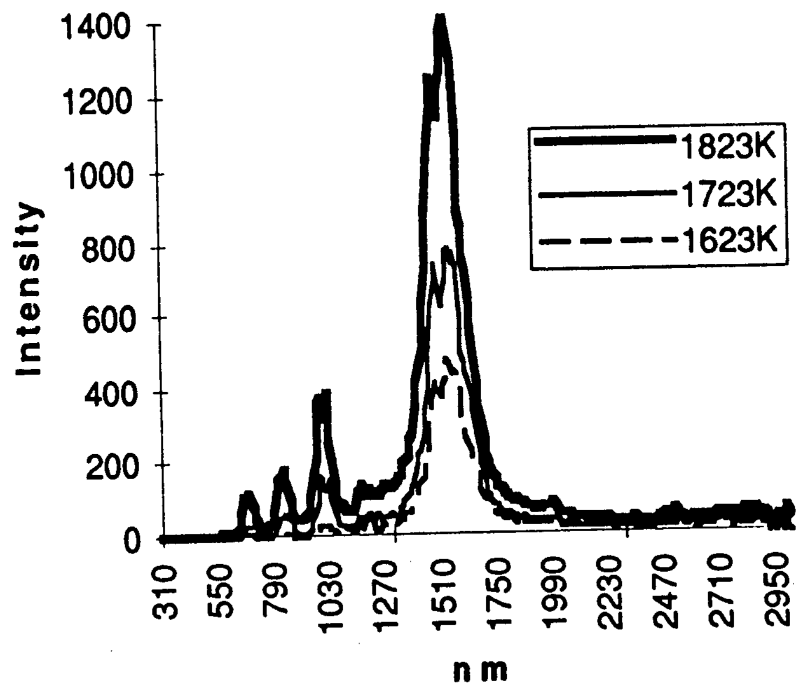
Design and test a small prototype TPV power generation unit that will supply power to a soldier in the battlefield

Emitter Developments

- Mechanical Strength (*Zheng Chen*)
- Influence of Temperature on Selective Efficiency for Erbia Emitters
- Spectra of Emitters Containing Erbia and Thulia
- Radiative Effects as a Function of Emitter Geometry in TPV System

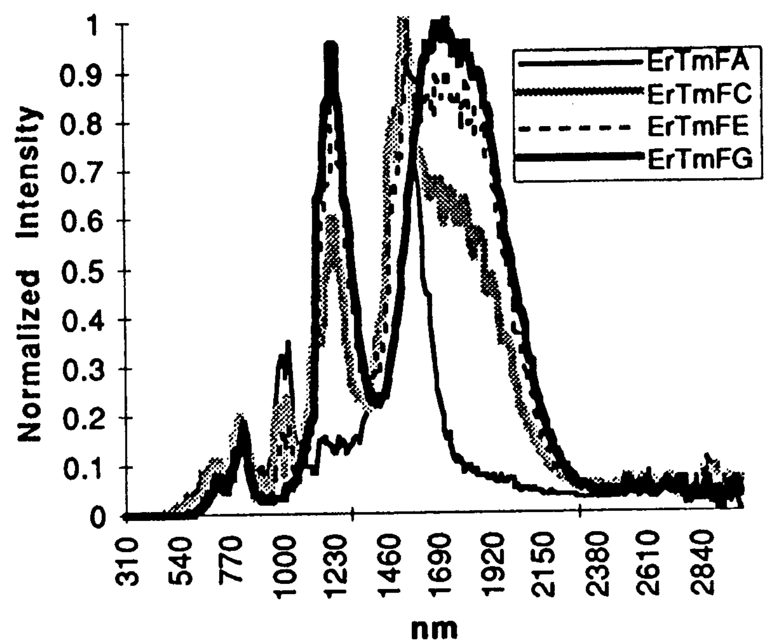
Emitter Temperature Effects

- Spectral radiation at 3 temperatures
- Efficiency defined between 1 and 2 μm
- Selective efficiency increases with temp.
- Reaches plateau of 29% after 1850K



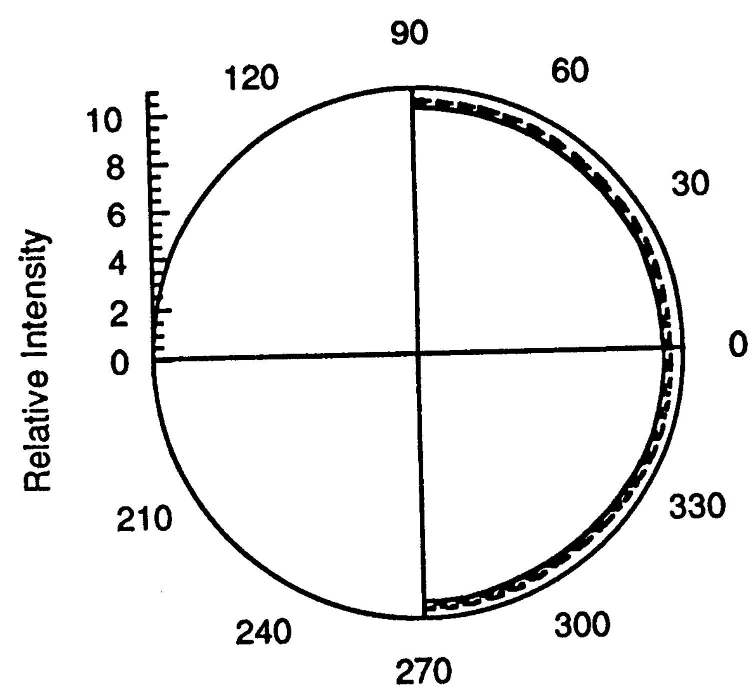
Erbia/Thulia Emitters

- Normalized radiant spectra of 4 emitters with erbia and thulia
- Highest selective efficiency was 42%
- Er/Tm mix can be used to increase output power density



Emitter Geometry Effects

- Uniformity of output radiation as a function of height and angle
- Tested several geometries
- Desire large radiating surface in small volume

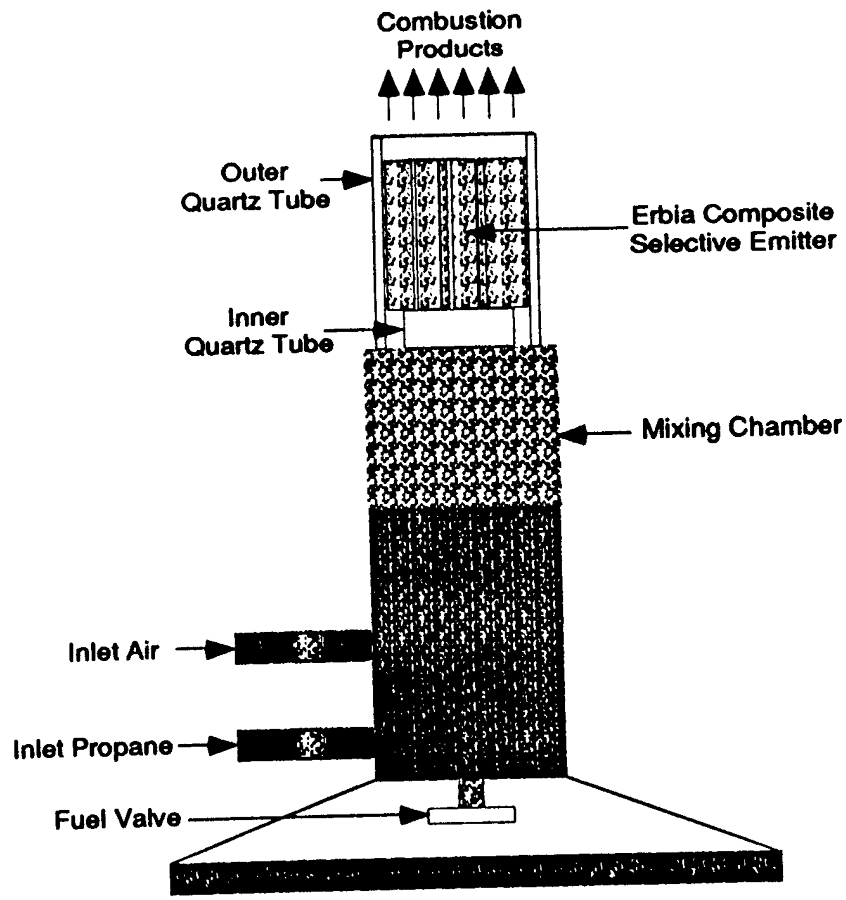


System Developments

- Gaseous burner system developed
- Radiant to electrical power conversion efficiency determined
- Laboratory TPV system designed
- Model for predicting TPV system performance (*Ken Schroeder*)

Burner System

- Diffusion type burner
- Flow rated propane and air used as inlet fuels
- Mixed gas exits vertically through wire screen

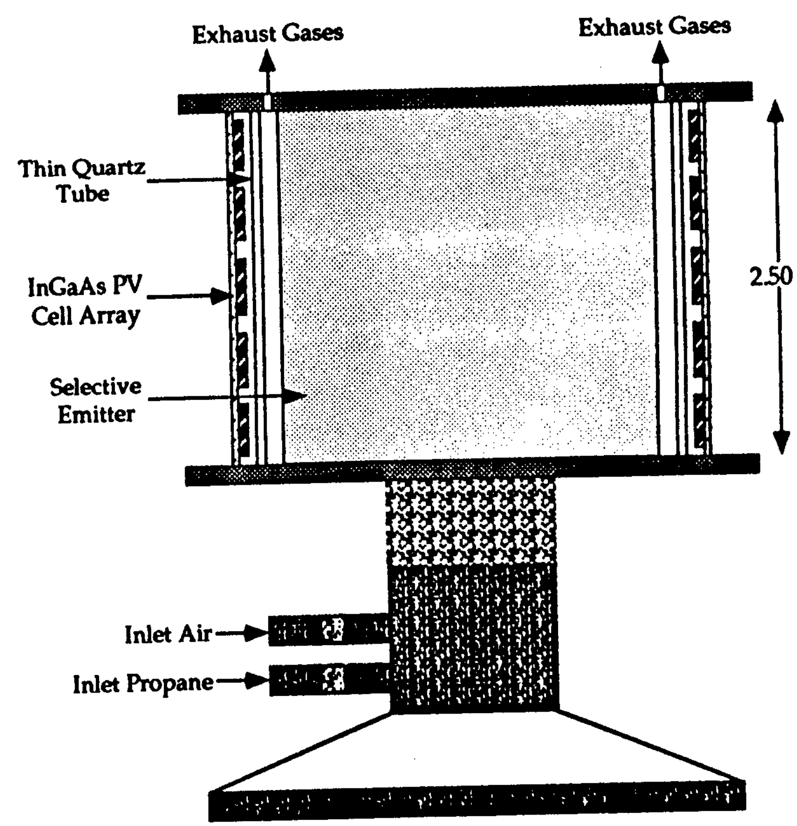


Conversion Efficiency

- 0.75, 0.66, and 0.60 eV InGaAs cells used (*NASA Lewis*)
- Illuminated by Er, Tm, Er/Tm, Ho, and SiC at same radiant power level
- Determined Er illuminating 0.75 eV cell has highest efficiency of 16%
- Conversion efficiencies of 8.4 and 5.7% with 0.66 and 0.60 eV cells with Er/Tm

TPV System

- Diffusion type burner
- 100 cm^2 0.75 eV lattice-matched InGaAs cells
- Cylindrical configuration



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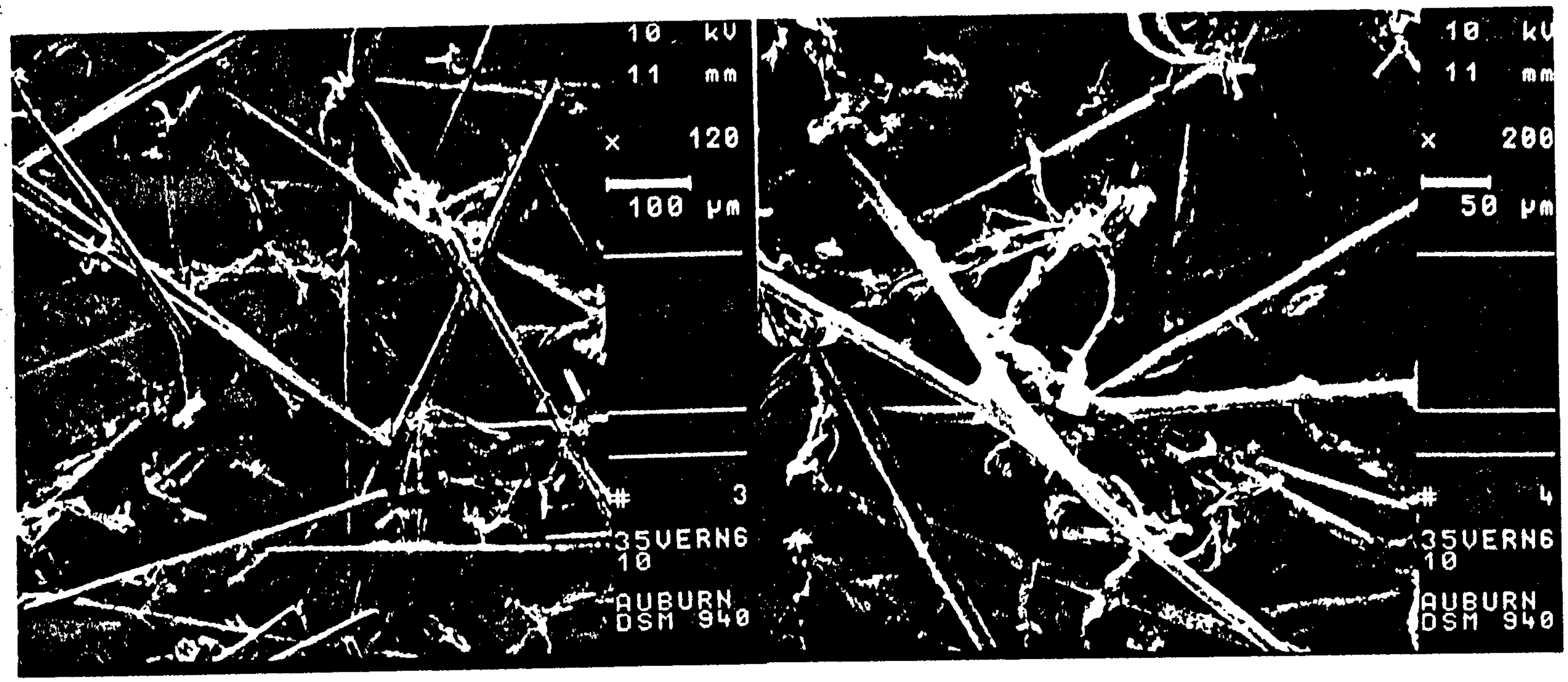
Characterization of Mechanical Strength of Fibrous Er_2O_3 Emitter

Zheng Chen
Space Power Institute
231 Leach Science Center
Auburn Alabama 36849

SEM Micrographs Show The Texture Of The Emitter



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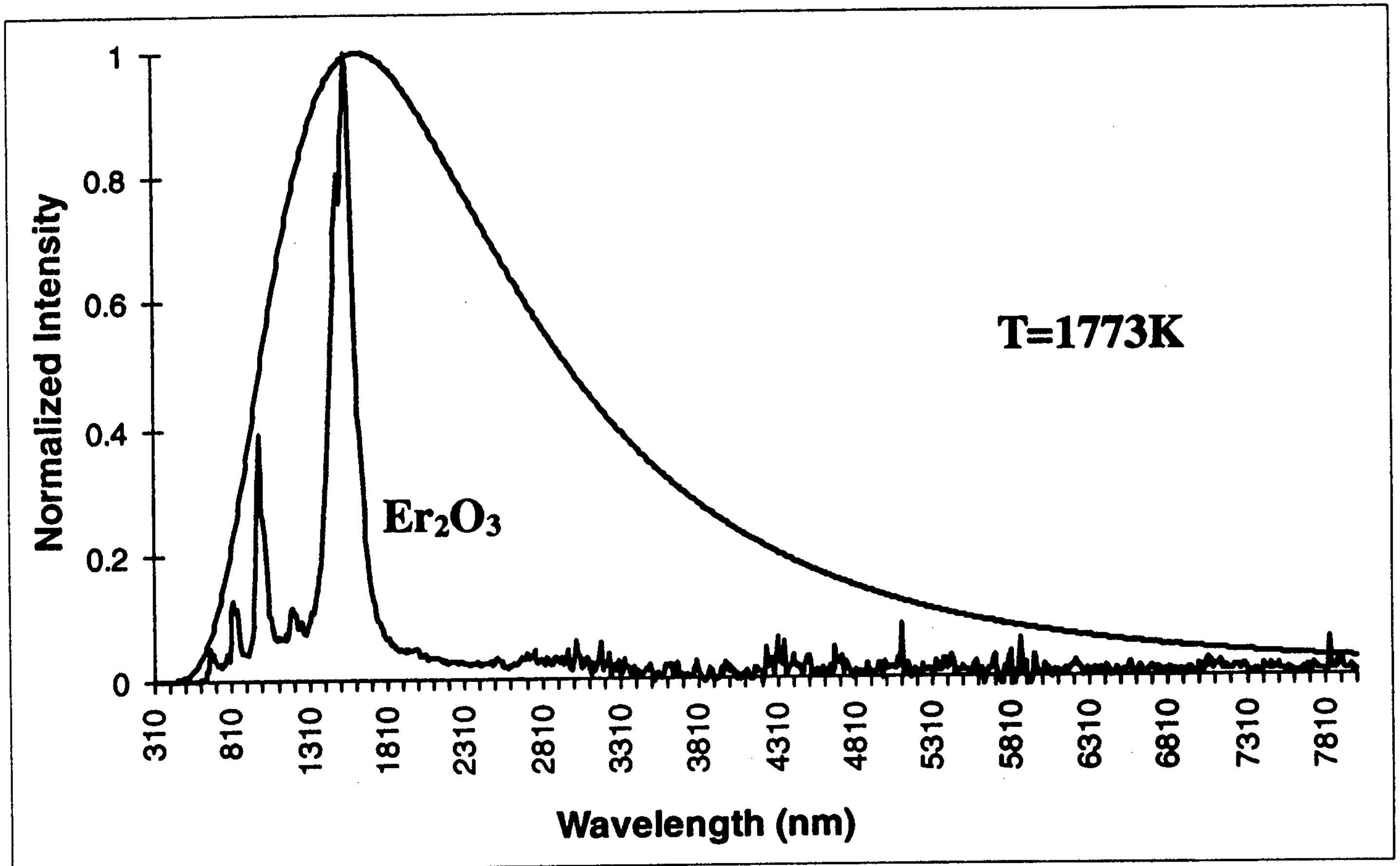
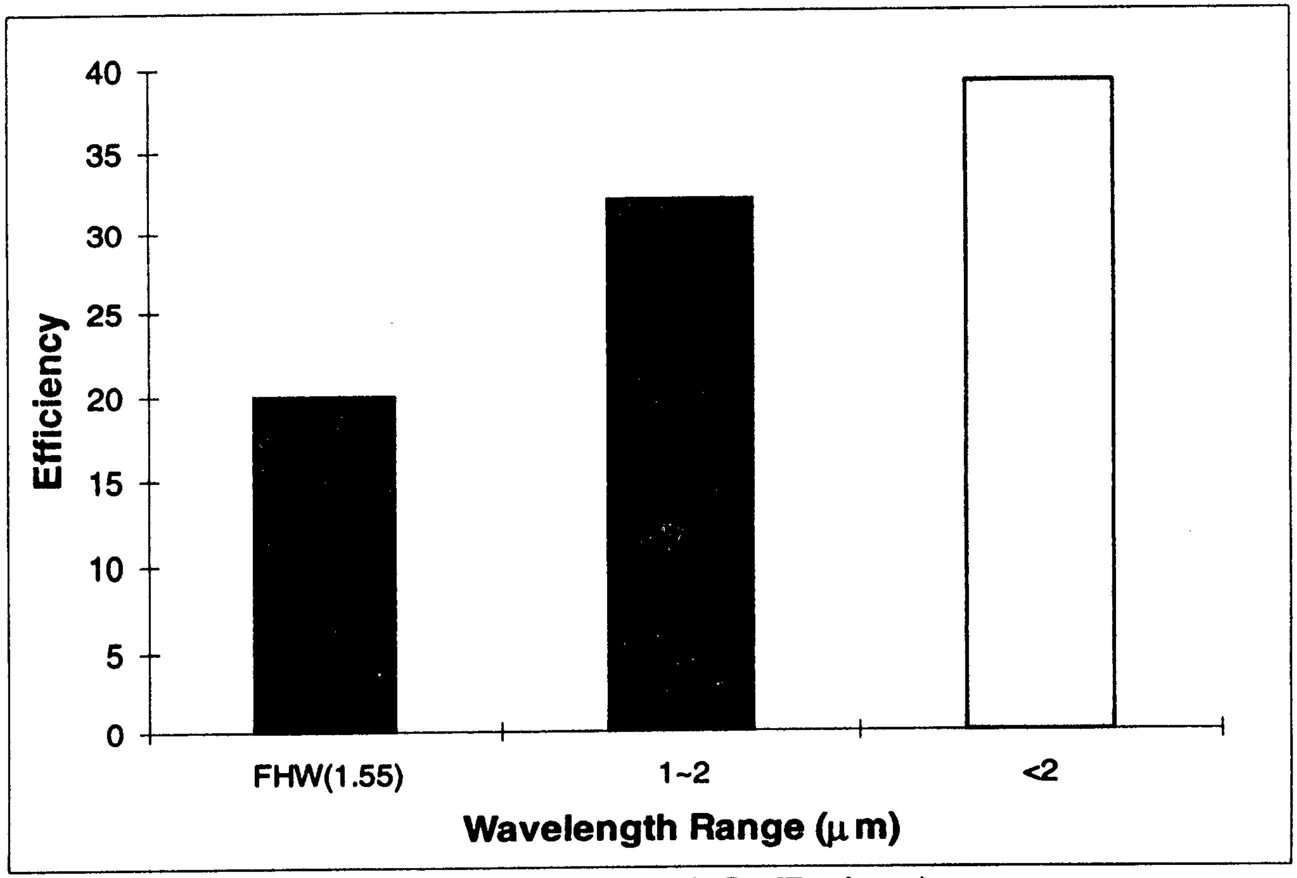
Er_2O_3/Al_2O_3 Emitters Shows Low Out-OF-Band Emission



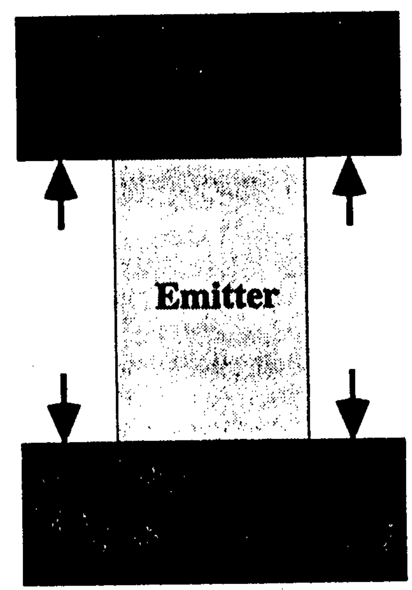
Peak/Background Ratio > 20

Efficiency Can Be Evaluated In Different Ways

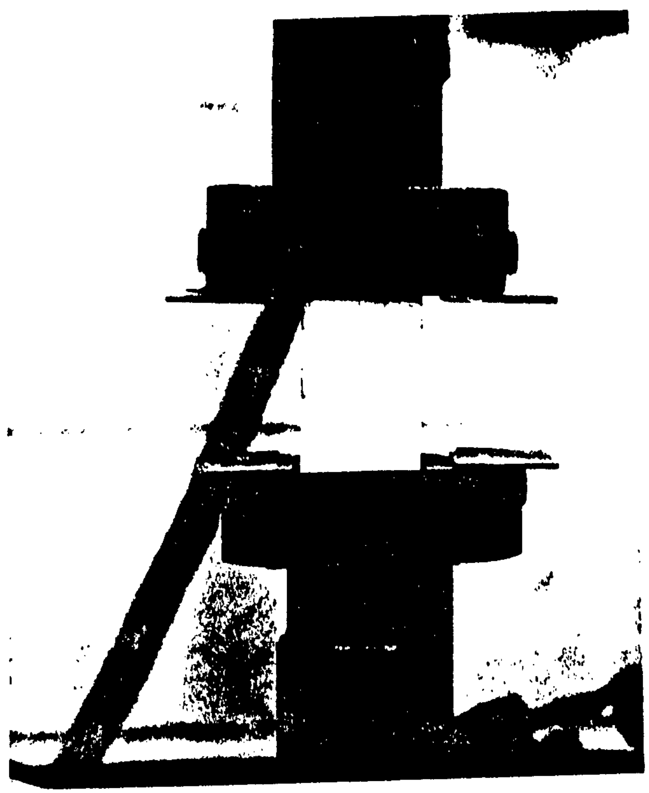


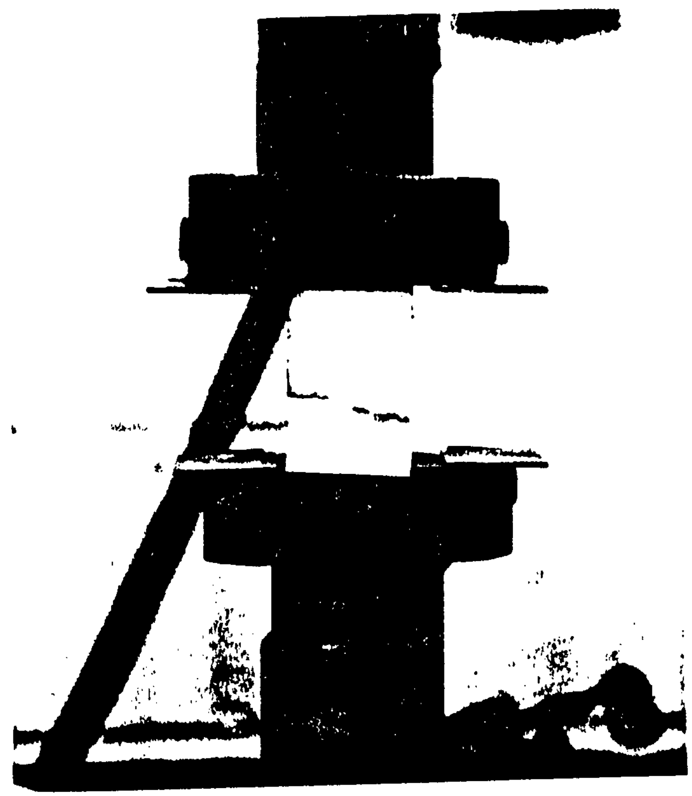
(Fibrous Er_2O_3/Al_2O_3 Emitter)

Specimen Is Deigned For Tensile Test



A Sample Was Testing In A Testing Machine





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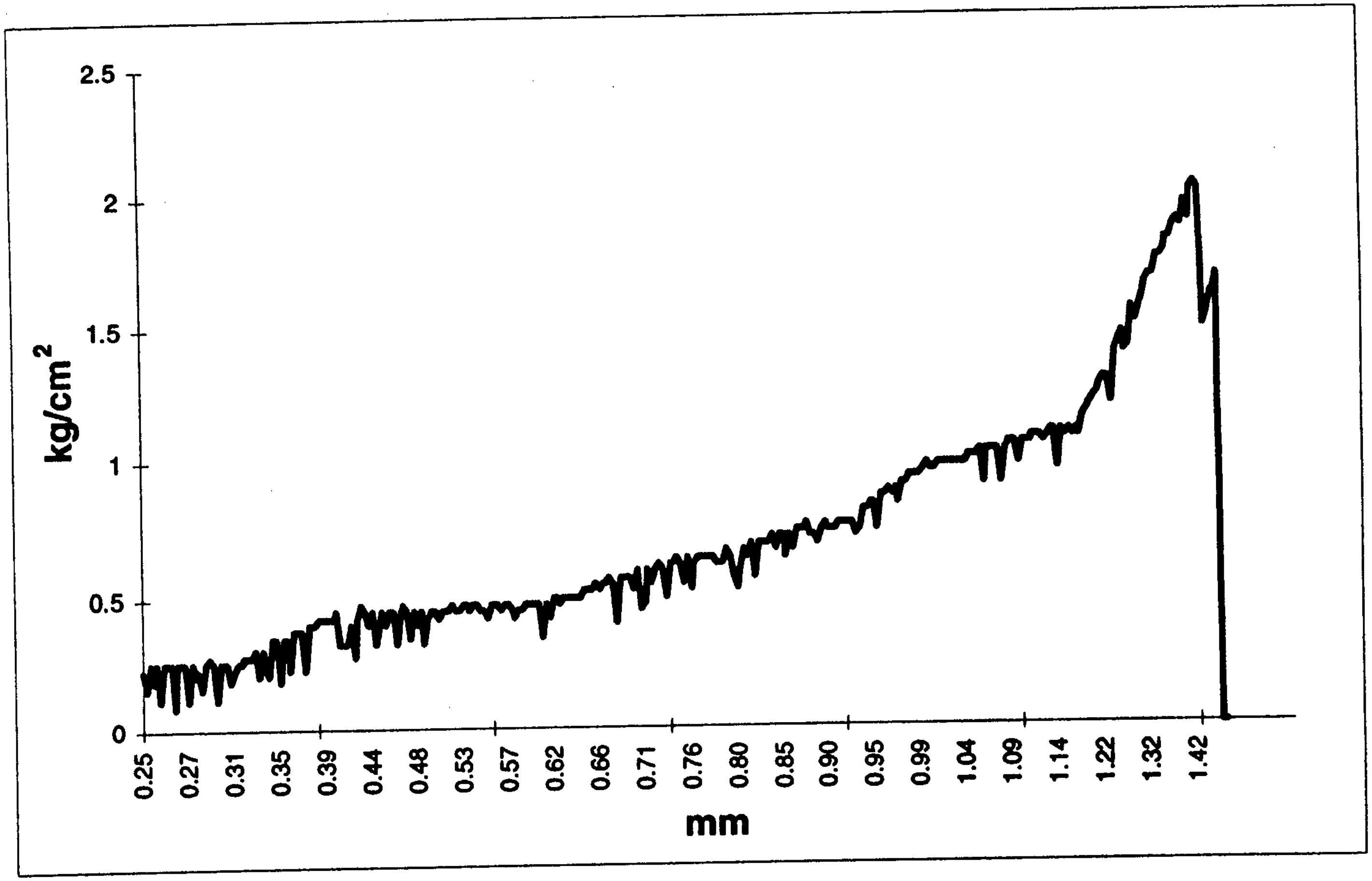
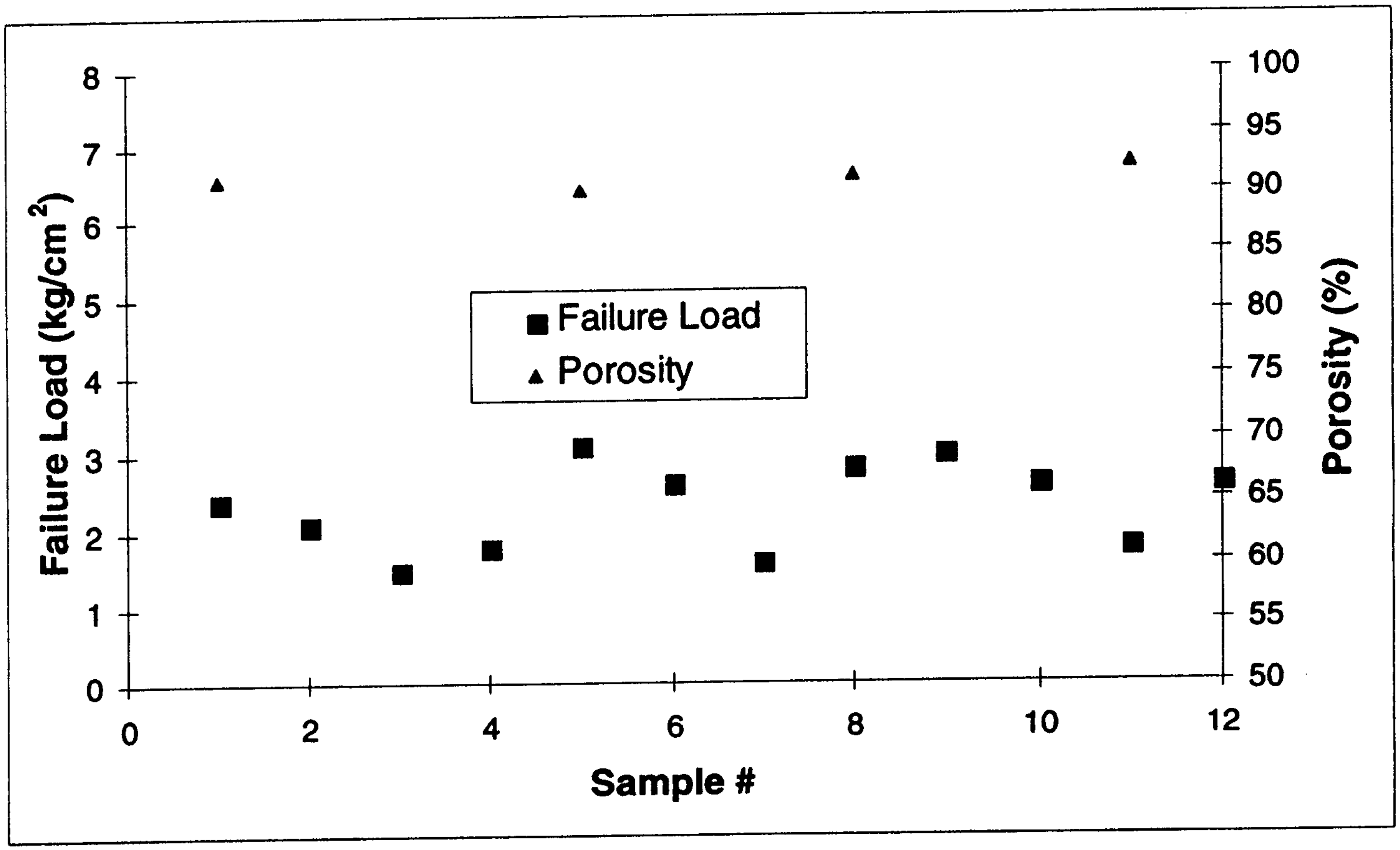
A Typical Load -Displacement Curve Of Fibrous Emitter



Failure Load and Porosity of Fibrous Emitters



Failure Load=2.3±0.5 kg/cm^2 and Porosity=91.2±0.8%

Conclusions

*A balance of mechanical robust and good in-band efficiency can be achieved.

*A compressed spectral power can be adjusted.

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A Model for Predicting TPV Systems Performance

Kenneth Schroeder
Space Power Institute
Auburn University, Alabama 36849

Research in TPV has primarily been focused at the component level (i.e. a particular type of emitter or photovoltaic). This has lead to the proposal of a wide variety of different system configurations. Unfortunately, the primary basis for these configurations often depends on whichever element is of particular interest to the researcher. While the performance of the element may seem to be promising, it may be degraded of out-weighed by the other components when incorporated into a system. Thus, a method is needed for evaluating these system effects and comparing the performance of the various system types.

A model is presented for predicting the performance of a TPV system. The system is assumed to be a combustion based system and is represented as two principal components: radiant transfer element and heat source. The model is energy based and initially considers the interaction between emitting source and the photovoltaic. These components and the thermal barrier / reflective filter separating them, make up the radiant transfer element of the system. The formulation of the transfer efficiency begins with the definition of photovoltaic efficiency and includes the photocell parameters as isolated terms . Additionally, the formulation is nondimensionalized in terms of the efficiency of the radiant source. Examples of typical values for these terms are presented. Once an emitter / pv configuration has be defined, experimental data can be used to calculate a radiant transfer efficiency and establish the thermodynamic requirements for the heat source. The analysis of the heat source considers the thermodynamic state of a combustor at six points: (a) input, (b) preheat, (c) combustion, (d) energy extraction and (e) ambient. The formulation of the thermal efficiency includes parameters for both thermal losses and heat recuperation, and a self consistent set of equations is derived in terms of the flow enthalpy. Since the overall system efficiency is the product of the radiant transfer and thermal efficiencies, the effect on system performance of the various component terms and parameters can be evaluate and examples of these effects are presented for several cases.

A Model for Predicting TPV Systems Performance

Kenneth Schroeder
Space Power Institute
Auburn University, Alabama 36849

Presented at Prospector VIII:
TPV - Update of DoD, Academic, Commercial Research
July 15, 1996

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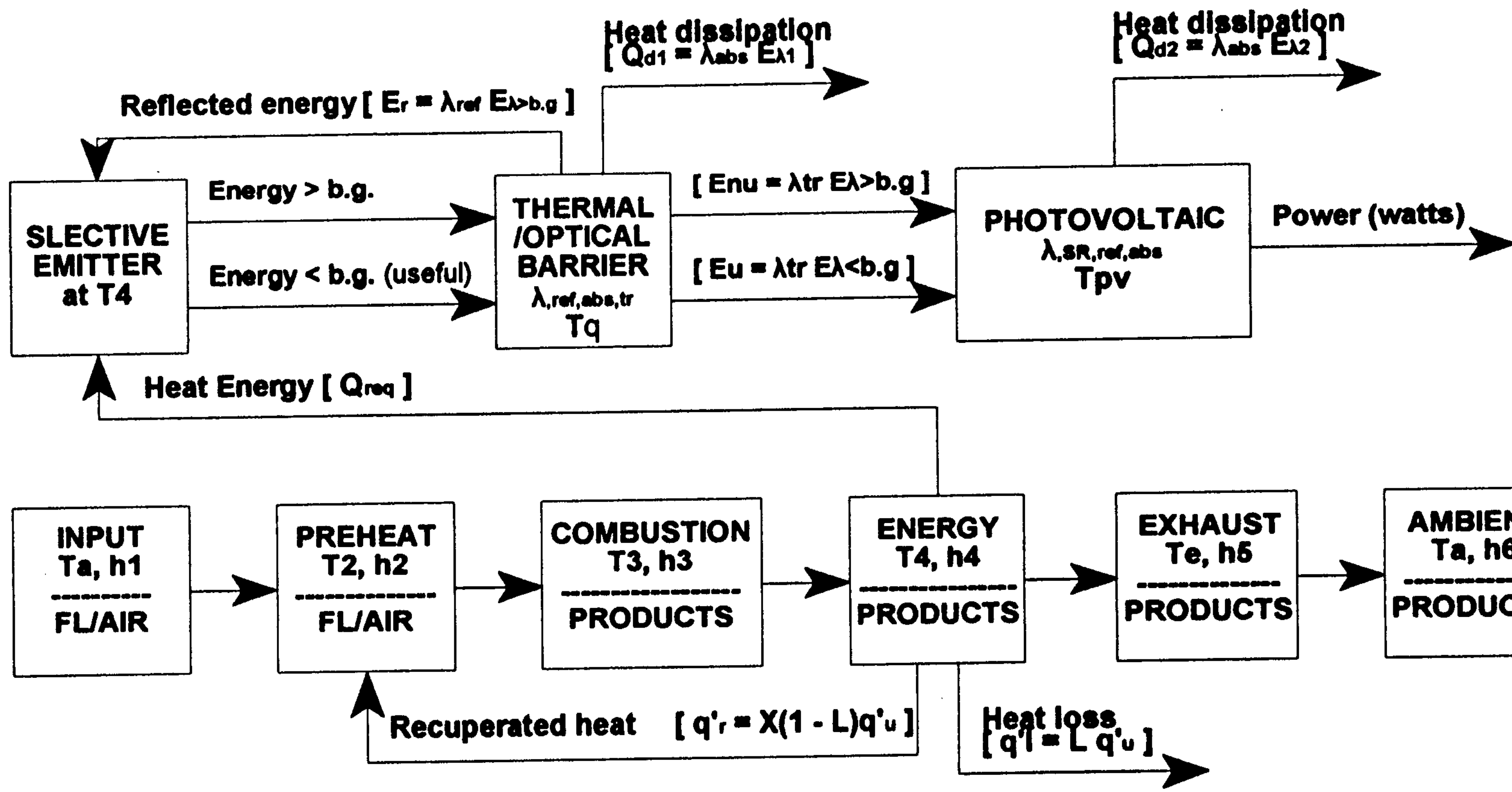
* This work was sponsored by the Army Research Office under contract DAAL039260205

Why develop a System Model?

Research in TPV has primarily been focused at the component level (i.e. a particular type of emitter or photovoltaic). This has led to the proposal of a wide variety of different system configurations. Unfortunately, the primary basis for these configurations often depends on whichever element is of particular interest to the researcher. While the performance of the element may seem to be promising, it may be degraded or out-weighed by the other components when incorporated into a system. Hence a method is needed for evaluating these system effects and comparing the performance of the various system types.

SYSTEM BLOCK DIAGRAM



Radiant Transfer Equations (overview)

For a photovoltaic the efficiency can be calculated as:

$$\eta_{PV} = \frac{P_m}{P_{in}} = \frac{V_{oc} I_{sc} FF}{incident\ power}$$

where V_{OC} is the open circuit voltage, I_{SC} is the short circuit current and FF is the fill factor. By evaluating the radiant transfer from the emitter to the p.v. on a per unit area basis and by considering the definition of external spectral response (SR_{EXT}), the transfer efficiency is defined as:

$$\eta_{RT} = V_{oc} FF \int_{\lambda = 0}^{\lambda = BG} SR_{EXT}(\lambda)\, SE(\lambda)\, d\lambda\, [(\eta_{E,BBG} + \eta_{E,IMP})\tau]$$

where SE represents the nondimensionalized spectral emissions of the radiating source and $\eta_{E,BBG}$ is the percentage of total useful power. The transmittance term τ is included in the formulation to account for the presence of the thermal barrier or filter. Any re-reflected radiation will result in an improvement in the effective percentage of useful power ($\eta_{E,IMP}$) and is addressed in terms of a single parameter ρ which is only applied to the nonuseful portion of the radiation spectrum.

$$\eta_{E,IMP} = \sum_{N=1}^{\infty} [(1 - \eta_{E,BBG})\rho]^N$$

The amount of energy required from the heat source is then evaluated in terms the power output required as:

$$Q_{REQ} = \frac{Electrical\ Power}{\eta_{RT}}$$

TABLE 1. PERCENT OF RADIATION BELOW THE PV BAND GAP

	Photovoltaic	Silicon	InGaAs	GaSb
Emitter	Temperature (°C)	$\eta_{E,BBG}$ (%)	$\eta_{E,BBG}$ (%)	$\eta_{E,BBG}$ (%)
Black body	1800	13.7	36.6	38.8
Ytterbia[a]	1800	36.0	39.8	40.0
Black body	1350	4.8	20.0	21.9
Erbia[b]	1350	7.6	40.3	43.8

[a] derived from Nelson's data as reported by White (1995)

[b] extracted from Adair (1995)

TABLE 2. Example values of photocell parameters*

	V_{OC}		FF	
	theo. max	typical	calc.	typical
Silicon	1.12	0.62	0.894	0.796
Silicon[a]	1.12	0.73	0.894	0.745
InGaAs	0.75	0.36	0.853	0.742
GaSb	0.73	0.40	0.851	0.800
GaSb[b]	0.73	0.49	0.851	0.813

* compiled from various sources

[a] 41x concentration

[b] 200 suns

Heat Source Equations (overview)

(a) Initially, fuel and air are input at a given mixture ratio and temperature T_1, with enthalpy content $h_1 = x_{OX}Cp_{OX}T_{1,OX} + x_{FU}Cp_{FU}T_{1,FU}$.

(b) The reactants are preheated prior to combustion by the addition of heat energy (q_R) recuperated from the exhaust. Thus, raising the reactant's temperature to T_2 and the enthalpy to $h_2 = h_1 + q_R$.

(c) Combustion occurs resulting in the formation of combustion products at an increased temperature T_3 with enthalpy content h_3. Combustion efficiency is included in the calculation of h_3 by reducing the value on the net heat of combustion (H_C) by a factor of $1.0 - \eta_{COMB}$.

(d) The energy required (Q_{REQ}) by the radiant transfer element is extracted from the flow at an effective temperature of radiation T_4, reducing the enthalpy of the products to h_4. The amount of fuel required can then be calculated as $mdot_{fu} = Q_{REQ} / (Sq_{34})$, where $q_{34} = h_3 - h_4$. Additionally, a portion of the remaining available heat ($q_U = h_4 - h_6$) is considered to be lost to the environment ($q_L = Lq_U$) and a portion is used for preheating the reactants in part (b), $q_R = X(1 - L)q_U$.

(e) The combustion products are exhausted with enthalpy content $h_5 = h_4 - q_L - q_R$ at the corresponding temperature T_5.

(f) Finally, the exhaust products equilibrate to the ambient temperature T_a with enthalpy content h_6.

The overall thermal efficiency of the heat source is then evaluated in terms of the required radiant output and the heat input of the fuel defined by

$$\eta_t = Q_{REQ} / (\dot{m}_f H_C)$$

Example of Component Effects on System Performance

Increased Incident Radiation	Increase Voc
	Increases Jsc
	Increased Cell Efficiency (for a small cell)
Increased PV Cell Temperature	Reduced Bandgap
	Reduced Voc
	Decreased Cell Efficiency
Increased Radiation Temperature	Increases Thermal Losses
	Increases Thermal Stresses
	Decreased Radiant Efficiency

Example of System Performance Trade-offs for Various Emitters/P.V. Combinations

Radiation Configuration	Silicon - Black body	Silicon - Ytterbia	* InGaAs - Erbia
P.V. bandgap (μm)	1.15	1.15	1.65
Emitter temp. (°C)	1800	1800	1350
Voc (volts)	0.55	0.55	0.365
Fill factor	0.70	0.70	0.694
Radiation eff. (%)	9.0	9.8	18.8
~~Radiation~~ THERMAL eff (%)	38.7	38.7	54.1
Overall eff. (%)	3.5	3.8	10.2

System Parameters:

- Re-reflected radiation - 95%
- Theoretical air - 110%
- Thermal losses - 10 %
- Combustion eff. - 90%
- Heat recuperation - 50%

CONCLUSION

The model allows use to evaluate performance trade-offs for various system configurations and identify system thermal management issues.

Near term revisions will include radiant transfer calculations for a variety of system configuration, the incorporation of the chemical kinetics code into the base model and the addition of a graphical user interface (GUI).

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Thermophotovoltaic Cell Development Issues

P.R. Sharps and M. L. Timmons

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Research Triangle Park, NC 27709

The two key issues in the development and use of thermophotovoltaic (TPV) cells are performance and cost. The performance issue can never be considered apart from overall system (burner, emitter, and recuperation) design. What works well in one design may be totally inappropriate for use in another design. One important issue in cell performance is spectral control, particularly for black body spectrums. In regards to cell cost, the cell fabrication method (epitaxial vs. diffused single crystal) and the substrate cost must be considered.

At RTI we have been looking at Ge, GaInAs, and GaInAsSb as possible materials for TPV cells. We have delivered pilot line quantities of lattice-matched and lattice-mismatched GaInAs cells. Further development work is still needed with Ge and GaInAsSb for TPV applications.

We will present data on performance and yield of pilot line quantities of both lattice-matched and lattice-mismatched GaInAs cells. Even though GaInAs TPV cells are available in limited quantities, there are still a number of issues that merit attention. The n-on-p polarity has, so far, been the device of choice. This is largely due to the lower emitter sheet resistivity, of paramount importance for high current TPV applications. However, the p-on-n polarity may have advantages in regards to spectral control and manufacturability. Also, there are still issues that need to be pursued to improve the n-on-p polarity performance. For example, heavily doping the InP window in lattice-matched devices leads to a 20% improvement in device performance. In lattice-mismatched devices, alternative step-graded buffer layers besides GaInAs also leads to improved device performance. While the yield and performance of pilot line quantities of cells are encouraging, more work is still needed to further improve the performance of the GaInAs devices.

GaInAsSb materials offer the advantage of lower bandgaps that can be lattice-matched to GaSb, growth of the material using organometallic vapor phase epitaxy (the method of choice for large scale epitaxial growth) is difficult with traditional OMVPE precursors. Again, furhter work is need to develop GaInAsSb as a TPV cell material. Germanium has the advantage of a lower cost substrate, but Ge devices have a problem with low voltages.

While certain types of TPV cells are available, further work is needed to improve the devices, and also to develop new materials for other TPV systems.

RTI

CELL DEVELOPMENT ISSUES

Prospector VIII Workshop

P. R. Sharps and M. L. Timmons
Research Triangle Institute
July 15th, 1996

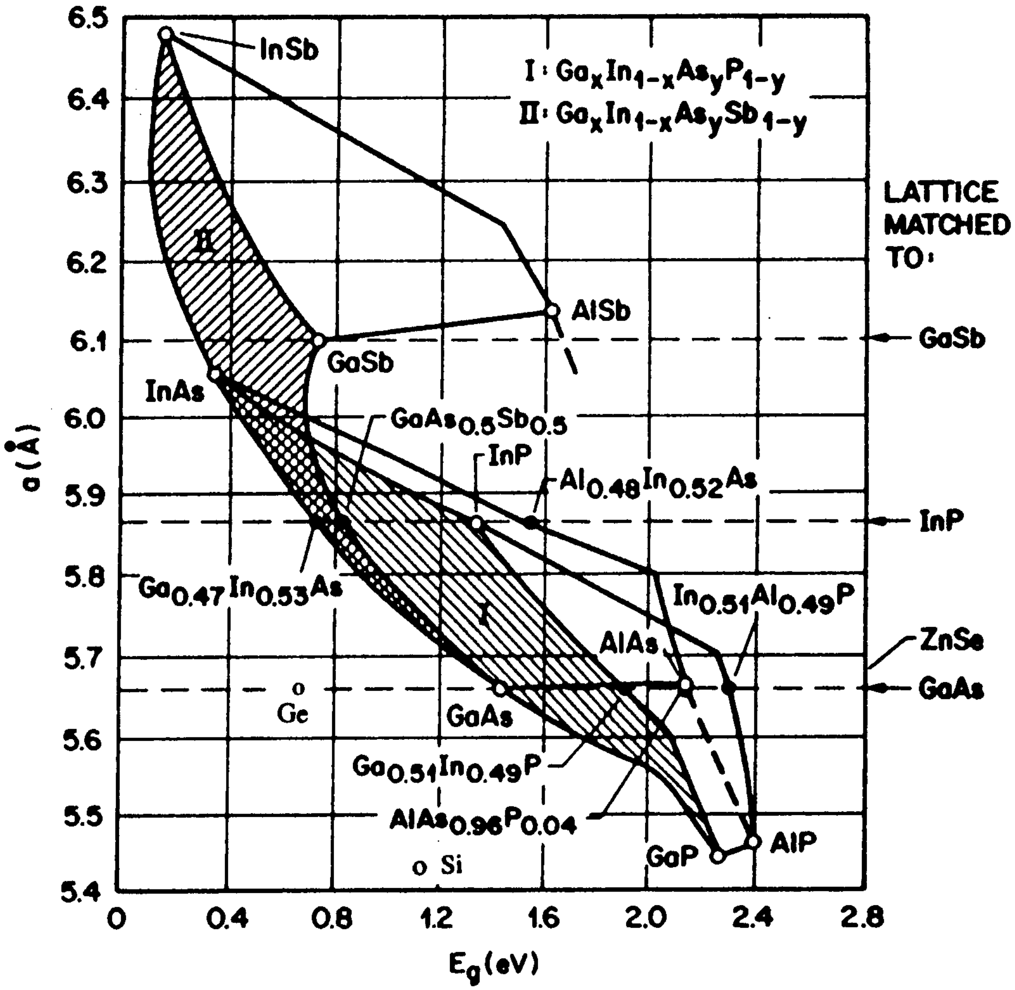
KEY CELL ISSUES

RTI

- Performance
  - System dependent
  - Spectral control
- Cost
  - Fabrication Method
  - Substrate Cost

III-V COMPOUNDS: LATTICE-CONSTANTS AND BANDGAPS

RTI



DEVICE POLARITY FOR TPV APPLICATIONS: P-ON-N OR N-ON-P ?

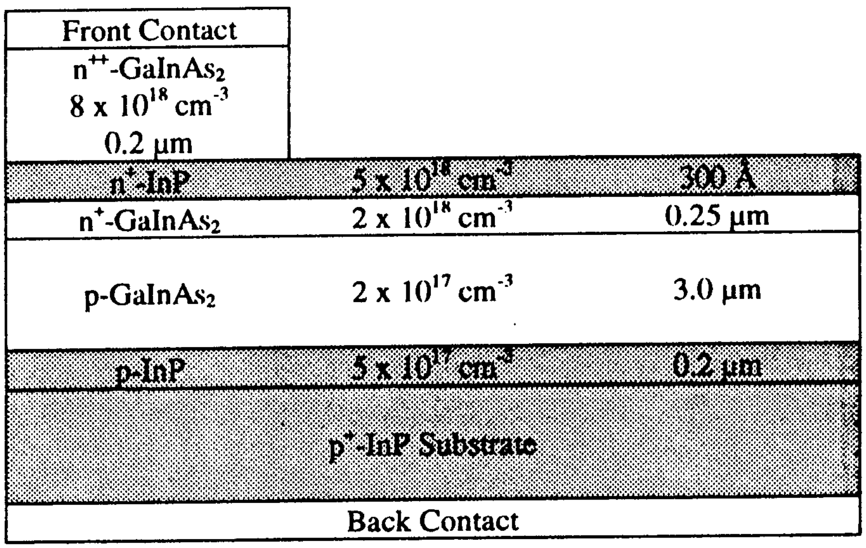
RTI

- N-ON-P
  1. Lower emitter sheet resistivities for high current applications
  2. Higher minority carrier diffusion length in base

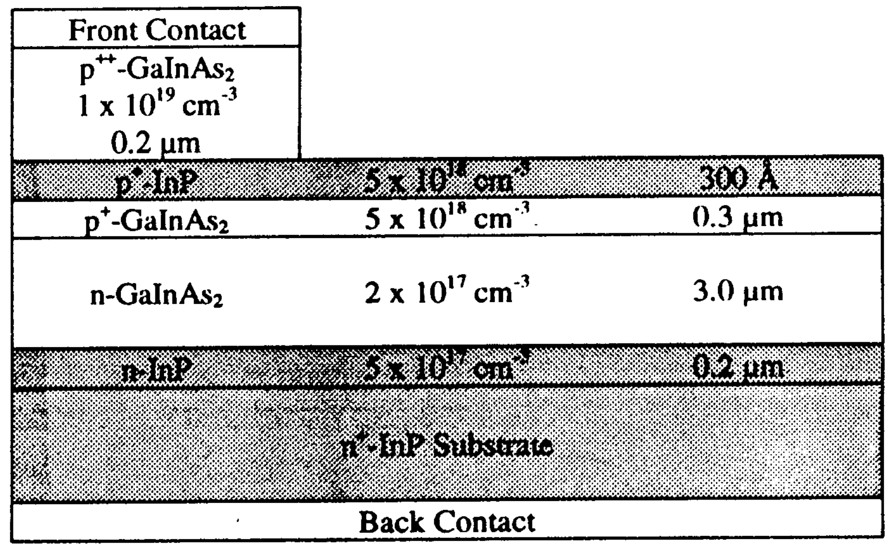
- P-ON-N
  1. Improved large scale manufacturing ability for epitaxial devices
  2. Lower free carrier absorption of long wavelength radiation

SCHEMATICS OF LATTICE-MATCHED DEVICES

RTI



N-ON-P DEVICE



P-ON-N DEVICE

VARIATION OF V_{OC} WITH WINDOW DOPING

RTI

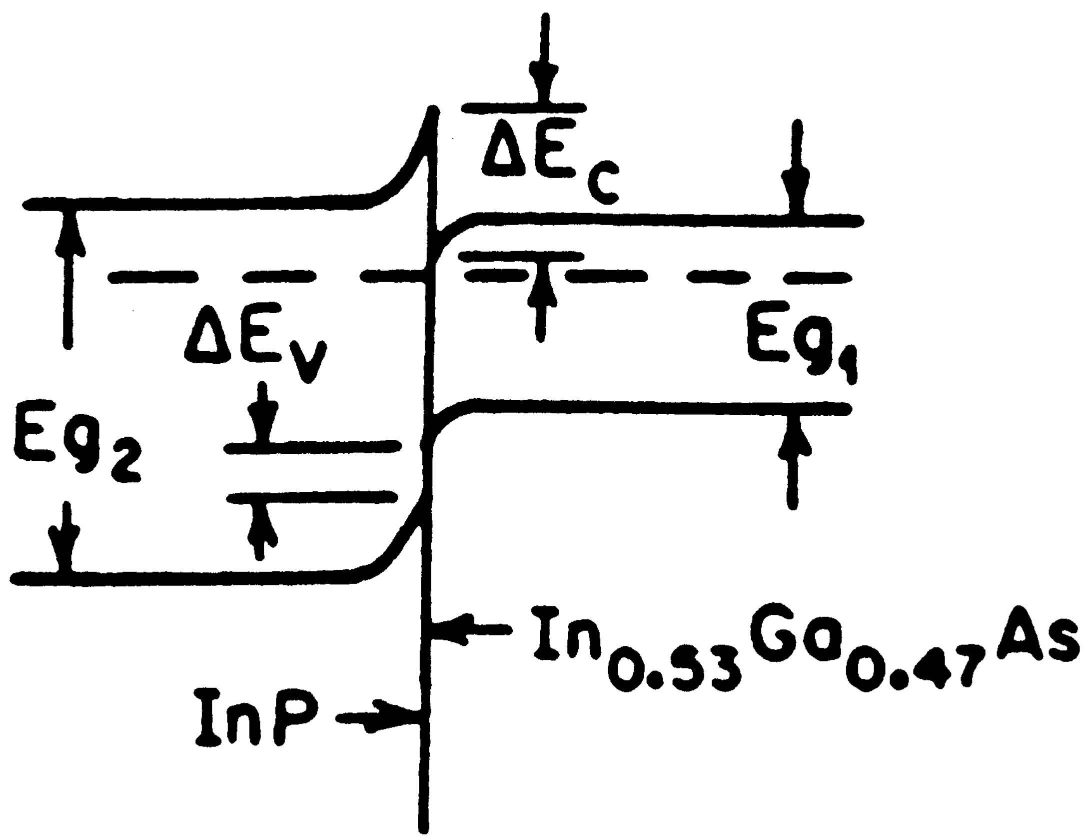
Subtle But Important Issues

Wafer (4 Devices)	H_2Se Flow For Window Layer (SCCM of 50 ppm)	V_{oc}, mV (Avg. over 4 1 cm^2 Devices)
6-2902	150	337
6-2903	200	356
6-2905	300	382
6-2928	300	408

All cells measures under AM0. J_{sc} and ff for each cell is ~40 mA/cm^2 and ~70%, respectively.

BAND STRUCTURE OF InP/InGaAs INTERFACE

Possible Defects At The Interface



SCHEMATIC OF P-ON-N LATTICE-MISMATCHED GaInAs DEVICES

RTI

Front Contact		
p^{++}-$Ga_xIn_{(1-x)}As$ 1×10^{19} cm^{-3} 0.2 µm		
Window	5×10^{18} cm^{-3}	300 Å
p^{+}-$Ga_xIn_{(1-x)}As$	3×10^{18} cm^{-3}	0.3 µm
n-$Ga_xIn_{(1-x)}As$	2×10^{17} cm^{-3}	3.0 µm
Back Surface Field	2×10^{17} cm^{-3}	0.1 µm
n-$Ga_xIn_{(1-x)}As$	2×10^{17} cm^{-3}	0.5 µm
Step-Graded Buffer Layers	2×10^{17} cm^{-3}	3-5 µm
n-InP	5×10^{17} cm^{-3}	0.2 µm
n^{+}-InP Substrate		
Back Contact		

III-V COMPOUNDS: LATTICE-CONSTANTS AND BANDGAPS

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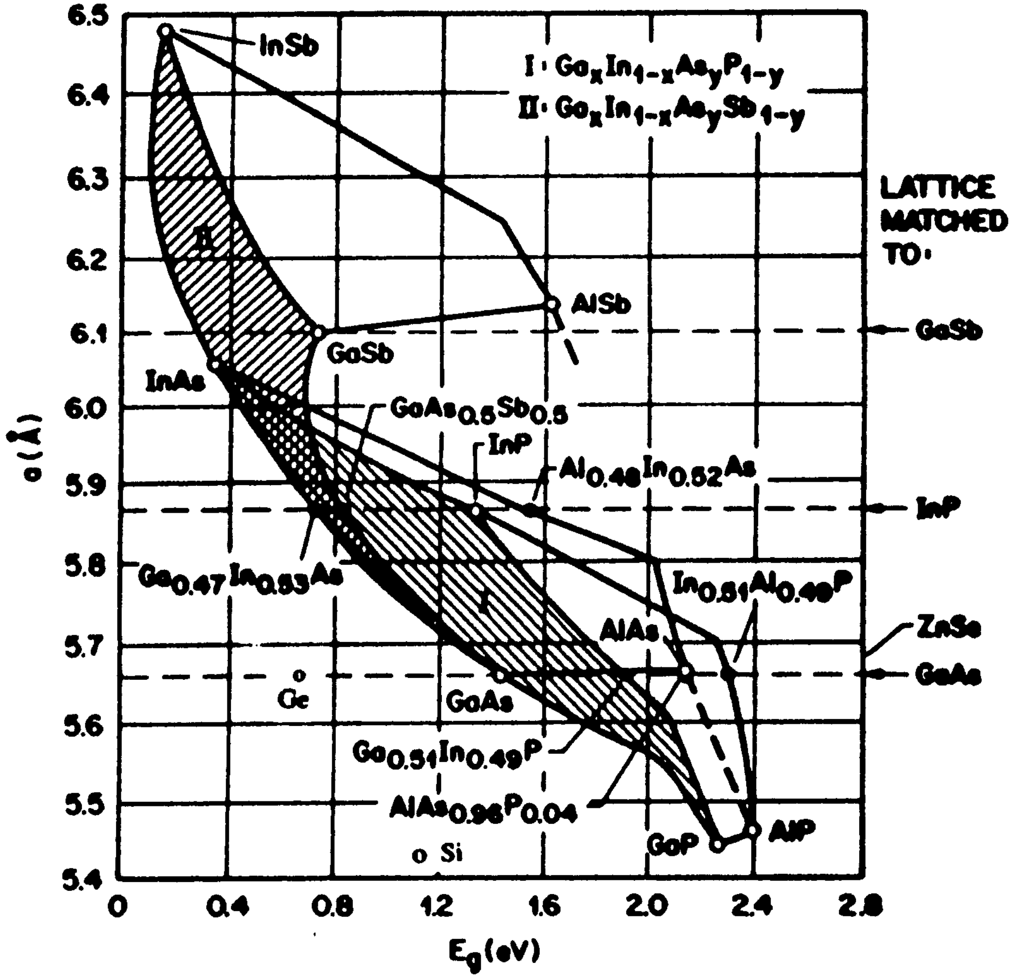
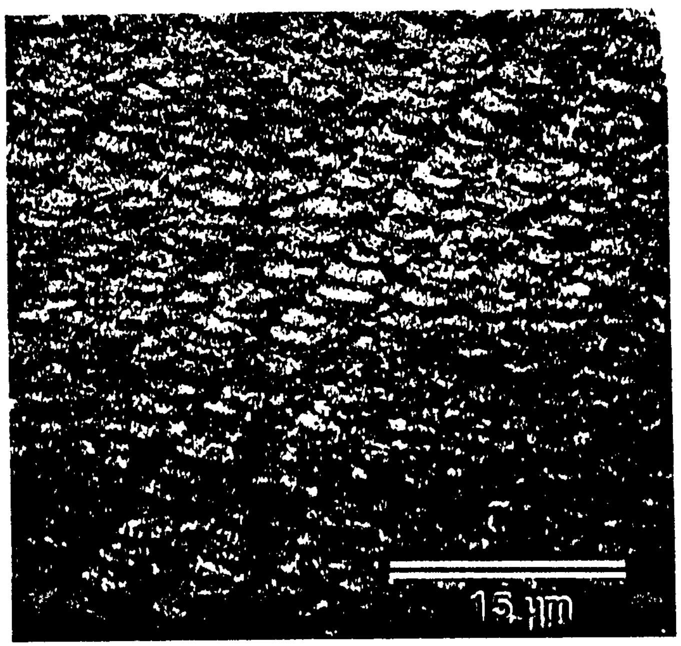
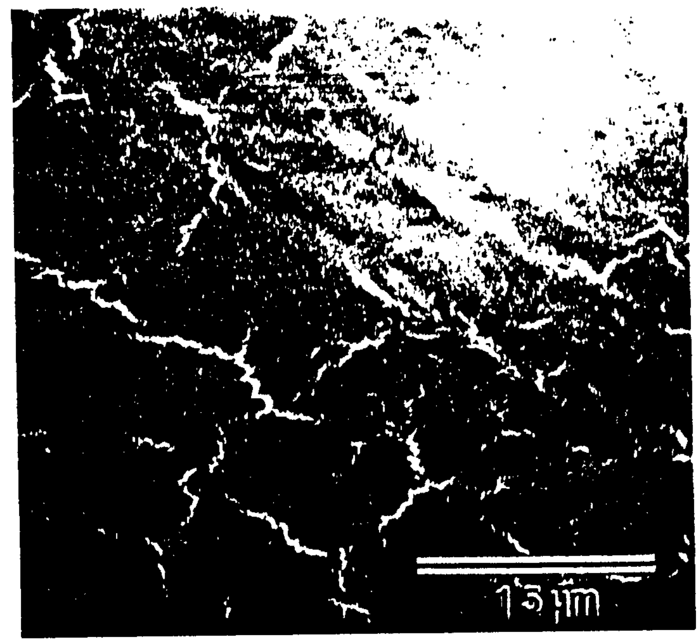


SEM PICTURES OF SURFACES GROWN WITH DIFFERENT BUFFERS

RTI



Cell 6-2531-3, grown with Buffer A



Cell 6-2527-7, grown with Buffer B

CELL RESULTS FOR P-ON-N LATTICE-MISMATCHED DEVICES

Cell #	6-2527-11	6-2528-6	6-2530-1	6-2531-3	6-2547-6
Cell structure	Buffer B BSF 1	Buffer B BSF 2	Buffer A BSF 1	Buffer A BSF 2	Buffer B BSF 3
V_{oc}, mV	266	271	271	254	287
J_{sc}, mA/cm^2	50.8	55.0	44.9	49.2	54.4
fill factor	66.5%	70.2%	64.5%	65.3%	69.5%

All cells are 0.25 cm^2, have a bandgap of 0.58 eV, and are measured under AMO illumination.

Thermal Photovoltaic Cells

RTI

Average I-V Characteristics:

Batch No.	Avg. Voc (mV)	Avg. Isc (mA)	Avg. FF (%)	Avg. P_{max} (mW)
Batch 1	274.3	641.8	65.2	108
Batch 2	282.0	634.1	65.3	117
Batch 3	287.7	654.4	66.2	125

- Batches 1 and 2 contain 100 cm^2. Batch 3 contains 50 cm^2.
- St. Dev./Mean ≈ 3 % for Batch 1 for parameters.
- St. Dev./Mean ≈ 2 % for Batches 2 and 3.

Thermal Photovoltaic Cells

RTI

Yield Statistics:

Growth Yield (%)	Processing Yield (%)	Electical Yield (%)	Overall Yield (%)
96	97	96	89

- Growth yield from 5 wafers of 130 wafer starts not processed.
- Production yield based on possible number of devices per batch.
- Electrical yield based on acceptance of processed devices.

CONCLUSIONS

RTI

- Pilot line quantities of cells available from several sources
- More research and development needed to further improve cell performance
  1. Subtle parameters
  2. New materials need to be developed
  3. Spectral control--systems issues
- Cell cost issues have to be dealt with
  1. Substrate costs
  2. Cell fabrication method
  3. Metallization

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TECHNOLOGY UPDATE 3

THERMOPHOTOVOLTAIC CONVERTER CHARACTERIZATION

Linda M. Garverick[†], Navid S. Fatemi[†], David M. Wilt[††], Phillip P. Jenkins[†], Richard W. Hoffman, Jr.[†], and David Scheiman[††]

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A thermophotovoltaic (TPV) converter normally consists of selective emitters or broadband blackbody emitters, filters, and photovoltaic (PV) cells. A TPV converter can be coupled to a variety of heat sources to form a complete TPV system. A number of TPV converter configurations were characterized at the heat source operating temperature of 1700 K.

All converters were tested by first carefully characterizing and testing each of their components separately. All of the measured parameters were then combined, in the methodology described below, to obtain converter output power density and efficiency values. First, the spectral irradiance (W/cm^2) of each selective emitter, as a function of wavelength, was calculated by multiplying the measured spectral emittance of the selective emitter by the well-known blackbody spectral irradiance (at 1700 K). The measured transmission versus wavelength of every filter was then multiplied by the respective selective emitter spectral irradiance. The result was the filtered spectral irradiance reaching the PV cell. The output current density (A/cm^2) of the PV cell was then calculated by integrating the product of the measured cell spectral response (A/W) and the filtered spectral irradiance over the wavelength range of interest, i.e. from near zero microns to the cutoff wavelength (λ_c) of the bandpass filter.

The open-circuit voltage (V_{oc}) and fill factor (FF) values of the PV cells were measured at the output short-circuit current density (J_{sc}) levels calculated above, by testing the cells under high sunlight concentrations, using a large-area pulsed solar simulator (LAPSS). This ensured accurate V_{oc} and FF measurements because the detrimental effects of cell series resistance were experimentally taken into account. The cell output power density (W/cm^2) was then simply calculated as the product of V_{oc}, J_{sc}, and FF.

In order to calculate the converter efficiency, the cell output power density calculated above was divided by the total selective emitter spectral irradiance, integrated over the wavelength range of interest. For the sake of simplicity, a 100% radiation recycling was assumed.

Rare-earth-doped yttrium aluminum garnet (YAG) and lutetium yttrium aluminum garnet (Lu,YAG) selective emitters, as well as blackbody emitters, were coupled to InP/InGaAs/InP photovoltaic (PV) cells and shortpass/infrared (IR) reflector filters. YAG-based selective emitters, originally developed at the NASA Lewis Research Center, were doped with 25% Ho (Ho-YAG), 30% Tm (Tm-Lu,YAG), and 40% Er (Er-YAG). PV cells grown via organometallic vapor phase epitaxy (OMVPE) had bandgaps of 0.51, 0.57, 0.69, and 0.74 eV. Shortpass dielectric stack filters had cutoff wavelengths (λc) of 1.7, 2.0, and 2.2 μm and in-band transmissions in the 85-90% range. When the shortpass filters were combined with IR reflector filters, the in-band transmissions were diminished to the 55-65% range, but the unwanted out-of-band transmittance was also reduced to near zero percent out to the wavelength of ~30 μm.

The output power density and efficiency results for the converters tested with shortpass/IR reflector combination filters and with shortpass-only filters are summarized in Tables I and II, respectively. Note that in Table II the efficiencies cited are for in-band radiation only since unlike the shortpass/IR reflector combination filters, the shortpass-only filters allow some transmission of longer wavelength radiation beyond their cutoff wavelength.

TABLE I.—TPV CONVERTER OUTPUT POWER DENSITY AND EFFICIENCY DATA WITH SHORTPASS/IR REFLECTOR COMBINATION FILTERS, FOR A SOURCE TEMPERATURE OF 1700 K.

Emitter	Filter λc (μm)	PV Cell Eg (eV)	Pout (W/cm^2)	Efficiency (%)
Ho-YAG	2.2	0.51	0.29	11.4
Tm-Lu,YAG	2.0	0.57	0.44	16.2
Er-YAG	1.7	0.69	0.78	29.0
Er-YAG	1.7	0.74	0.80	29.7
Blackbody	1.7	0.69	1.94	26.9
Blackbody	1.7	0.74	1.90	26.0

TABLE II.—TPV CONVERTER OUTPUT POWER DENSITY AND EFFICIENCY DATA WITH SHORTPASS-ONLY FILTERS, FOR A SOURCE TEMPERATURE OF 1700 K.

Emitter	Filter λc (μm)	PV Cell Eg (eV)	Pout (W/cm^2)	Efficiency (%)
Ho-YAG	2.2	0.51	0.52	11.8
Tm-Lu,YAG	2.0	0.57	0.82	15.9
Er-YAG	1.7	0.69	1.00	26.7
Er-YAG	1.7	0.74	1.01	29.8
Blackbody	1.7	0.69	2.48	25.8
Blackbody	1.7	0.74	2.40	25.0

As shown in the tables, higher bandgap InP/InGaAs/InP PV cells performed far better than the lower bandgap cells. As a result, the converters with the Er-YAG selective emitters showed superior performance than the converters with the Ho-YAG and the Tm-(Lu,YAG) selective emitters. Also, as expected converters with shortpass-only filters had significantly higher output power densities. Additionally, although selective emitter-based converters were generally more efficient than the blackbody emitter-based converters, the latter showed significantly higher output power densities.

In closing, we anticipate that our improved PV cells and selective emitters currently under development will enable the development of TPV converters with higher output power densities, as well as, efficiencies well into the 30% range.

TPV CONVERTER CHARACTERIZATION

Linda M. Garverick[†], Navid S. Fatemi[†], David M. Wilt[††], Phillip P. Jenkins[†]
Richard W. Hoffman, Jr.[†], and David Scheiman[††]

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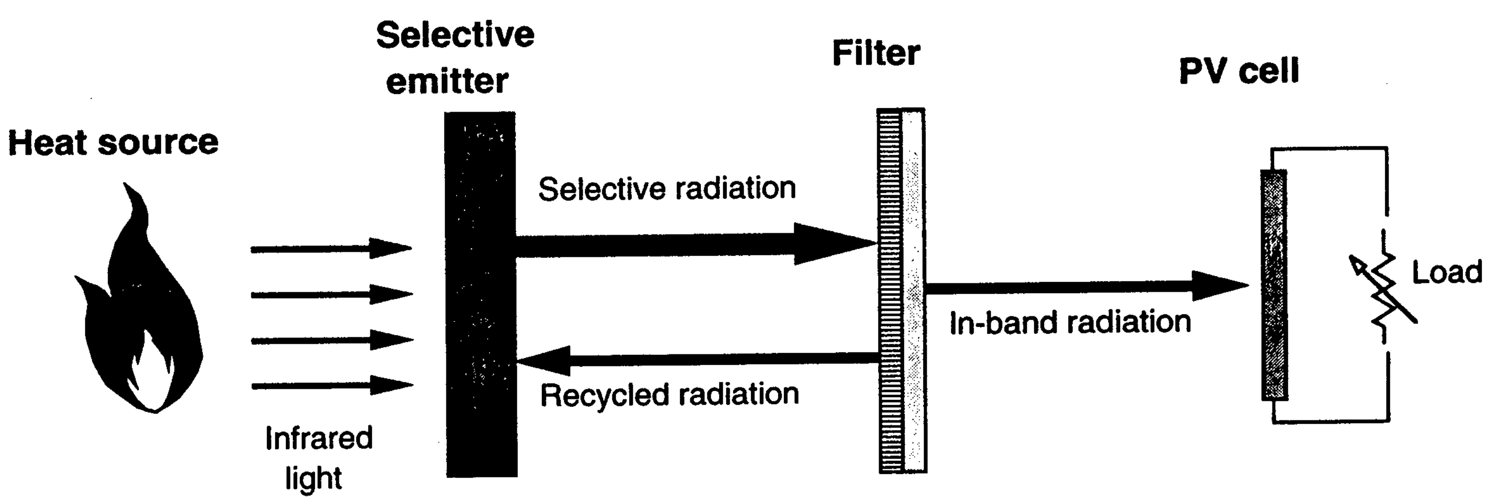
Elements of TPV



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TPV CONVERTER COMPONENTS

1. Emitters:

   -Ho-YAG (2.0 μm, 0.62 eV) Selective Emitter
   -Tm-Lu,YAG (1.7 μm, 0.73 eV) Selective Emitter
   -Er-YAG (1.5 μm, 0.83 eV) Selective Emitter
   -Broadband Blackbody

2. Filters:

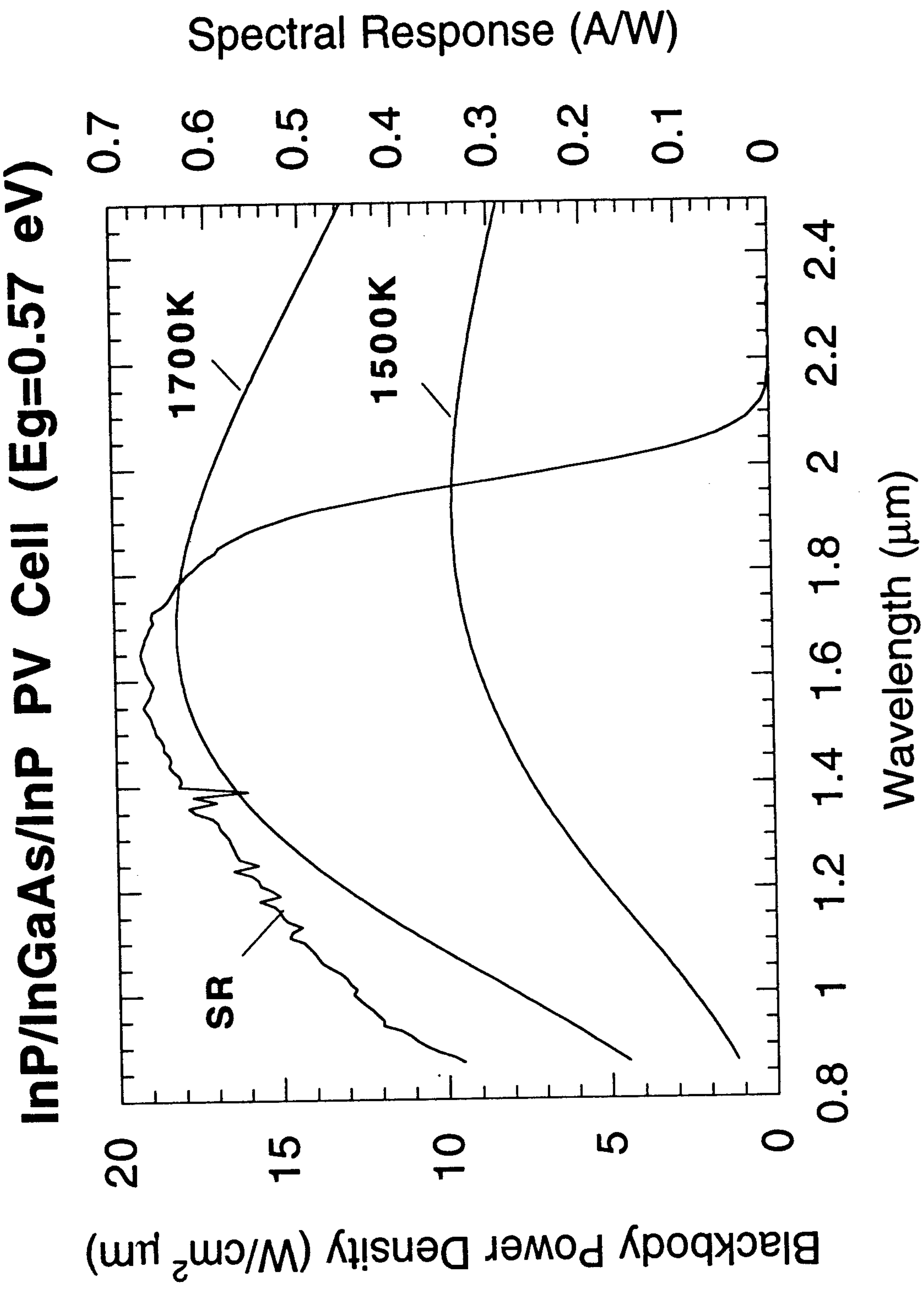
   -IR Reflector
   -Shortpass Dielectric Stack with $\lambda c = 1.7, 2.0$, and 2.2 μm
   -Shortpass/IR Reflector Combination

3. PV Cells:

   -InP/InGaAs/InP with $Eg = 0.51, 0.57, 0.69$, and 0.74 eV.

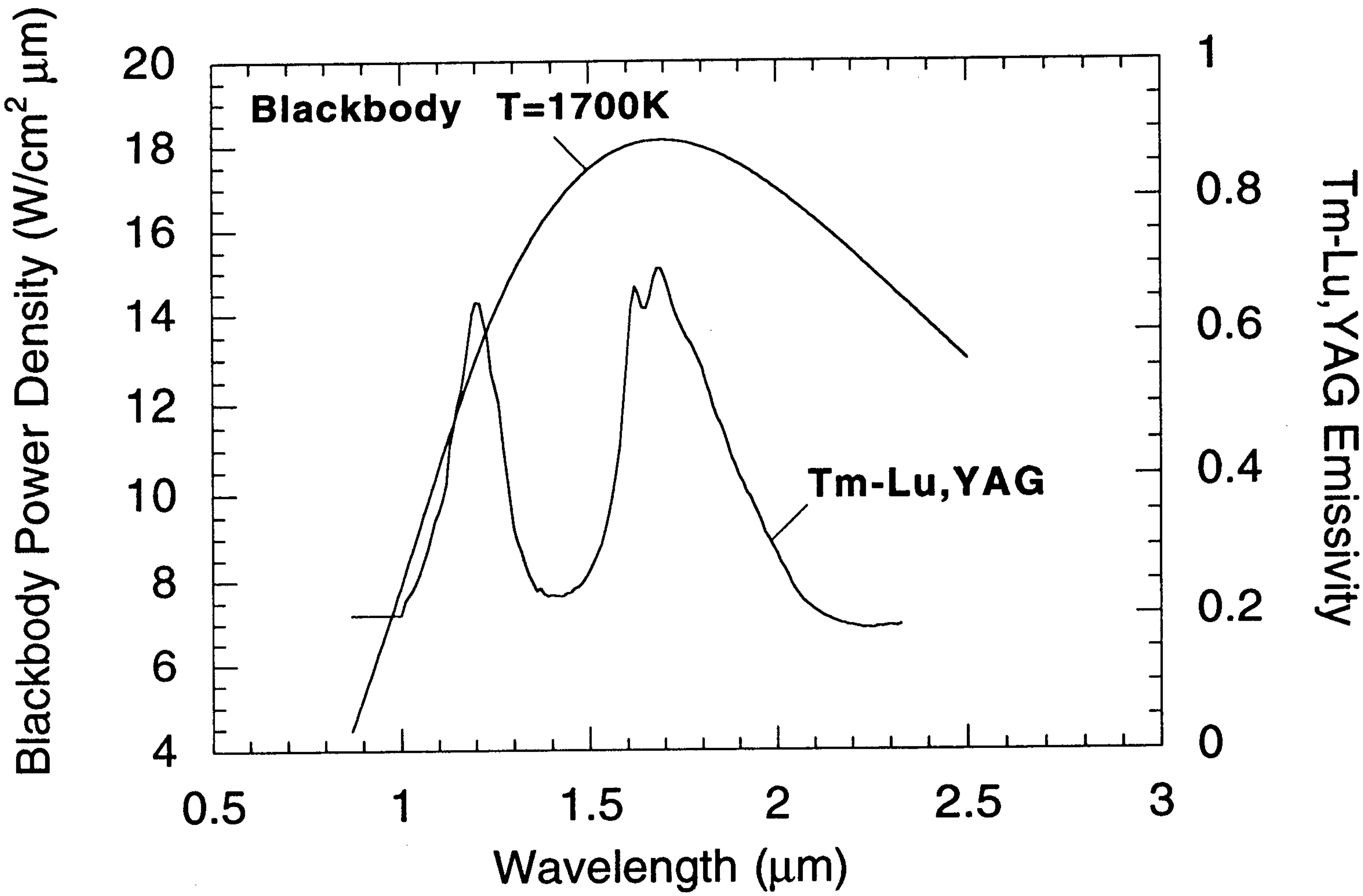
TPV CONVERTERS

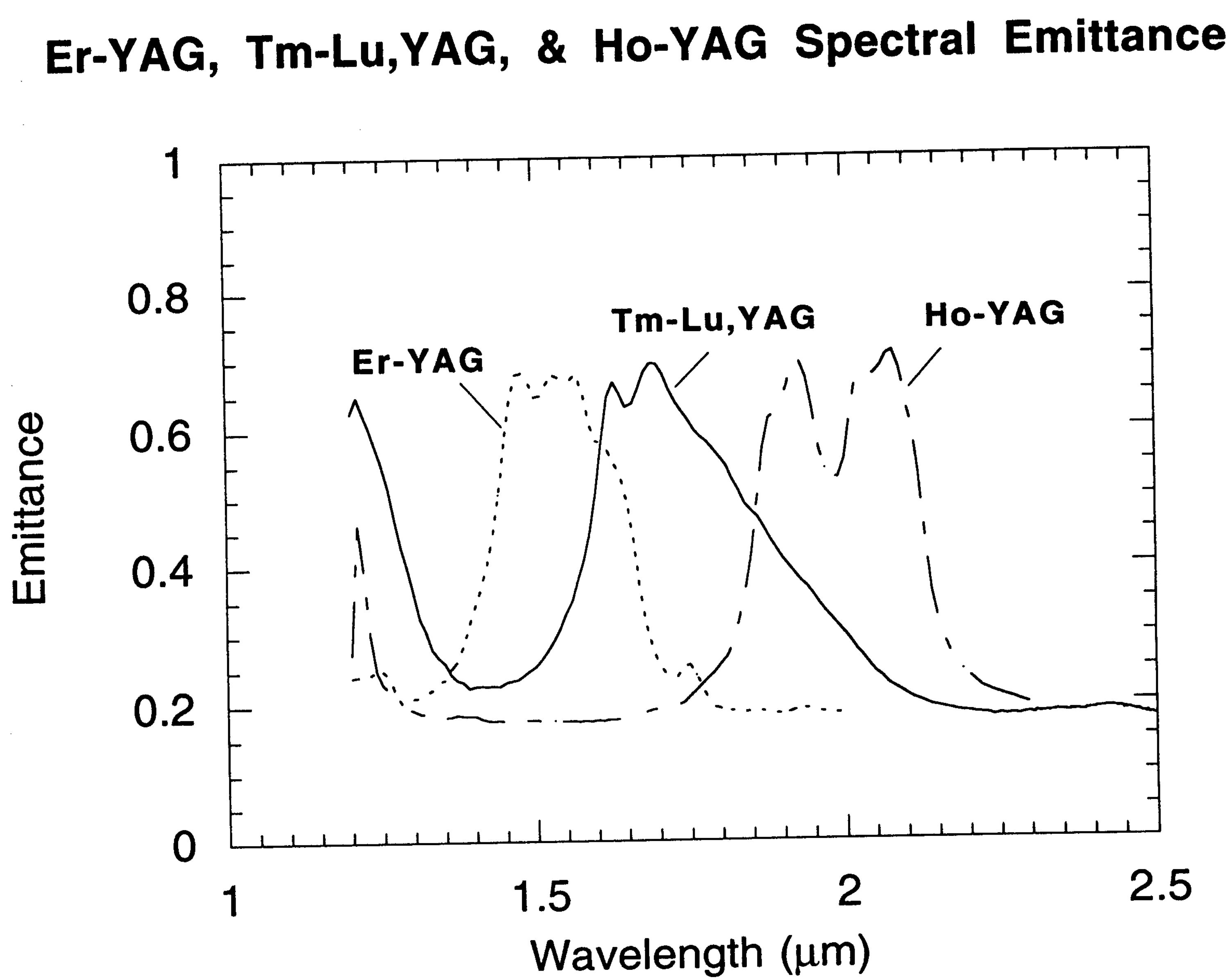
Emitter	Filter λc (μm)	PV Cell Eg (eV)
Ho-YAG	2.2	0.51
Tm-Lu,YAG	2.0	0.57
Er-YAG	1.7	0.69
Er-YAG	1.7	0.74
Blackbody	1.7	0.69
Blackbody	1.7	0.74



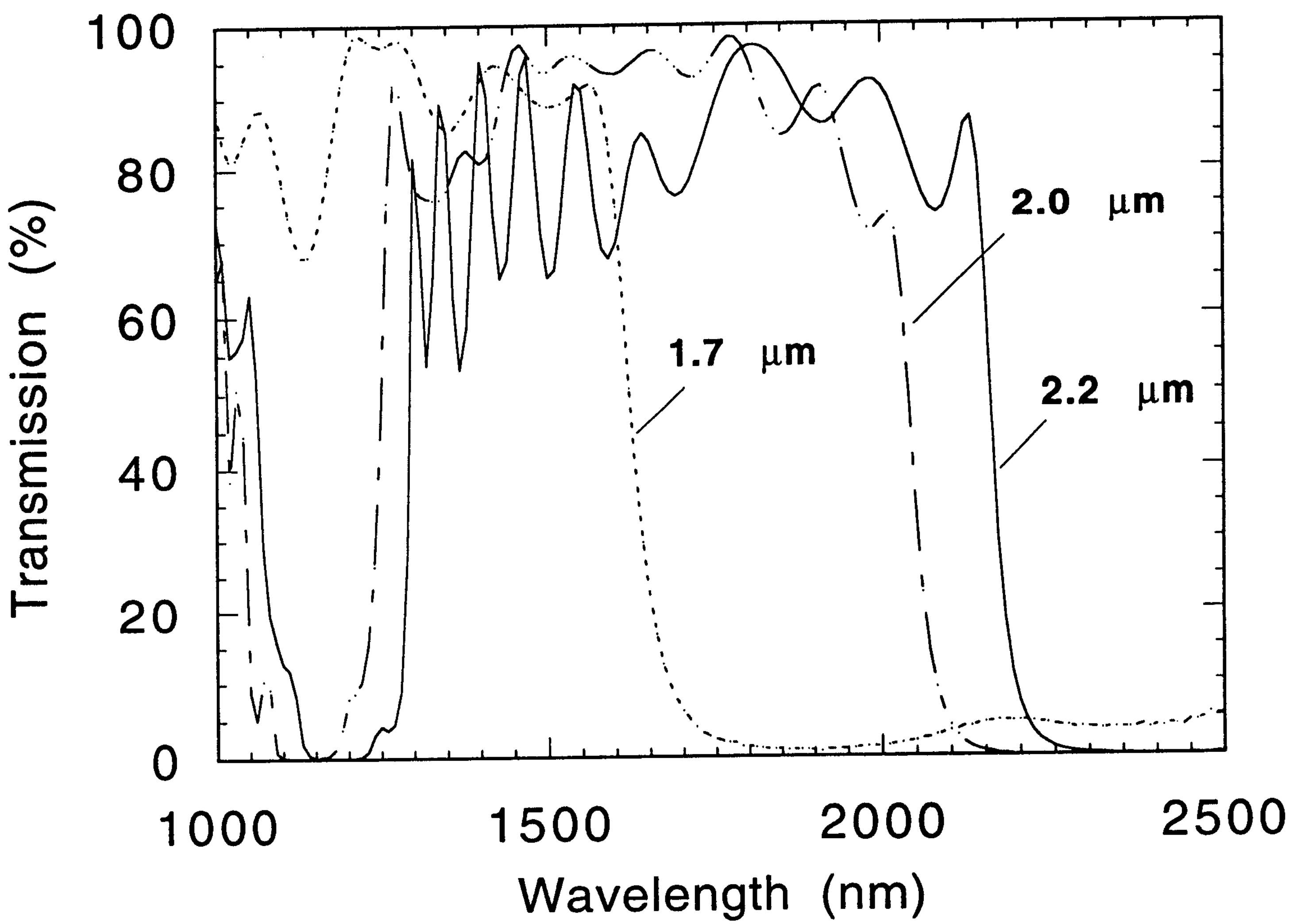
InP/InGaAs/InP PV Cell (Eg=0.57 eV)
Spectral Response (A/W)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Blackbody Power Density (W/cm² µm)
20
15
10
5
0
Wavelength (µm)
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4
1700K
1500K
SR

Lu,YAG Doped with 30% Tm Selective Emitter

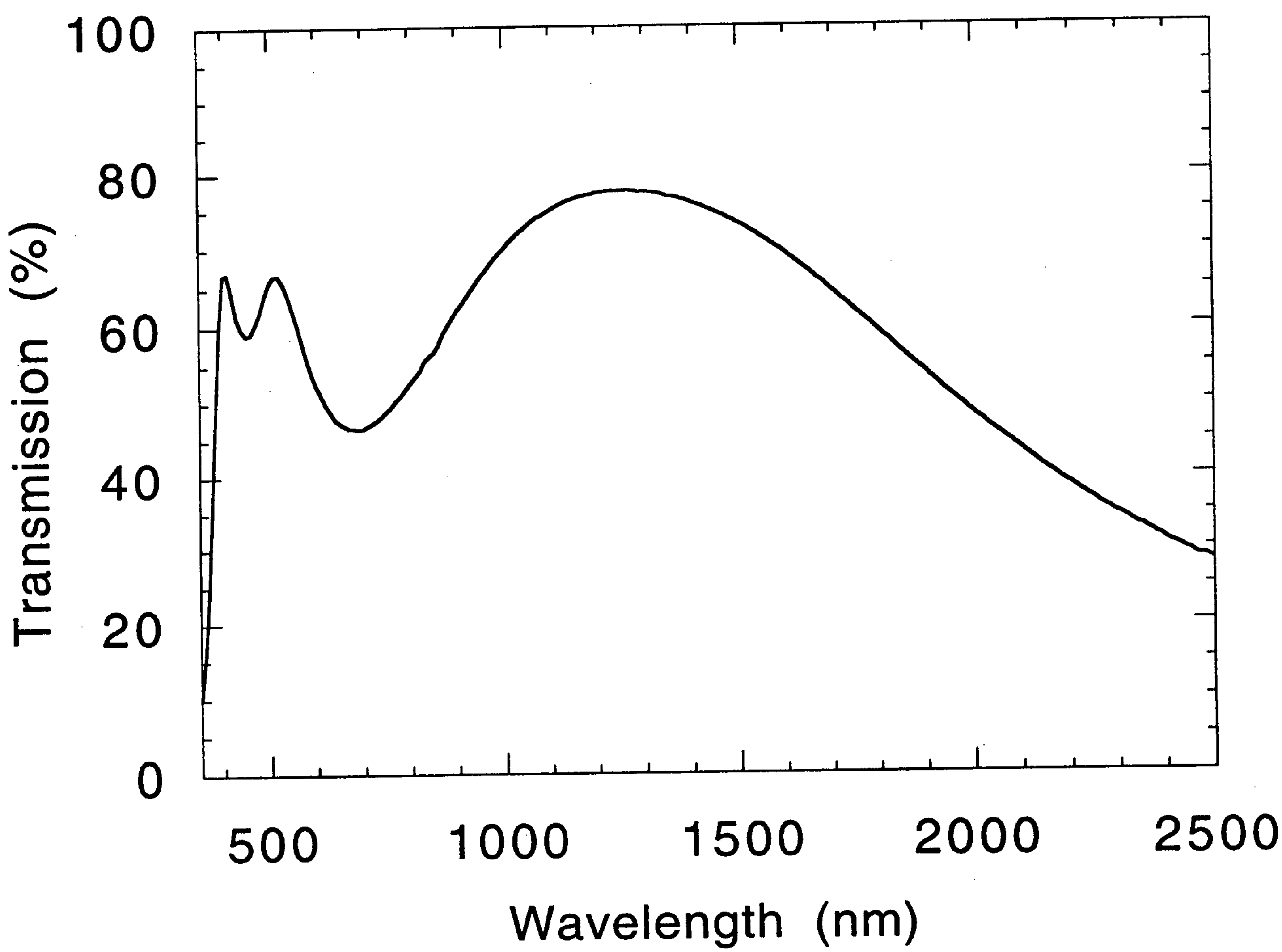



Er-YAG, Tm-Lu,YAG, & Ho-YAG Spectral Emittance
Er-YAG
Tm-Lu,YAG
Ho-YAG
Emittance
0
0.2
0.4
0.6
0.8
1
1
1.5
2
2.5
Wavelength (μm)

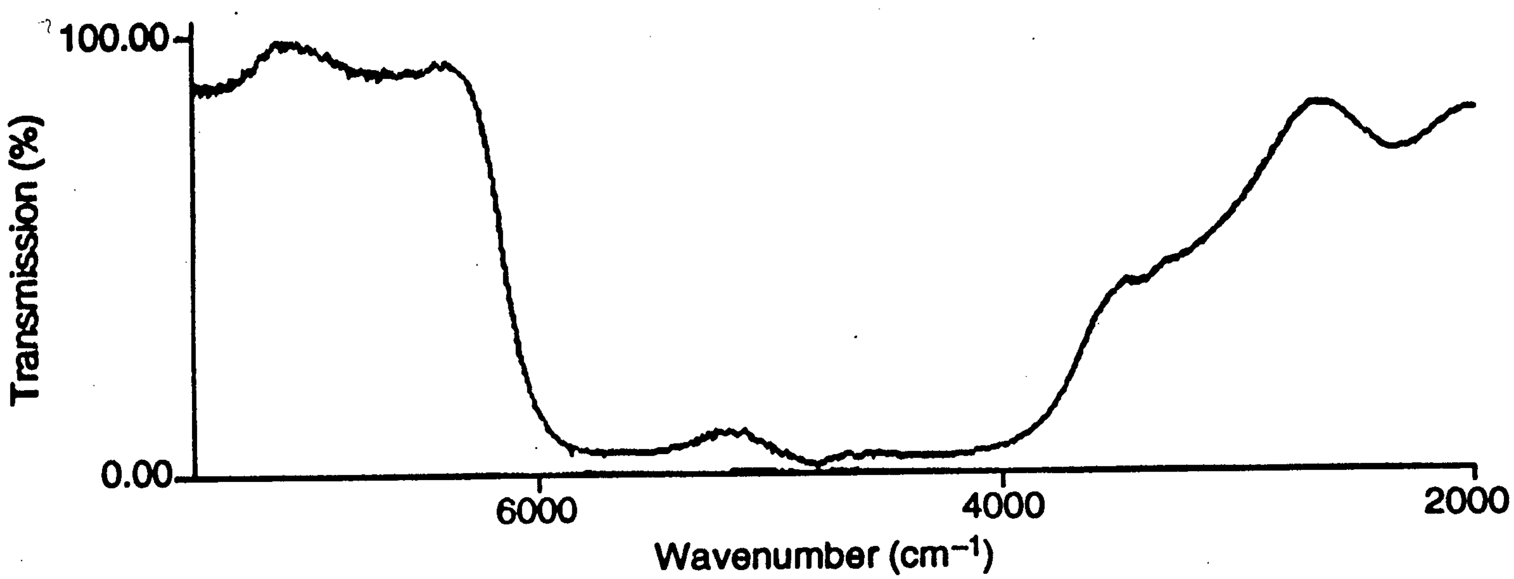
Shortpass Dielectric Stack Filters



IR Reflector Filter on Sapphire



Dielectric Stack Bandpass Filter Design Cut-off Frequency: 1.7 μm



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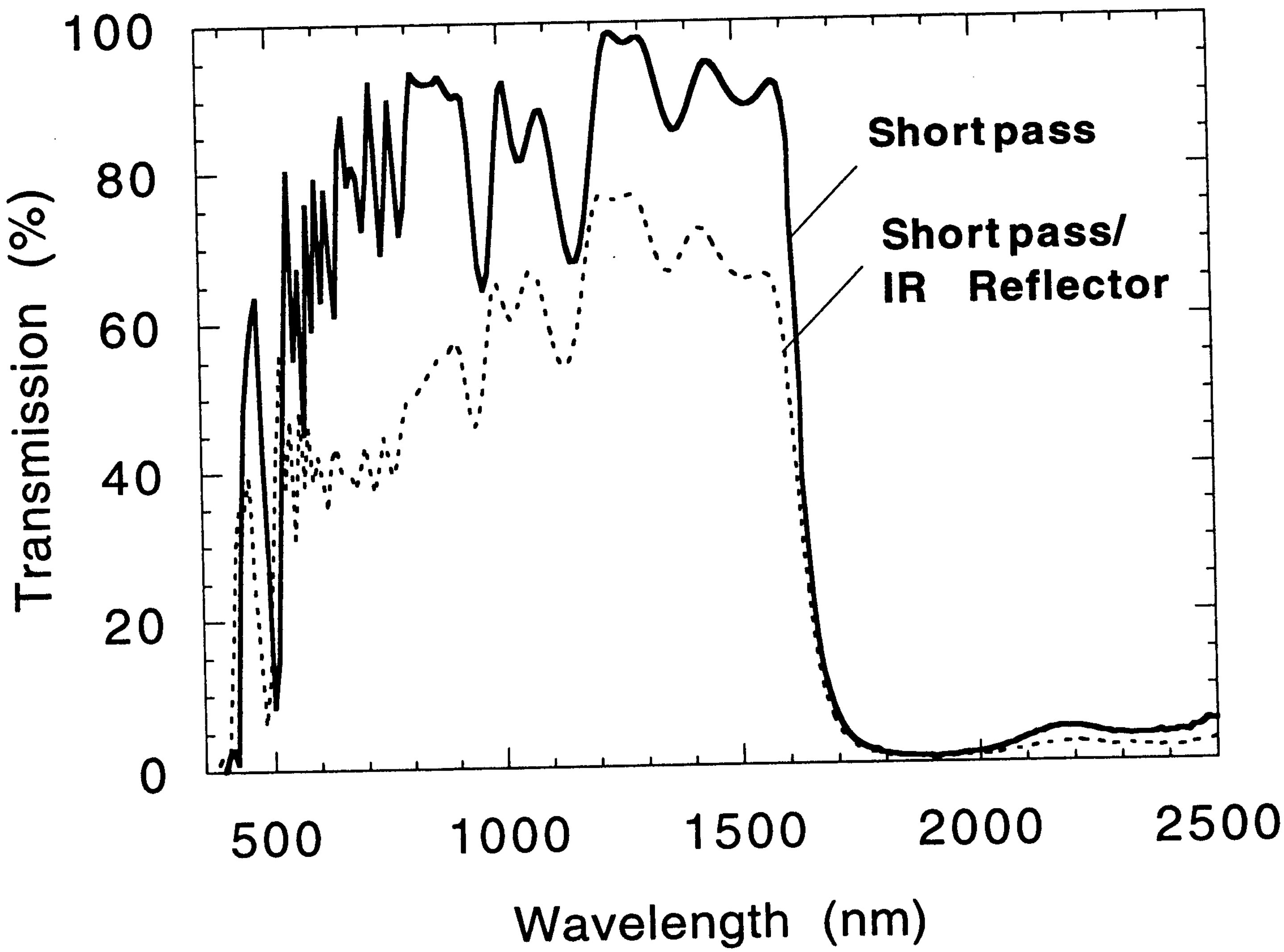
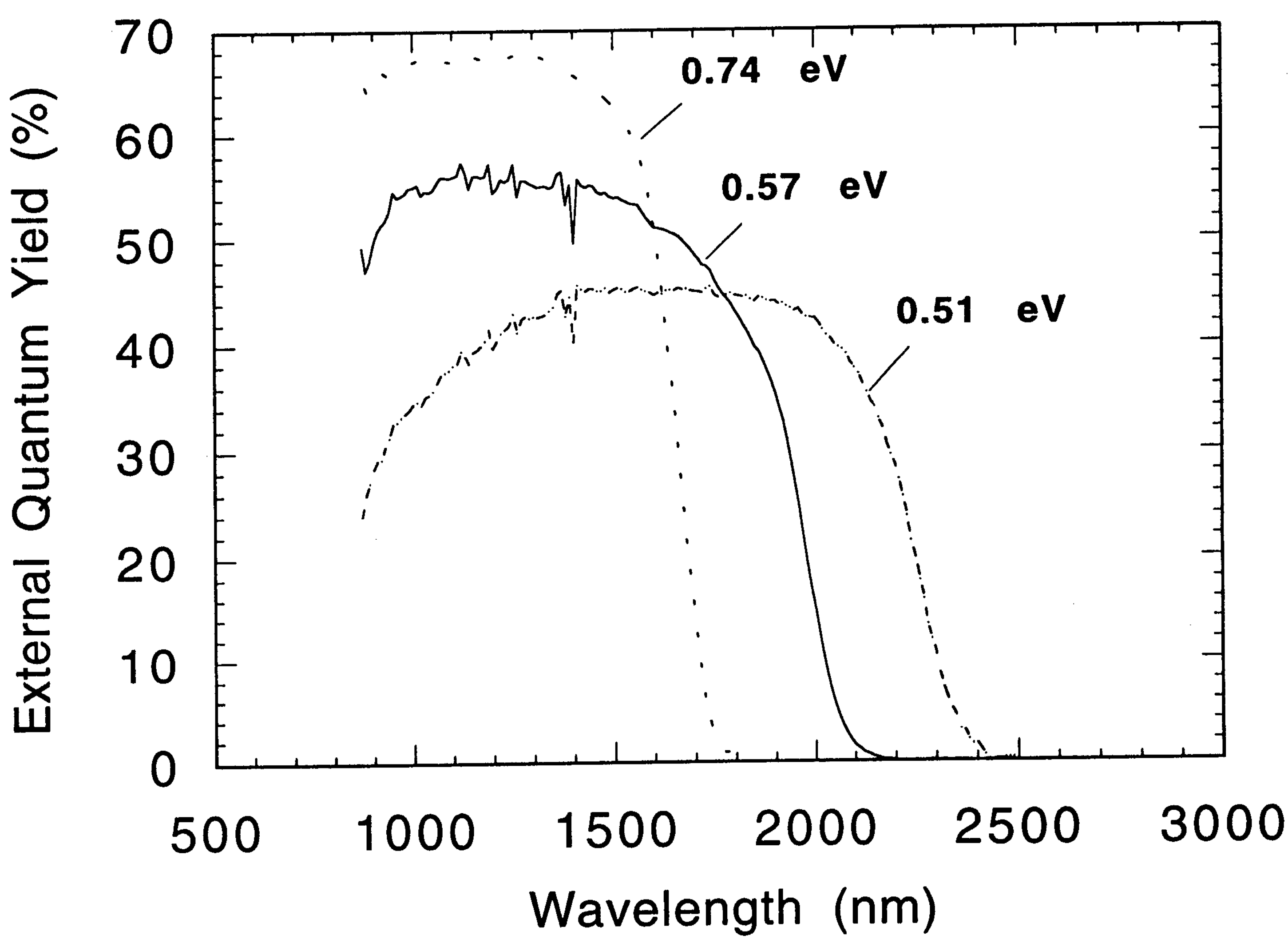
ER-96-016

Shortpass & Shortpass/IR Reflector Filters



InP/InGaAs/InP PV Cell External Quantum Yields



Variation of Open-Circuit Voltage at High Injection

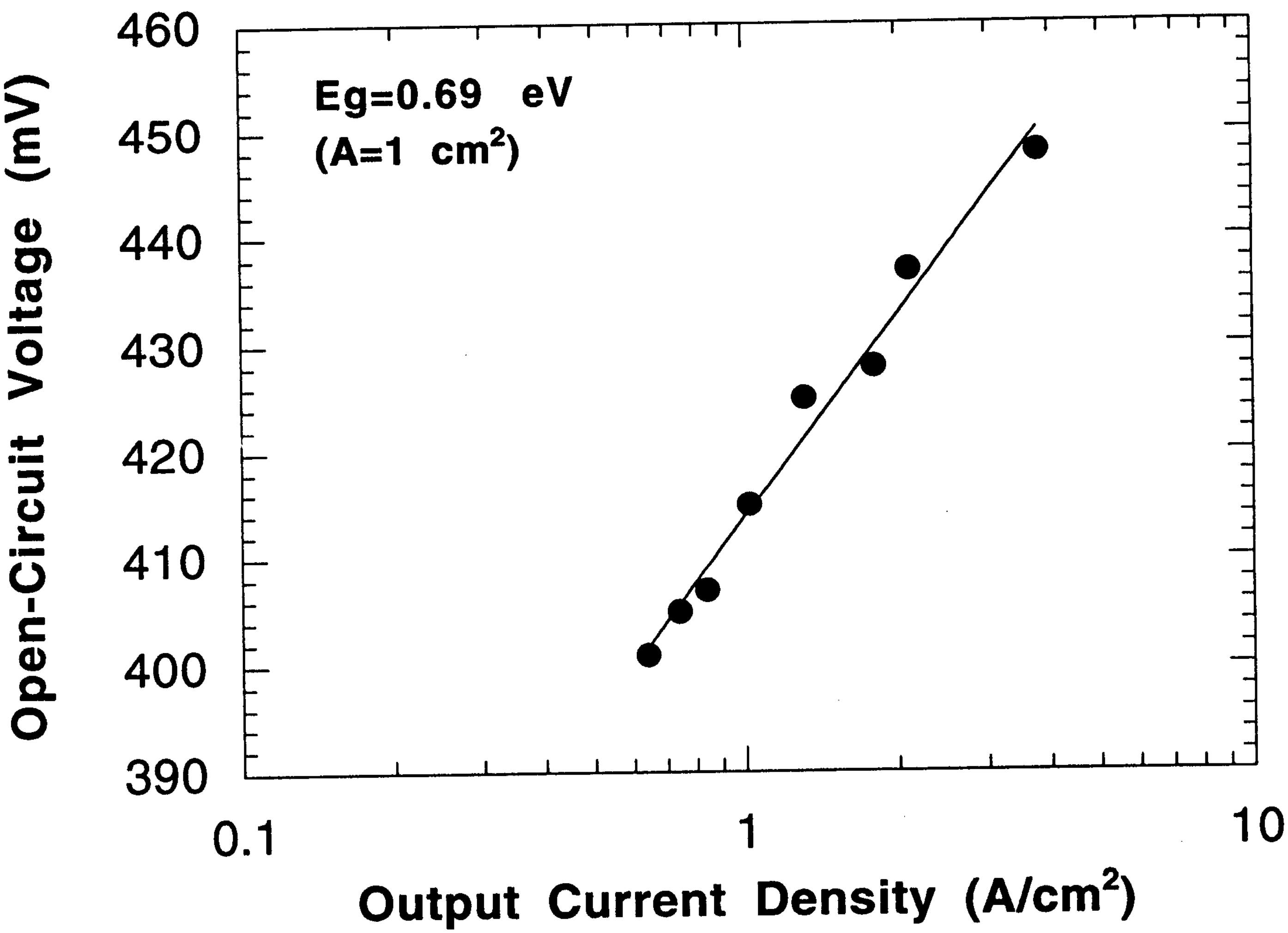
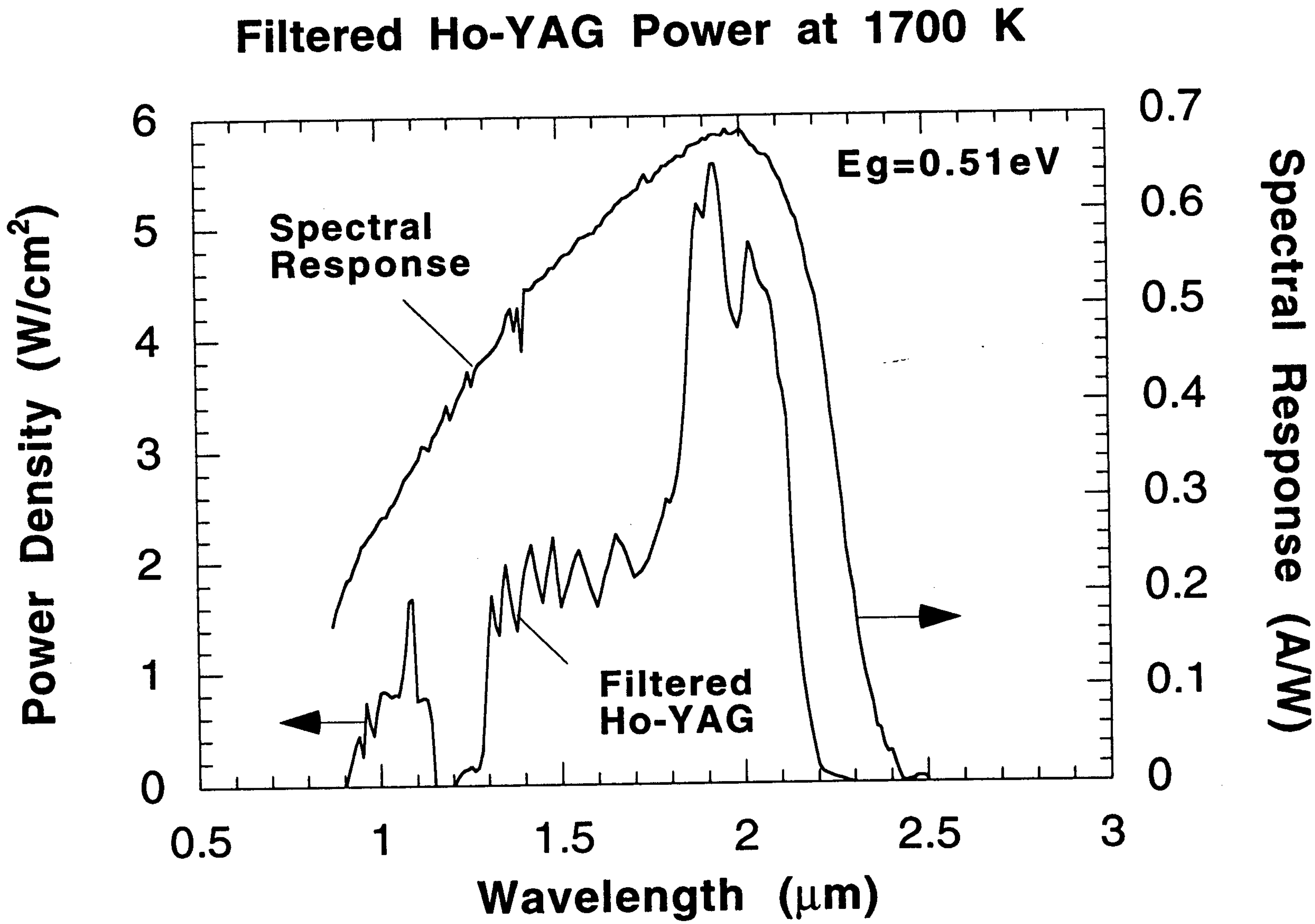
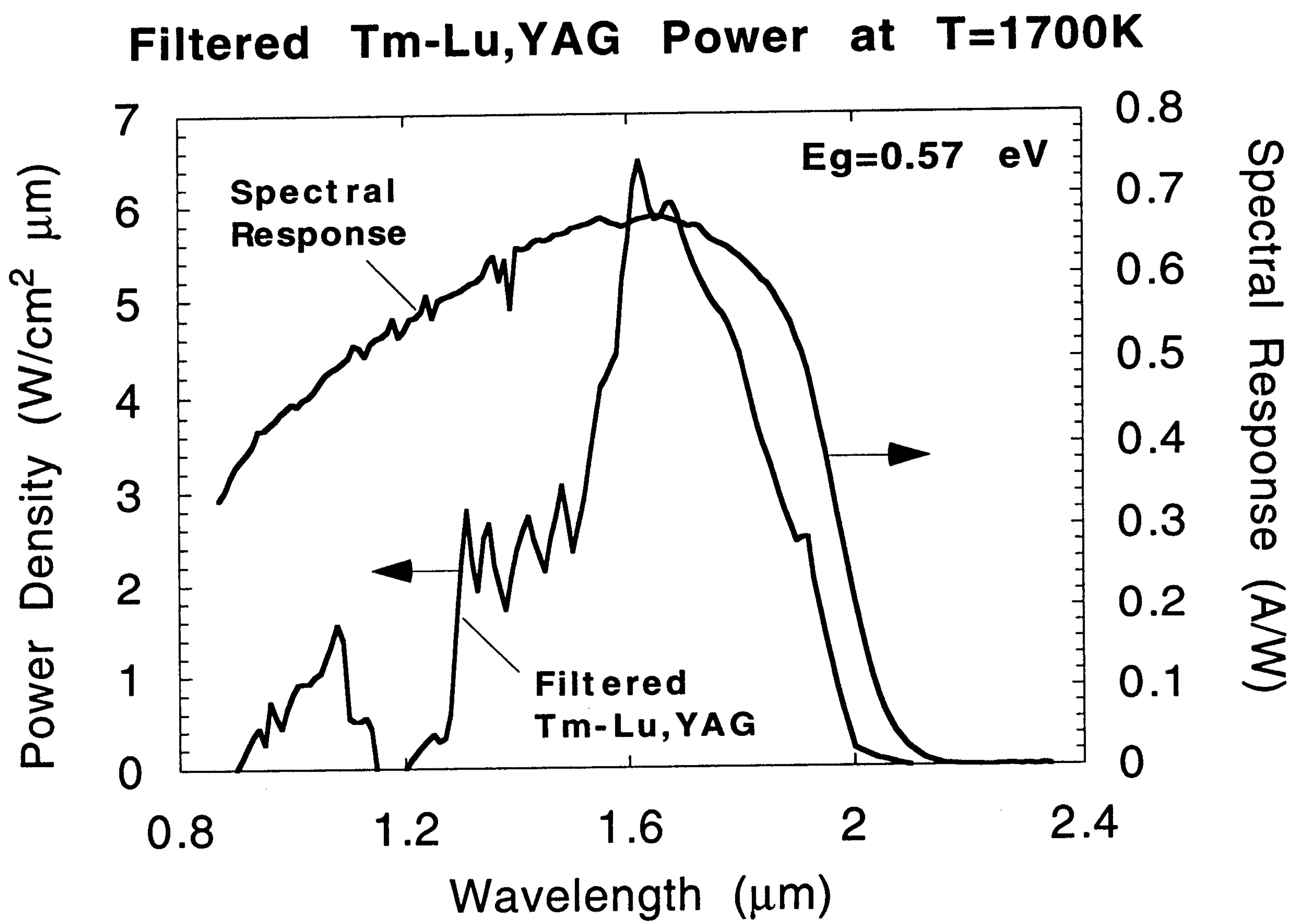


TABLE I.—HIGH INJECTION I-V DATA (25 °C) FOR PV CELLS WITH Eg=0.51-0.69 eV.

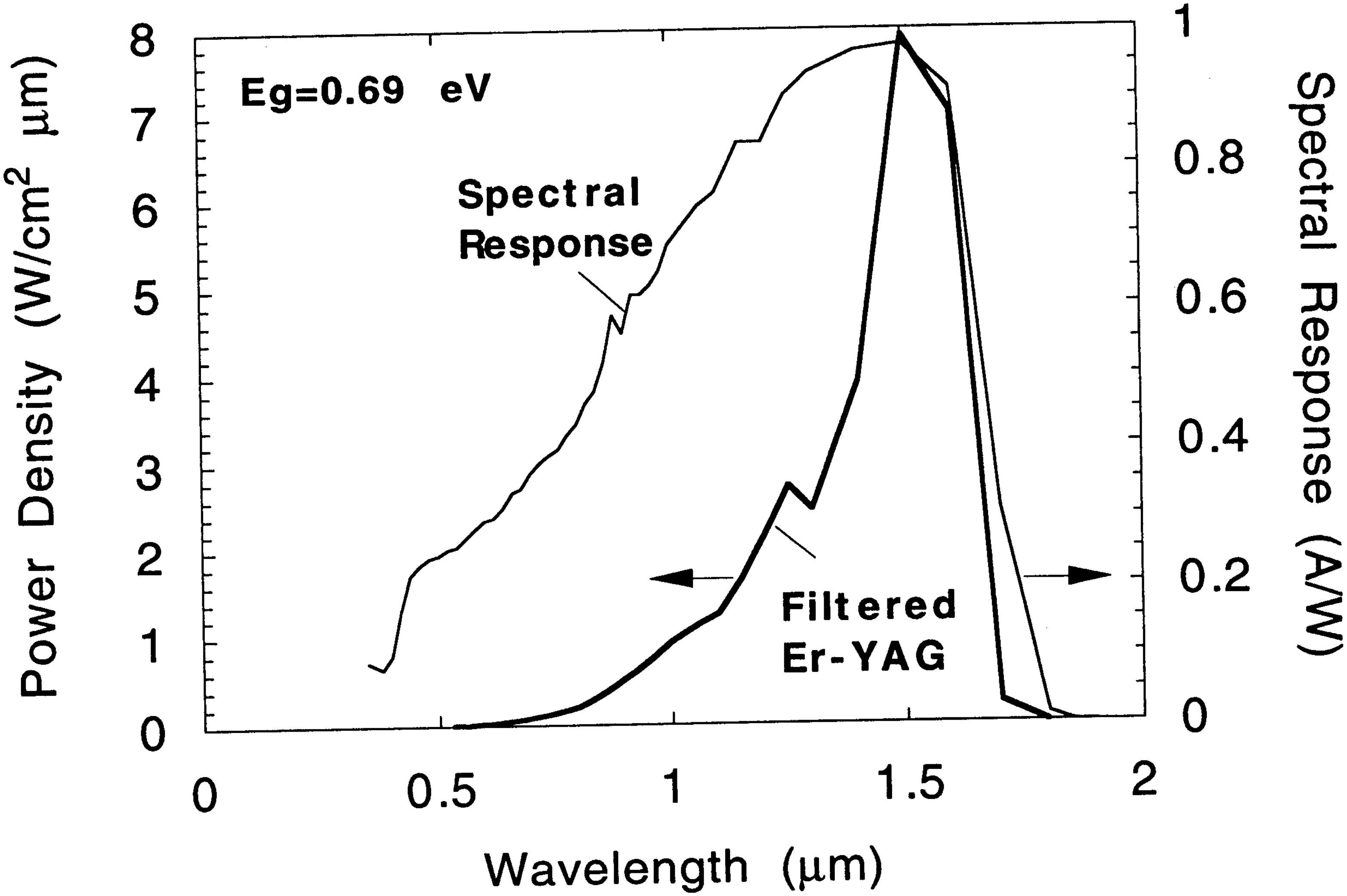
PV Cell Eg (eV)	J_{sc} (A/cm^2)	V_{oc} (mV)	FF (%)	Area (cm^2)
0.51	2.05	252	56.0	0.36
0.57	2.24	325	60.0	0.36
0.69	2.44	451	70.6	1.00
0.69	6.29	477	64.7	1.00


Filtered Ho-YAG Power at 1700 K
Power Density (W/cm2)
Spectral Response (A/W)
Wavelength (μm)
Spectral Response
Filtered Ho-YAG
Eg=0.51eV
0
1
2
3
4
5
6
0.5
1
1.5
2
2.5
3
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

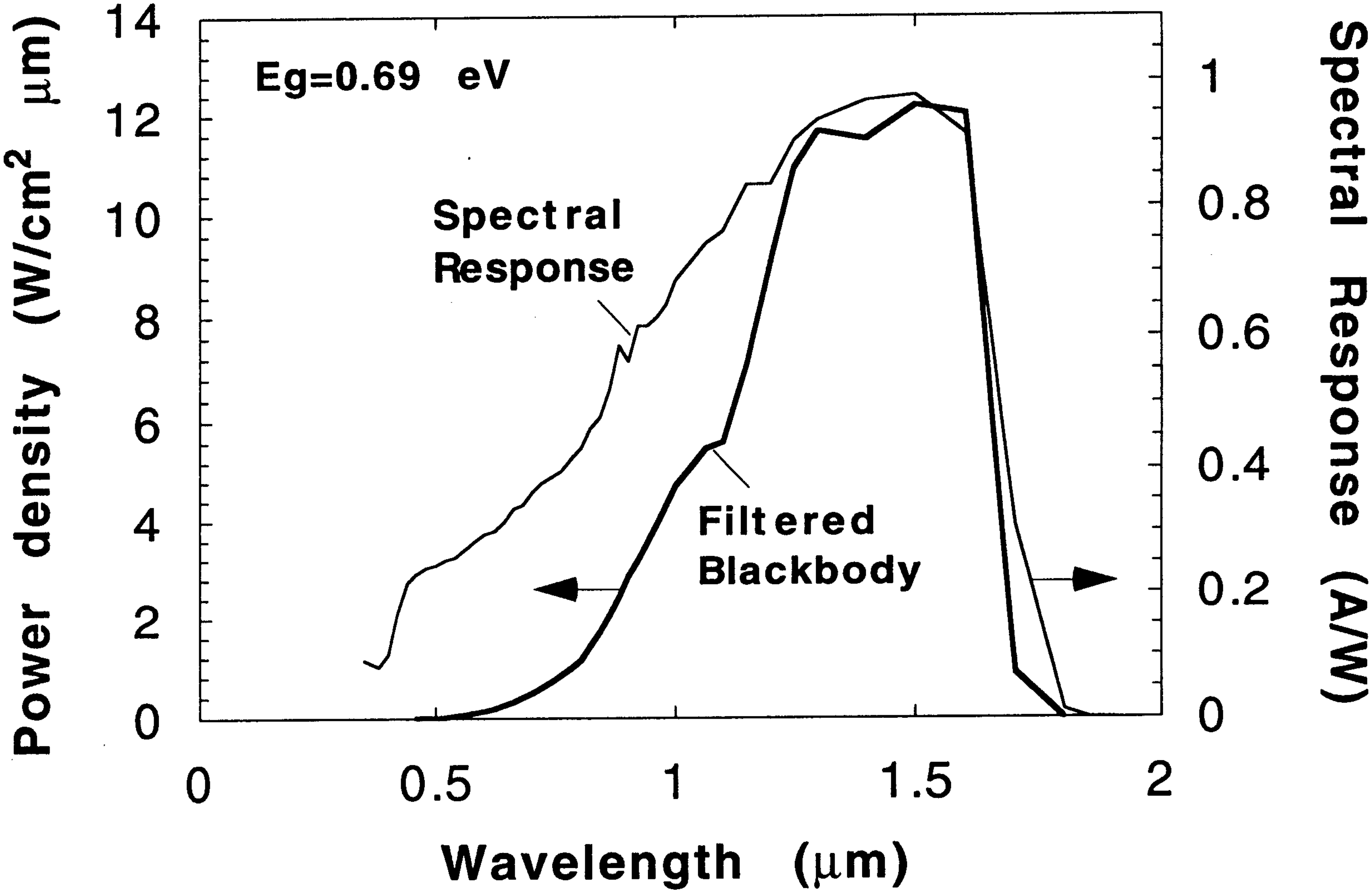


Filtered Tm-Lu,YAG Power at T=1700K
Eg=0.57 eV
Spectral Response
Filtered Tm-Lu,YAG
Power Density (W/cm² µm)
Spectral Response (A/W)
Wavelength (µm)
0.8
1.2
1.6
2
2.4
0
1
2
3
4
5
6
7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

Filtered Er-YAG Selective Emitter Power at 1700K



Filtered Blackbody Emitter Power at 1700 K



TECHNOLOGY UPDATE 3

Converters with Shortpass/IR Reflector Combination Filters

Selective Emitter	Filter λc (μm)	PV Cell Eg (eV)	Pout (W/cm^2)	Efficiency (%)
Ho-YAG	2.2	0.51	0.29	11.4
Tm-Lu,YAG	2.0	0.57	0.44	16.2
Er-YAG	1.7	0.69	0.78	29.0
Er-YAG	1.7	0.74	0.80	29.7

Converters with Shortpass-Only Filters

Selective Emitter	Filter λc (μm)	PV Cell Eg (eV)	Pout (W/cm^2)	Efficiency (%)
Ho-YAG	2.2	0.51	0.52	11.8
Tm-Lu,YAG	2.0	0.57	0.82	15.9
Er-YAG	1.7	0.69	1.00	26.7
Er-YAG	1.7	0.74	1.01	29.8

Converters with Shortpass/IR Reflector Combination Filters

Selective Emitter	Filter λc (μm)	PV Cell Eg (eV)	Pout (W/cm^2)	Efficiency (%)
Er-YAG	1.7	0.69	0.78	29.0
Er-YAG	1.7	0.74	0.80	29.7
Blackbody	1.7	0.69	1.94	26.9
Blackbody	1.7	0.74	1.90	26.0

Converters with Shortpass-Only Filters

Selective Emitter	Filter λc (μm)	PV Cell Eg (eV)	Pout (W/cm^2)	Efficiency (%)
Er-YAG	1.7	0.69	1.00	26.7
Er-YAG	1.7	0.74	1.01	29.8
Blackbody	1.7	0.69	2.48	25.8
Blackbody	1.7	0.74	2.40	25.0

Conclusions

1. At the source temperature of 1700 K, Er-YAG based converters have higher output power density and are more efficient than Tm-Lu,YAG or Ho-YAG based converters due to their coupling to the more efficient higher bandgap PV cells.

2. Converters with filtered YAG-based selective emitters are generally more efficient than filtered blackbody based converters, however, they produce significantly lower output power.

3. Converters with shortpass/IR reflector combination filters are more efficient than shortpass-only filter based converters, however, they produce substantially lower output power.

4. Current technology allows for the fabrication of efficient (~30%) TPV converters based on filtered YAG-based selective emitters or broadband blackbody emitters and InP/InGaAs/InP PV cells.

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HYDROCARBON FIRED THERMOPHOTOVOLTAIC GENERATOR PROTOTYPES USING LOW BANDGAP GALLIUM ANTIMONIDE CELLS

Lewis Fraas, Huang Han Xiang, John Samaras, Russ Ballantyne, Douglas Williams, James Avery, She Hui, and Luke Ferguson

JX Crystals Inc., Issaquah, WA

Low bandgap gallium antimonide photovoltaic cells now make hydrocarbon-fired thermophotovoltaic generators practical. Traditional cells such as silicon cells have higher bandgaps suited to radiation from extremely high temperature sources. Gallium Antimonide (GaSb) cells respond to infrared radiation with wavelengths up to 1.7 microns, so they are able to capture much more of the available energy from a hydrocarbon-fired emitter.

To illustrate the use of GaSb cells in practical thermophotovoltaic generators, we describe four different systems. In our smallest unit, we simply surround a kerosene lamp flame with a bracelet containing 16 GaSb cells, each measuring 1 cm^2. This unit produces 0.1 Watts, enough power to operate a small transistor radio. A bracelet consisting of similar sized silicon cells produced one quarter of the power. Carbon particles burning at 1950 C produce the yellow flame and the useful IR in this lamp unit.

The power produced in the lamp unit is small because the carbon particle density is very small. Inserting an infrared (IR) emitter with larger surface area in a flame dramatically increases the cell convertible IR energy. In our second, we insert a catalytic emitter coil in a Bunsen burner flame and surround this IR emitter with 20 GaSb cells. This unit produces over two Watts of electric power, enough to operate a "boom box" radio/tape player. In this unit, the catalytic emitter operates at a temperature of 1520 C.

While this two Watt unit was created as a demonstration, it has stirred considerable interest. Many modern commercial gas meters have electronics for data acquisition and telemetry, and are using batteries as a power source. Since the batteries must be replaced regularly and natural gas is easily accessible, our two Watt unit appears to be a more economical alternative. Also, this unit may be convertible to a camping unit that can be used for cooking and battery trickle charging.

A third unit is a wall mounted combination room heater and battery charger for off-grid remote applications. This unit uses a ribbon burner with a larger area linear emitter. Rows of cells are mounted in front of and behind the IR emitter. The exhaust heat from the burner passes upward into a wall mounted heater panel which heats the room. Meanwhile, the cells produce electricity to charge a battery. This unit can heat a room overnight and produce enough electricity to operate a color television during evening hours. For remote locations, the fuel of choice for this application will be propane.

The fourth unit is a more efficient cylindrical generator complete with exhaust heat regeneration and IR filters to recycle non-useful IR back to the emitter. Units this size running on propane and complemented by a small bank of batteries would meet the electrical and heating needs of a small remote cabin.

The advantage of TPV over conventional solar for these remote applications is dependent on an available source of fuel (propane, natural gas or potentially diesel). If fuel is available, that advantage lies in the power density of the cells. Conventional cells with 10% efficiency generate approximately 0.01 Watts per cm^2 in full sunlight. In northern climates in wintertime, this can mean daily power per cm^2 of cell area of only 0.02 to 0.05 Watt-hours. At the same time, fuel is being burned for heating. A TPV unit can run 24 hours per day with power densities of two Watts per cm^2 of cell area for a daily generation of almost 50 Watt-hours per cm^2. The fuel is then being used with the 90% efficiencies found in home furnaces. With over one thousand times the daily power generation per unit area, GaSb cells can be cost effective at prices hundreds of times higher than current silicon solar cells.

Larger versions of the "Midnight Sun" are under development, with the potential for cogeneration of heat and electricity in homes currently connected to the electric grid. The likely fuel for this system will be natural gas.

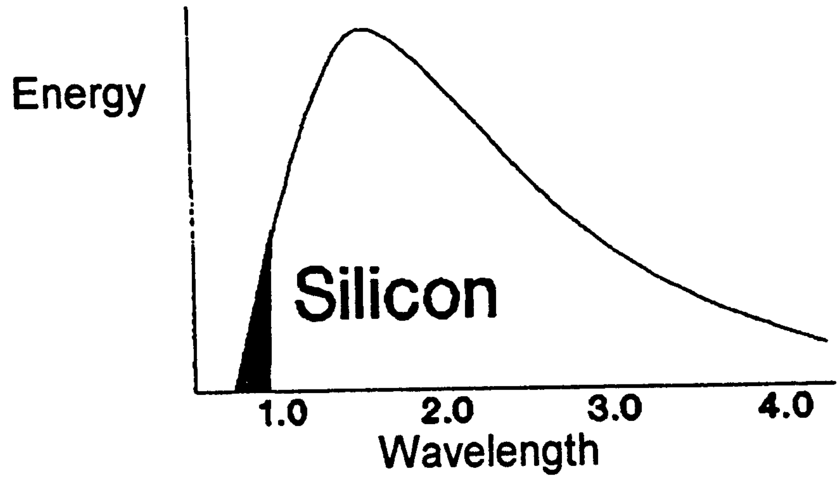
HYDROCARBON FIRED THERMOPHOTOVOLTAIC GENERATOR PROTOTYPES USING LOW BANDGAP GALLIUM ANTIMONIDE CELLS

Lewis Fraas, Huang Han Xiang, John Samaras, Russ Ballantyne, James Avery, Douglas Williams, She Hui, and Luke Ferguson

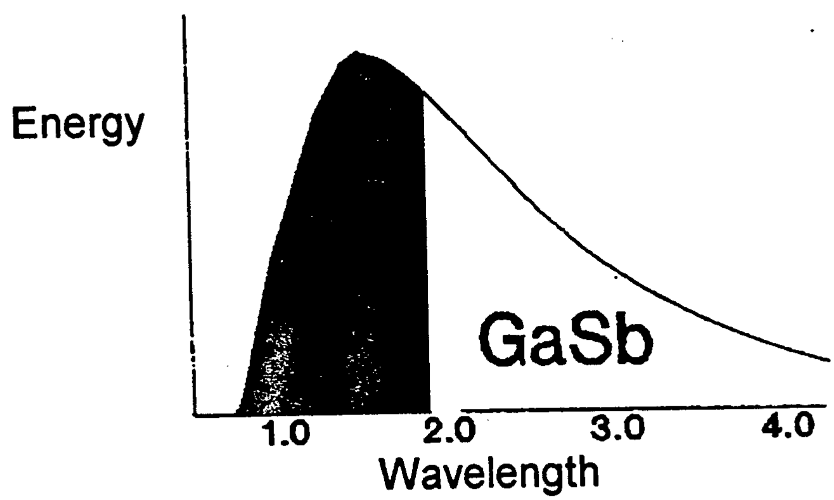
JX Crystals Inc., Issaquah, WA

Gallium Antimonide vs. Silicon

(1700° C blackbody source)



Silicon cells are insensitive to infrared energy from man-made heat sources



Our GaSb cell is an ideal energy converter for infrared radiant energy

JX Crystals Inc.

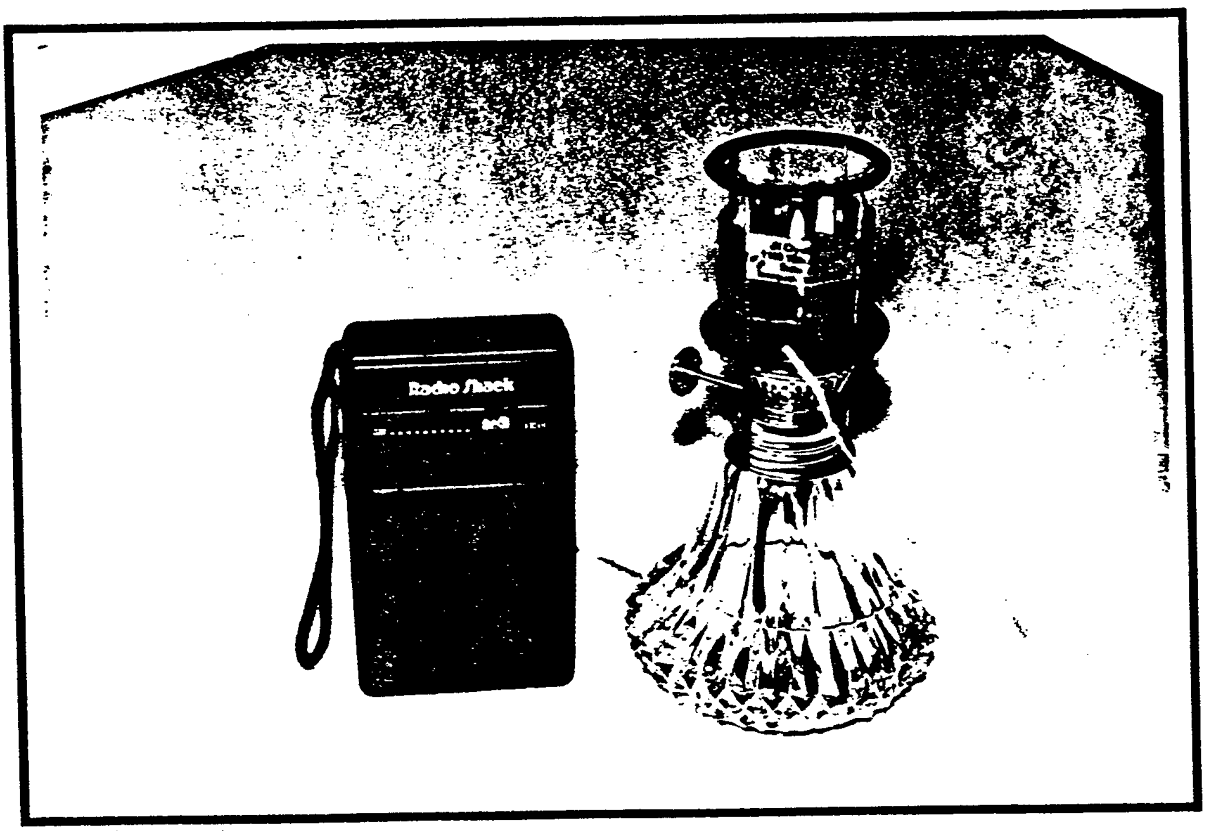
Highlights:

1.) Low bandgap diffused junction Photovoltaic Cells are enabling for thermophotovoltaic generators.

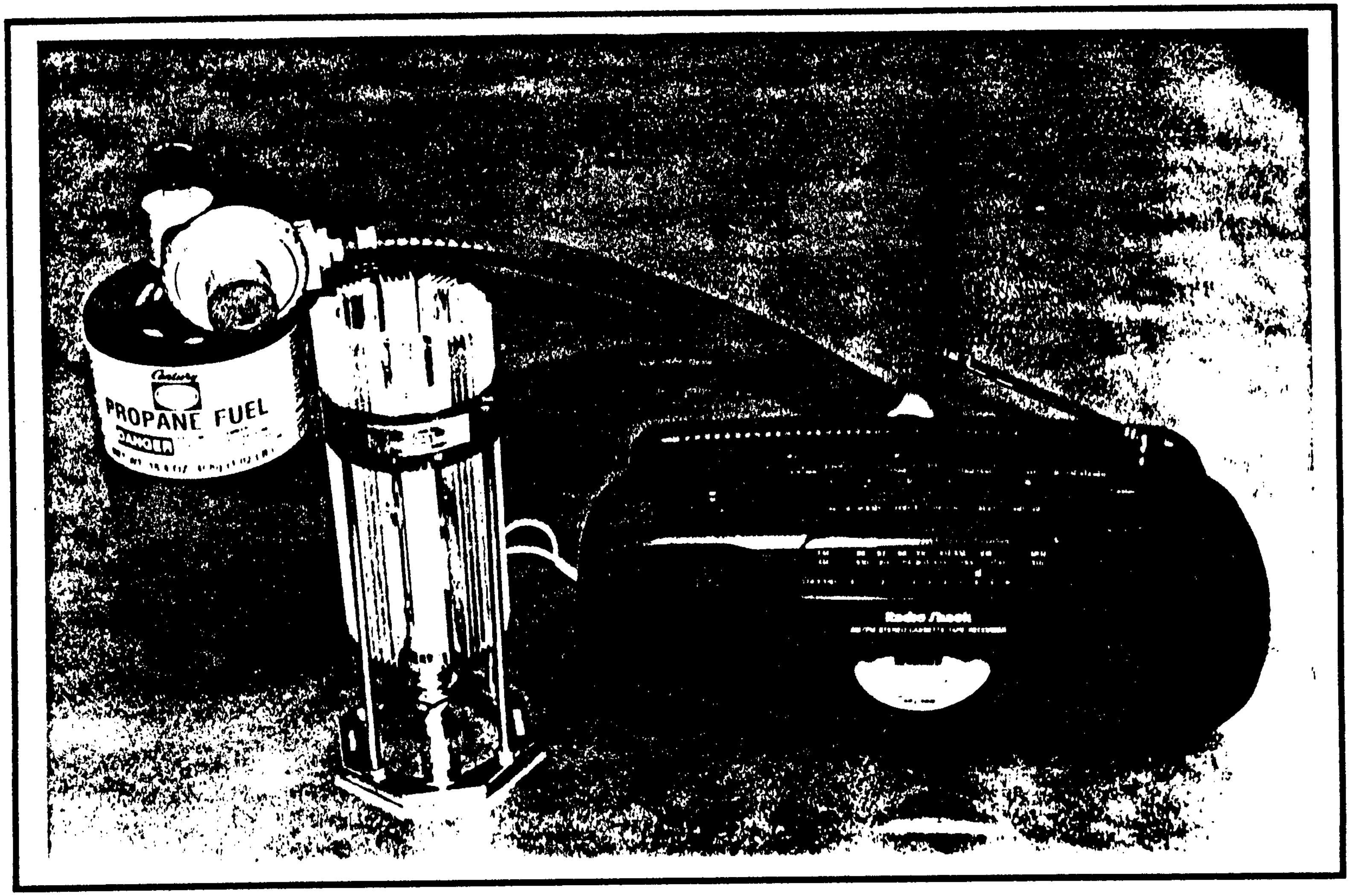
2.) These cells are potentially low cost since diffusion is much cheaper than epitaxy and no toxic gases are used.

3.) To illustrate this, we have fabricated four prototype TPV generators.

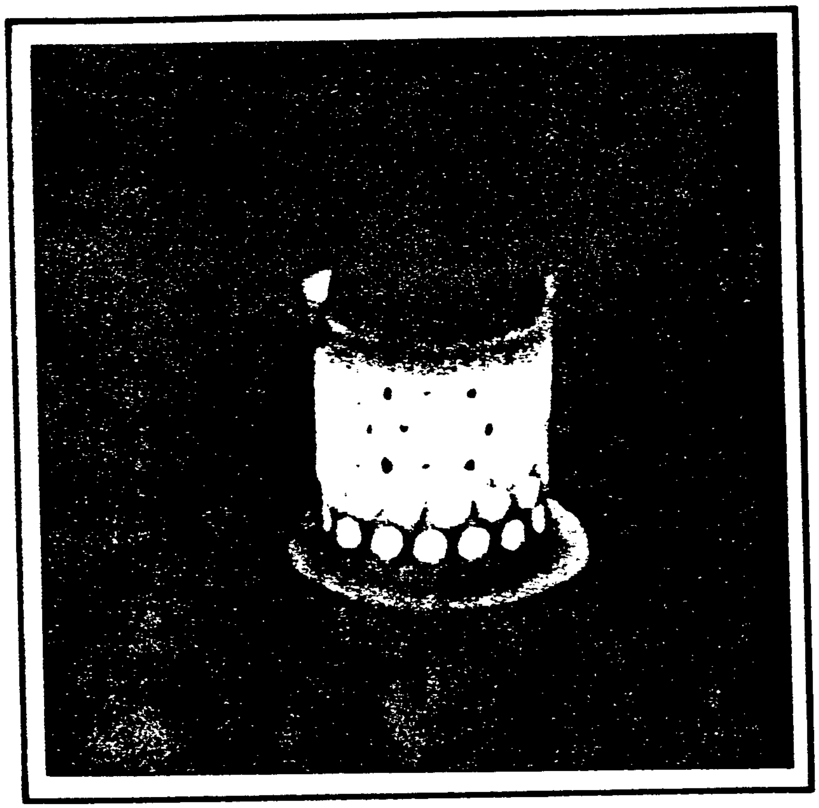
a: Candle powered radio	0.1 Watts electric.
b: Bunsen burner portable electric generator	2 Watts electric.
c: Cogenerative wall heater	30 Watts electric.
d: Air cooled cylindrical generator with heat exchanger	130 Watts electric



JX Crystals' Candle-Powered Radios using GaSb Cells

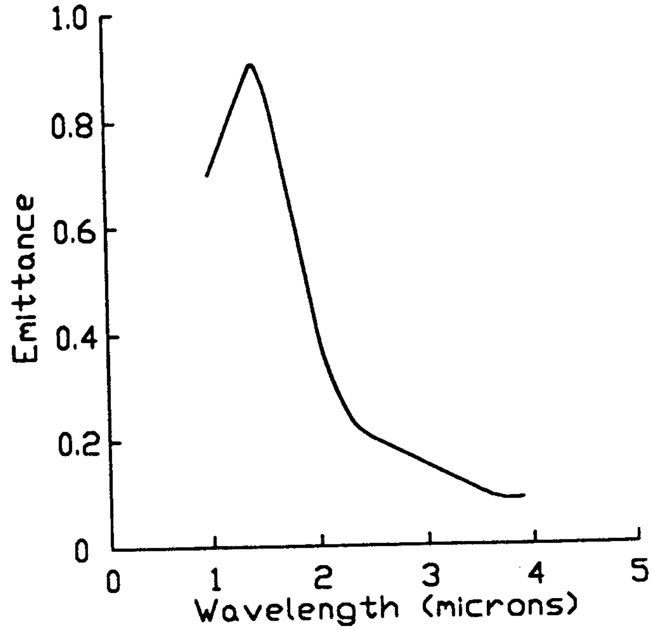


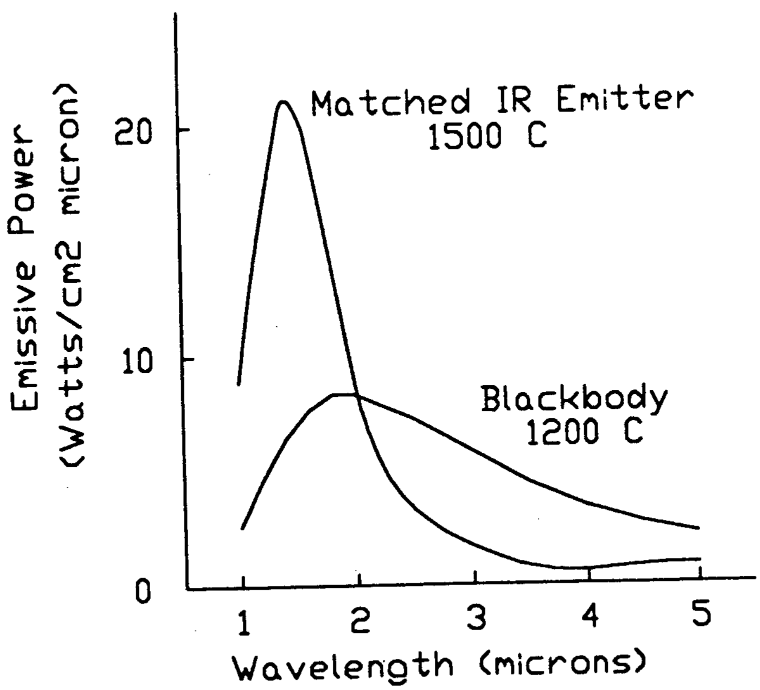
Two Watt Propane-Fired Midnight Sun® Demonstration Unit

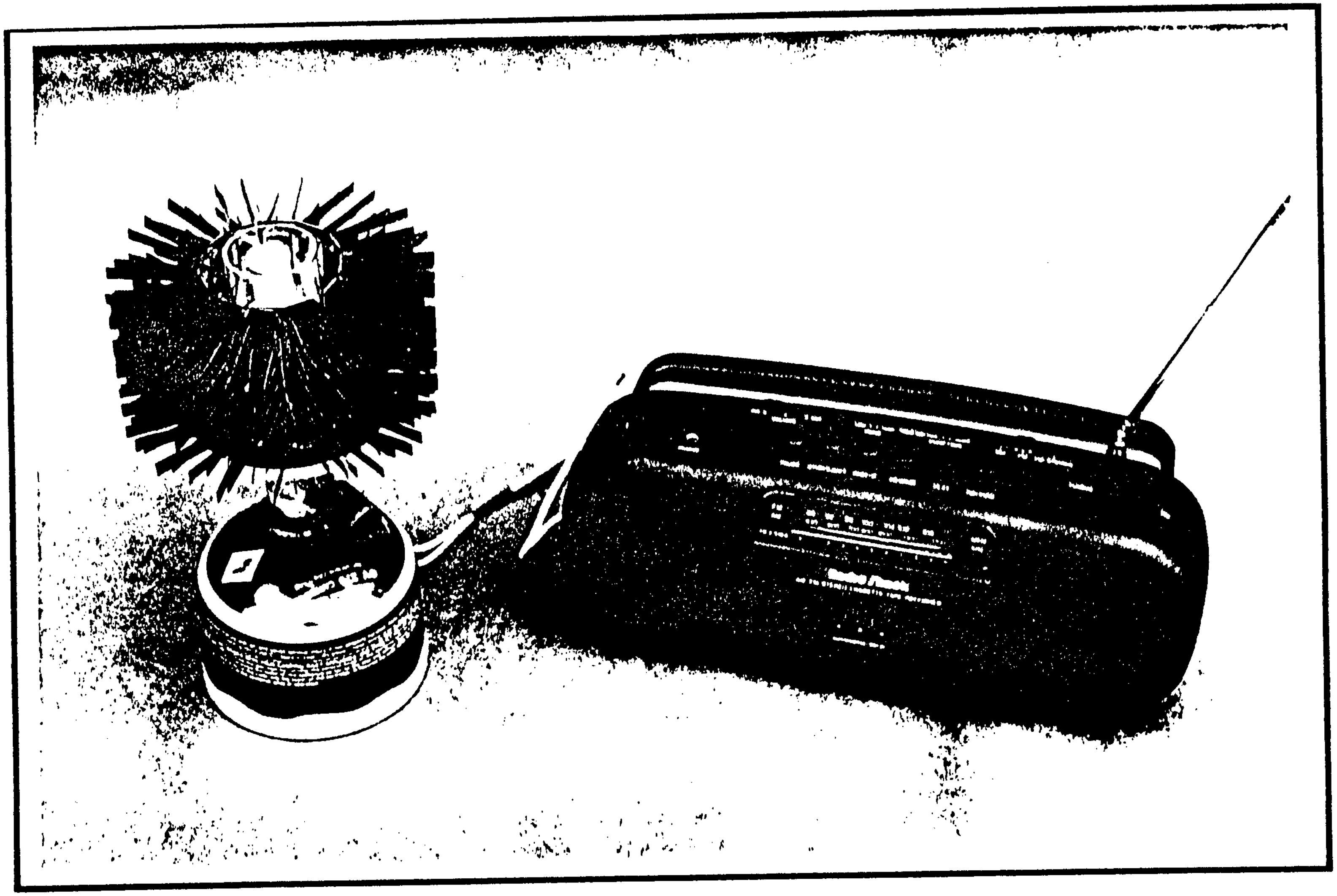


Matched Emitter for GaSb Photovoltaic Cells

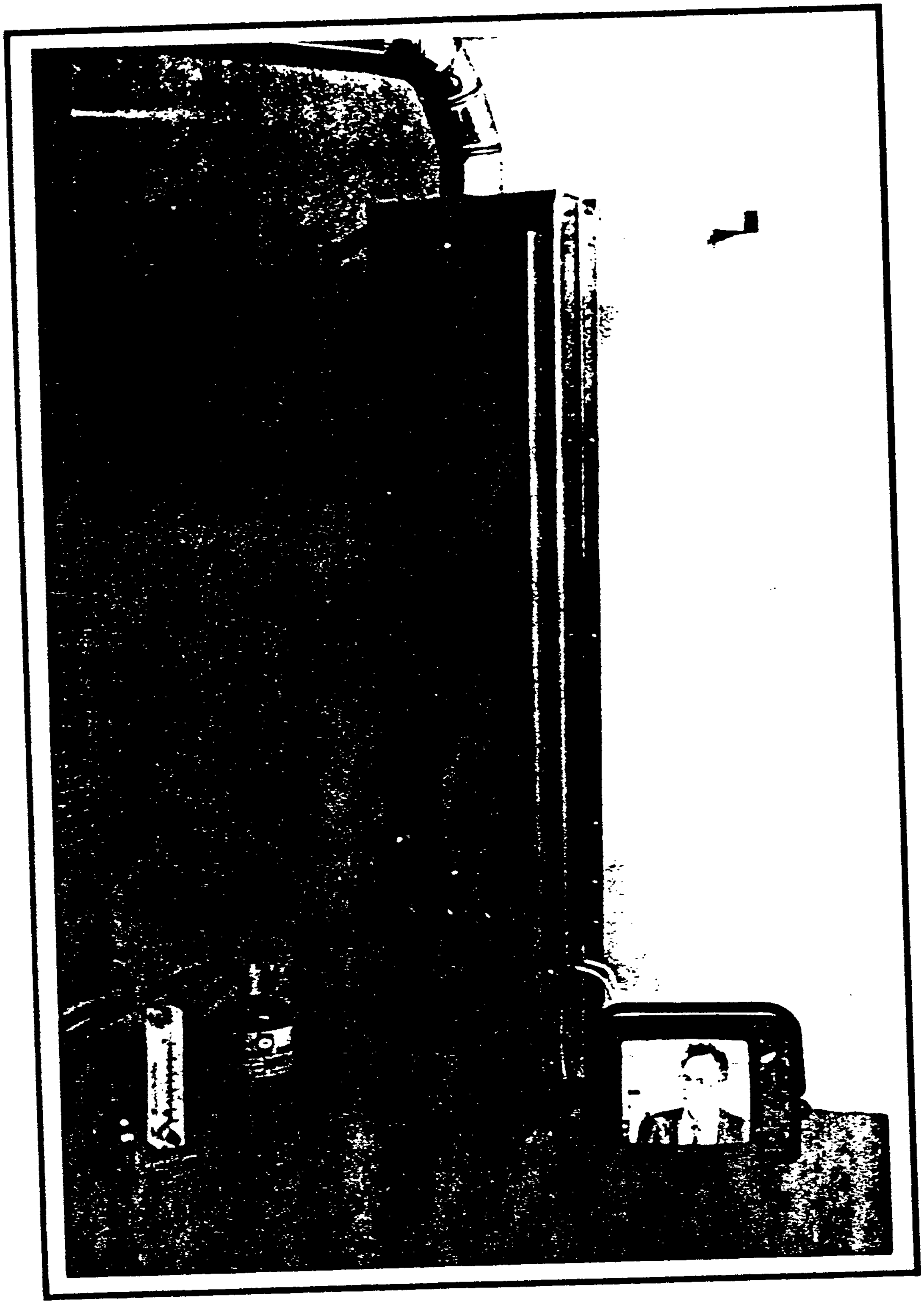
JX Crystals Inc
Matched IR Emitter



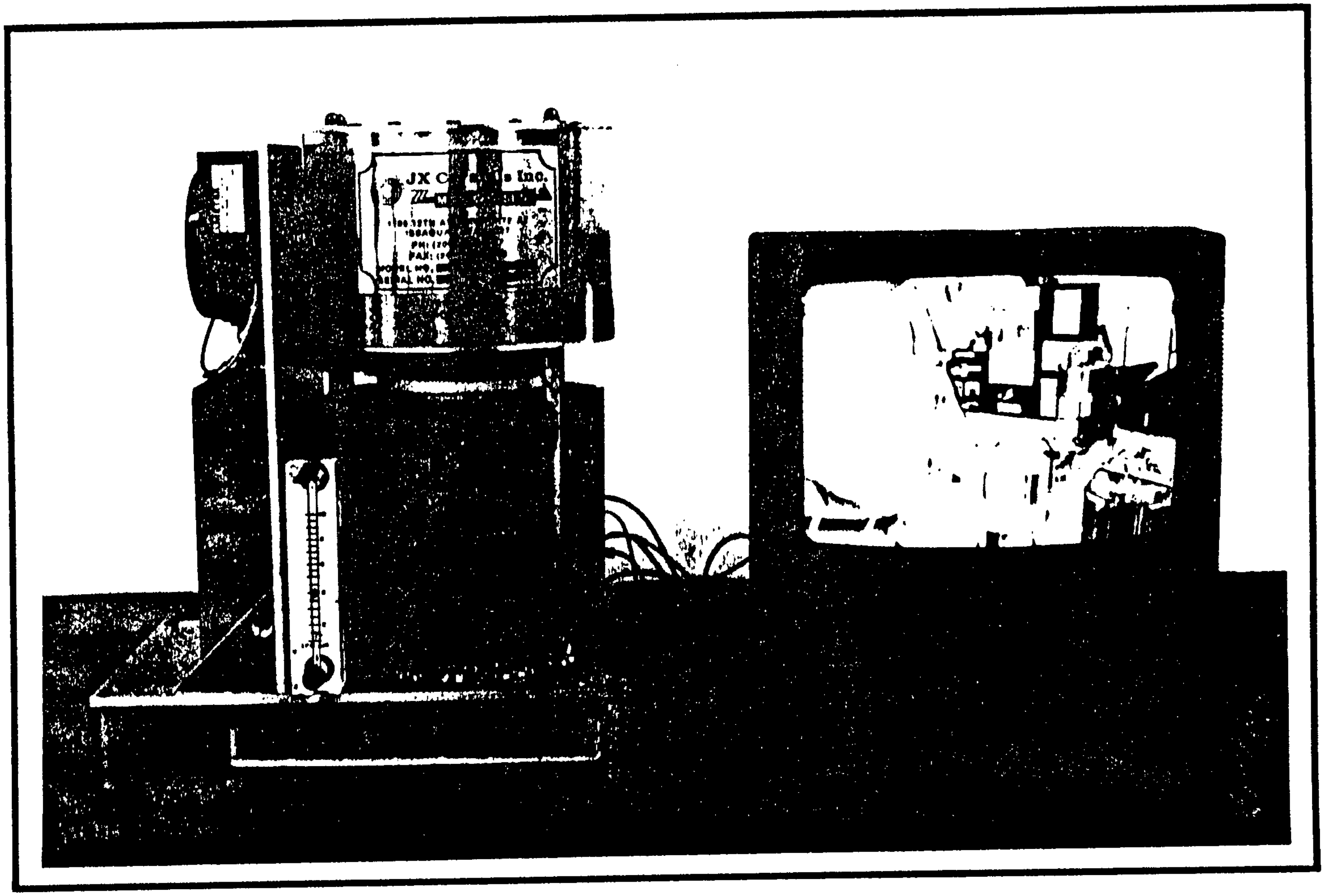




Two Watt Butane-Fired Midnight Sun® Demonstration Unit



30 Watt Midnight Sun® Heater Unit
(Propane-Fired)



130 Watt Midnight Sun® Cogenerator with Heat Exchanger
(Natural Gas-Fired)

Conclusions:

1.) Low bandgap diffused junction Photovoltaic Cells are enabling for thermophotovoltaic generators.

2.) To illustrate this, we have fabricated four prototype TPV generators.

3) New matched emitters should allow improvements in power density and efficiency.

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Low Cost, Low Bandgap Thermophotovoltaic Cells

Lewis Fraas, Huang Han Xiang, Russ Ballantyne,
James Avery, Paul Custard, She Hui, and Ye Shi-Zhong

JX Crystals Inc
Issaquah, WA

Thermophotovoltaic generators allow heat and electricity to be quietly and reliably generated from a single unit; at a low enough cost, such a unit could replace a home furnace and dependence on the electric grid at the same time. Using low bandgap gallium antimonide (GaSb) photovoltaic cells, JX Crystals has recently demonstrated prototype TPV generators. The major cost item in these TPV generators will be the low bandgap cells, and the target cell cost for the home cogeneration unit will be $1 per Watt. The three cost elements in TPV cell cost are materials cost, process cost, and overhead cost. In the following, these three costs are discussed in more detail.

While it is generally believed that the cost of materials makes non-silicon photovoltaic cells prohibitively expensive and that this forces one to do research to develop thin film cells, this thesis is wrong. Specifically for the GaSb cell, JX Crystals' cells have an area of 1.4 cm^2 and routinely produce 2 Watts each in a TPV configuration. Each of these cells weighs 0.45 gm, of which 36% is Ga and 64% is Sb. We pay 45 cents per gram for Ga and 25 cents per gram for Sb. The cost, therefore, for the Ga and Sb in a GaSb TPV cell is:

$$((45¢ \times 36\%) + (25¢ \times 64\%)) \times 0.45 \text{ grams} = 7.3¢ + 7.2¢ = \mathbf{14.5¢}$$

Since each cell produces 2 Watts, the material contribution to the electric power cost is only **7.3 cents per Watt**. This is an amazing fact.

The reader may then immediately ask: Why then are GaAs and GaSb cells currently expensive? The answer to this question has to be broken down into an answer for GaAs and a different answer for GaSb.

First, GaAs solar cells are inherently expensive not because of the materials incorporated in the cells, but because of the inherently expensive processing used to fabricate the cells. GaAs cells are formed by growing GaAs junction layers and AlGaAs window layers in a chemical vapor deposition (CVD) reactor using large quantities of very toxic gases. The CVD reactor is very costly and its production throughput is low. Furthermore, the safety equipment required for the use of the toxic gases is expensive and safety precautions further slow down the process. Put together, these process steps make GaAs cells intrinsically expensive.

Another example of a cell using intrinsically expensive processing is the InGaAs on InP low bandgap cell. Like the GaAs cell, this cell is fabricated using low throughput CVD with toxic gases. A second source of high process cost is the requirement for a high pressure puller for InP crystal growth.

Concurrently, silicon cells are inexpensive because the processes used are less costly and allow higher throughput. Silicon crystals are grown at low pressure, silicon cell junction formation is done by diffusion, and no toxic gases are required. All of these significant attributes are inherent in the processing of JX Crystals' GaSb cells, so with comparable volume production GaSb cells can achieve similar pricing.

Our thesis here is that GaSb cells can be made inexpensively in high volume by continuing to copy the low cost silicon solar cell process. Specifically, the following four process innovations can be implemented to reduce the ultimate cost of GaSb cells:

1) Replace the expensive wafer polishing step with a less expensive wafer etch step prior to diffusion.

2) Slice up the crystal using a multiple-wire saw rather than the traditional inner-diameter saw. This will increase throughput and reduce kerf loss and decrease saw damage.

3) Decrease labor cost in the photolithography steps through the use of a gentle wafer track.

4) Develop an automatic crystal diameter control for crystal growth for the production of 4" wafers. This will reduce the waste of perimeter material from the GaSb crystal.

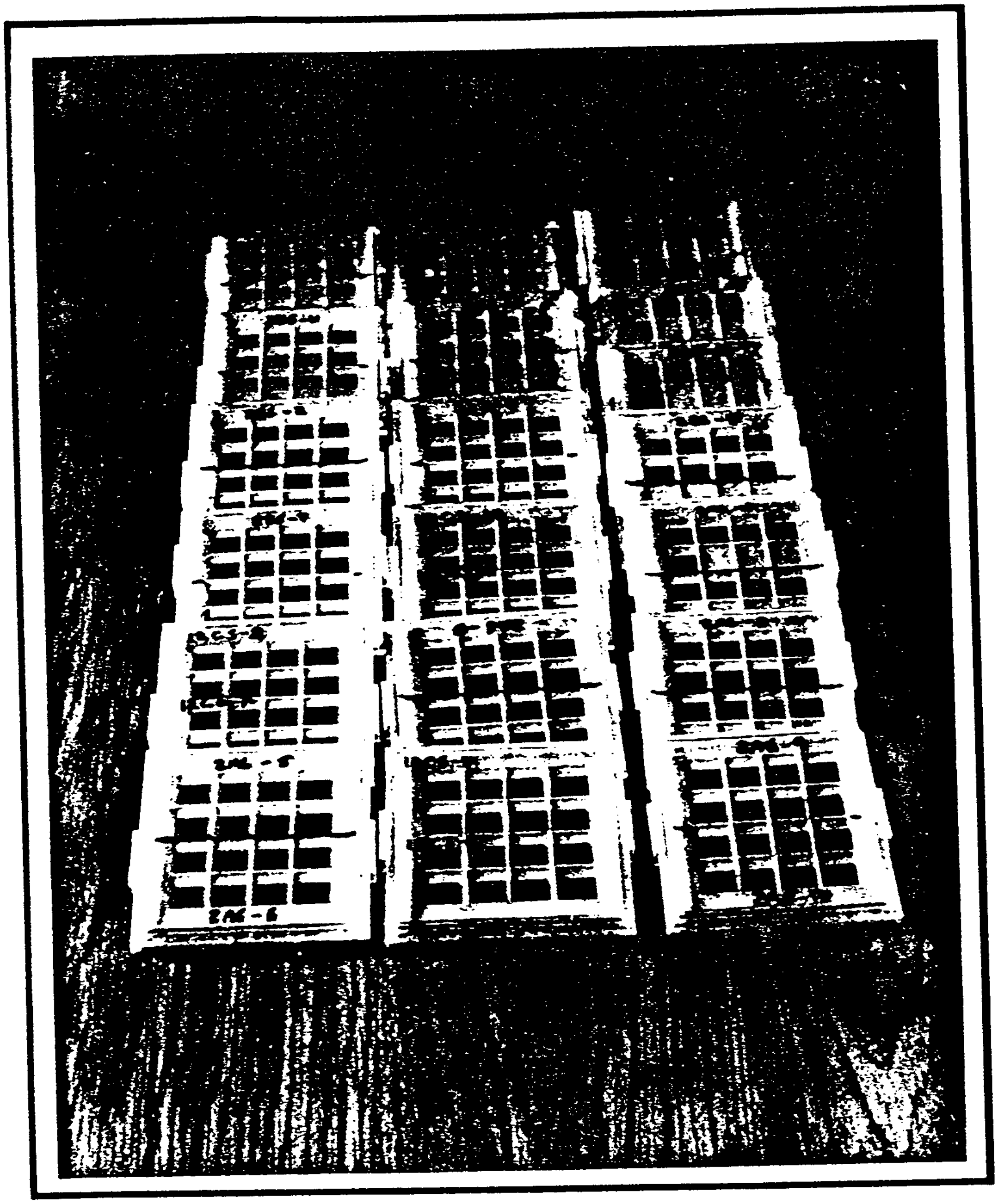
DARPA and the Army are interested in TPV electric generators because of their quiet and potentially light weight features. However, these TPV generators will have to be price competitive with existing generators which currently cost approximately $1 per Watt. Given that the balance of system costs for a TPV generator will not be zero, the cost of the low bandgap photovoltaic converters must eventually be on the order of $1 per Watt or less.

The reason why GaSb cells are currently expensive is that they are made in low volume where R&D overhead costs dominate.. Since low bandgap infrared cells are enabling for TPV generators and since these cells are not commercially available in quantity, JX Crystals has recently written a business plan defining a path for cell commercialization. Our business plan focuses on creating markets for TPV and investment for production scale up

LOW COST, LOW BANDGAP GALLIUM ANTIMONIDE TPV CELLS

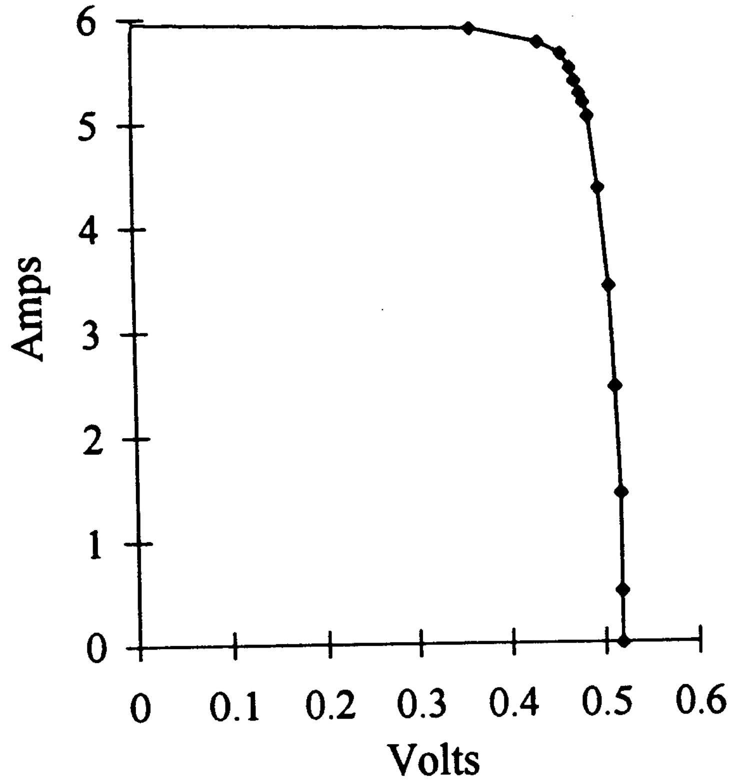
Lewis Fraas, Huang Han Xiang, Russ Ballantyne,
James Avery, Paul Custard, She Hui, and Ye Shi-Zhong

JX Crystals Inc., Issaquah, WA



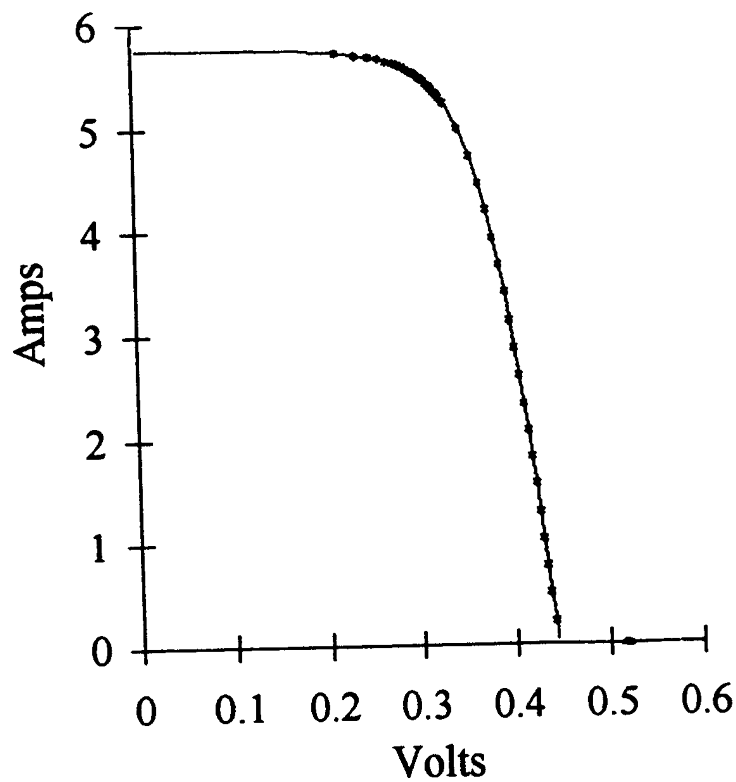
JX Crystals' GaSb Cells

JX Crystals GaSb cells



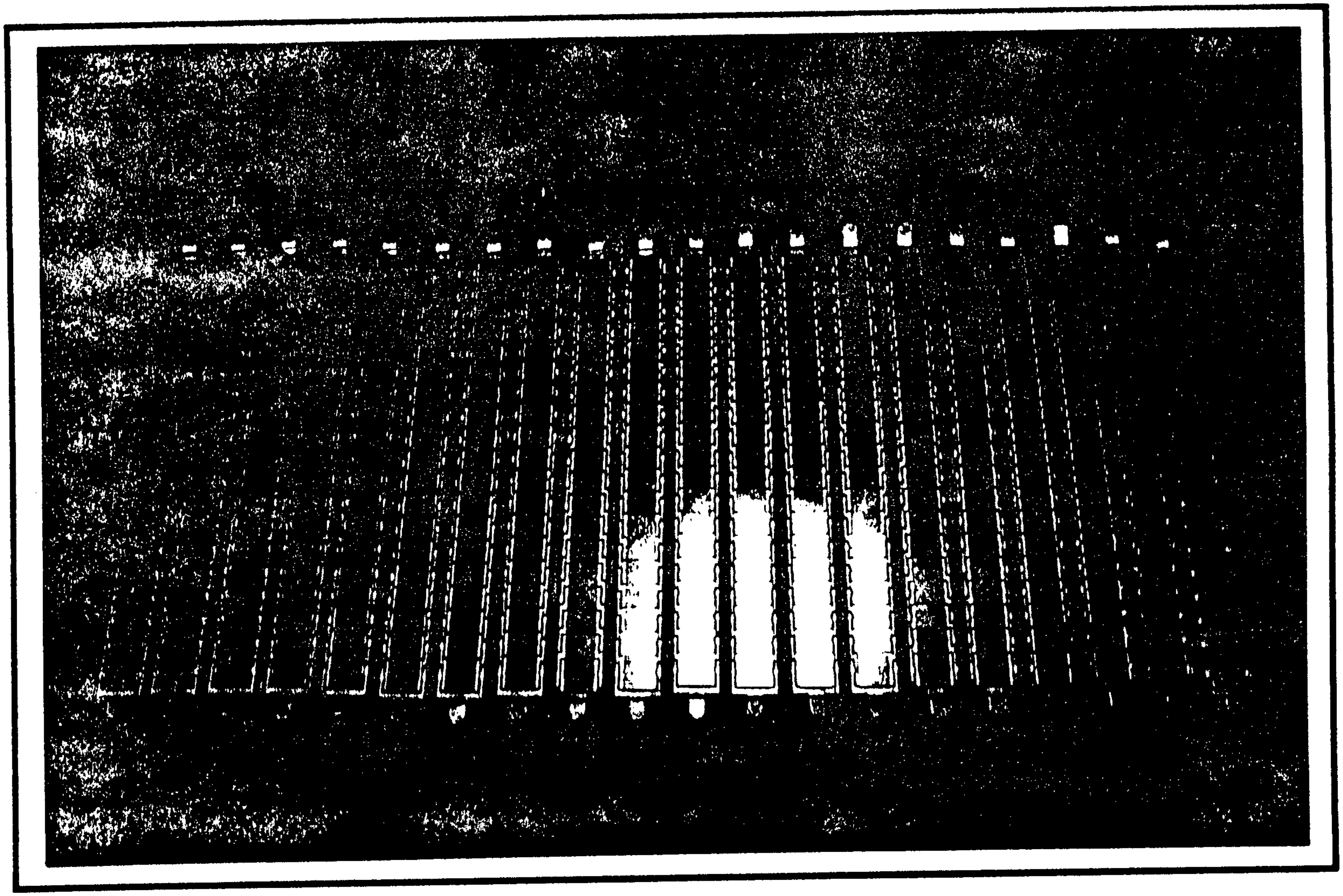
FF = 0.84
Voc = 0.52 V
Isc = 5.95 A
Imax = 5.63 A
Vmax = 0.46 V
Pmax = 2.59 W

Flash Tested Best Cell



FF = 0.67
Voc = 0.44 V
Isc = 5.87 A
Imax = 5.36 A
Vmax = 0.33 V
Pmax = 1.76 W

Standard Cell held in front of 1380° C SiC glowbar



20 GaSb circuits for a one kilowatt TPV unit

Elements of Cell Cost:

1) Materials Cost

2) Process Cost

3) Overhead Cost

GaSb Cell Materials Cost

1) Each 1.4 cm^2 cell produces 2 Watts.
2) Each cell weighs 0.45 gm of which 36% is Ga and 64% is Sb.
3) Ga cost 45 cents per gram and Sb cost 25 cents per gram.
4) The cost, therefore, for the Ga and Sb in a GaSb TPV cell is:
((45¢ x 36%) + (25¢ x 64%)) x 0.45 grams = 7.3¢ + 7.2¢ = **14.5¢**
5) The materials part of the electric power cost is **7.3 cents per W.**

This is an amazing fact !!!

GaSb Process Cost

Process costs dominate at high volume production.

The GaSb cell process copies the silicon solar cell process for low cost. This will allow a high volume cost of below $1/W.

Specifically:

a. We use diffusions for junction formation, not epitaxy.

b. No toxic gases are used anywhere in the process.

c. We use converted Si Czochalski pullers for crystal growth. No high pressure pullers are required.

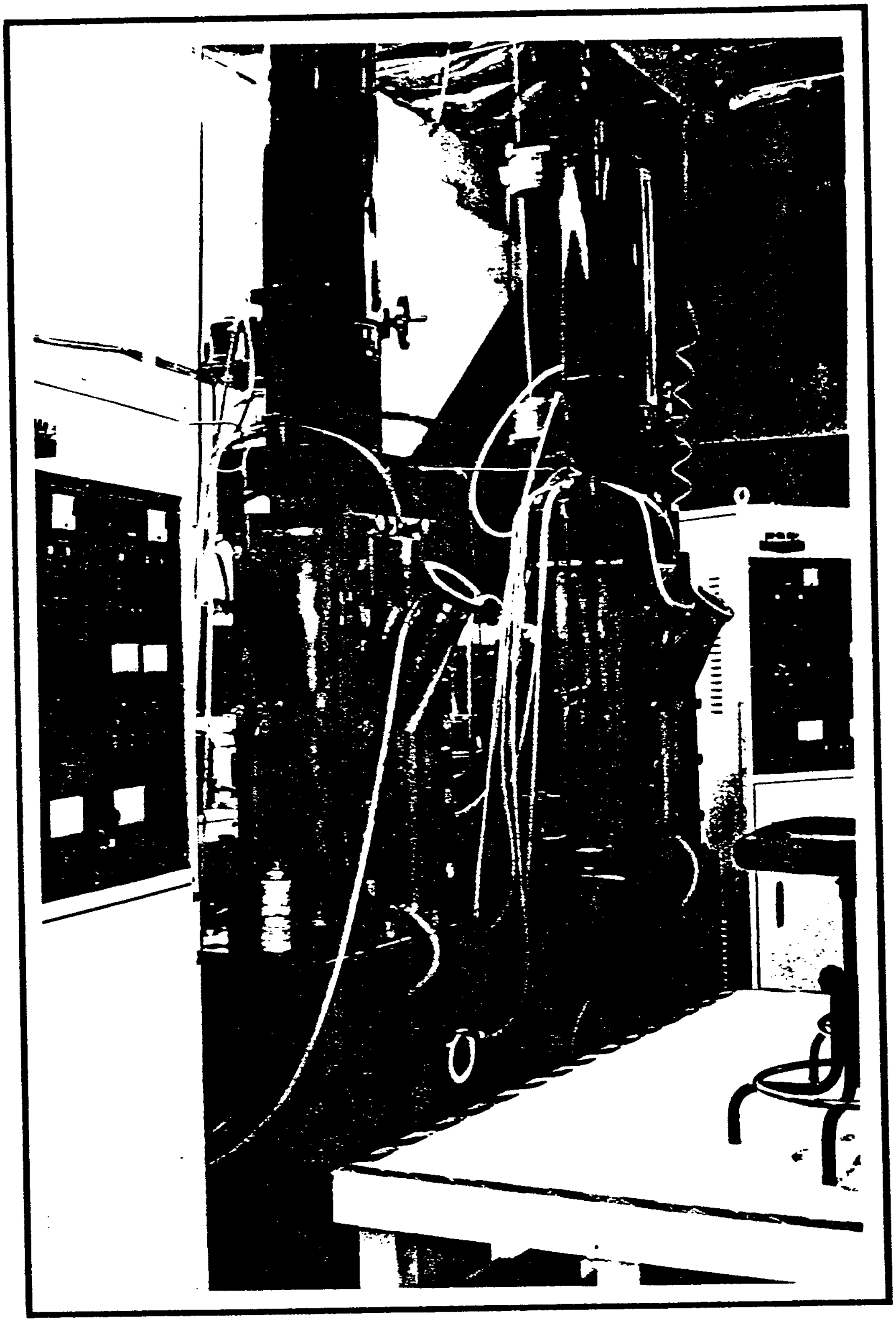
d. Wafers are simply etched before diffusion and after crystal slicing. No wafer polish step is required.

Table 1:GaSb Cells: Polished vs Etched

2/3/96

1A6 Cell Testing, 5 Starting Wafers, 25 Cells,

Wafer	Cell	FF	Voc	Isc	Imax	Vmax	Pmax
1a6-11	1-2	0.764	0.493	5.733	5.232	0.413	2.159
1a6-11	2-1	0.776	0.493	5.750	5.294	0.416	2.200
1a6-11	2-2	0.778	0.495	5.853	5.404	0.417	2.254
1a6-11	2-3	0.784	0.493	5.699	5.317	0.415	2.204
1a6-11	3-2	0.786	0.495	5.751	5.294	0.423	2.238
1a6-12	1-2	0.755	0.497	5.865	5.378	0.409	2.200
1a6-12	2-1	0.716	0.497	5.864	5.381	0.388	2.086
1a6-12	2-2	0.706	0.498	5.971	5.397	0.389	2.100
1a6-12	2-3	0.697	0.496	5.922	5.404	0.379	2.048
1a6-12	3-2	0.685	0.494	5.777	5.312	0.368	1.956
1a6-13	1-2	0.766	0.496	5.957	5.518	0.411	2.266
1a6-13	2-1	0.766	0.497	5.913	5.317	0.423	2.251
1a6-13	2-2	0.780	0.498	6.026	5.470	0.428	2.340
1a6-13	2-3	0.747	0.496	5.859	5.293	0.410	2.171
1a6-13	3-2	0.767	0.495	5.875	5.382	0.415	2.234
Front-Side Cell Average (**polished**)		0.752	0.496	5.854	5.360	0.407	**2.180**
1a6-14	1-2	0.757	0.490	5.783	5.271	0.407	2.147
1a6-14	2-1	0.753	0.491	5.833	5.232	0.412	2.156
1a6-14	2-2	0.740	0.485	5.855	5.205	0.404	2.102
1a6-14	2-3	0.773	0.489	5.730	5.227	0.414	2.164
1a6-14	3-2	0.734	0.481	5.918	5.362	0.390	2.092
1a6-15	1-2	0.737	0.494	5.744	5.189	0.403	2.090
1a6-15	2-1	0.732	0.491	5.665	5.144	0.396	2.037
1a6-15	2-2	0.742	0.492	5.748	5.250	0.399	2.097
1a6-15	2-3	0.703	0.477	5.729	5.144	0.374	1.922
1a6-15	3-2	0.706	0.485	5.782	5.186	0.381	1.978
Back-Side Cell Avg (**etched**, not polished)		0.738	0.488	5.779	5.221	0.398	**2.079**



GaSb Crystal Pullers at JX Crystals

Overhead Costs Dominate for R&D Company with Low Volume Cell Sales

Minimal man power:	9= $900k
Management	1
Marketing	1
Wafer Fab	2
Cell Fab	2
Circuit Fab	1
Testing	1
Facility	1

Assume:
- 2W / cell
- 5000 cells/yr
- 10 kW/yr
- 2” wafers

Result:
- $90/Watt

Cost vs Volume

Volume	Cost
1) 5000 cells/yr; 10 kW/yr; 2” wafers	$90/Watt
2) 50,000 cells/yr; 100 kW/yr; 3” wafers	$9/Watt
3) 2 MW/yr; 4” wafers; Low cost process	$1/Watt

Conclusions:

1) Materials costs are small for GaSb TPV cells.
2) Overhead costs dominate at low production volumes.
3) Process costs dominate at high production volumes.
4) The process costs for GaSb cells are low because we copy the silicon cell process.
5) Low cost, low bandgap GaSb cells are enabling for economical TPV generators.

Presentation at the Prospector VIII Workshop, "Thermophotovoltaics -- An Update on DoD, Academic, and Commercial Research", Durham, NC, July 14-17, 1996.

InGaAs Thermophotovoltaic Cells

Steven J. Wojtczuk and Harvey B. Serreze
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One Patriots Park
Bedford, MA 01730

Abstract

Thermophotovoltaic (TPV) cells fabricated from indium gallium arsenide ($In_xGa_{1-x}As$) epitaxial layers grown on indium phosphide (InP) substrates are capable of high performance and offer advantages over alternative approaches. Made by the production-scalable, metalorganic chemical vapor deposition (MOCVD) process, $In_xGa_{1-x}As$ cells are able to cover a wide range of bandgap depending on the value of x. Small bandgap 0.55 eV $In_xGa_{1-x}As$ cells (x = 0.72) use much more of the long wavelength energy emitted from low temperature (<1200°C) thermal sources than either Si or GaSb TPV cells. Such low temperature sources are encountered in applications as diverse as radioisotope-powered General Purpose Heat Sources (GPHS) for space applications, liquid-fuel powered TPV generators for soldier use, and small, natural-gas powered TPV generators for home and consumer use. Furthermore, the availability of large diameter (currently up to 3-inch) InP substrates will help to increase device processing throughput and will contribute to reduced cell manufacturing costs.

Statistically significant numbers (>2500) of n/p InGaAs/InP TPV cells have been made and tested at Spire. The detrimental effects of lattice mismatch between the InP substrate and the $In_xGa_{1-x}As$ active region are reduced by using a grading layer in the epitaxial structure between the substrate and the active region. At 1.2 A/cm^2 short-circuit current density, average open-circuit voltages of 283 mV are obtained with 60% fill factors. The external quantum efficiency of AR-coated cells is nearly 90% in the 1.4 to 1.8 μm wavelength range.

Future activities and plans at Spire include the development of monolithic interconnection schemes similar to approaches previously developed for laser power converters to increase the useful operating voltage of TPV devices, the improvement of voltage and fill factor through reductions in dark current, and further reduction in cell cost through such approaches as growth on alternative substrates.

InGaAs Thermophotovoltaic Cells

Steven Wojtczuk and **Harvey B. Serreze**

Spire Corporation

One Patriots Park

Bedford, MA 01730-2396

spire

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Introduction - About Spire

- Spire is a 25-year old small business
- ~$18M in annual sales
  - ~50% commercial and 50% R&D
- Optoelectronics Division ~1/3 of sales
  - MOCVD epitaxial materials
  - laser diodes
  - photovoltaic power converters
- TPV cells are a spinoff from InGaAs LPCs

spire

Why InGaAs for TPV?

- Useful for low temp. (<1200C) heat sources
- Ability to adjust the cutoff wavelength
- Large three-inch diameter InP wafers used
  - twice as many cells as on a two-inch wafer
  - readily available from several vendors
  - wafer development supported by optoelectronics industry

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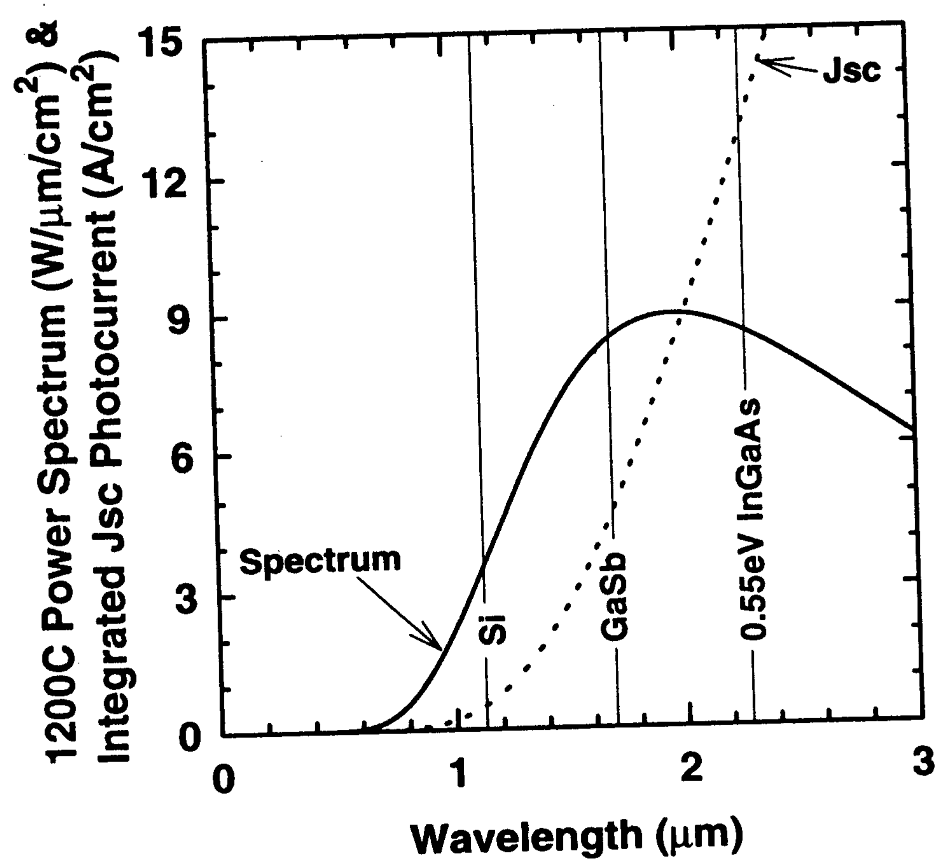
Why 0.55 eV InGaAs cells?



Lower bandgap cells use more spectrum

Trade-off in Voc and FF versus Jsc

However, overall, more power from InGaAs for low temperature sources

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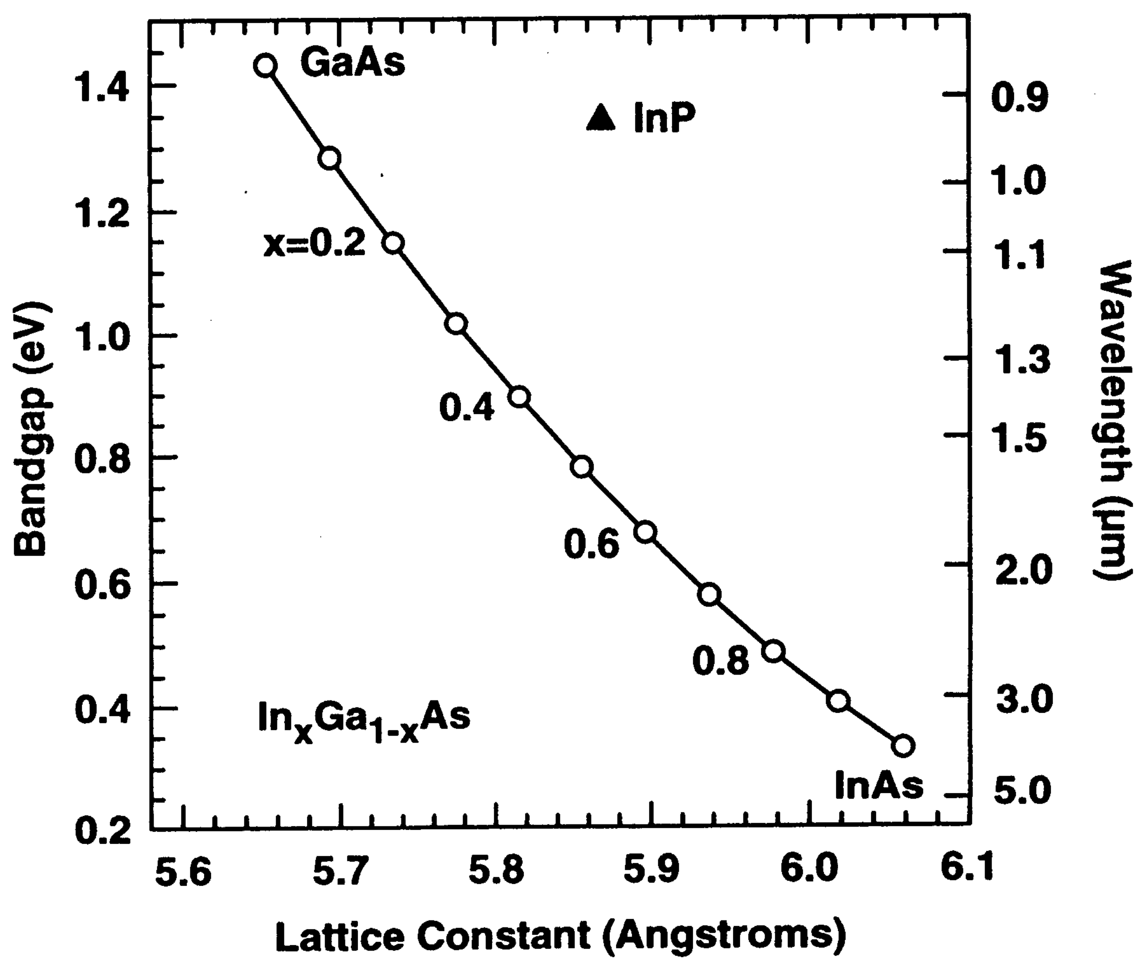
InGaAs Eg vs. Lattice Constant



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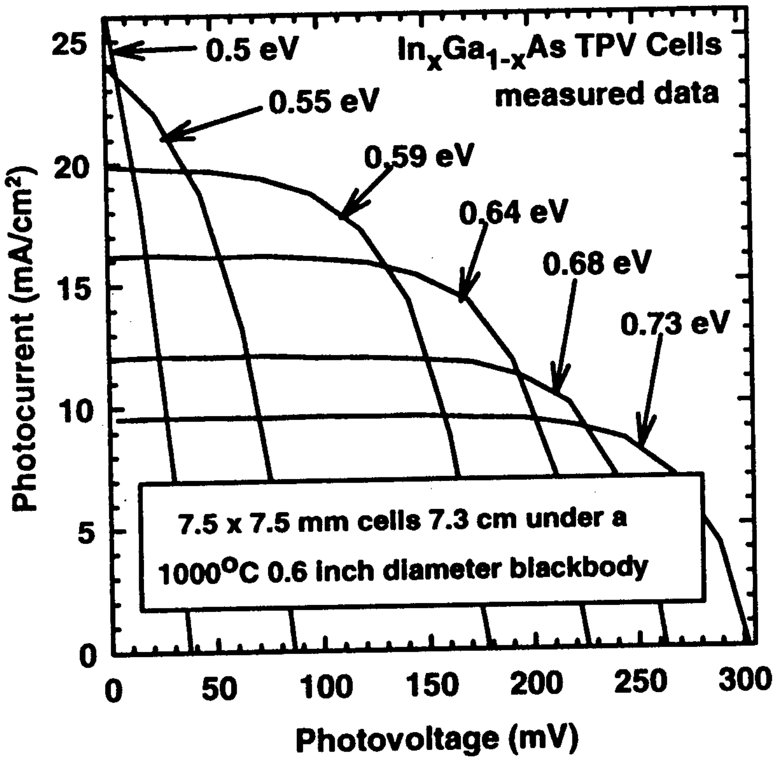
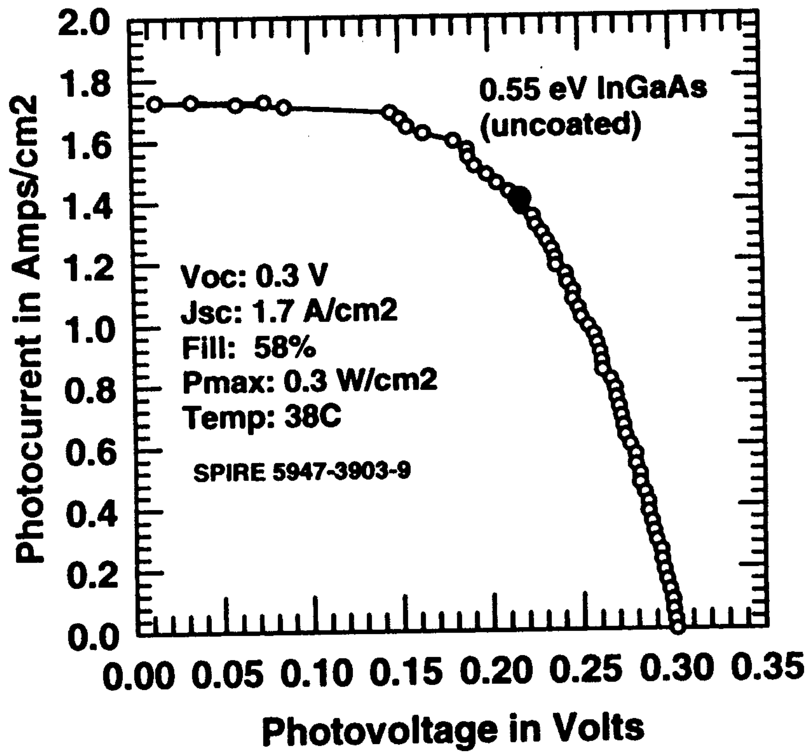
Spire InGaAs TPV Cell I-Vs



Early cells; no grade



Recent cells; grade

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Epilayer Structure of 0.55 eV Cell

N++ higher bandgap window
N+ In(72%)Ga(28%)As emitter
P- In(72%)Ga(28%)As base
P+ higher bandgap back surface field
P+ step grading layer In(72%)Ga(28%)As to In(53%)Ga(47%)As
P+ InP buffer layer
P+ InP wafer

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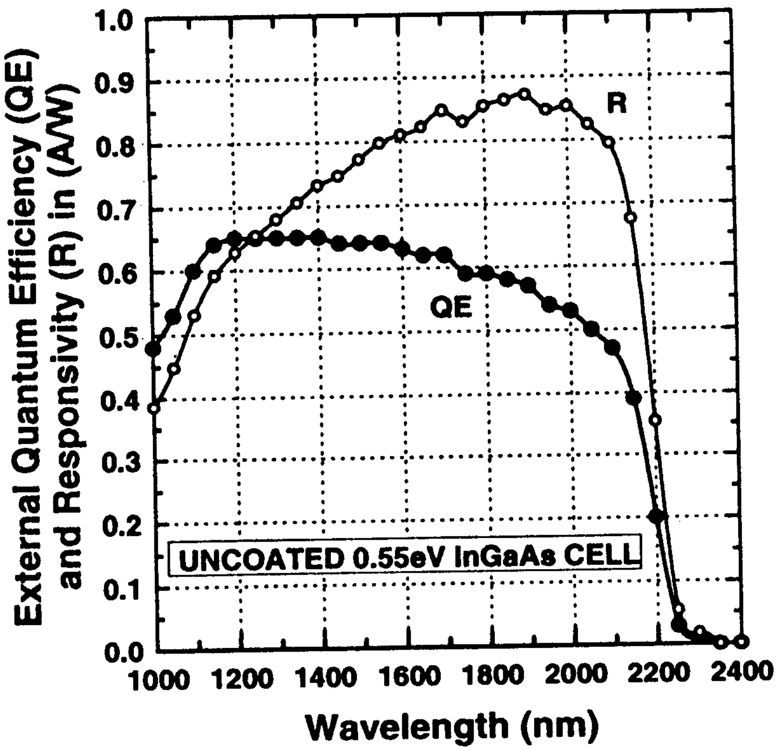
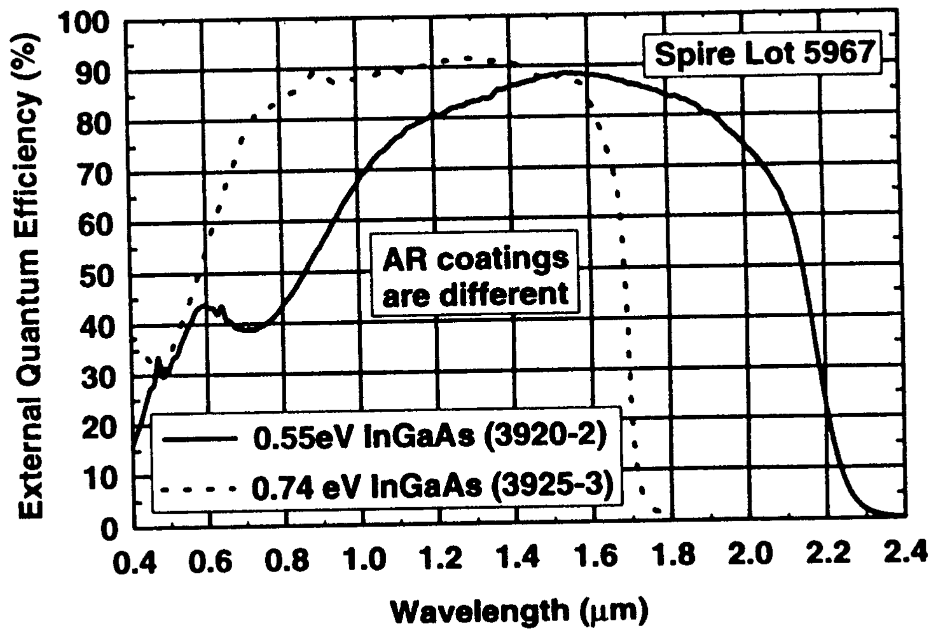
Measured Quantum Efficiency



Uncoated



MgF2/ZnS AR

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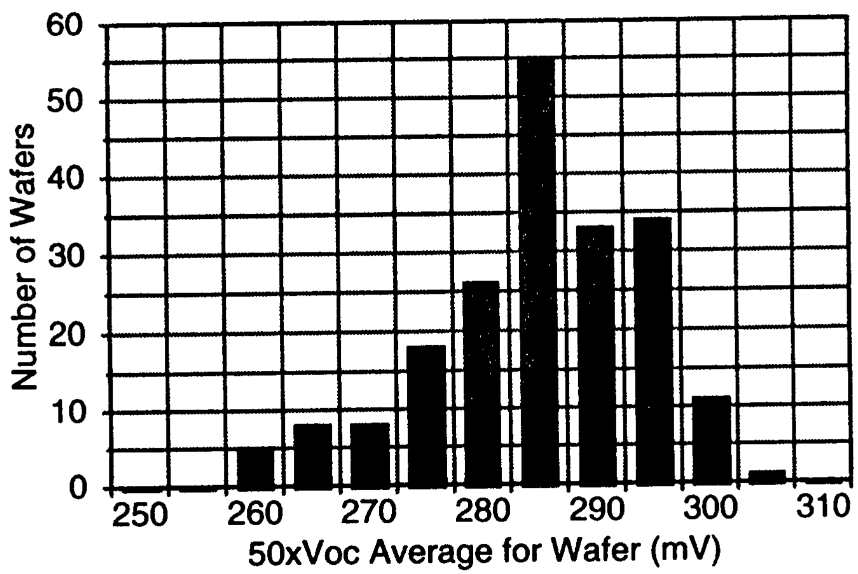
TPV Cell Production Experience



Over 2500 0.55eV Cells

Avg. Voc: 283mV S.D. 9mV

Avg Fill: 60% S.D. 3%

Avg. Test Jsc: 1.2 A/cm2

Also, over 600 0.74eV Cells

480mV Voc at 67% Fill at Test Jsc of 5.1 A/cm2

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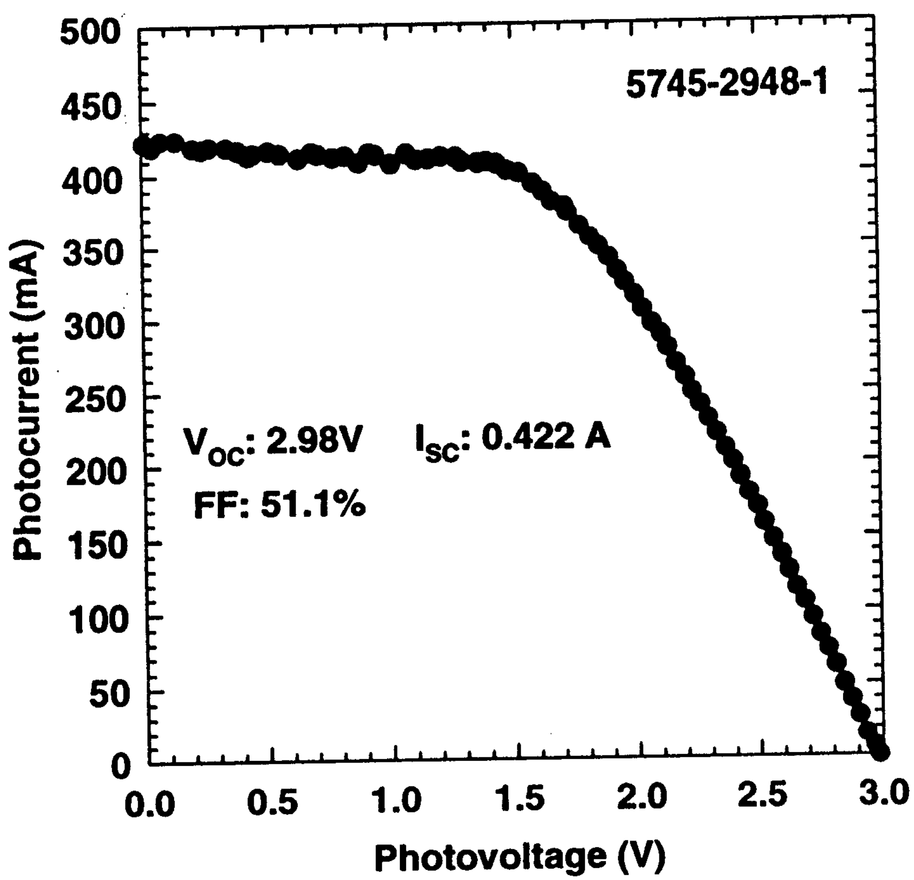
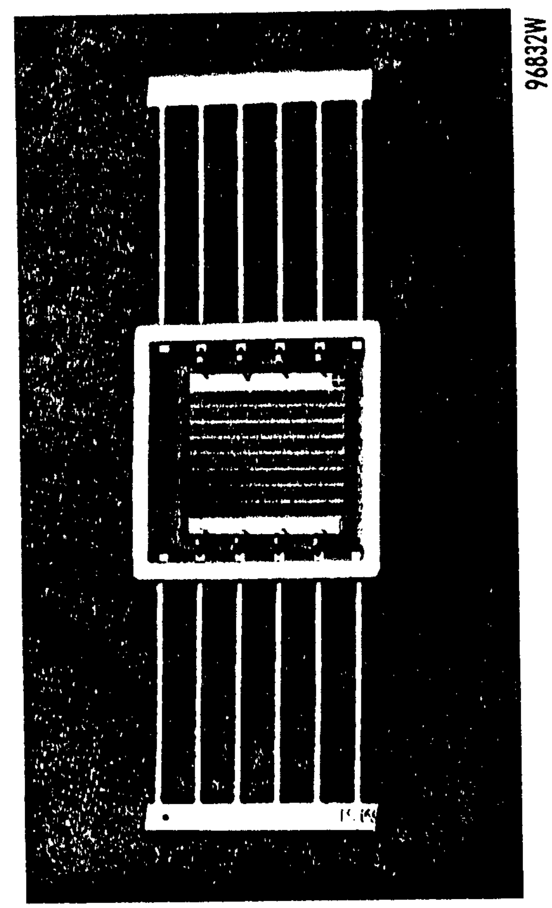
Multijunction (8) InGaAs TPV





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Future Plans

- Improve performance of 0.55eV cells
- R&D on novel ideas (multijunction TPV)
- Explore ways to reduce cell cost
- Spire wants to be a cell supplier
- Spire does not envision making complete TPV systems in the near future

spire

Low cost Thermophotovoltaic Generator using $CuInSe_2$ Solar Cells

Prospector VIII Conference

July 14-17, 1996

W. J. Biter Sensortex, Inc
J. E. Phillips Institute of Energy Conversion
University of Delaware

Low cost Thermophotovoltaic Generator using CuInSe2 Solar Cells

W. J. Biter Sensortex, Inc
J. E. Phillips Institute of Energy Conversion
University of Delaware

Using a combination of techniques, it is possible to produce a low cost, high efficiency thermophotovoltaic system. The described approach uses a selective emitter in combination with a cold surface optical filter and a lower bandgap but conventional solar cell.

The major component is an induced transmission filter. (IDT). This is a simple three component filter using a thin metal film (gold) sandwiched between two dielectric layers. This filter achieve high performance by using a high index dielectric film with relatively thick gold films. This increases the peak at the pass band while the IR reflection is controlled by the gold film.

These metal film filter are usable only to the near IR but can achieve very high performance. Teamed with a lower bandgap conventional solar cell, specifically CuInSe2 which has absorption extending out to 1.3 μm, this very simple system predicts a radiation conversion efficiency over 16% with a total system efficiency near 10 %.

Sensortex, Inc.
Institute of Energy Conversion/University of Delaware

Low Cost TPV System

Approach:

Use Highly reflective filters
-shift emitted energy to match conventional solar cells.

Combination of complementary Techniques

Low Bandgap solar cell - copper indium diselenide

Selective emitter (Yb_2O_3)

IR filter

1- dielectric stack filter

2- 3-layer IDT Filter (gold)

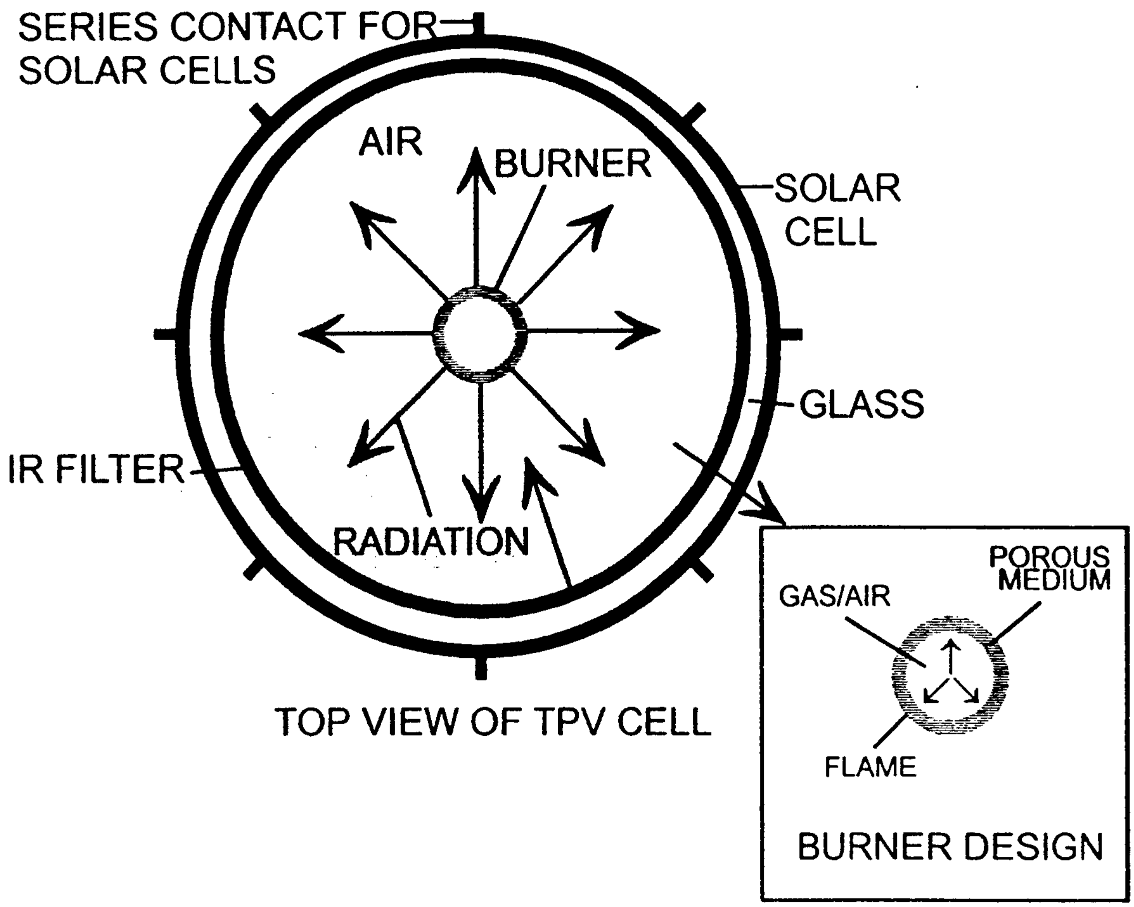
High Efficiency with single filter design

Low Cost
$\eta \sim 9\%$ at $T_s = 1100°C$ (Total Conversion Eff.)
$\eta \sim 20\%$ at $T_s = 1800°C$

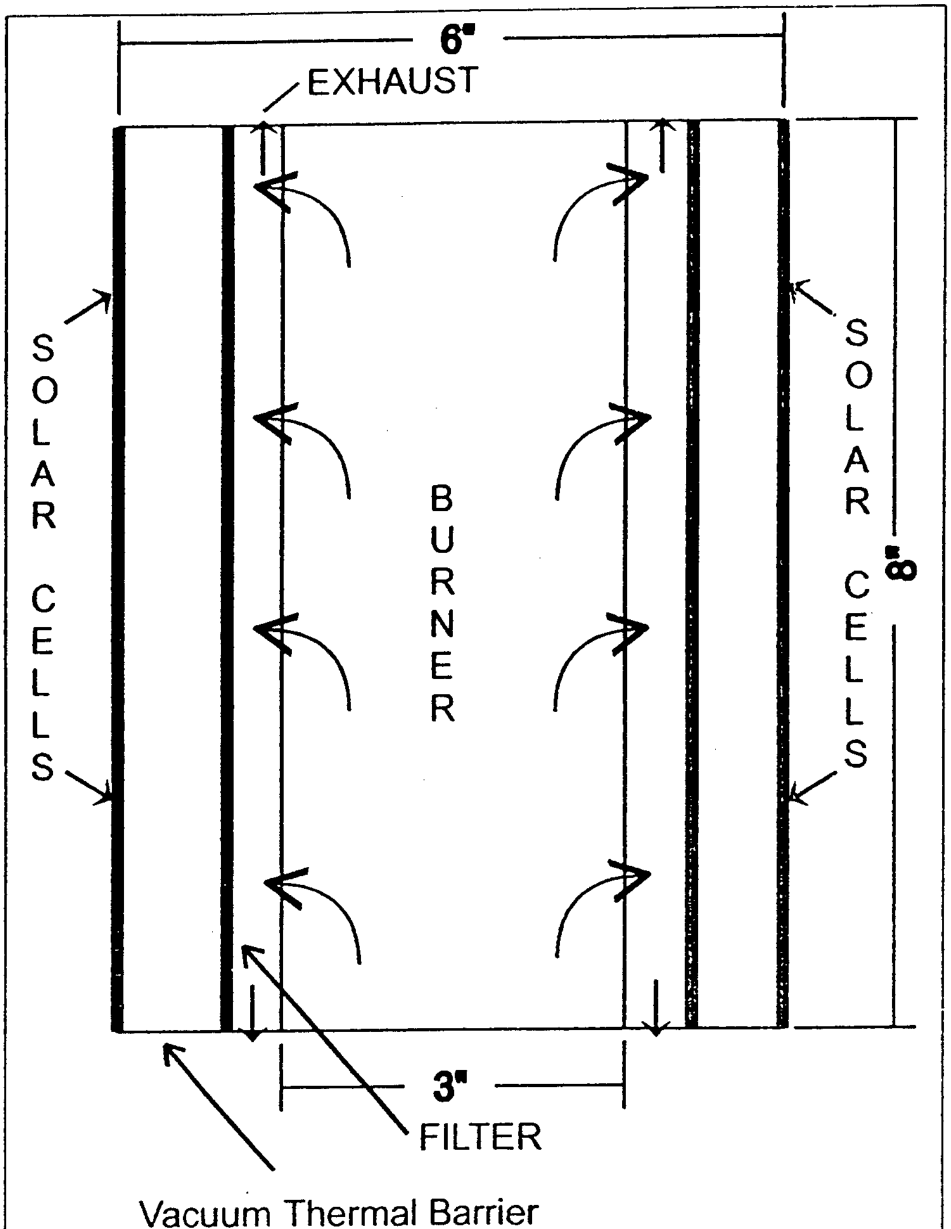
Advantages:

No new solar cell technology required.
No technological breakthroughs required.
Low Cost Components

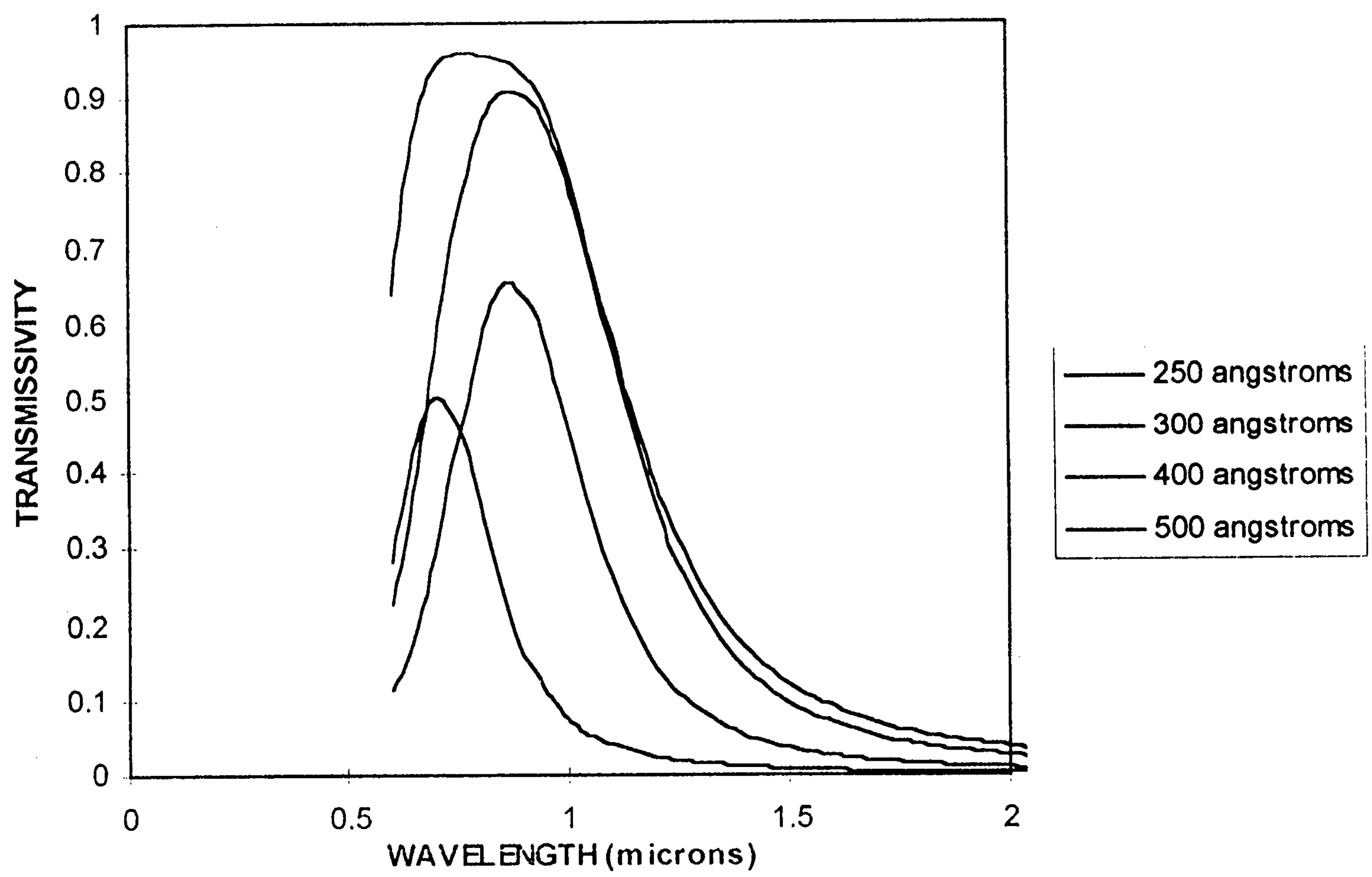
Sensortex, Incorporated



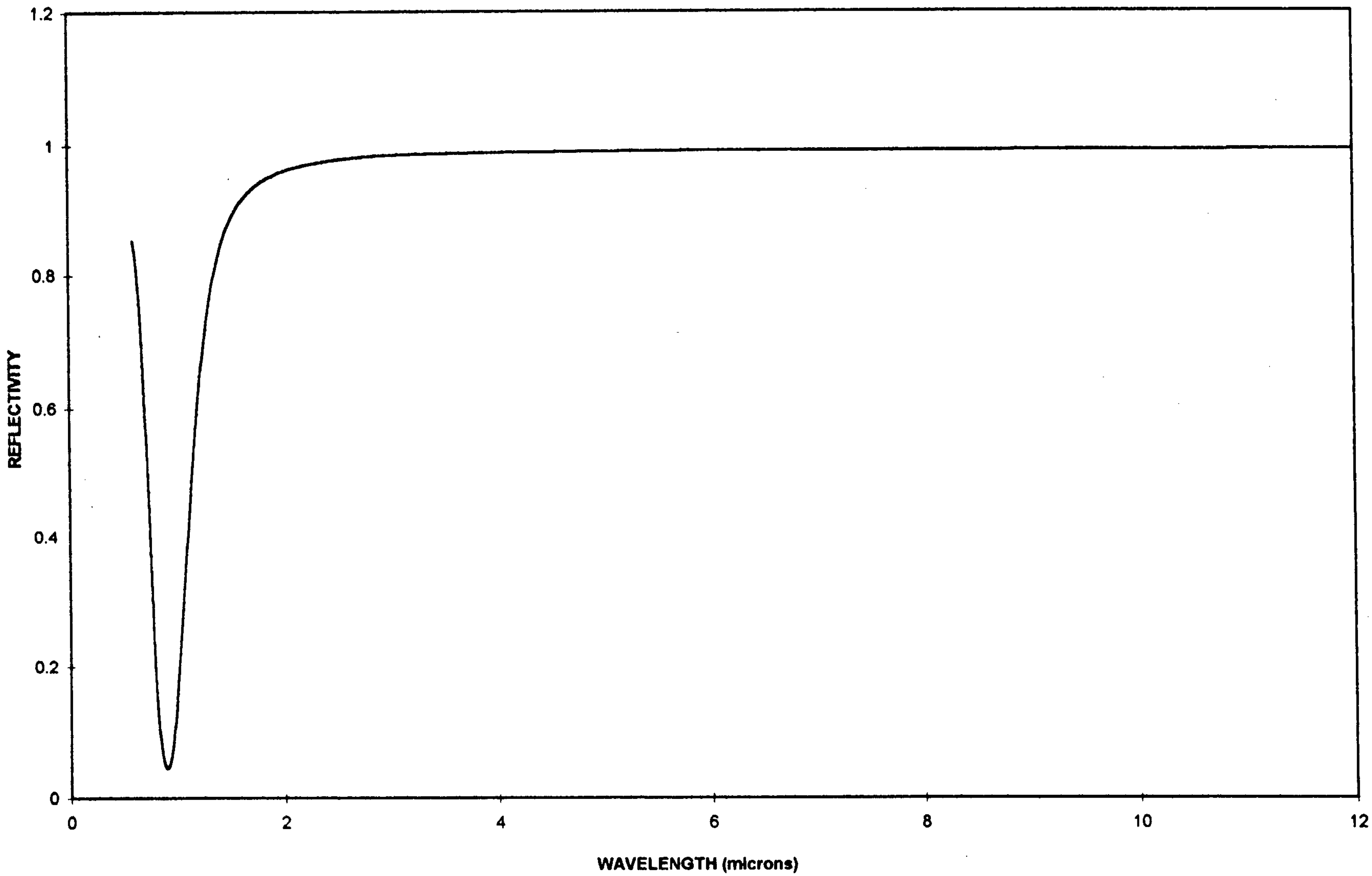
Top view of TPV system. Inner cylinder is burner and outer cylinder is filter/solar cell. Reflected energy (longer wavelengths) is reabsorbed by burner.



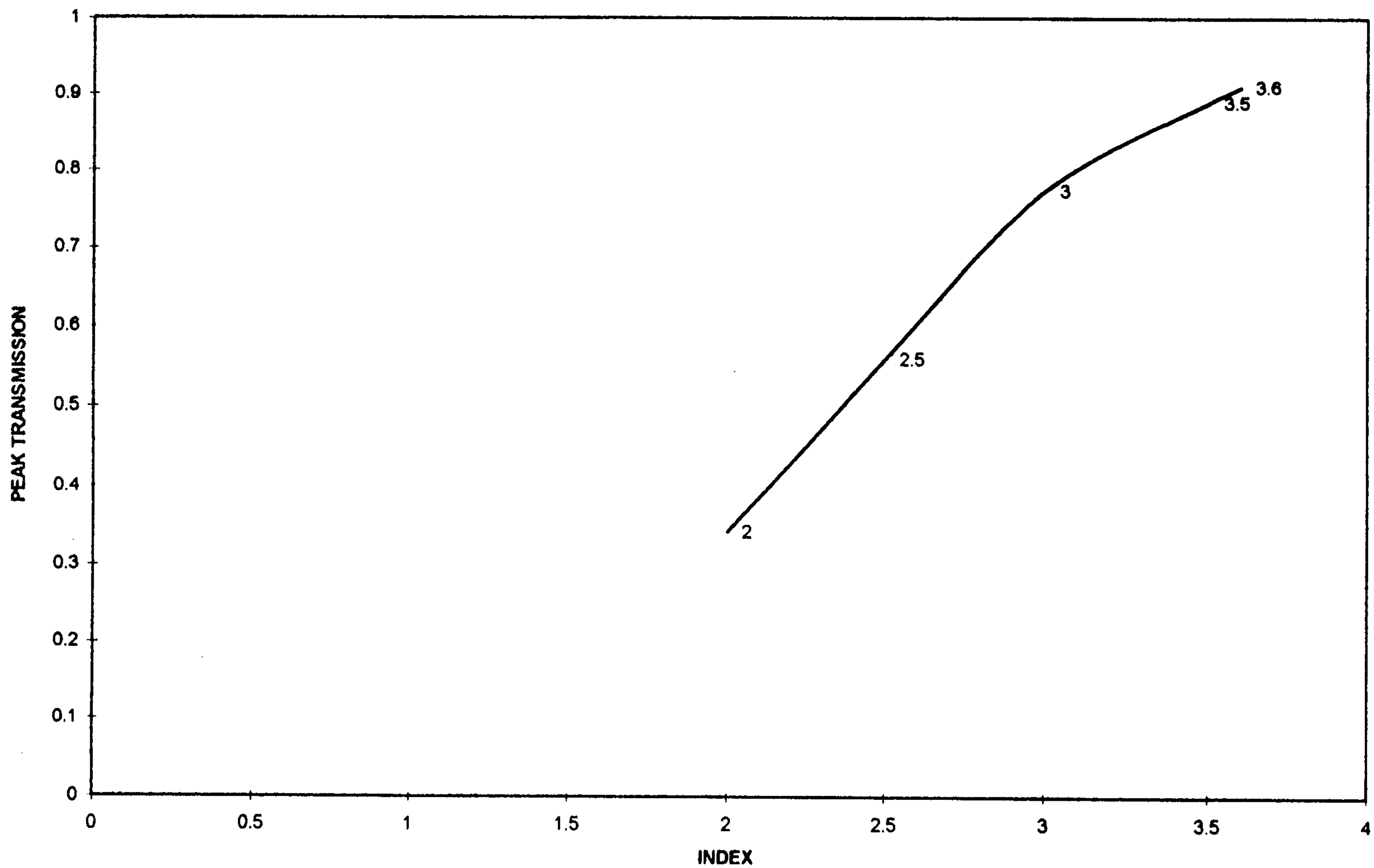
More compact design. Burner design 3" diameter X 8" long and uses vacuum thermal barrier.



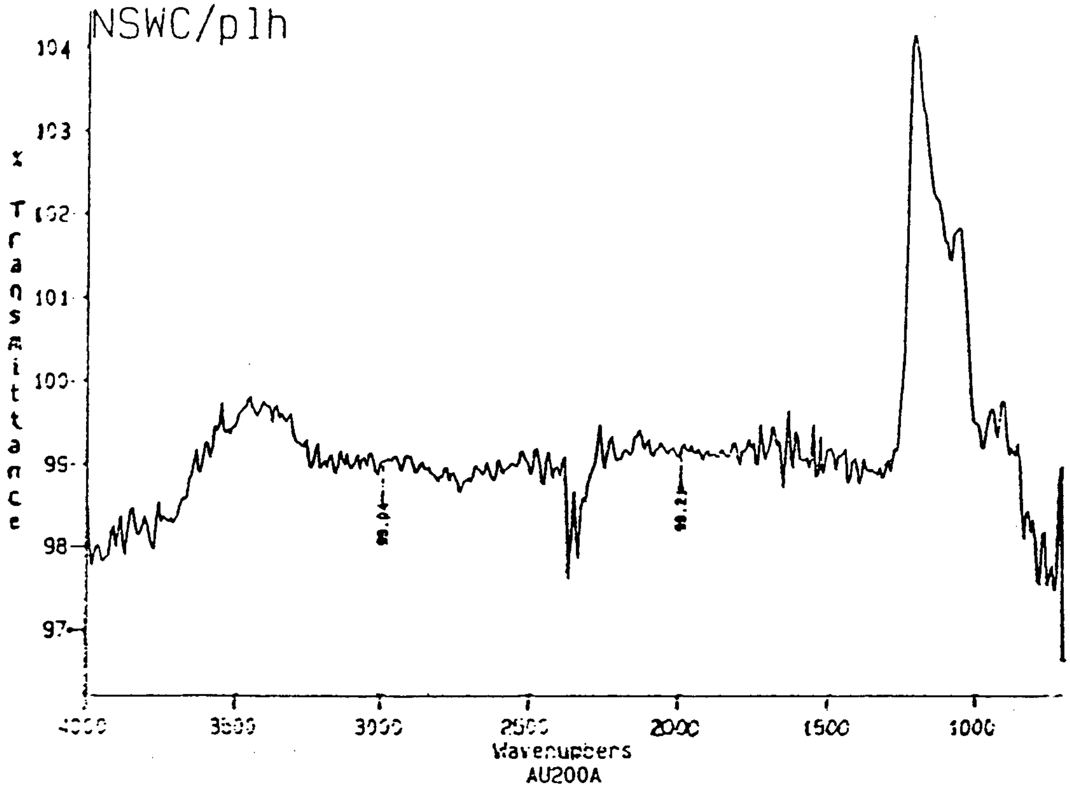
Transmissivity versus wavelength for the different filter designs.

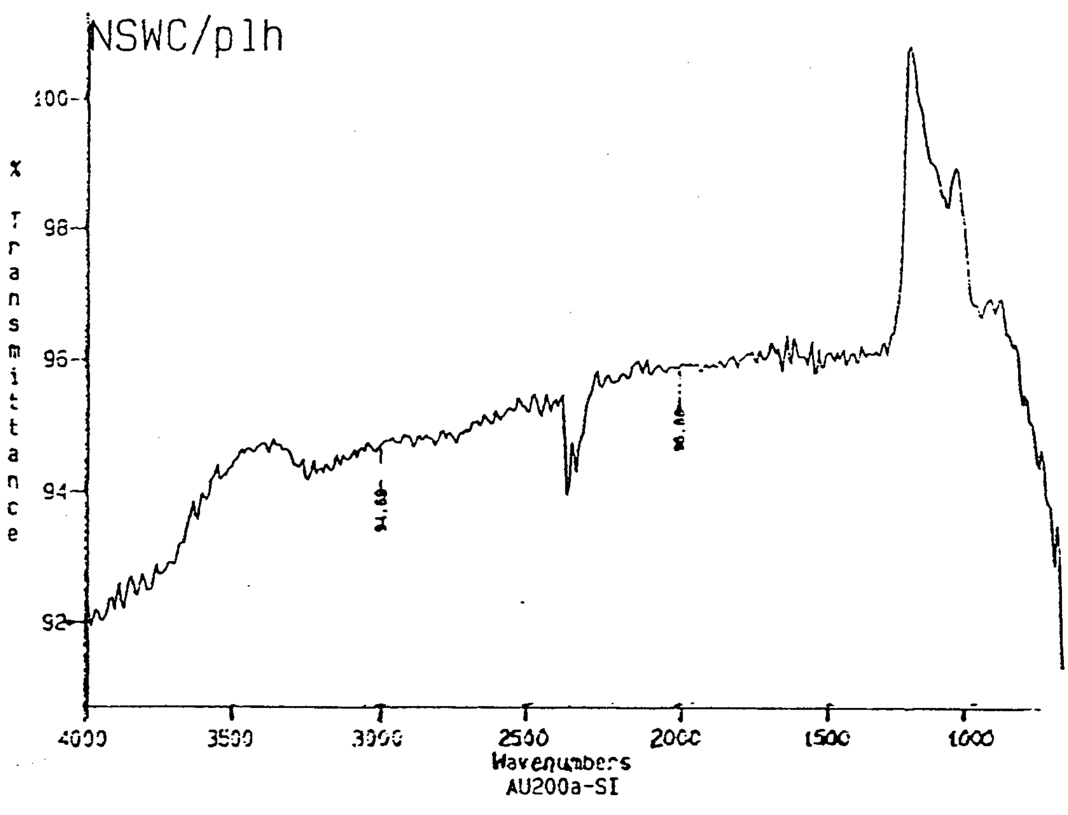


Calculated reflection versus wavelength for filter ordered from BRI.

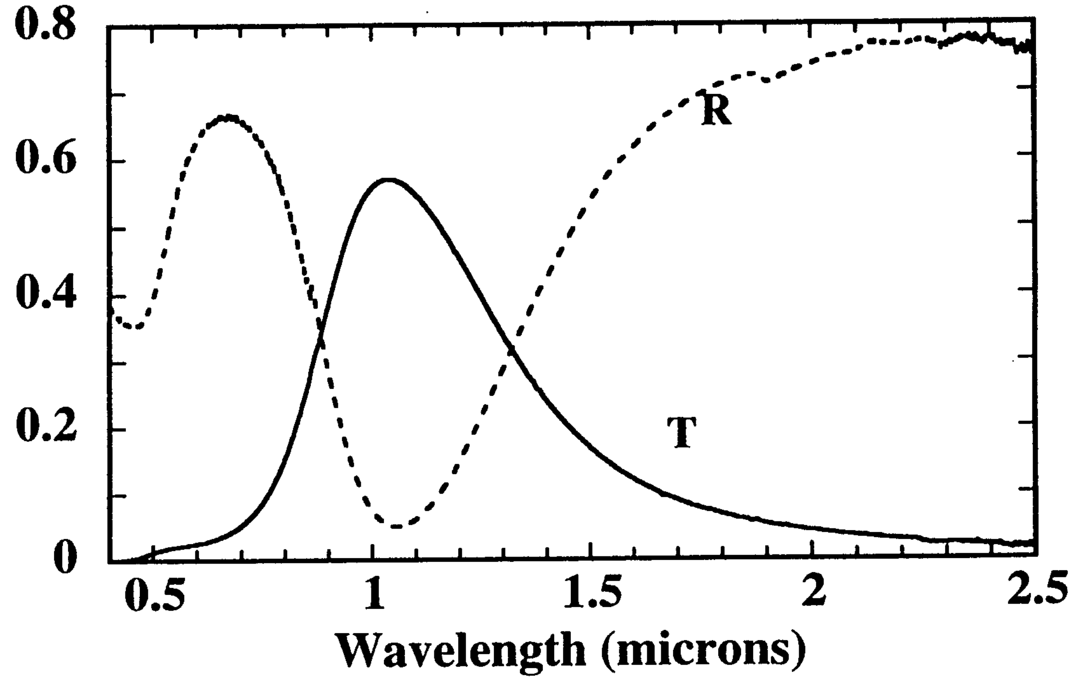


Peak transmission versus index of reflection of dielectric layer for induced transmission filter (300 angstrom Au).


NSWC/plh
% Transmittance
Wavenumbers
AU200A


NSWC/plh
% Transmittance
Wavenumbers
AU200a-SI

Transmission & Reflection for 630Å_Si/315Å_Au/630Å_Si/7059_glass



$CuInSe_2$ Solar Cell

$T_{Cell} = 25\ °C$

$A = 1.4$

$R_S = 0.1\ \Omega\text{-cm}^2$

$J_0 = 1.0 \times 10^{-8}\ A/cm^2$

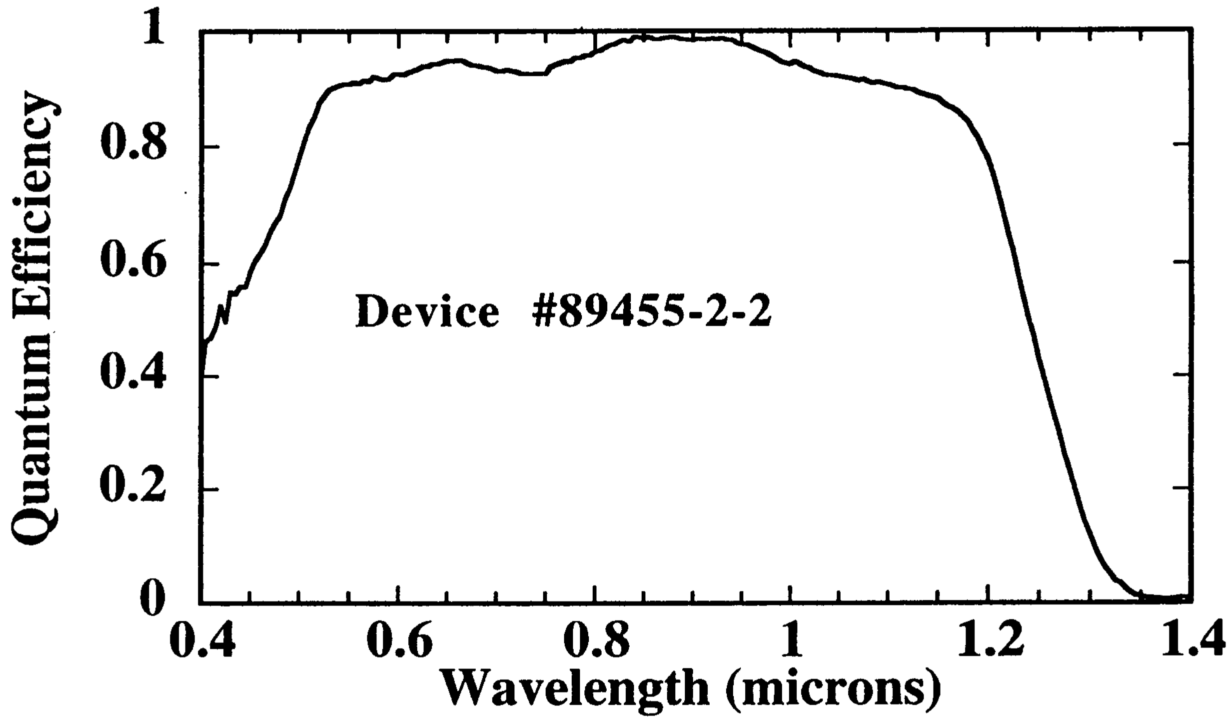
$J_{SC} = 0.772\ A/cm^2$

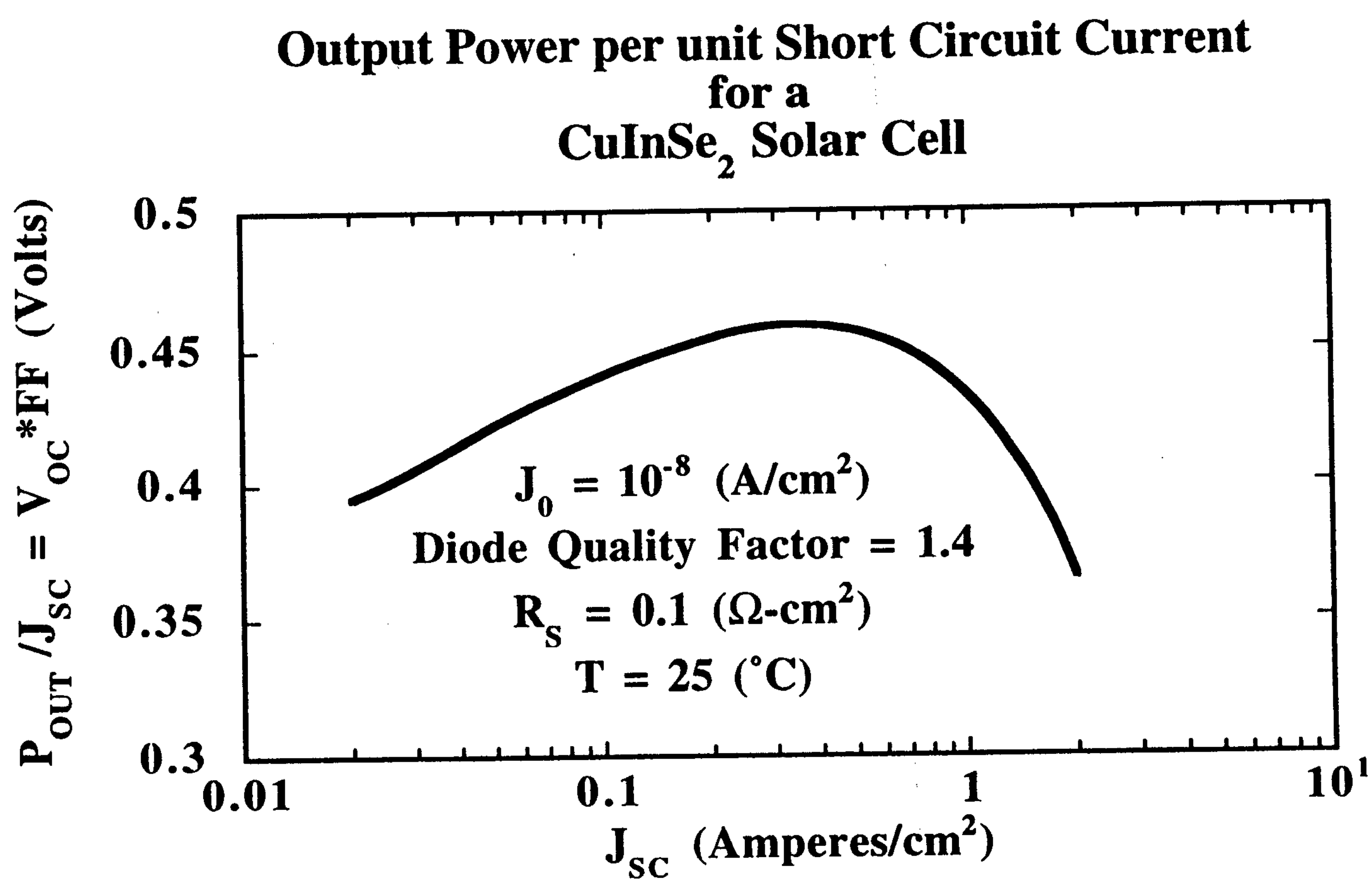
$V_{OC} = 0.653\ V$

$FF = 68.4\ \%$

$P_{OUT} = 0.345\ W/cm^2$

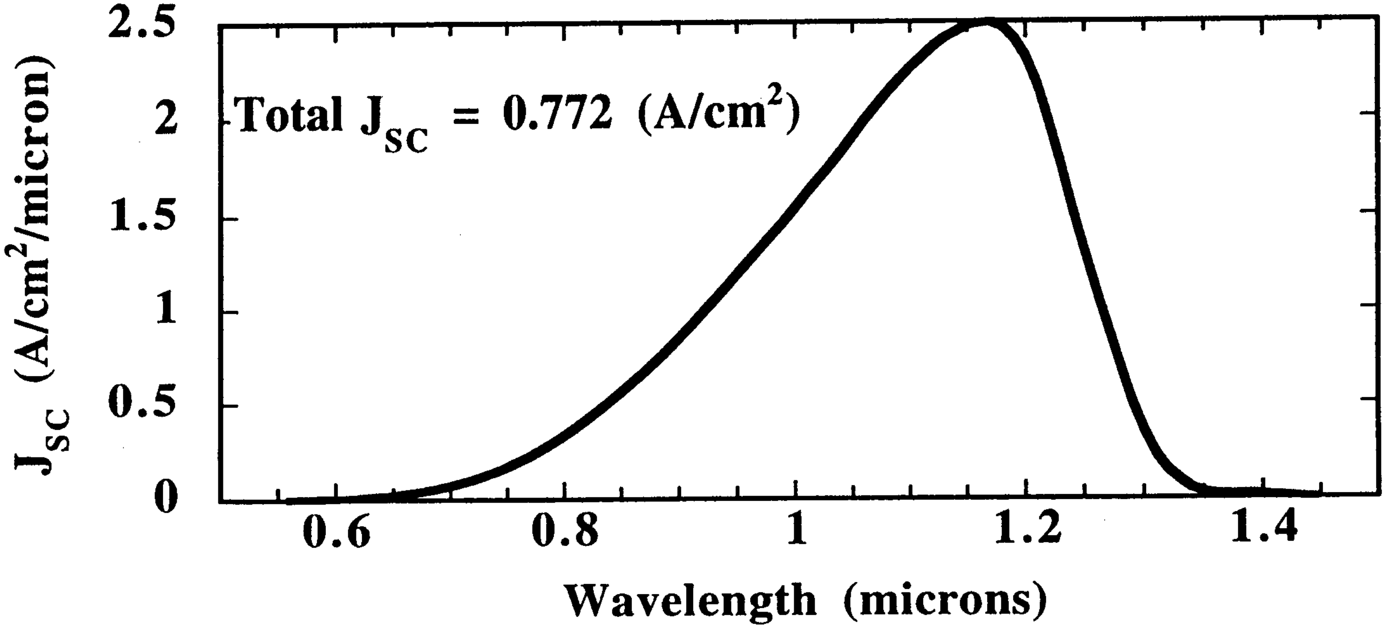
QE for $CuInSe_2$ Solar Cell
Prepared by Selenization of Cu & In

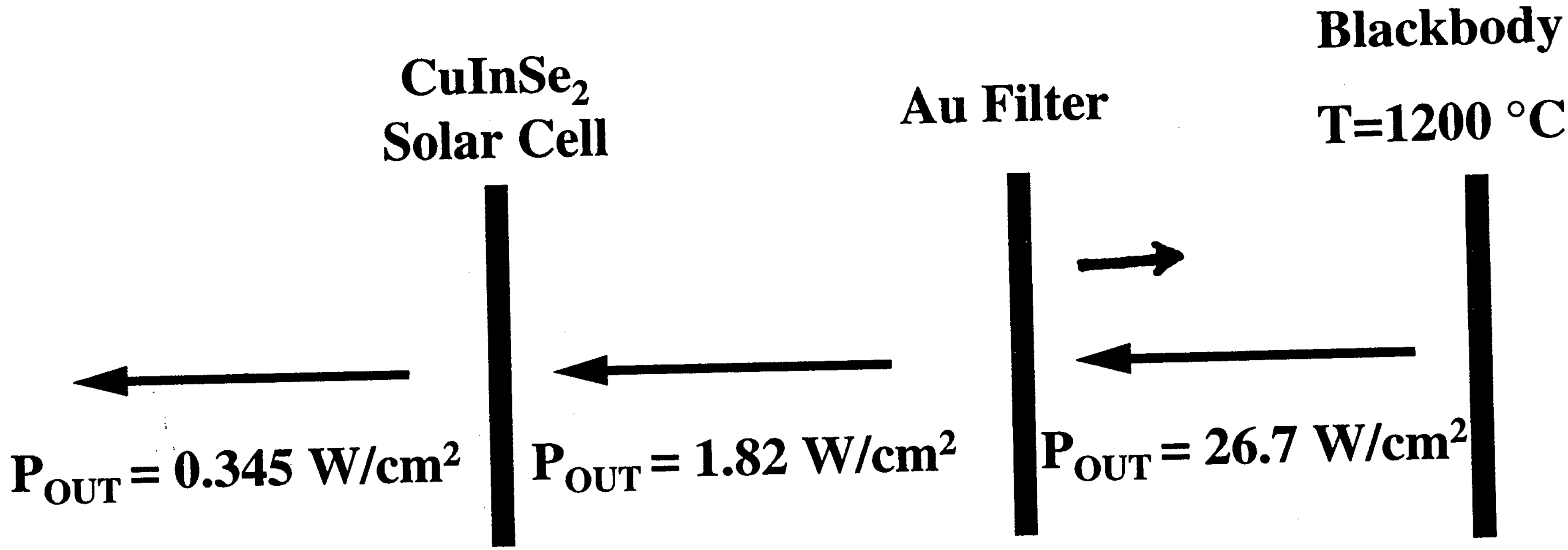




Output Power per unit Short Circuit Current
for a
CuInSe2 Solar Cell
POUT /JSC = VOC*FF (Volts)
0.5
0.45
0.4
0.35
0.3
0.01
0.1
1
10^1
JSC (Amperes/cm^2)
J0 = 10^-8 (A/cm^2)
Diode Quality Factor = 1.4
RS = 0.1 (Ω-cm^2)
T = 25 (°C)

J_{SC} vs. Wavelength
of a $CuInSe_2$ Solar Cell
Illuminated with a
1200 °C Source + Au Filter





Blackbody
T=1200 °C
Au Filter
CuInSe2
Solar Cell
POUT = 26.7 W/cm2
POUT = 1.82 W/cm2
POUT = 0.345 W/cm2

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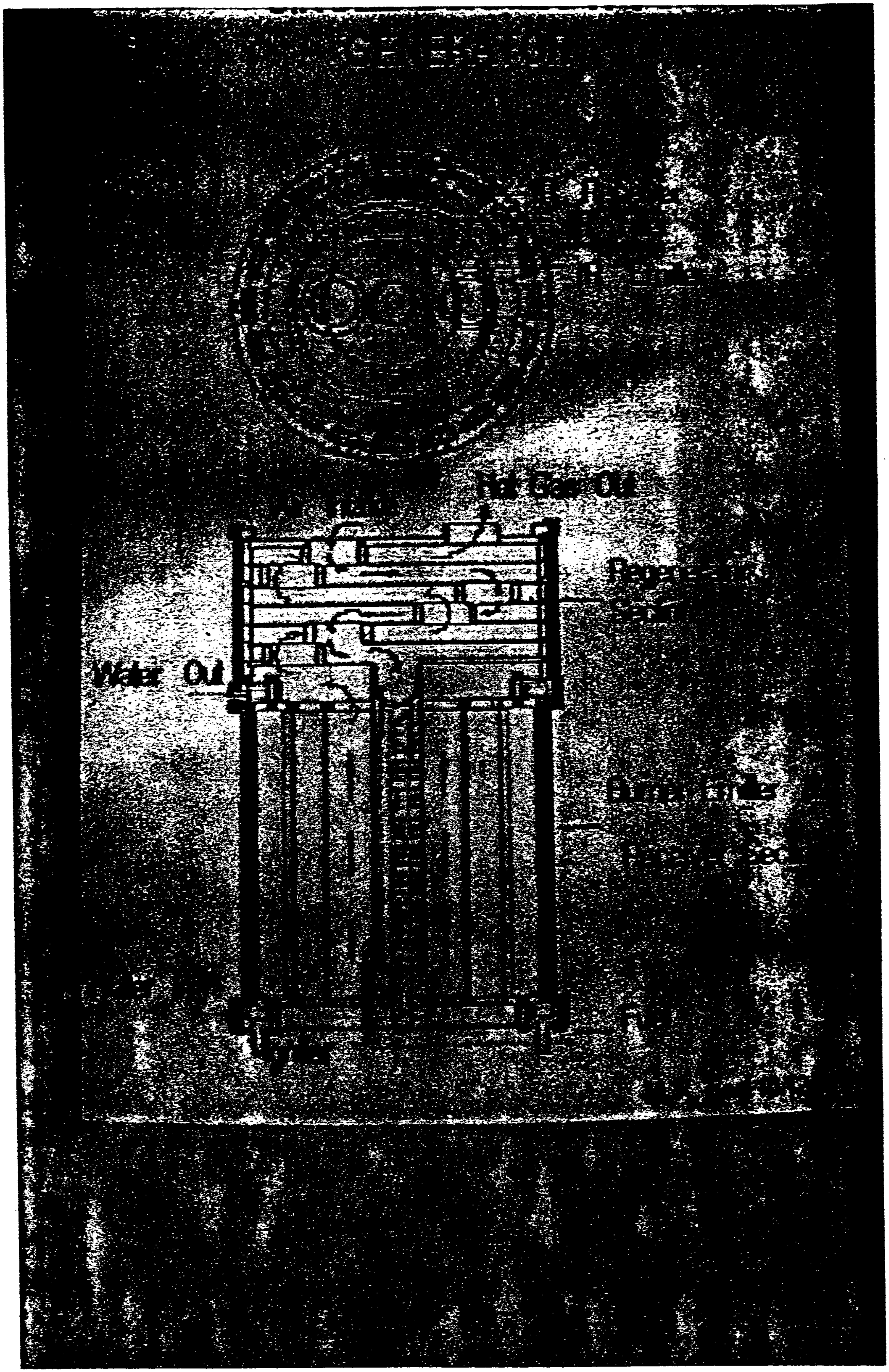
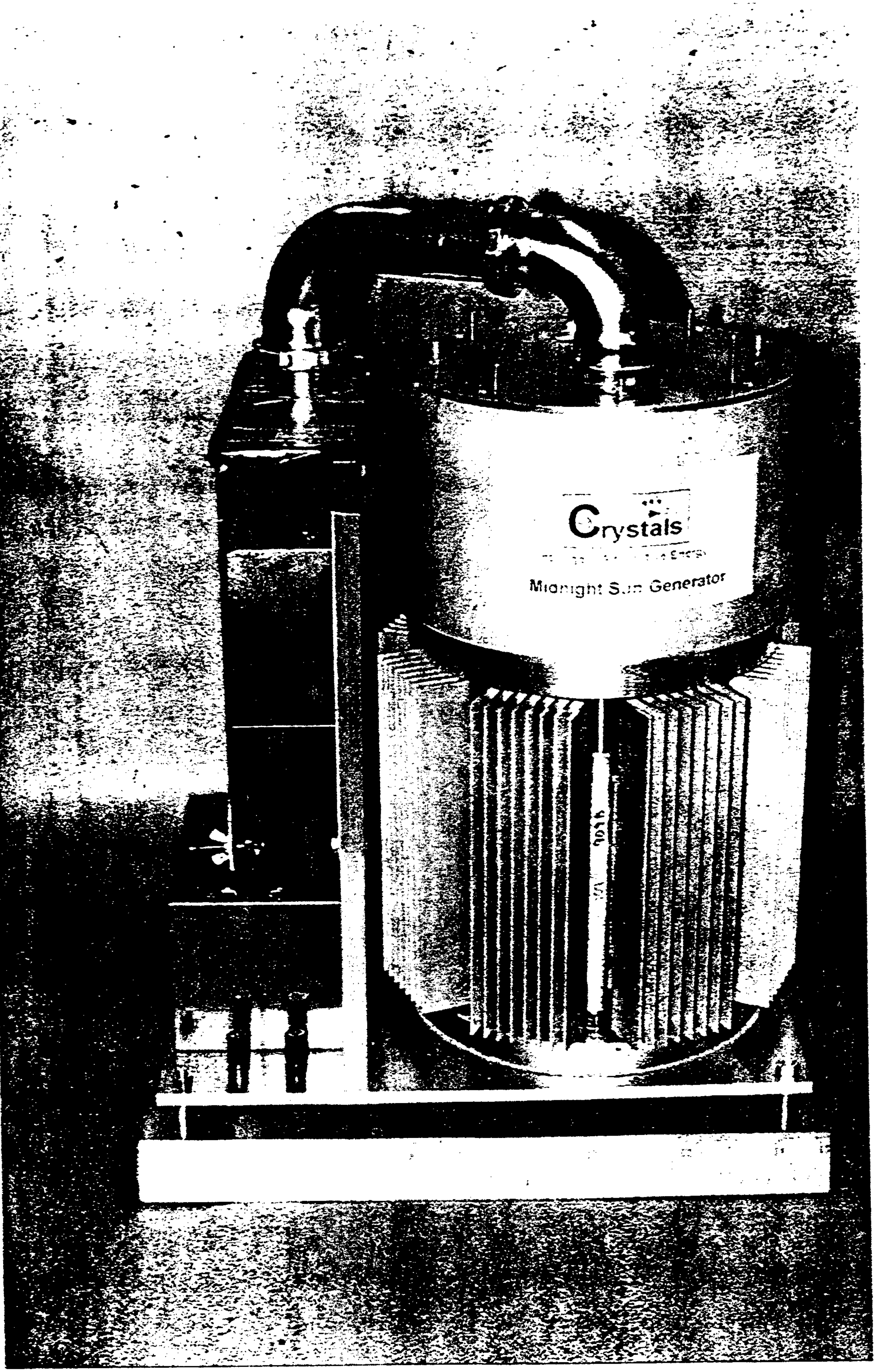
THERMOPHOTOVOLTAIC ELECTRIC HYBRID VEHICLES

Dr. Michael R. Seal, Director
Vehicle Research Institute
Western Washington University
Bellingham, WA 98225

CALCULATED TPV GENERATOR EFFICIENCY FOR 1800 K BLACKBODY EMITTER

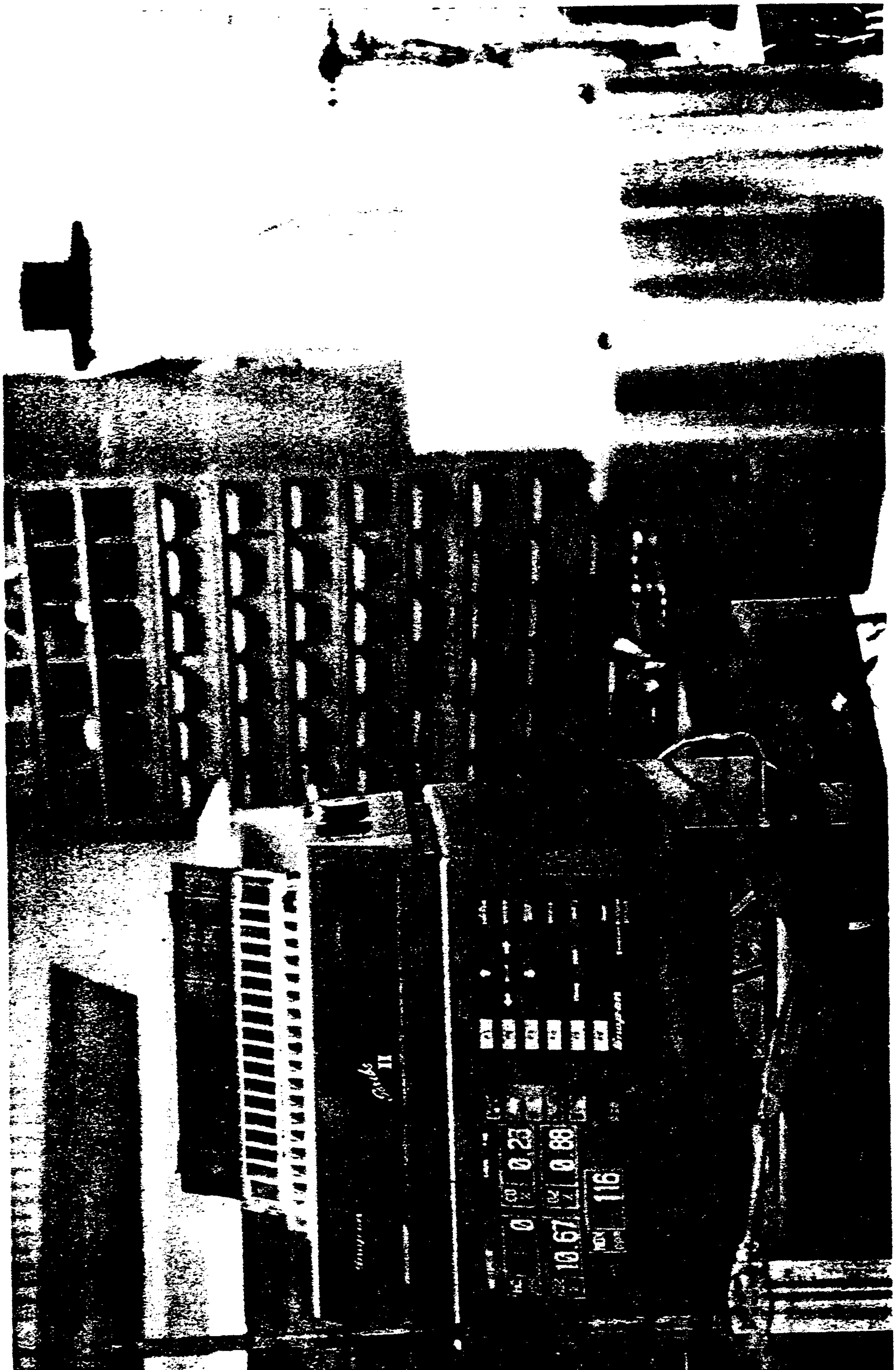
Total Radiated Energy Density	59.5	$Watts/cm^2$
Reflected by dielectric filter	39.1	$Watts/cm^2$
Lost by dielectric Filter	6.3	$Watts/cm^2$
Lost by Convection	1.0	$Watts/cm^2$
Transmitted to Cell	13.1	$Watts/cm^2$
Optical Efficiency		80%
Cell Efficiency		39%
Heat Exchanger Efficiency		85%
Cell Electrical Power Density	4.0	$Watts/cm^2$
System Overall Efficiency		17%


Water Out


Crystals
Generator

A TPV GENERATOR SHOULD RUN CLEAN

- An internal combustion engine operates with periodic explosions
- Short duration explosions lead to incomplete combustion with hydrocarbon & carbon-monoxide emissions
- The high peak temperature explosions combine N_2 & O_2 to produce nitrous-oxides
- A TPV generator can operate with complete combustion at temperatures low enough to limit nitrous-oxide production
- We have already measured low hydrocarbon and carbon monoxide emissions from a TPV natural gas burner


0
0.23
10.67
0.88
116

Applications Summary for Thermophotovoltaic Generators

Market Sector	Electric Power per Unit	Heating Capacity	Advantages
Small Cogenerator	200 W	2 kW	Quiet, Clean, & Portable
Home Cogenerator	2 kW	8 kW	Quiet, Clean, & Efficient
Electric Vehicle	20 kW		Clean, Light Weight, & Efficient

SUMMARY

1.) Low bandgap PV cells are **ENABLING** for TPV generators

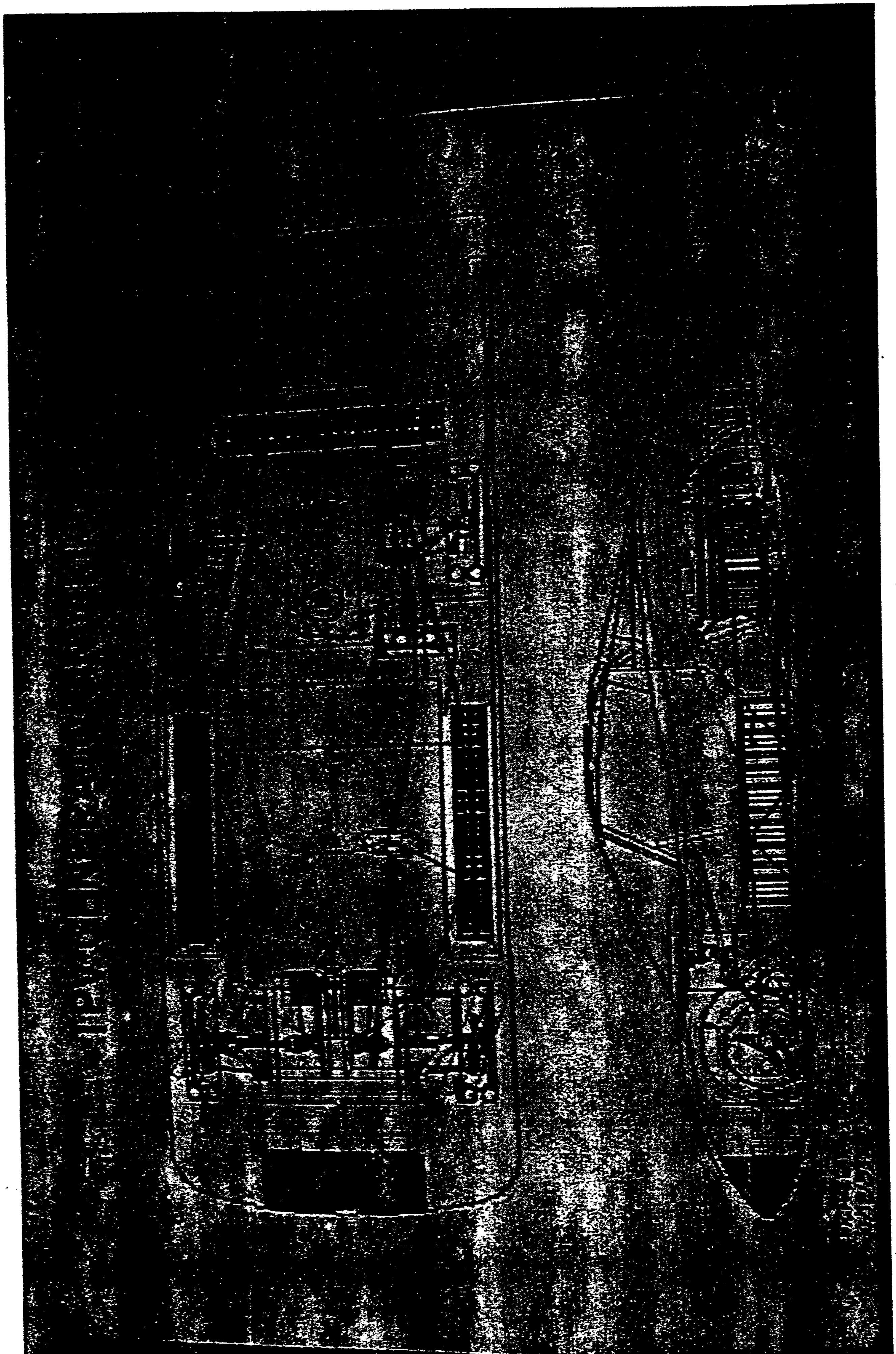
2.) High cell power densities will make TPV generators **ECONOMICAL**.

3.) Continuous hydrocarbon burners for TPV generators will run **CLEAN** and **QUIET**.

4.) Clean and quiet TPV generators can operate indoors as small scale **COGENERATORS** producing both **HEAT** and **ELECTRICITY**.

TPV SERIES HYBRID

- PRINCIPLE OF TPV OPERATION
- ADVANTAGES of a TPV SERIES HYBRID VEHICLE
  - No separate generator needed
  - TPV operates at constant at most efficient load
  - Exhaust emissions are extremely low
  - Unit sounds about the same as a desktop PC
  - No vibration
  - Operation is just like an electric car with no range limitation
  - Multi-fuel capability
- DISADVANTAGES OF TPV SERIES HYBRID VEHICLE
  - Hasn't been done yet
  - Costs will be very high at first



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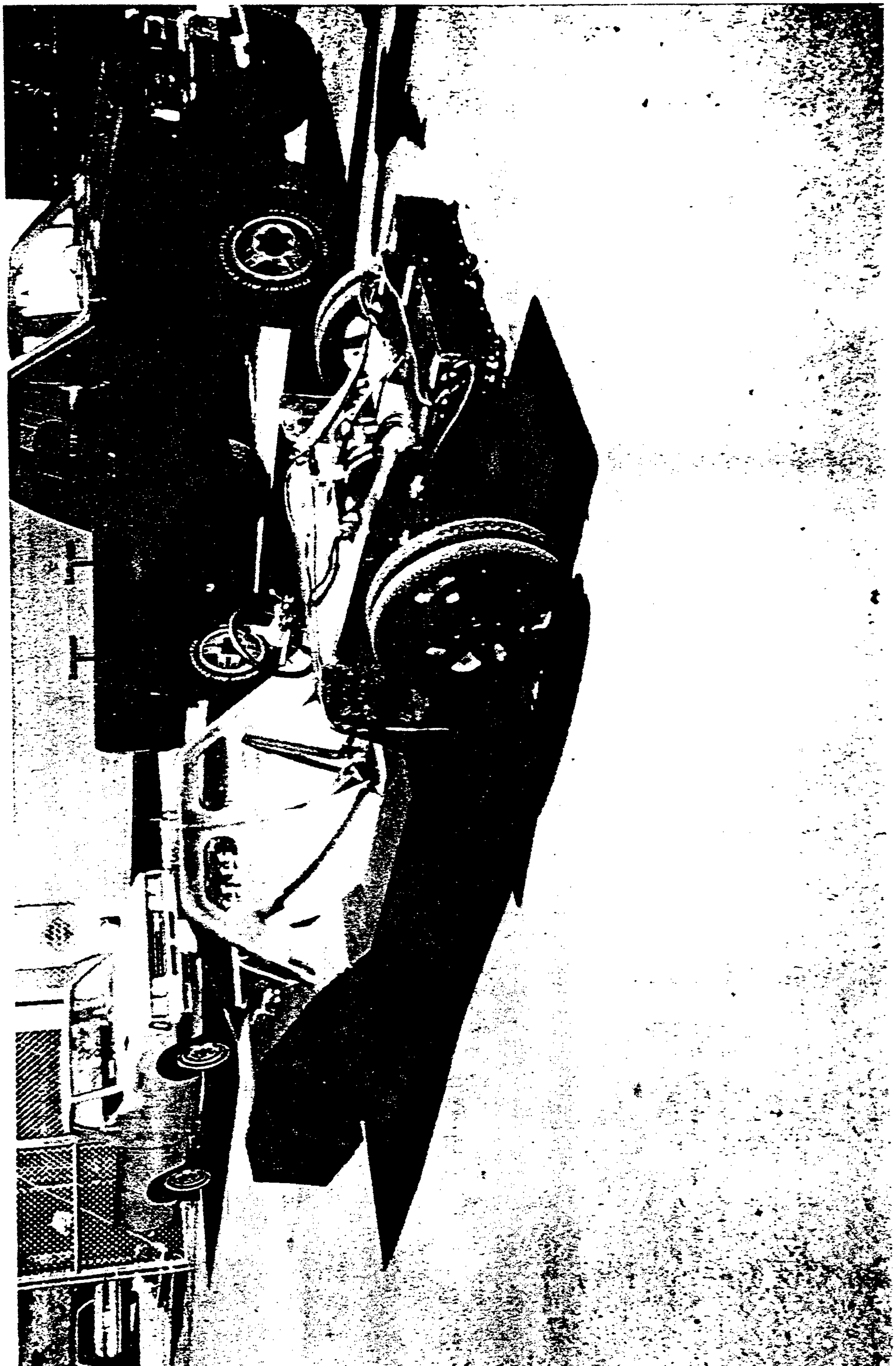

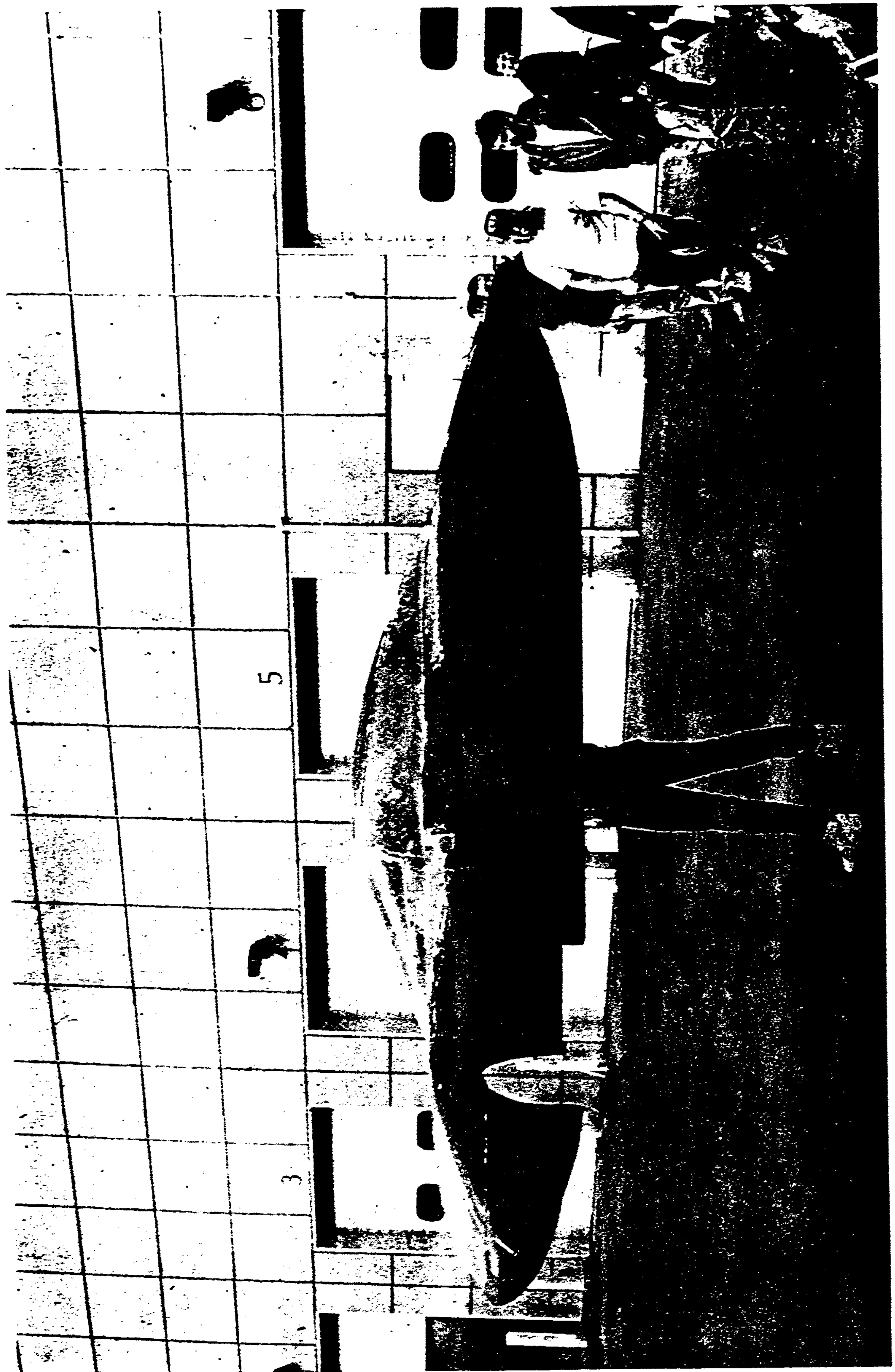
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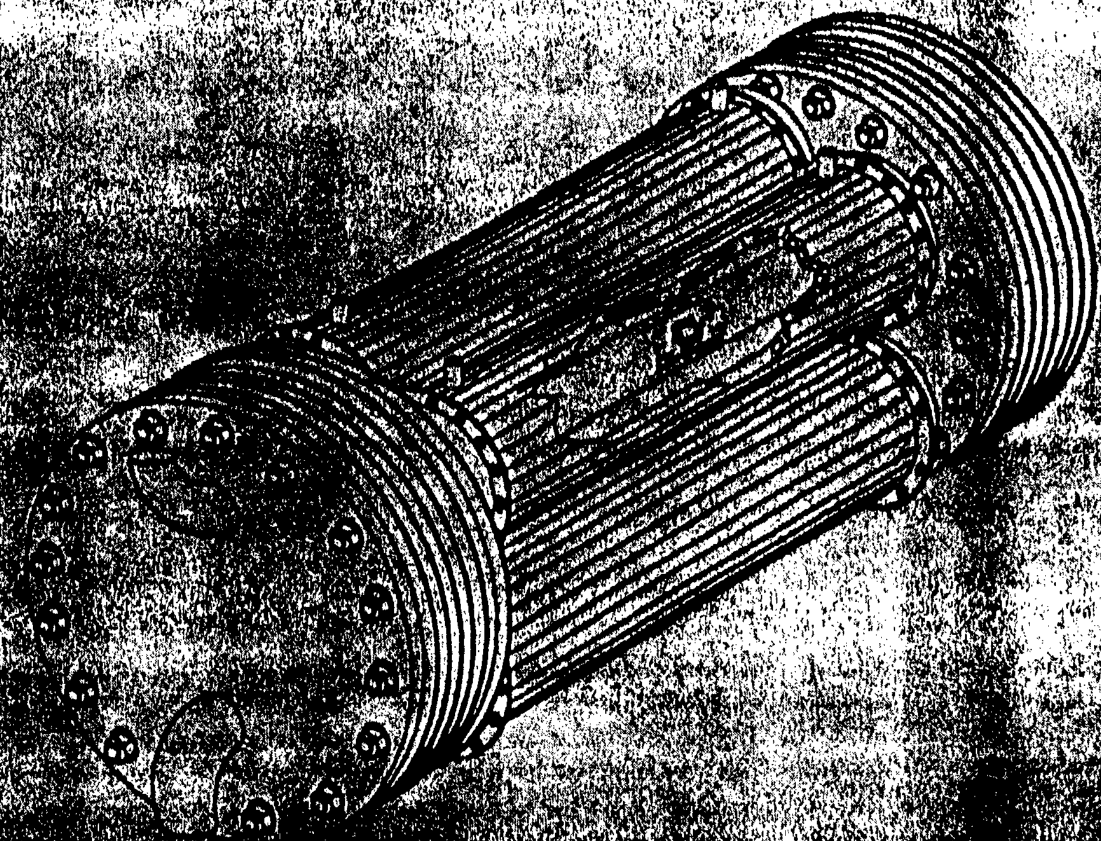
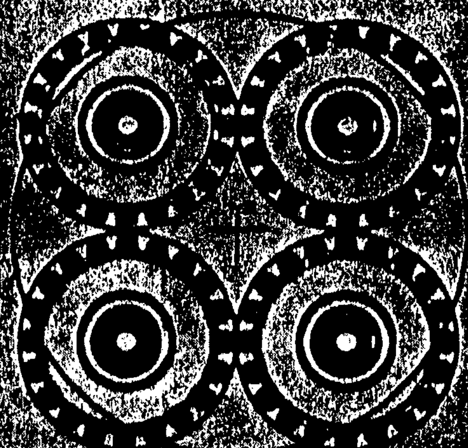
3

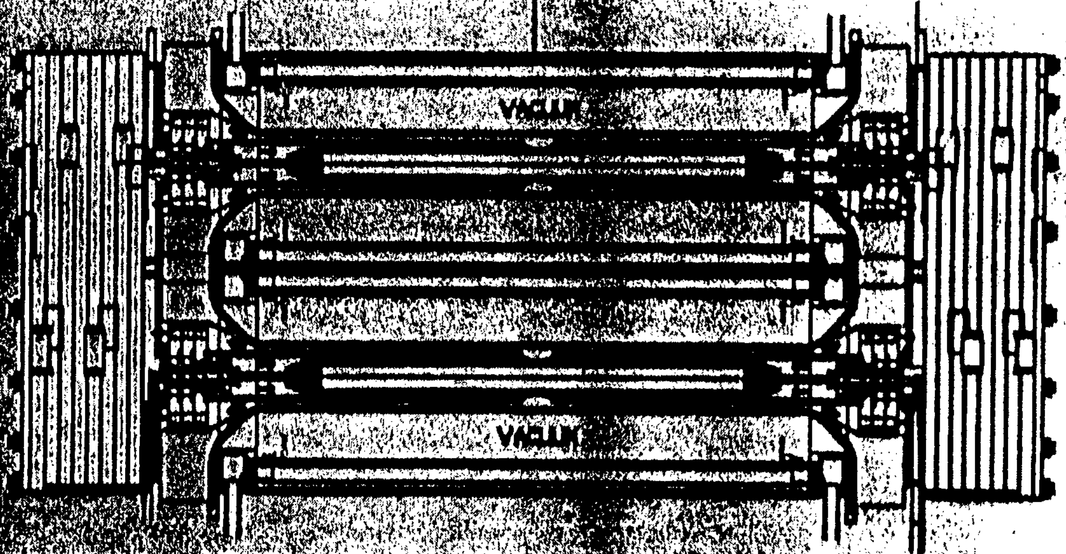

SOLAR ELECTRIC
METHANE HYBRID
SOLAR ELECTRIC
METHANE HYBRID
VIKING23

VIKING 29 TPV GENERATOR

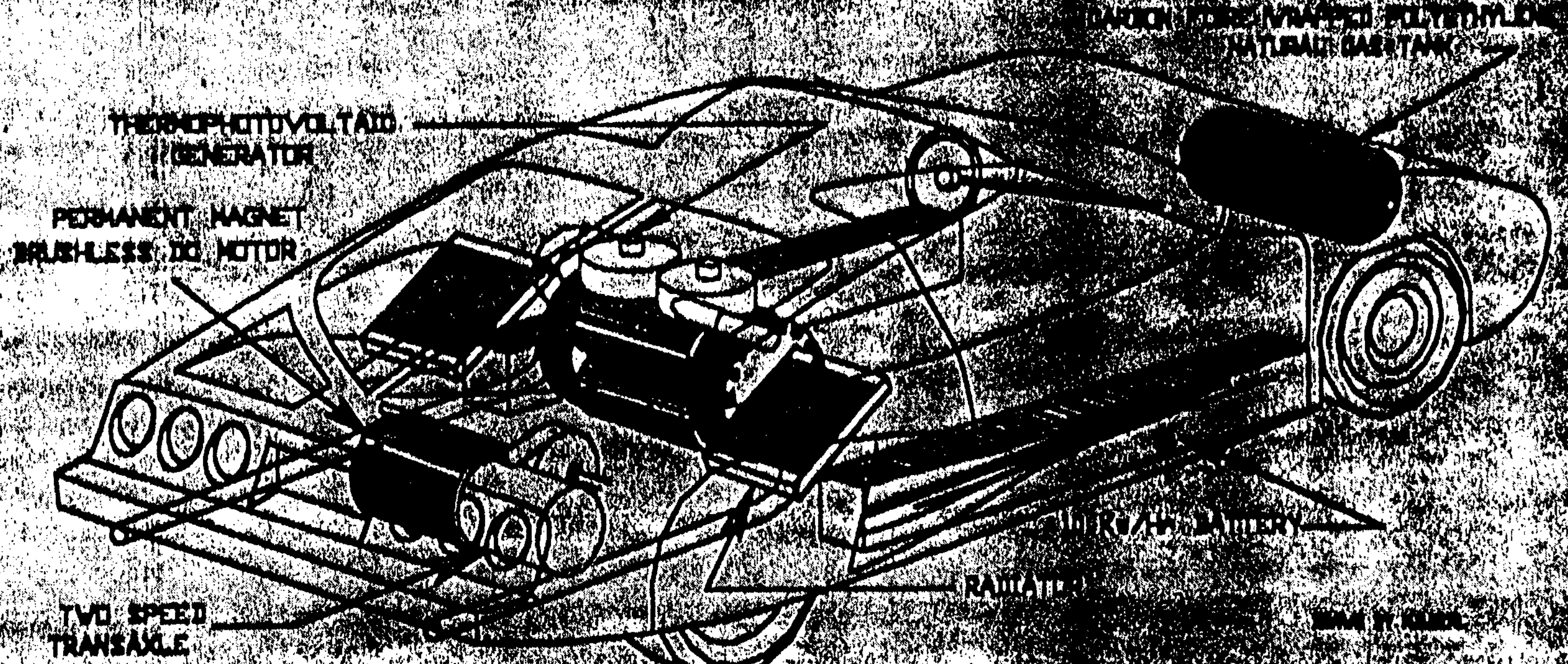


TPV GENERATOR





VIKING 29 - TPV ELECTRIC HYBRID



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"TPV MARKET OPPORTUNITIES & ISSUES"

Dr. Eric Barringer

Babcock & Wilcox
Lynchburg, VA 24506

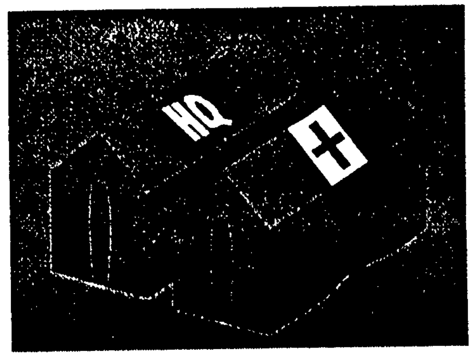
Thermophotovoltaic (TPV) Power Generation Program

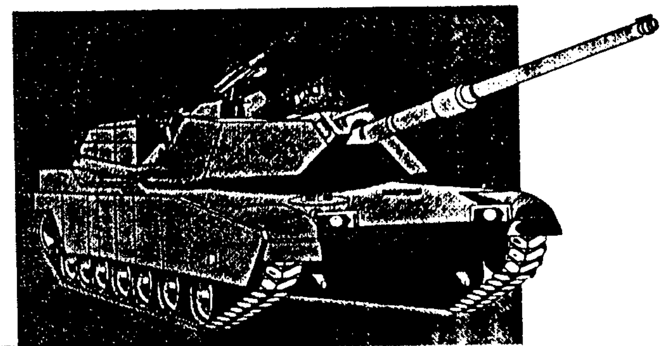
The Babcock & Wilcox Company

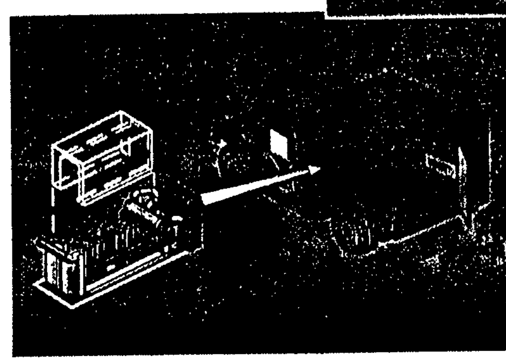
TPV Power Generation

- *Portable generator markets and TPV prospects*
- Can TPV meet market requirements?

Military Has Wide Range of Power Needs







Drivers: Stealth
Mobility
Reliability
No environmental restrictions

FAB 4/8/96 / 2

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Military Market Drivers

- Increased emphasis on small unit operations
- Increased power usage
- Enhanced stealth and survivability
- Improved reliability / maintenance
- Increased mission duration
- Improved power quality (computers and communications)
- Elimination of military specifications for standard generator sets
- First cost and life-cycle cost reductions

Military Market

- Total military generator base: 80k - 100k units
- Standard military generator sets
  - Bulk of DoD market (~ 75%)
  - Mature technologies required
  - Move toward commercial spec equipment ($.75 - $1.00 per Watt)
  - Typical purchase: 2 - 10k units for specific generator
- Special generators and APUs
  - Command price ~2X high-end commercial units ($1.50 - $2.00 per Watt)
  - Small orders (< 2000 units) on irregular basis
  - Requirements / purchase driven by individual PMs

Military Applications

Application	Power Output	TPV Fit
Man-Portable Power (Individual Soldier)	50W - 200W	No?
Portable Generator/ Battery Charger	150W - 2kW	Yes
Special Generators for Line Operations	1kW -	Yes
Auxiliary Power Units	2kW - 10kW	Yes
Standard Generator Sets	3kW -	Yes?

Civilian Market Drivers

- Lower cost
- Reduced noise and pollution
- Improved reliability and maintenance
- Improved power quality (telecom / computers)

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Civilian Market

- Demand is highly elastic in most segments
- Very competitive market — many OEMs
- Rapid technology shift
  - Permanent magnet alternators
  - Solid-state power electronics
  - Sophisticated, low-cost controls
- Noise / pollution sensitivity varies across segments
- Improved reliability / maintenance has value

Potential Entry Markets

- TPV appears best suited for low power levels (100W - 20kW?)
- TPV suited for "premium" power applications (special requirements)
- TPV favored in segments where operating characteristics provide tangible value to customer

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Civilian Applications

Application	Power Output	TPV Fit
Outdoor Recreation	200W - 2kW	??
Portable Battery Charger	200W - 500W	??
Residential/Commercial Building Back-up Power	1kW -	??
Industrial/Construction	2kW -	??
Commercial - Premium Back-up	3kW -	Yes
RV Generators	3kW - 8kW	Yes
Marine Generators	3kW - 8kW	Yes
Residential/Commercial Power	1kW -	Yes?

TPV Power Generation

Will TPV Succeed in Marketplace?

- **Potential TPV Attributes/Advantages**
  - Energy source independent
  - Lightweight and compact
  - System simplicity - few moving parts
  - Low noise and pollutant emissions
  - Rapid start-up and load response
- **Can we engineer cost-effective products that meet customer requirements?**

BABCOCK & WILCOX

Issues:

- **Market Driven Development**
  - Customer/Application requirements
  - System focussed - as opposed to components or subsystems
  - Cost driven solutions
- **Realistic Assessment of Competition**
  - Danger in comparing future TPVs with present competition
  - Don't underestimate the competition
- **Customer Expectations**
  - Inflated, unrealistic claims
  - TPV community credibility

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Issues

- **Strategic Partnerships**
  - Few firms have all of the technical skills and market access
- **Funding for Development and Commercialization**
  - Critical role for DoD funding for R&D
  - Commercialization ultimately driven by commercial sector
- **"Market" Development**
  - Education programs
  - Legislative action

ABSTRACT
CATERPILLAR'S VIEW
ELECTRIC POWER NEEDS

Electric power generation machinery at Caterpillar is based on the following: We produce machinery for the energy producing industry and we manufacture durable and cost effective engines for electrical generation. In particular, 20% of our machine sales go to energy related industries and 6% of our sales are used in generating electricity.

The mix of total energy used in the world is changing from approximately 25% electrical today to near 50% by 2020 while central plant and distribution systems are increasing at a constant rate. It is expected that the short-fall will be filled by traditional rotating generators driven locally and other emerging competing technologies. Thermo-Photo-Voltaics is one such technology.

The kW-HRs/Person/ Year distribution in the world suggests that large infrastructure will not be put in place to transmit electricity. The remoteness of many of these areas and the cost of fuel will dictate the need for high efficiency local generation.

The final requirement is for ever-decreasing system costs. This translates into modules with smaller packages that are mixed with existing infrastructure producing significant power levels.

The current state of each of these design constraints is discussed in this presentation, along with some estimates of what future trends will be.

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INTERNET MAIL: SZENTJF@CAT.COM

ELECTRIC POWER WORLD GROWTH

CATERPILLAR'S EPG VIEWS ON APPLICATIONS PULL

John F.Szentes
Staff Engineer
E&E/R&D

CAT — ELECTRONICS

CATERPILLAR

- WHY IS THE COMPANY HERE TODAY
- WHO ARE WE AS A COMPANY
- WHAT DOES COMPANY PRODUCE
  - TRADITIONAL
  - INDUSTRIAL EPG
- WHAT IS MARKET PULL
- TODAY'S ENVIRONMENT - video
- SUMMARY

CAT — ELECTRONICS

Electric Power Generation Trends

Fuel Prices ↓ 2%
Electric Prices ↓ 4%
Power Plant Capital Cost ↓ 3-9%
Power Plant Avg. Size ↓ 70%
Power Plant Build Time ↓ 3-9%
Employees / MW ↓ 3-12%
IRR ↓ 7%

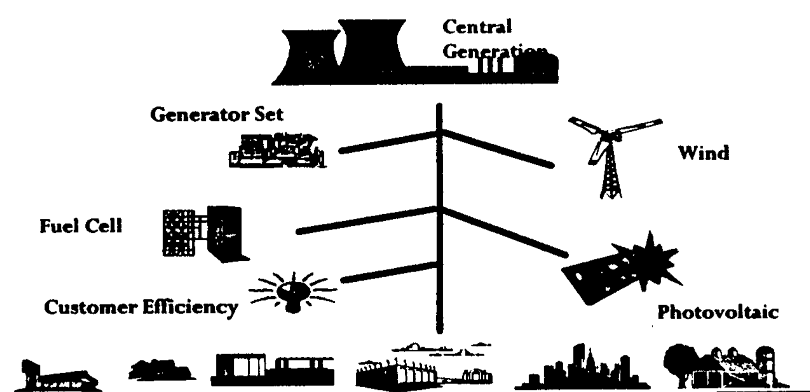
Electric Demand ↑ 2-[illegible]
IPPs ↑ 1,000%
Gas Fuel Use ↑ 30%
Trans. & Dist. Cost ↑ 100%

SHIFT OF	FROM	TO
Funds	Public	Private
Generation	Central Plant	Distributed Gen.

CAT — ELECTRONICS

CATERPILLAR
EPG

Tomorrow's Distributed Utility?



CAT — ELECTRONICS

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PRODUCT LINE

- HEAVY EQUIPMENT
  - EARTHMOVING
  - CONSTRUCTION
  - MINING
- ENGINES
  - DIESELS, 40 HP TO 7300 HP
  - NAT. GAS, 40 HP TO 4700 HP
  - TURBINES, 1300 HP TO 13000 HP
- GLOBAL MARKET
  - 52% OVERSEAS SALES
  - U.S. #2 NET EXPORTER
  - #1 DEALER/DISTRIBUTION NETWORK
  - 74% OF EMPLOYEES IN U.S.

CAT ELECTRONICS

CORE TECHNOLOGIES (1)

- HYDRAULICS
  - HIGH PRESSURE VALVES
  - PUMP & MOTOR BEARINGS
  - LINER, FITTINGS, SEALS (ABRASION & TEMP RESISTANT)
  - CONTAMINATION - TOLERANT DESIGNS
- COMBUSTION & TURBOMACHINERY
  - EMISSIONS
  - EFFICIENCY
  - NOISE
  - ALTERNATIVE FUELS
- MECHANICAL POWER TRANSMISSION
  - DESIGN
  - MANUFACTURING

CAT ELECTRONICS

CORE TECHNOLOGIES (2)

- TRIBOLOGY
  - LUBRICATED & UNLUBRICATED
  - WEAR/GALLING (HYDRAULIC SYSTEMS, BEARINGS, COATINGS
- ELECTRONICS
  - CONTROLS & COMMUNICATION
  - MONITORING/DIAGNOSTICS
  - SENSORS & DISPLAYS
- MATERIAL
  - CERAMICS
  - COMPOSITES
  - HIGH STRENGTH STEELS
  - FLUIDS
  - PROCESSES

CAT ELECTRONICS

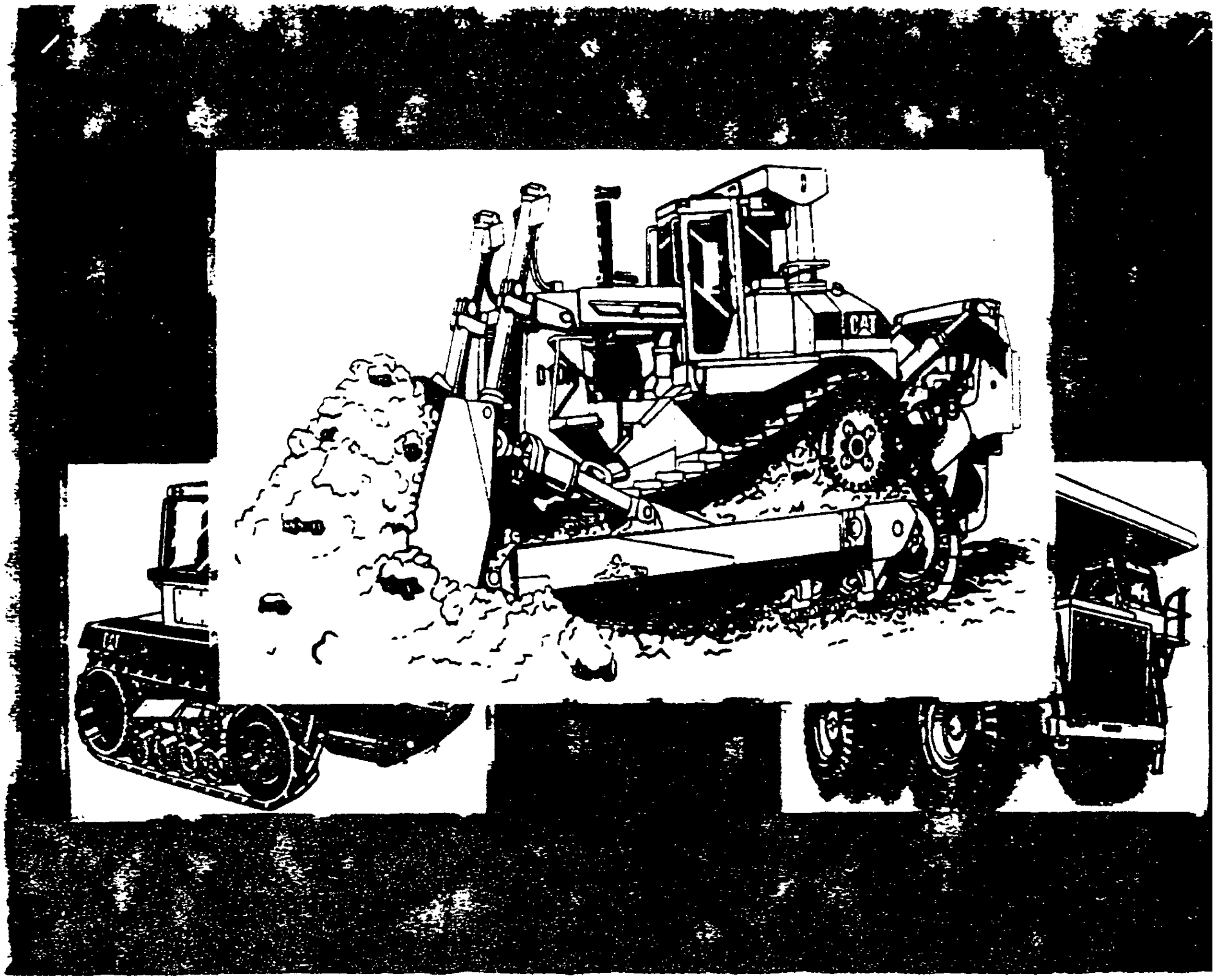
CATERPILLAR 1995 SALES/REVENUE ($ MILLIONS)

1995	SALES/ REVENUE	PROFIT AFTER TAXES
CONSOLIDATED	16,070	1,136
		OPERATING PROFIT
MACHINERY	11,336	1,210
ENGINES	4,115	462
FINANCIAL PRODUCTS	621	88

SOURCE: 1995 ANNUAL REPORT

ENERGY PRODUCING MACHINERY IS 20% OF OUR BUSINESS
ELECTRIC POWER GENERATION IS 6% OF OUR BUSINESS

CAT ELECTRONICS

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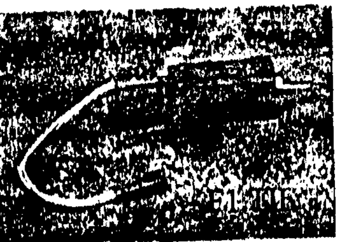

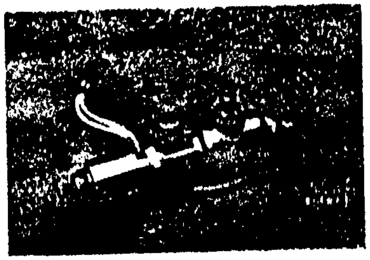

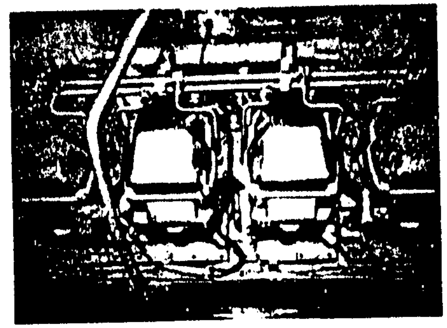

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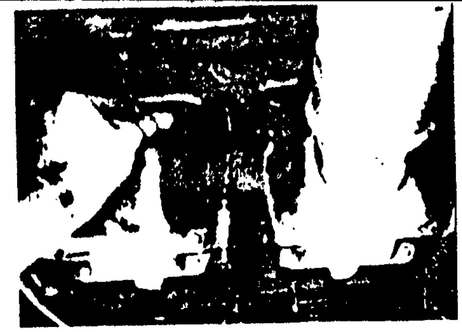

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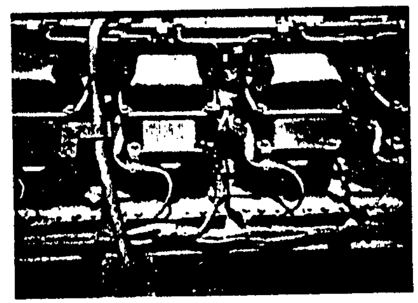

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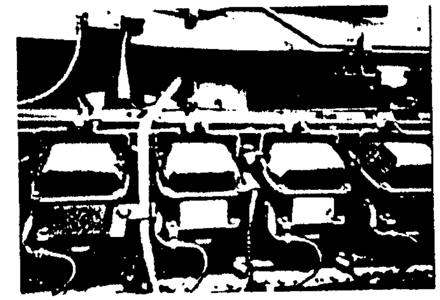

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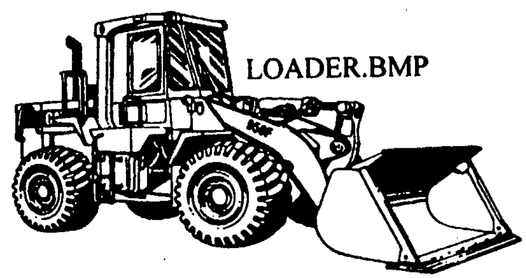

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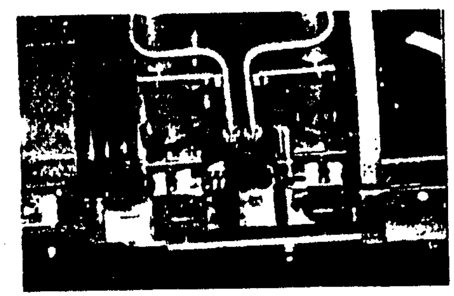

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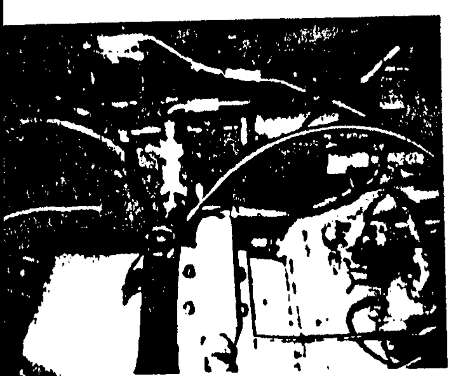
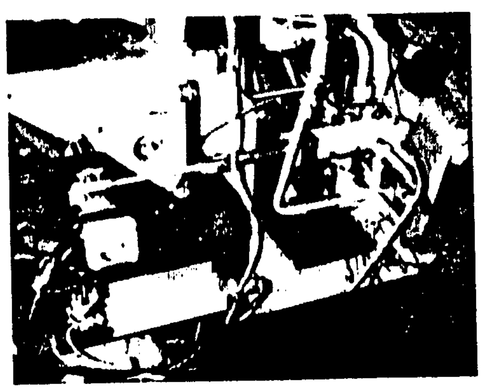
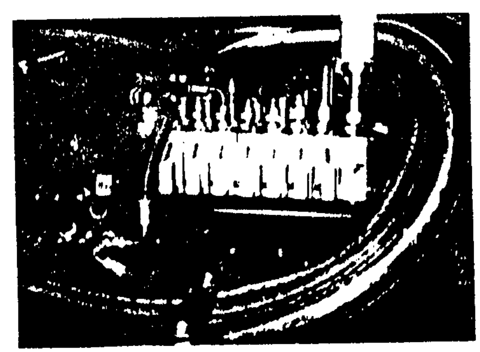


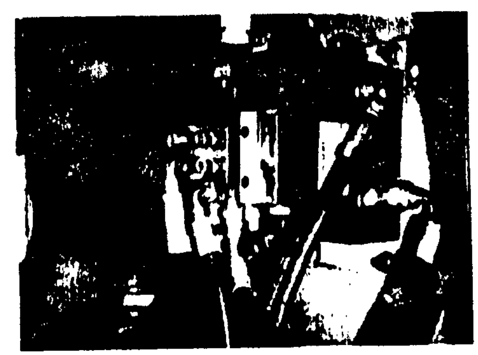
SI1.BMP



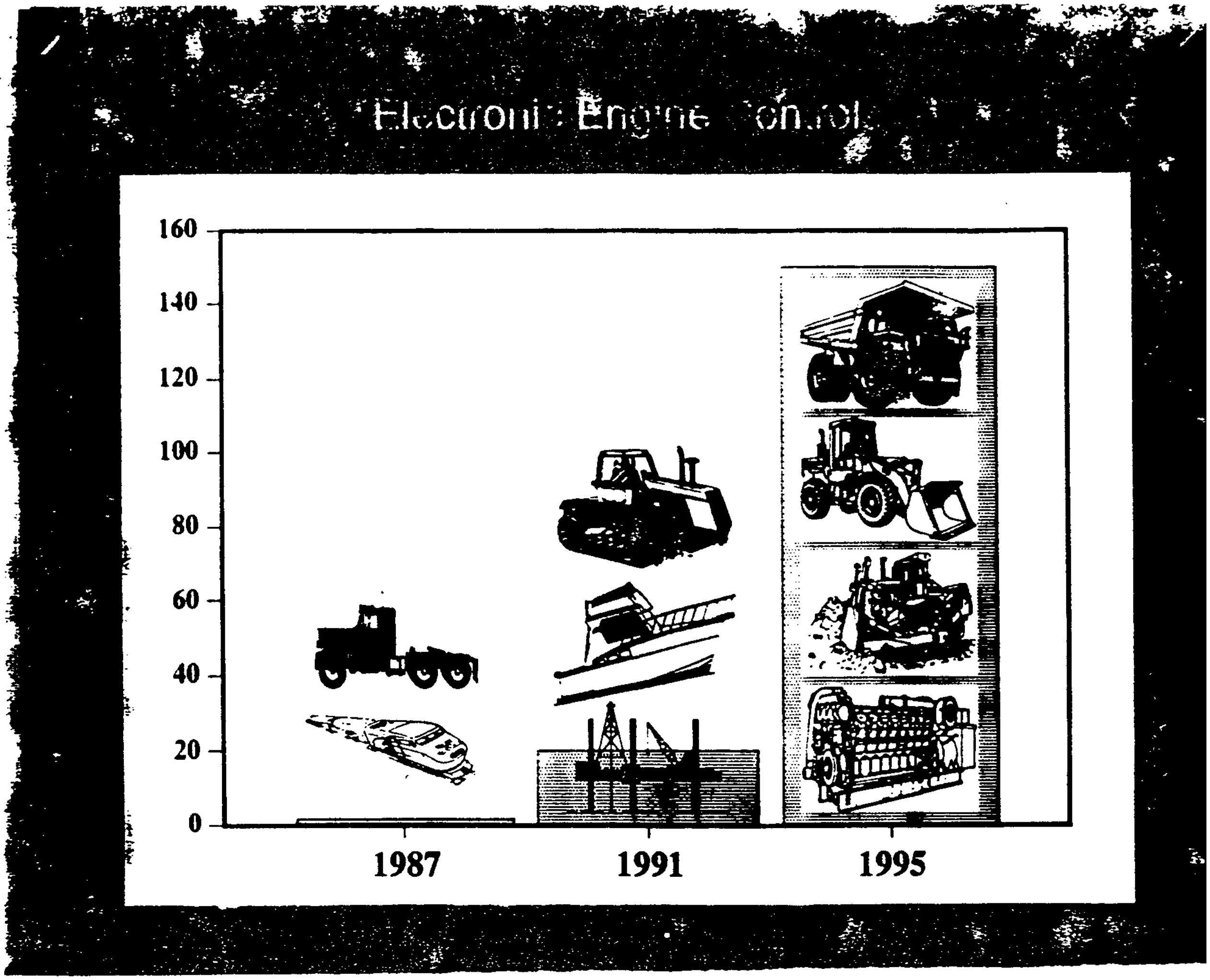
SI2.BMP

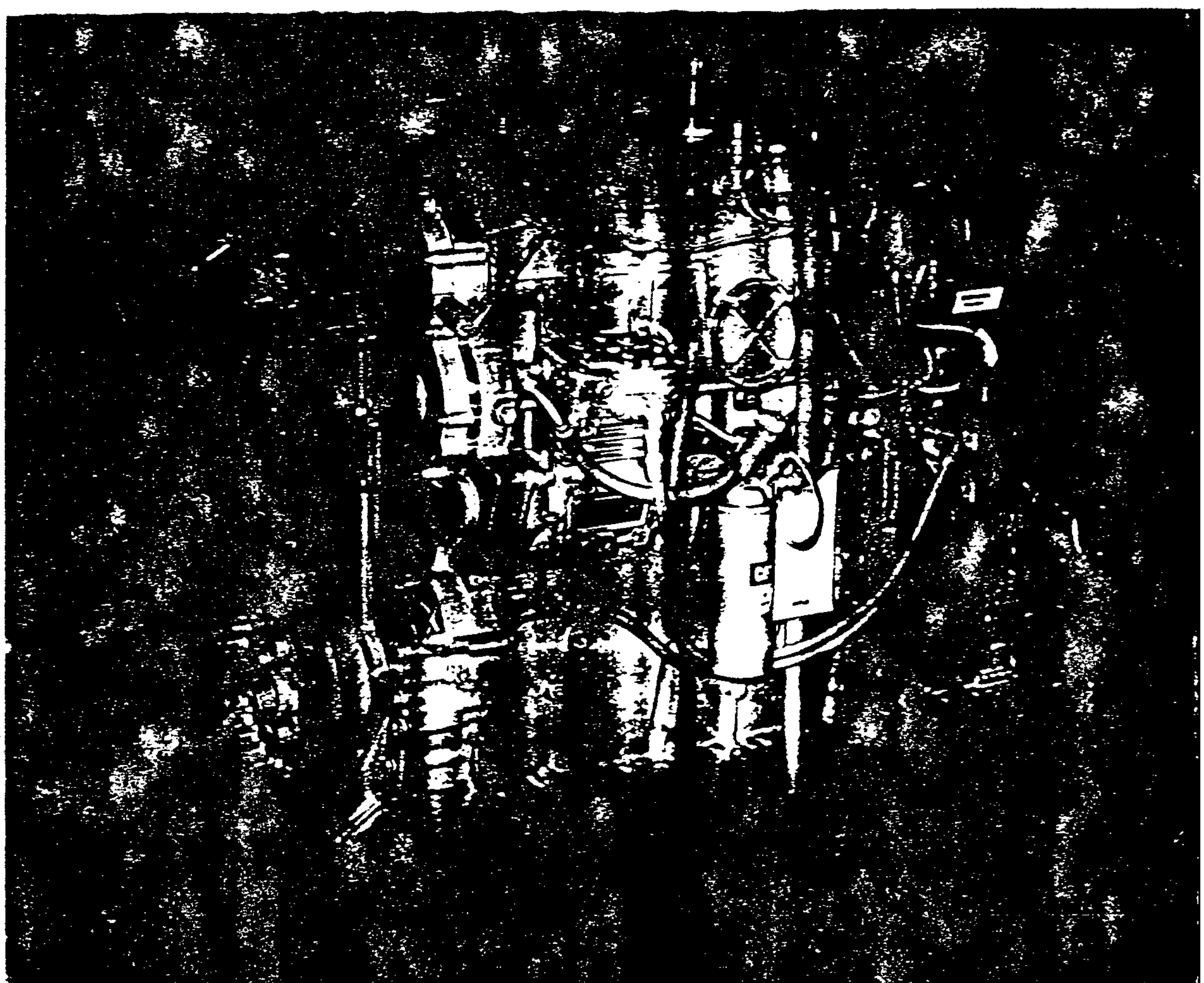


VALVE_GP.BMP



EV_VALVE.BMP

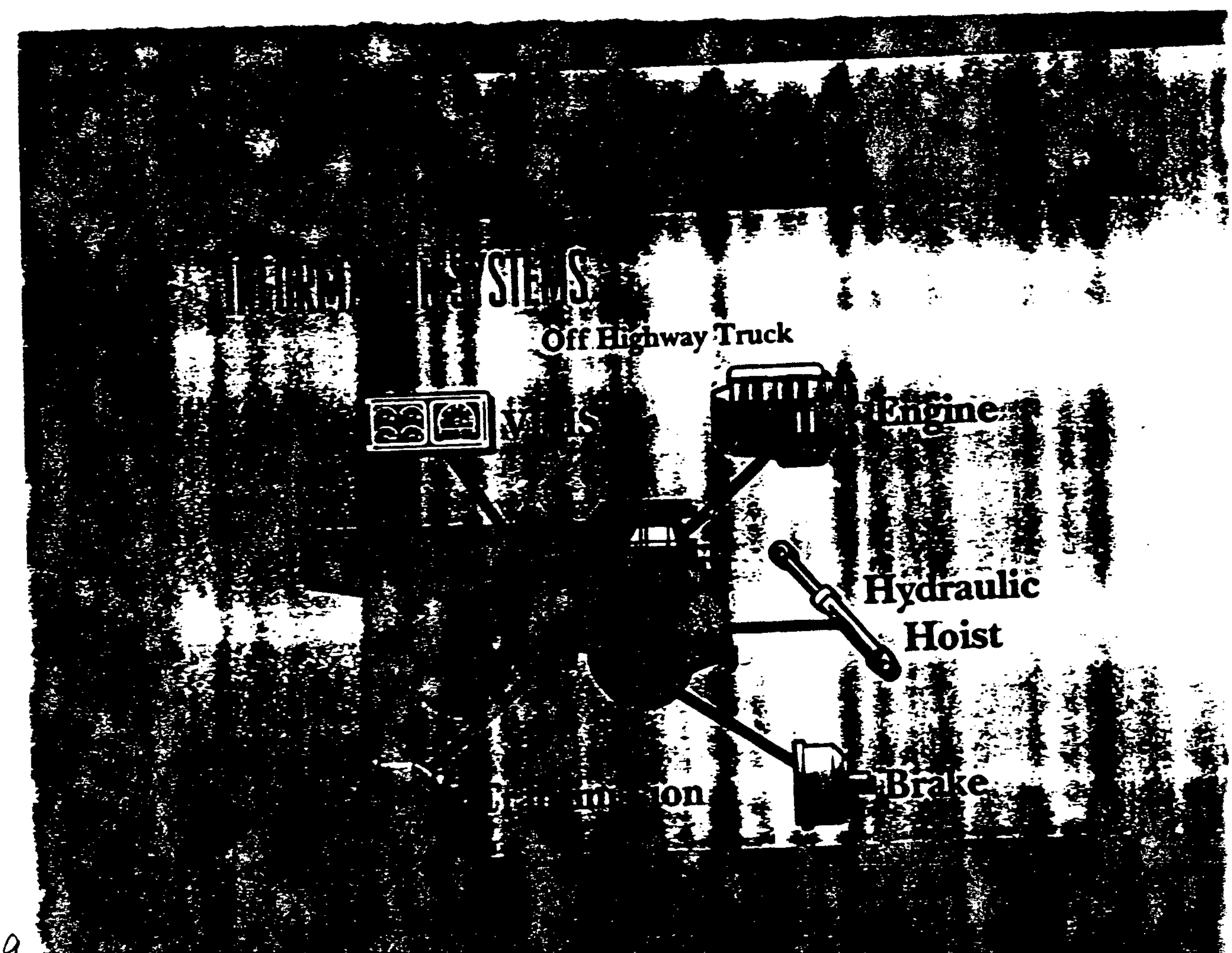

Electronic Engine Controls
160
140
120
100
80
60
40
20
0
1987
1991
1995

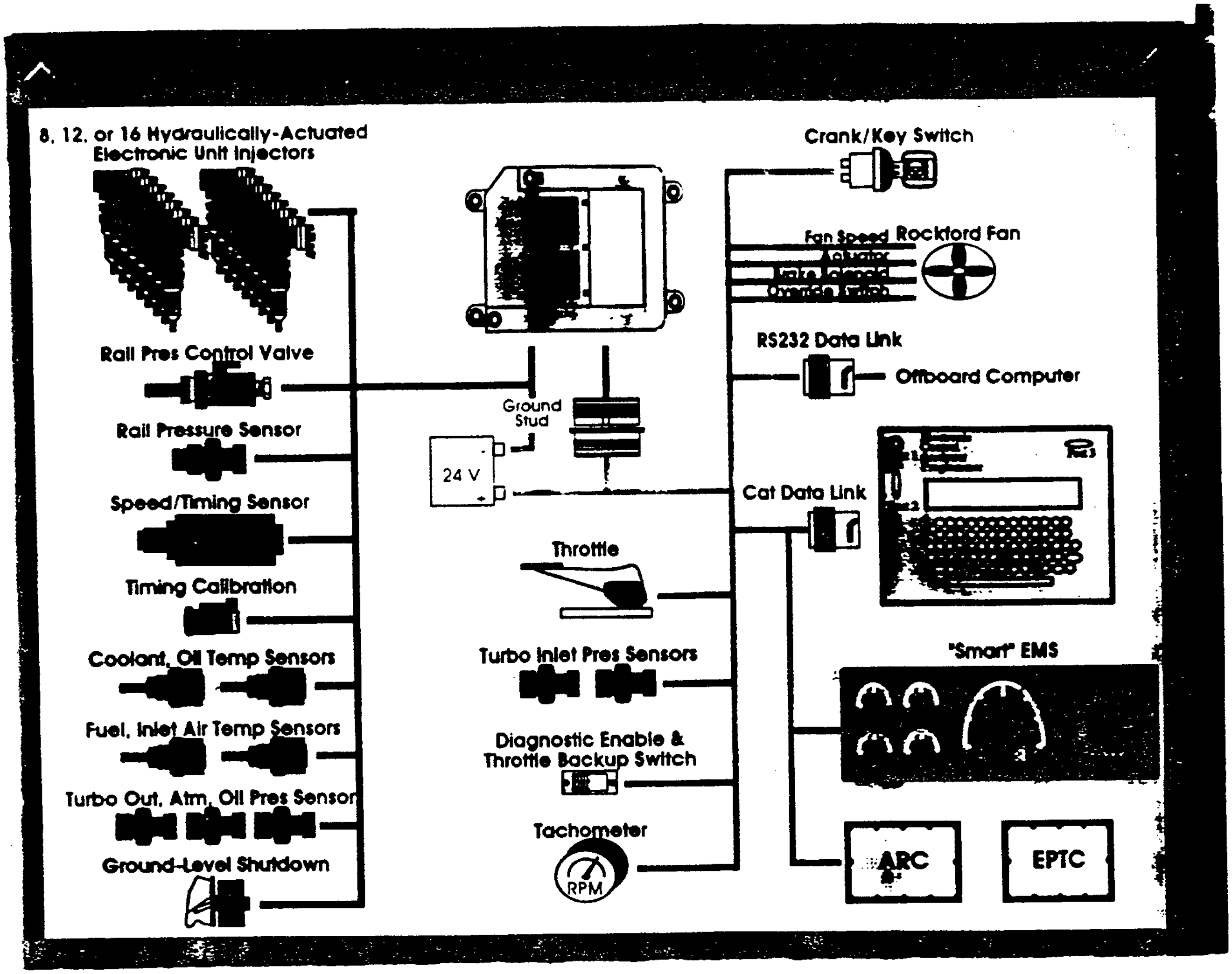


Off-Highway Truck

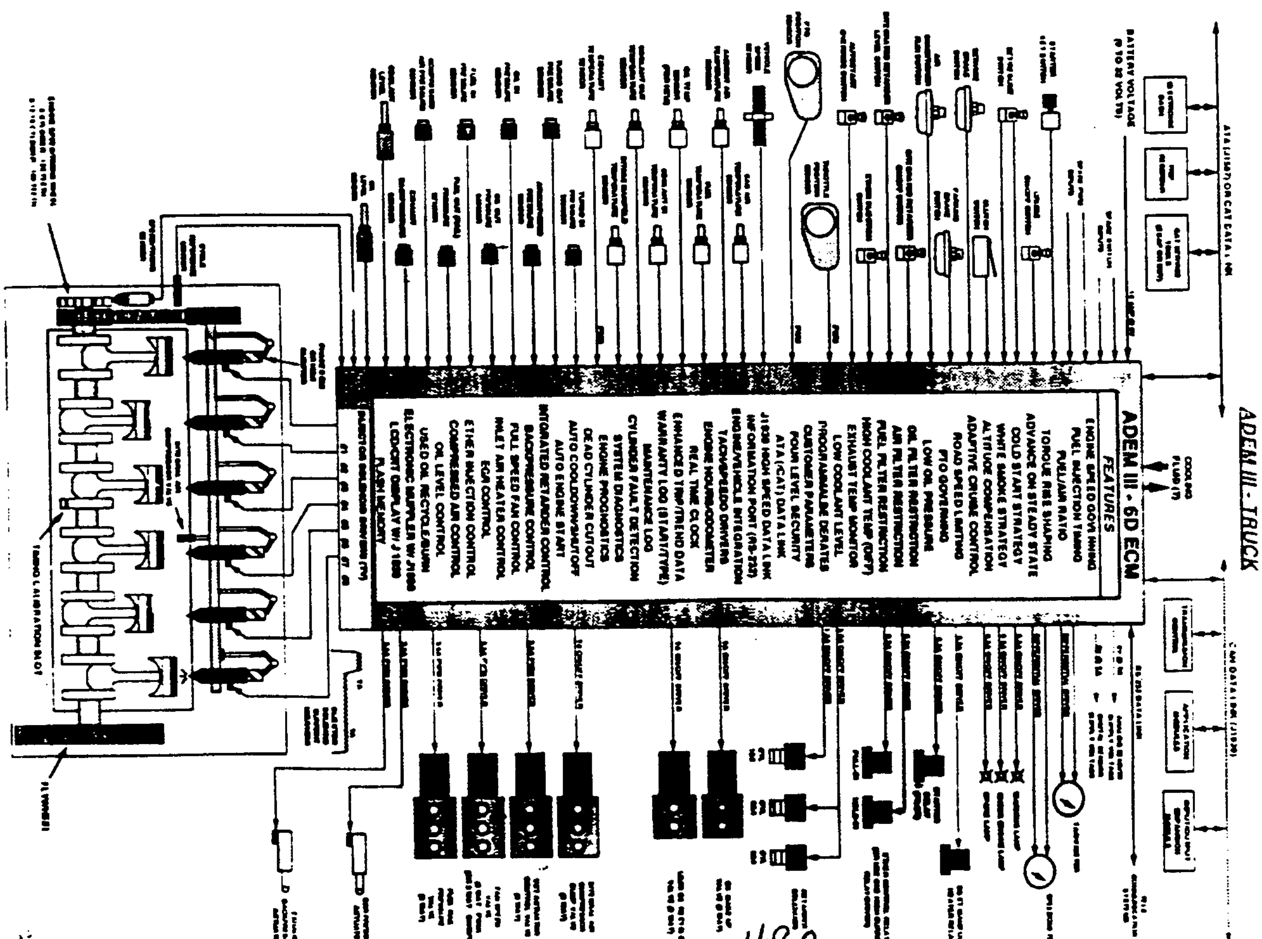
Benefits

- Powertrain Integration
  - Controlled Throttle Shifting
  - Directional Shift Management
  - Elevated Idle in Neutral Coast
- Altitude Compensation
- Air Filter Restriction Compensation
- Simpler Ether Injection System
- Elevated Low Idle
- Engine Monitoring
  - High Coolant Temperature
  - Low Oil Pressure
  - Engine Overspeed
- Integration with EMS and Dash





8, 12, or 16 Hydraulically-Actuated Electronic Unit Injectors
Rail Pres Control Valve
Rail Pressure Sensor
Speed/Timing Sensor
Timing Calibration
Coolant, Oil Temp Sensors
Fuel, Inlet Air Temp Sensors
Turbo Out, Atm, Oil Pres Sensor
Ground-Level Shutdown
Ground Stud
24 V
Throttle
Turbo Inlet Pres Sensors
Diagnostic Enable & Throttle Backup Switch
Tachometer
RPM
Crank/Key Switch
Fan Speed
Rockford Fan
RS232 Data Link
Offboard Computer
Cat Data Link
"Smart" EMS
ARC
EPTC



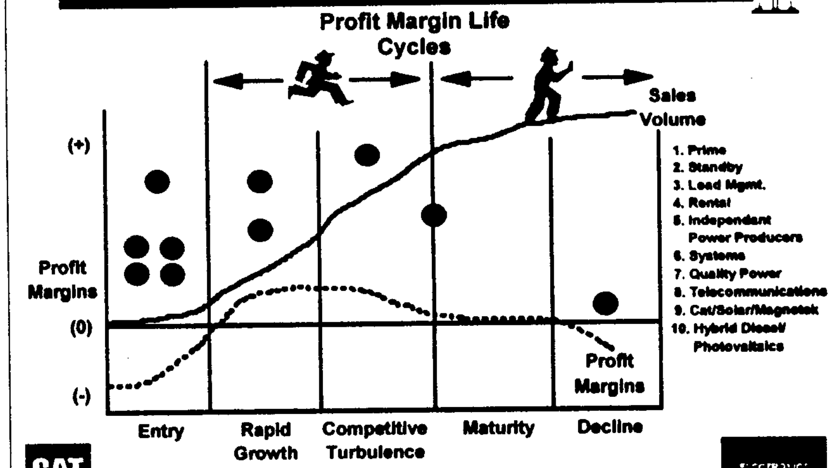
ADEM III - TRUCK
ADEM III - 6D ECM
FEATURES

INDUSTRY TRENDS

- PRODUCT MATURITY
- CUSTOMER EMPHASIS ON IMPROVING PROCESS
- MACHINES THAT ENHANCE OPERATOR SKILL
- MACHINE DESIGNS EXPLOITING ELECTRONICS
- POWER MARKET GROWTH

CAT ELECTRONICS

CATERPILLAR®
EPG



CAT

Caterpillar Interests

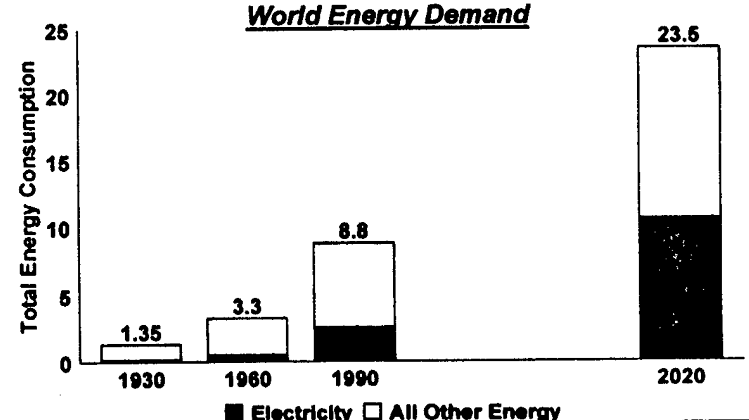
- Sell Energy
- Emerging Technologies
  - TPV "engines"
  - New "Green" projects
  - Hydrogen Fuel - Nickel Hydrides Storage
  - New Batteries from Electric Car Programs
- Stay in Power Business - Long Term

CAT ELECTRONICS

Electric Power Generation

(as % of)

World Energy Demand



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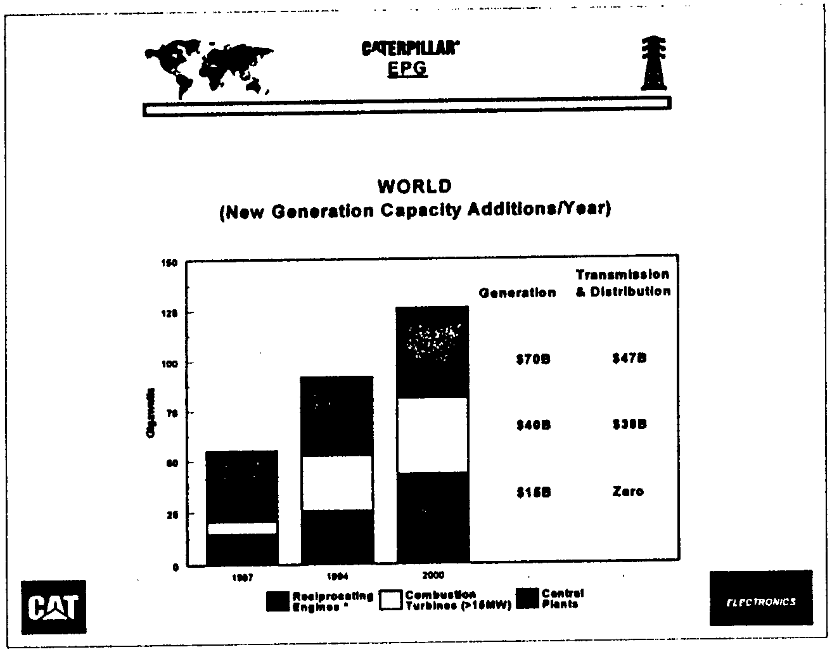
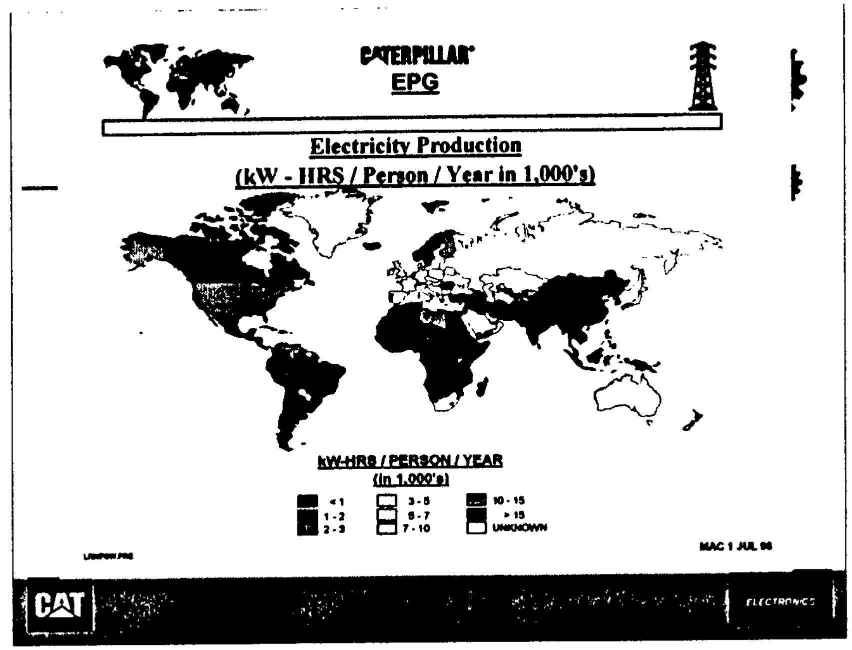
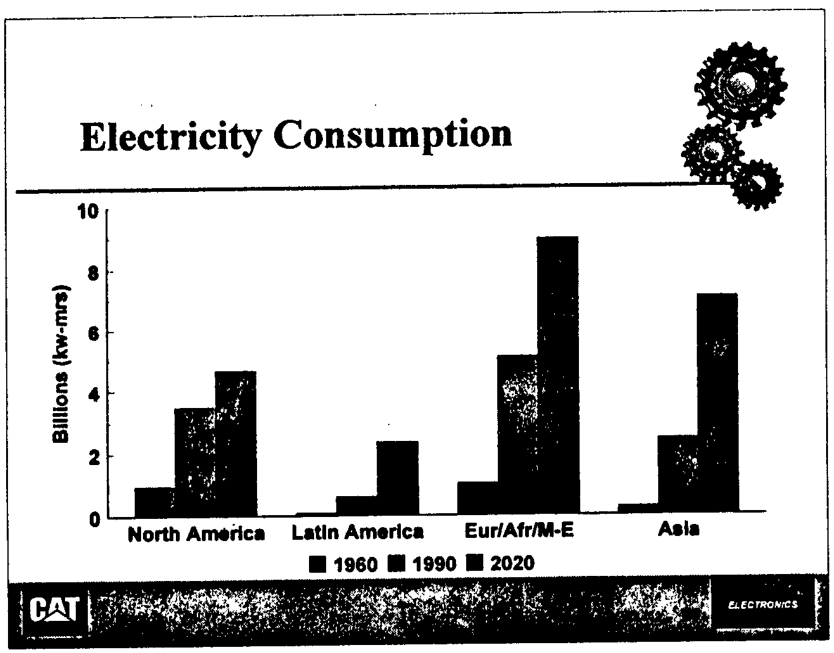
Source: World E







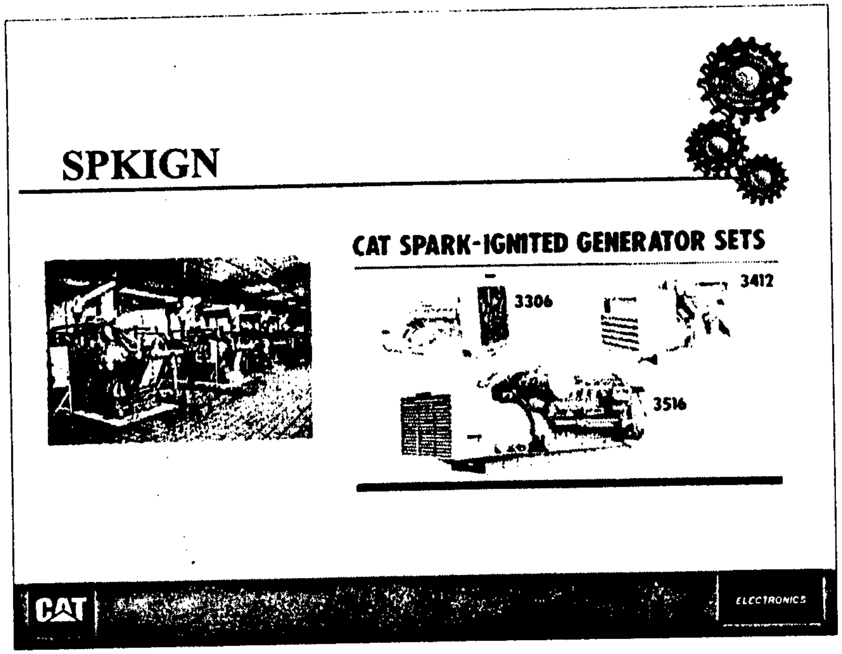
CATERPILLAR
EPG

Growth Rates for Electricity Consumption % per Annum

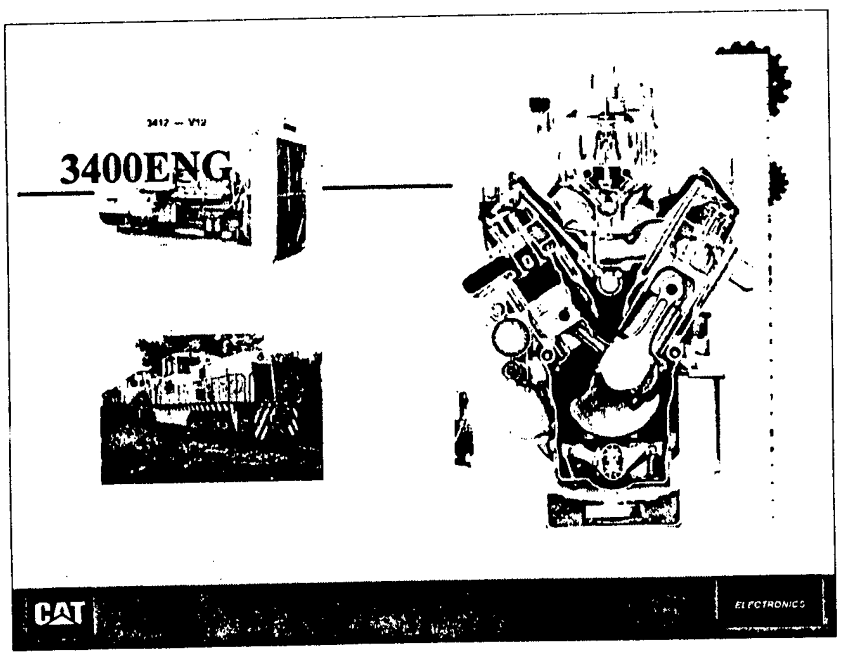
	1960-1970	1970-1980	1980-1990	1990-2020*
North America	6.8	4.0	2.4	1.0
Latin America	8.3	9.1	4.5	4.7
Western Europe	7.3	4.3	2,6	1.5
Central & Eastern Europe	9.5	6.2	0.7	1.7
CIS	9.7	5.7	3.0	1.1
Sub-Saharan Africa	9.4	7.2	4.2	3.9
Pacific 1 (includes CPA) 1	10.3 (7.2)	6.9 (9.7)	5.8 (7.0)	3.4 (4.5)
South Asia	12.1	7.0	9.4	4.7
World	8.0	5.2	3.5	2.3

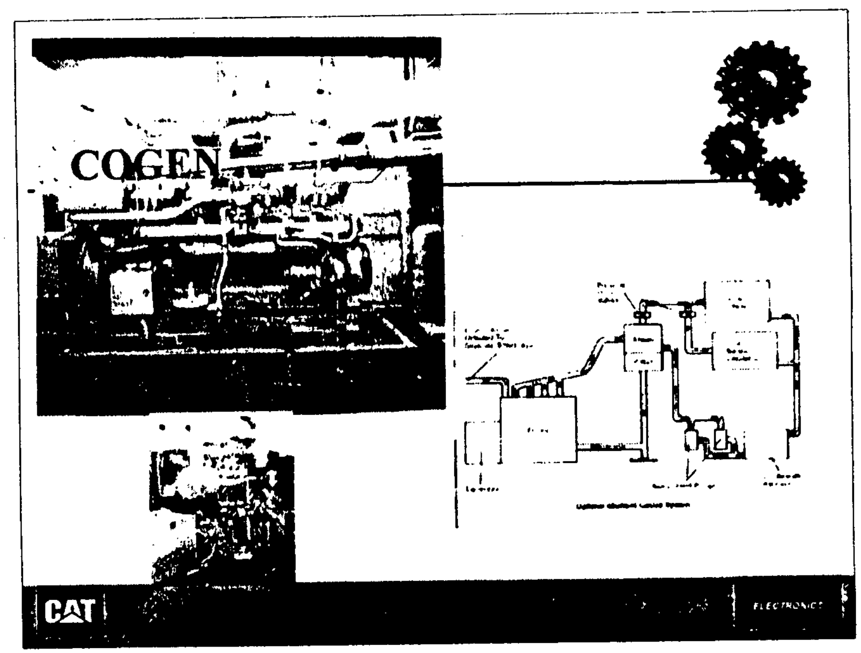
Data for Pacific Region include Centrally Planned Asia, which are also shown separately
* Projection by WEC - Case B
Sources: UN Energy Statistics Yearbook; WEC

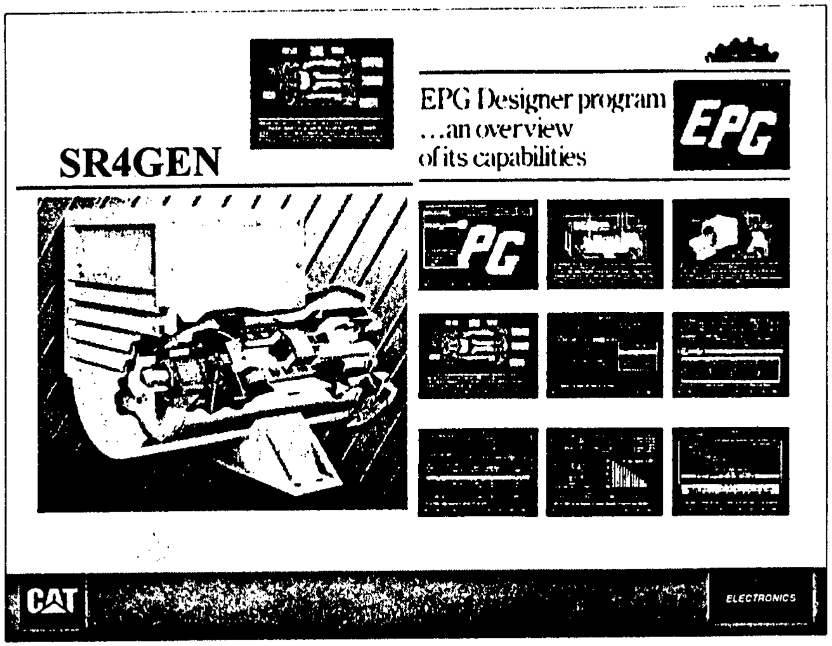
CAT


SPKIGN
CAT SPARK-IGNITED GENERATOR SETS
3306
3412
3516
CAT
ELECTRONICS


CAT
ELECTRONICS


3412 — V12
3400ENG
CAT
ELECTRONICS


COGEN
CAT
ELECTRONICS

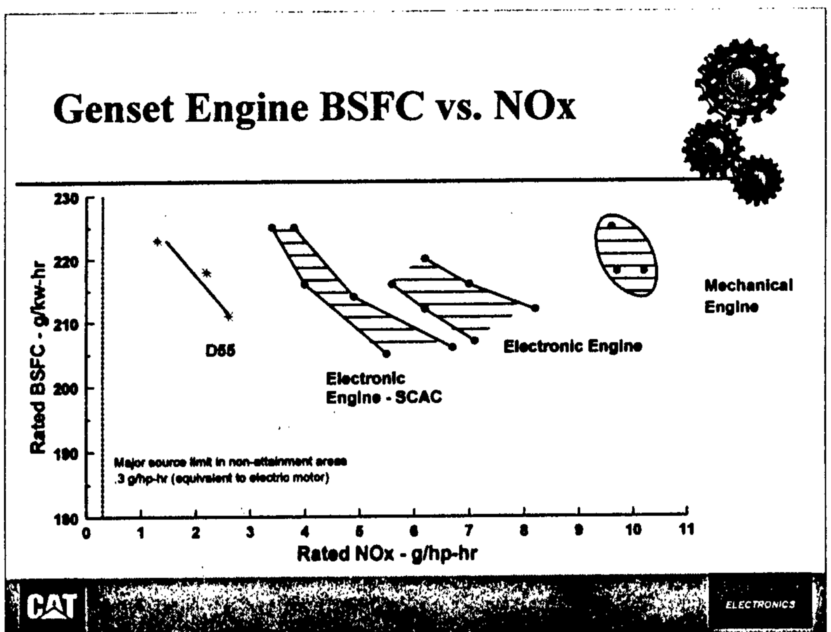


CATERPILLAR®
EPG

EPG Buyer Wants

NEEDS	CONSULTANT	CONTRACTOR	END-USER
1. Preaquisition Assist.	X	X	X
2. Installation Assist.		X	X
3. Operational Assist.		X	X
4. Low Operating Costs	X		X
5. Reliability	X		X
6. Durability			X
7. Environmental Req.	X		X
8. Electrical Perf.	X		X
9. Financial Assist.			X
10. Sophisticated Controls	X		X
11. KW Range	X	X	X
12. Availability		X	X
13. Code Req.	X	X	X
14. Alternate Fuels	X		X
15. Thermal Energy	X	X	X
16. Low Initial Price		X	X
17. High Resale Value			X

CAT ELECTRONICS



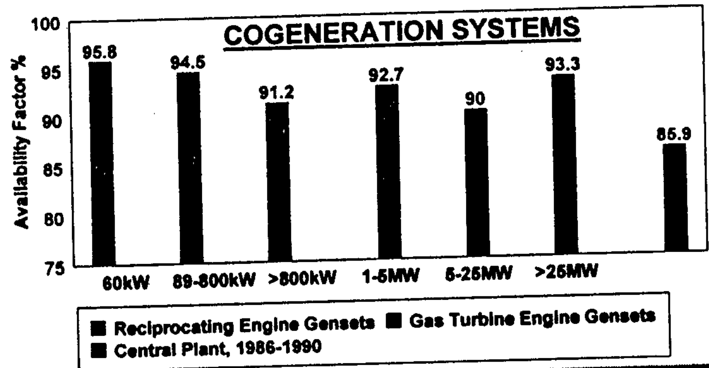
EMISSIONS & FIG. of MERIT

Without After-Treatment		SOx	NO	p	Total	Capital	Operatio
Diesel Engine	(1)	0.80	9.64	0.27	10.71		
Central Coal Plant	(2)	9.77	1.57	1.93	13.27		
Natural Gas Engine	(3)	0	24.12	NIL	24.12		
Natural Gas Engine, LB	(4)	9	2.00	NIL	2.00		
With After-Treatment							
Diesel Engine-SRC	(5)	0.80	0.48	0.27	1.55	+50	+50
Central Coal Plant	(6)	1.36	1.57	0.36	3.29	UNK	UNK
Natural Gas Engine-SCR		0	0.94	NIL	0.94	+12	0
Natural Gas Engine-3WC	(7)	0	0.30	NIL	0.30	+15	+3

1) 0.2% SULPHUR IN THE FUEL (DIESEL OIL)
2) 1.0% SULPHUR IN THE FUEL (COAL)
3) STOICHIOMETRIC COMBUSTION
4) LEAN BURN
5) 95% EFFICIENCY OF SELECTIVE CATALYTIC REDUCTION (SRC) EQUIPMENT
6) 86% EFFICIENCY OF AFTER TREATMENT EQUIPMENT
7) 99% EFFICIENCY OF THREE-WAY CATALYST (3WC) EQUIPMENT

CAT ELECTRONICS

RELIABILITY OF NATURAL GAS FUELED



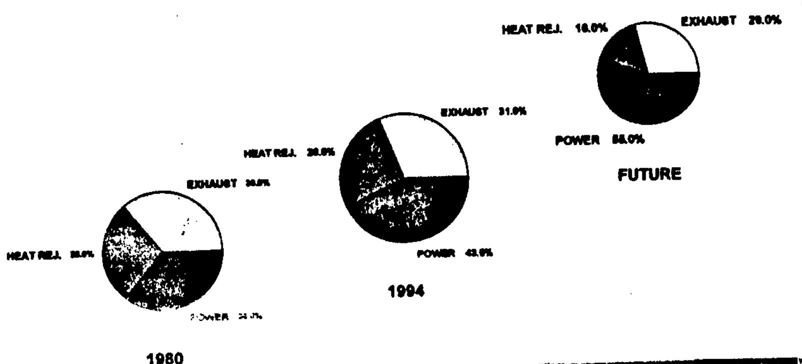
CAT ELECTRONICS

TPV Power Systems

- What is Required
  - Efficiency matching diesel engine
  - Capital costs
  - KW-HR costs to produce
  - System costs ~ $/W - 20 yr life

CAT ELECTRONICS

Diesel Efficiency Progress



CAT ELECTRONICS

Central vs. On-Site Power Plants

	Capital	O&O Costs	Construction Time	Eff. at P[oint] of Use
	($/kW)	(¢/KW-HR)	(years)	(%)
Central Plant				
Hydro, Nuclear, Fossil, Turbine*	1,200 to 4,800	2-4	1-10	25-35
Mobile & On-Site				
Turbine, Engine (Gas, Diesel, HFO)	300 to 800	3-10	1/3-1	35-75**

* Includes cost of transmission & distributors
** Cogeneration

Boats & Buckets!

CAT ELECTRONICS

SUMMARY OF ELECTRIC COST (¢/KW-HR)

APPLICATION	CAT ENGINE MODEL	HRS/YR	¢/K[illegible]
EMERGENCY STANDBY	D3612 M	100	[illegible]
	D3512 H	100	[illegible]
PEAK SHAVING	D3612 M	400	[illegible]
	D3512 H	400	[illegible]
PRIME POWER / BASE LOAD	D3512 H	8,000	9.33
	D3612 H	8,000	8.10
	G3512 H	8,000	3.94
	G3612 M	8,000	3.34
CO-GENERATION	G3512 H	8,000	2.89
	G3612 M	8,000	2.37
CO-GENERATION W/SCR EMISSION EQUIP.	G3512 H	8,000	2.99
	G3612 M	8,000	2.51
CENTRAL PLANT (A)	LAC-1988	8,000	4.10

ASSUMPTIONS:

1. Fuel Price — Diesel: 25.8 cent/litre; Natural Gas: 6.4 cent/cubic metre
2. Oil Price — $1.87/litre
3. Operation — Prime Power: 8,000 hrs/yr at 65% load factor; Peak Shaving: 400 hrs/yr at 65% load factor; Standby: 100 hrs/yr at 65% load factor
4. Labour cost for repairs/maintenance @ $28/hour
5. All costs are in US dollars or cents
6. Costs are before tax
7. Interest on capital = 15% per year

(A) A 1991 World Bank preliminary study of 25 countries in Latin America and the Caribbean (LAC) region showed the average cost of electricity from all forms of central plants at 4.1¢/KW-HR in 1988. Approximately 70% of LAC central plants are hydro-electric - normally the lowest cost of most central plants.

D - Diesel
G - Natural Gas
M - 900 RPM
H - 1800 RPM

NOTE: HEAVY FUEL OIL COSTS ARE SIMILAR TO NATURAL GAS

CAT ELECTRONICS

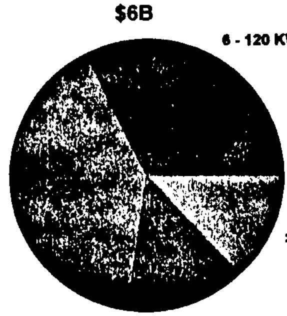
TPVPower System

- Identify TPV HYBRID (200-400KW)
- Define Location installation - US/India/Canada?
- Statement of Interest - Market Potential
- Define R&D Program - 5-10 yrs, DOE/etc

CAT ELECTRONICS

ENGINE OPPORTUNITY by SIZE

GENERATOR SET 1995
$6B



CAT ELECTRONICS

SUMMARY FOR TPV ENERGY

- PULLED BY CUSTOMER DEMANDS FOR SIMPLER SYSTEMS
- PUSHED BY DESIGNERS AS LIMITS REACHED
- WILL USE WHEN AVAILABLE
- MUST HAVE PROVEN RELIABILITY
- ATTENTION TO DETAILS FOR CONSTRUCTION, RELIABILITY AND DURABILITY

CAT ELECTRONICS

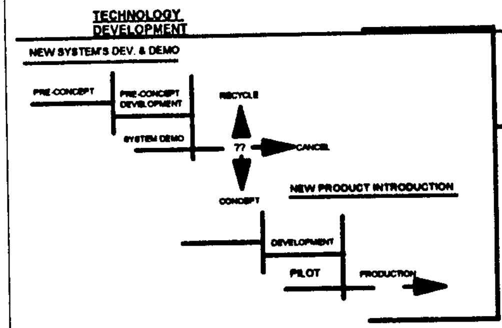
CATERPILLAR ELECTRONICS

- Systems, Sensors, Actuators & Comp.
  - a. Electro-Hydraulic Engine Injection
  - b. Engine Valve Control
  - c. Electro-Hydraulic Implement Control
  - d. Integration of Machine Functions

John F.Szentes
Staff Engineer
E&E/R&D

CAT ELECTRONICS

TECHNOLOGY ADVANCEMENT PROCESS



TECHNOLOGY ADVANCEMENT
- ✓ JOINT OWNERSHIP
- ✓ PATH TO NPI
- ✓ DIFFERENTIATED PRODUCT

TEAMWORK
- ✓ ESTABLISH COMMON GOALS
- ✓ SHARED RESOURCES

CAT ELECTRONICS

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DEMONSTRATIONS, DISPLAYS,

&

POSTER SESSIONS

Vertical Multi-Junction (VMJ) Photovoltaic (PV) Cell for TPV Energy Conversion

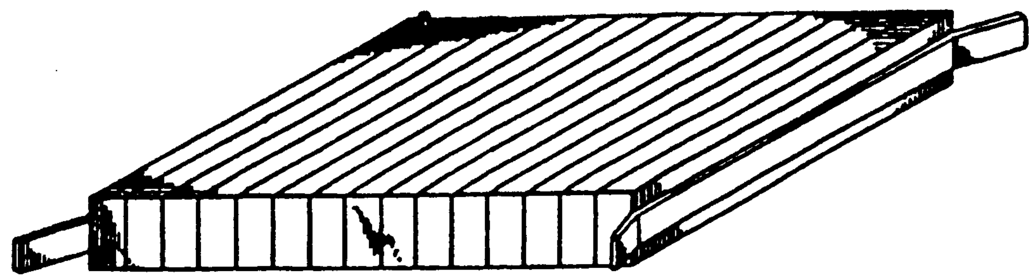
***

Bernie Sater, Photovolt, Inc.

Don Chubb, NASA Lewis

TPV Cell Requirements:

- Good spectral response for all usable photons
  - especially for near-bandgap photons
- Low absorption and reflection of unusable photons
  - > 95% reflection important for heat recycling
- Efficient operation at high power densities demands
  - High voltage and low series resistance output
  - Very high current densities are generated
    - J_{sc} for 2000°K > 100 suns intensity
- The VMJ cell provides these characteristics

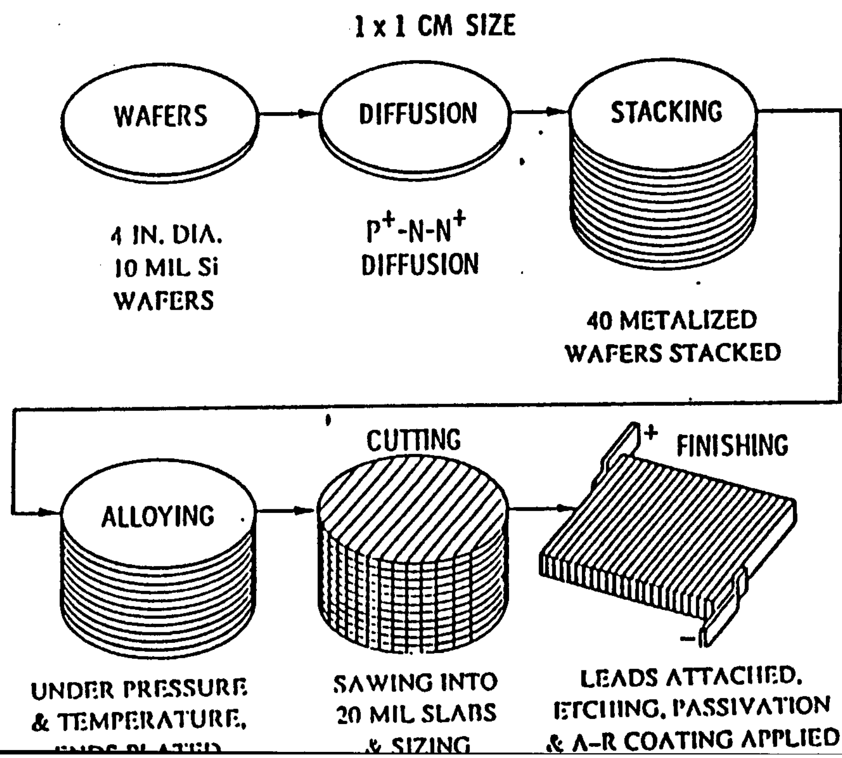


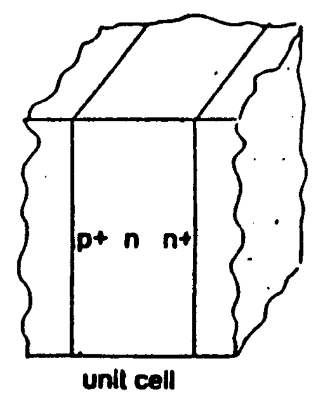
Schematic of VMJ cell structure

- integrally bonded
- series connected array
- miniature vertical junction p+nn+ unit cells
  - 1 cm^2 VMJ cell has 40 unit cells
  - electrical connections on ends

The VMJ Cell Fabrication Processes:

- Key feature is design simplicity
  - one optimized wafer design for all intensities
  - a single high temperature step
  - no photolithography processing
  - suitable for silicon or germanium
  - yields can be high, > 1000 in example





MAJOR FEATURES AND ADVANTAGES OF THE VMJ CELL

1. **Edge illumination** - eliminates front and back ohmic contacts; there is no sheet resistivity component in series resistance; there is equal collection probability for excess carriers generated at any depth with vertical junctions improving spectral responses for both the short UV and long IR regions of the solar spectrum; it is more responsive to photons incident at relatively large angles as associated with concentrating optics because of the absence of a dead layer at the surface of incidence and internal reflection from the metallization contacts at each unit cell side.

2. **Series connection** - provides a high voltage, low current operation, a better compatibility to power processing loads, and a tolerance to series resistance values within the electrical system.

3. **Use of high resistivity base material** - gives a high minority carrier lifetime, allows the use of thicker starting wafers which reduces the manufacturing costs but does not contribute to series resistance or degrade voltage.

4. **Use of rather deep p+n and nn+ junctions** - minimizes carrier recombination at contact surfaces while the use of nn+ high-low junction provides an electrostatic drift field for considerably improved generated carrier collection and gives a higher open circuit voltage.

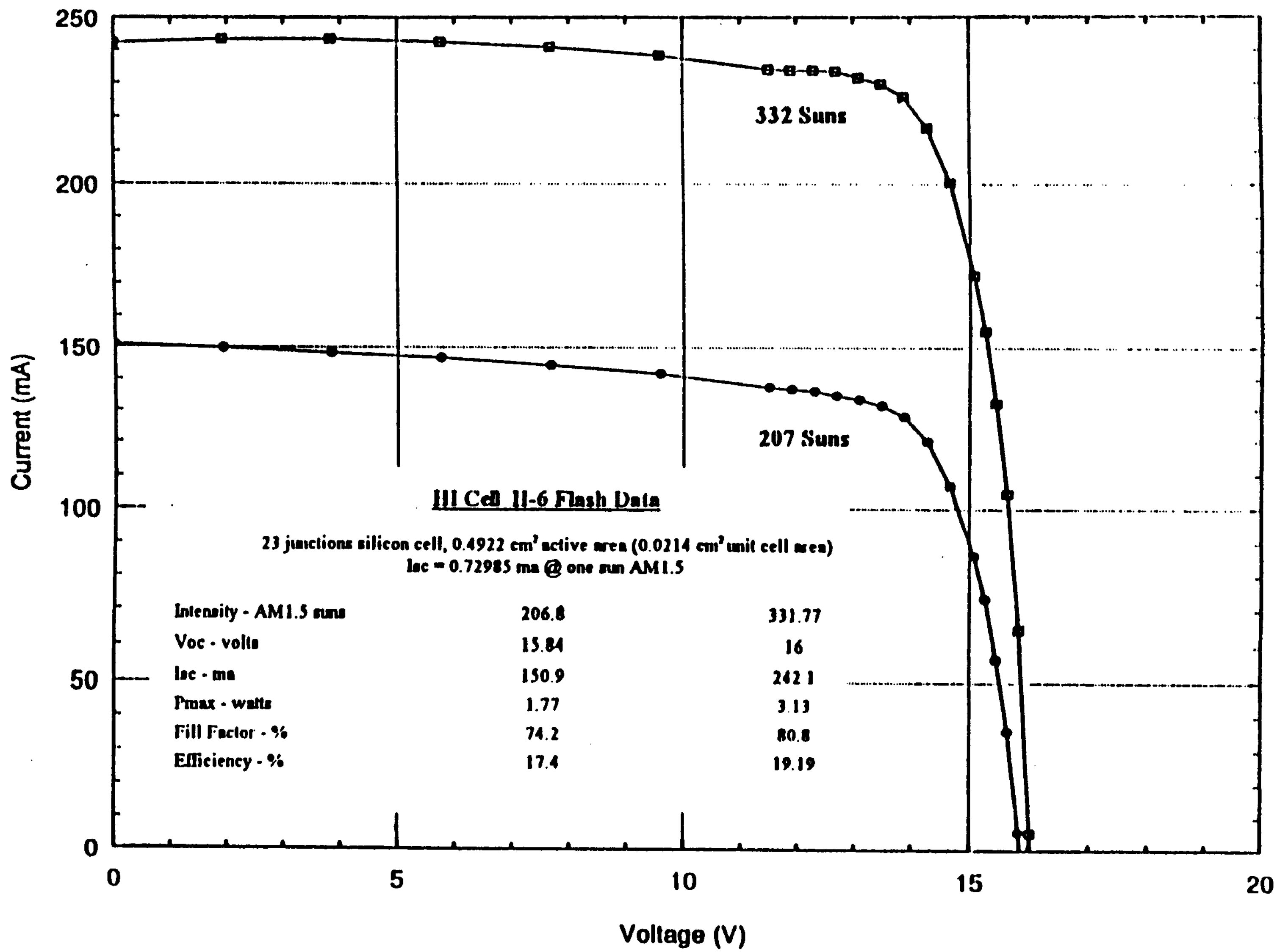
5. **Non-absorbing reflecting back surface** - doubles the effective photo-generation path of all usable near-bandgap photon radiation; it also effectively reflects unusable photons with quantum energies less than the bandgap to minimize heat dissipation in the cell heat sink.

6. **Very low series resistance at high incident intensities** - provides an almost linear reduction of the series resistance with increasing intensity due to conductivity modulation throughout the bulk region; increasing voltage and efficiency with increasing intensities while decreasing the efficiency degradation with increasing temperature coefficient.

7. **Structural configuration** - provides an extremely rugged structure; electrically, mechanically and thermally which permits high packing densities with easy interconnecting of electrical output leads in high power density HCPV systems.

SILICON VMJ

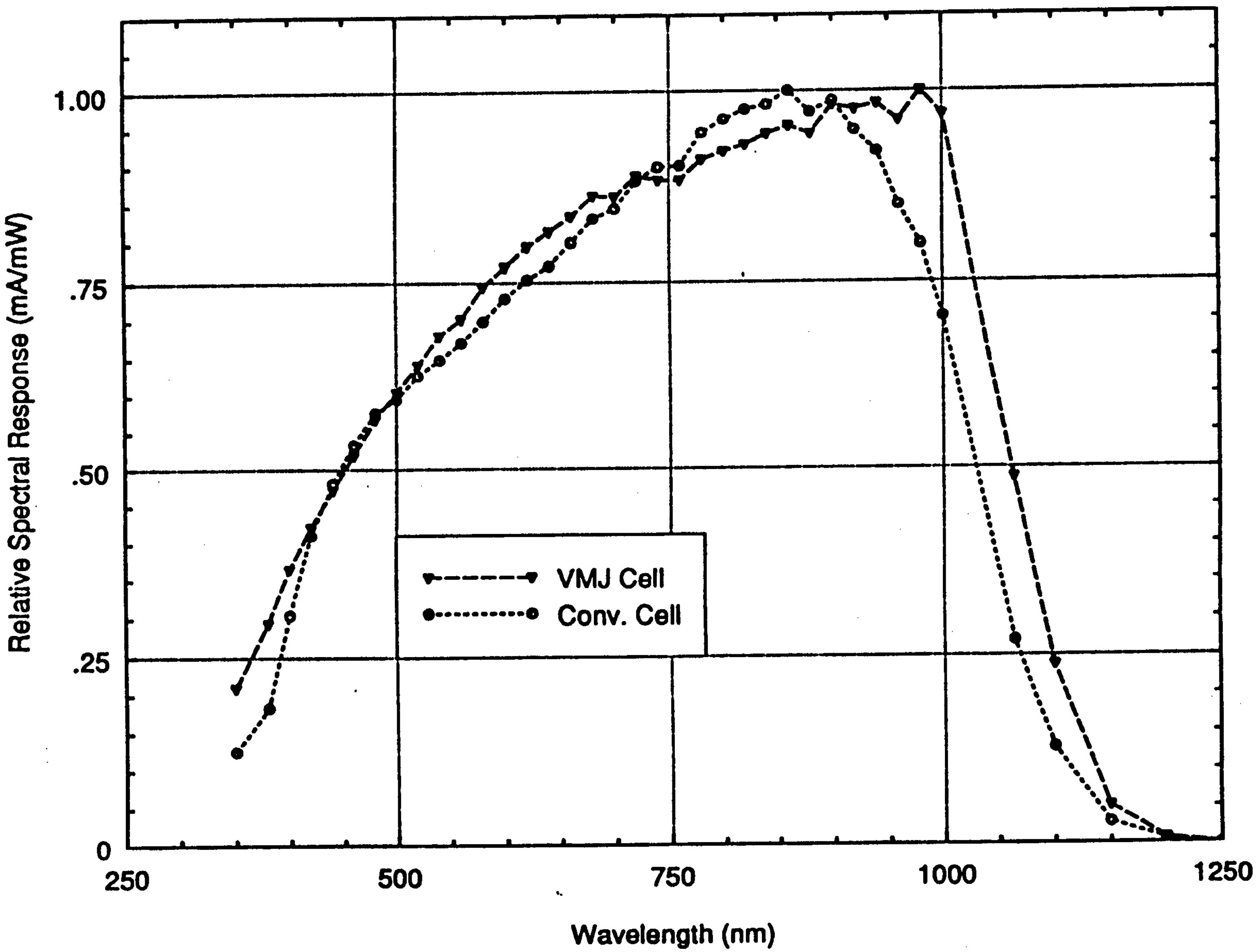
H6 side 2 (with AM 1.5 filter, under concentration)



Current-Voltage Characteristics

Silicon VMJ

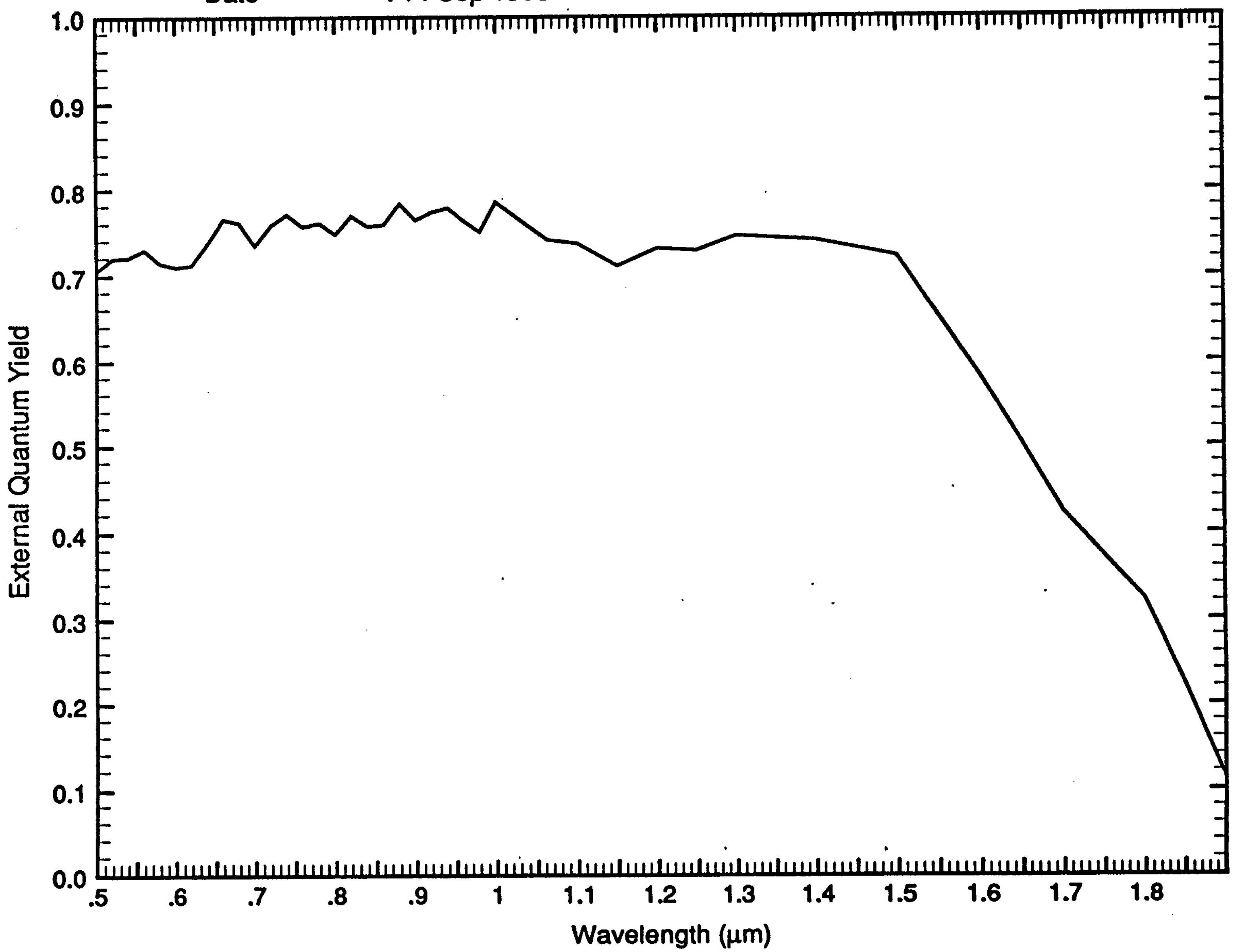
Spectral Response Characteristics



NASA **Lewis Research Center**

External Quantum Yield GE PLANAR

Cell ID	: Ge-1 (2 days)
Active Area	: .932 cm^2
Temperature	: 25°C
Date	: 14 Sep 1995



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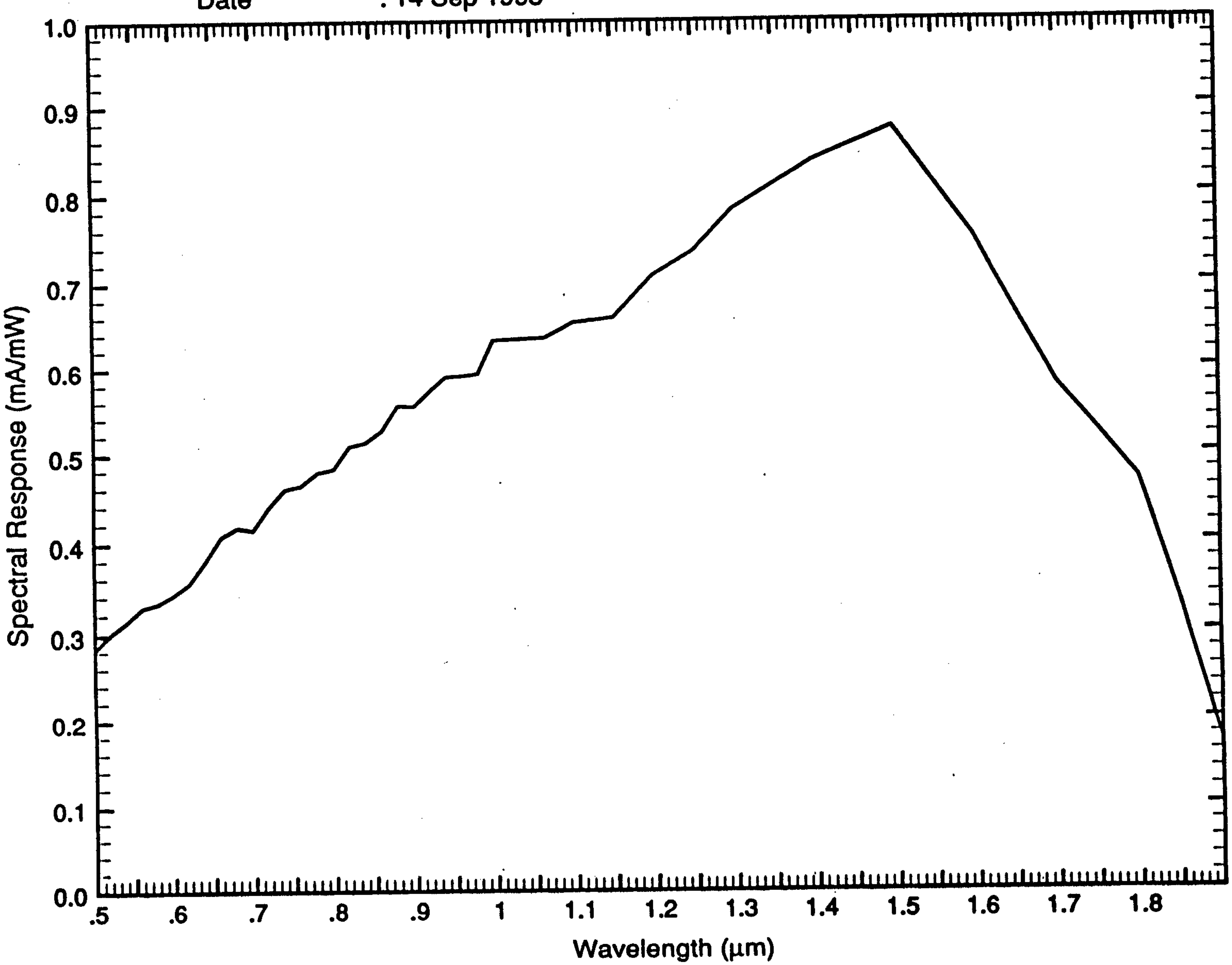
NASA **Lewis Research Center**

Spectral Response GE PLANAR

Cell ID : Ge-1 (2 days)
Active Area : .932 cm^2
Temperature : 25°C
Date : 14 Sep 1995



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Effect of Geometry on TPV Performance

***

Don Chubb, NASA Lewis

National Aeronautics and Space Administration

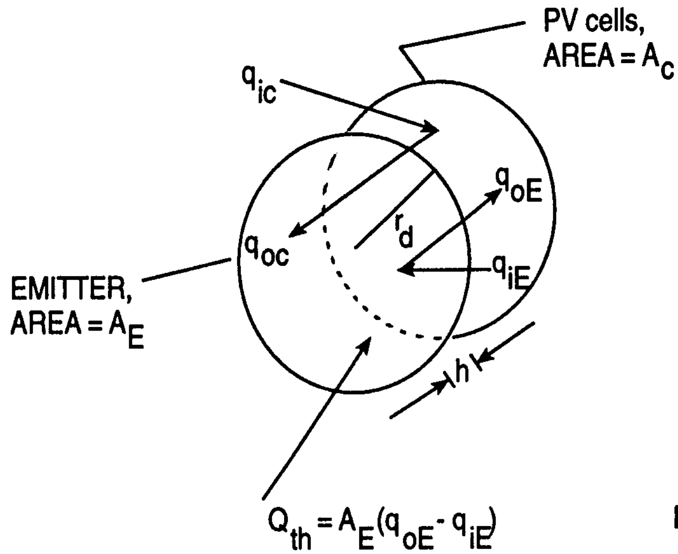
Lewis Research Center

EFFECT OF GEOMETRY ON TPV PERFORMANCE

POWER TECHNOLOGY DIVISION

TWO BASIC GEOMETRIES:

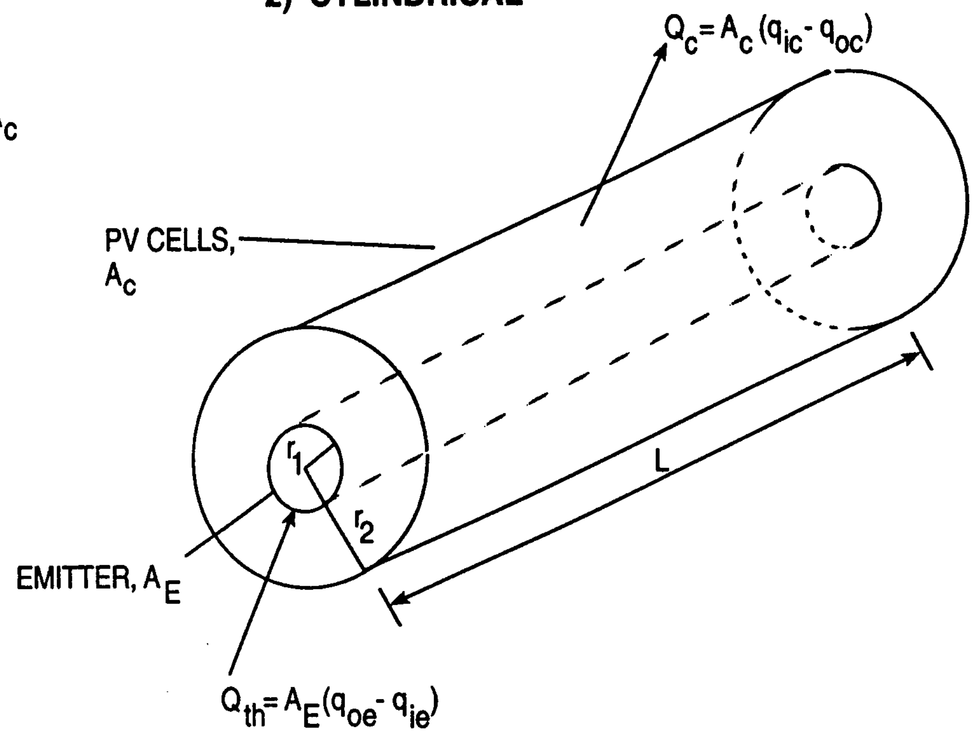
1) PLANAR



q_o = OUTGOING RADIATION FLUX, W/cm^2 μm

q_i = INCOMING RADIATION FLUX, W/cm^2 μm

2) CYLINDRICAL



THERMAL ENERGY INPUT TO EMITTER = $Q_{th} = A_E(q_{oE} - q_{iE})$

USEFUL RADIATION TO PV CELLS = $Q_c = A_c(q_{ic} - q_{oc})$

RADIATION LOSS = $Q_L = Q_{th} - Q_c$

500

National Aeronautics and
Space Administration

Lewis Research Center

RADIATION LOSS FOR PLANAR AND CYLINDRICAL TPV GEOMETRIES

POWER TECHNOLOGY DIVISION

ASSUMPTIONS:

1) UNIFORM q's
2) FILTER AND PV CELLS TOGETHER ($F_{fc} = F_{cf} = 1$)

IDEAL CASE FOR PHOTON ENERGY, $E \geq$ PV CELL BANDGAP ENERGY, E_g (FILTER TRANSMISSION = 1.)

$$\frac{Q_L}{A_E} = \varepsilon_E e_b (T_E, E) \left[1 - F_{EC}\right]$$ - APPLIES TO BOTH PLANAR AND CYLINDRICAL GEOMETRIES

IDEAL CASE FOR $E < E_q$ (FILTER REFLECTIVE = 1.0)

$$\frac{Q_L}{A_E} = \varepsilon_E e_b (T_E, E) \frac{1 - F_{EC} F_{CE}}{1 - (1 - \varepsilon_E) F_{EC} F_{CE}}$$ - PLANAR

$$\frac{Q_L}{A_E} = \varepsilon_E e_b (T_E, E) \frac{1 - F_{EC} F_{CE} - F_{CC}}{1 - (1 - \varepsilon_E) F_{EC} F_{CE} - F_{CC}}$$ - CYLINDRICAL

ε_E = EMITTER SPECTRAL EMITTANCE

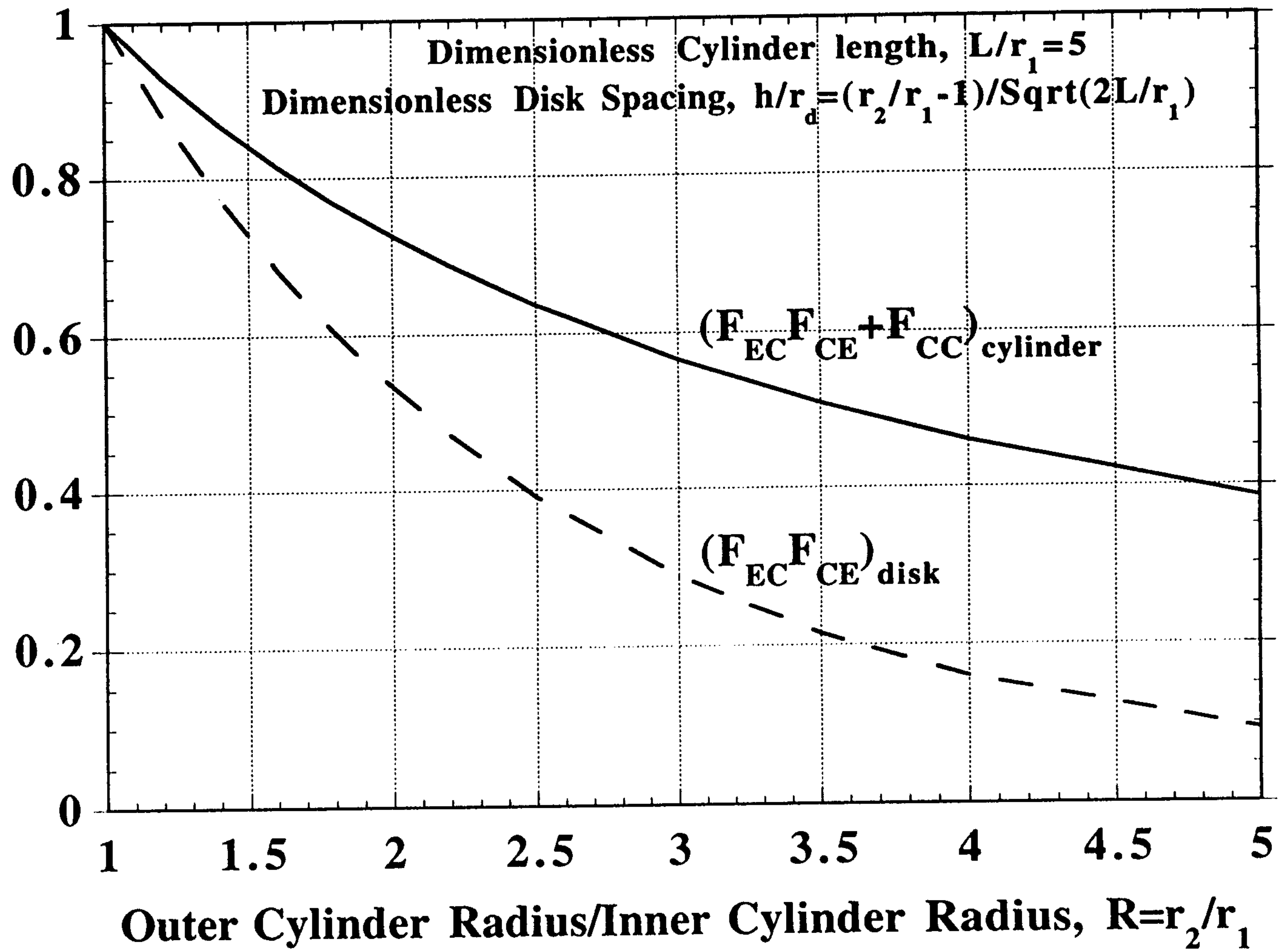
$e_b(T_E, E)$ = BLACK BODY EMISSIVE POWER FOR EMITTER TEMPERATURE, T_E

F_{EC} = EMITTER TO PV CELL VIEW FACTOR

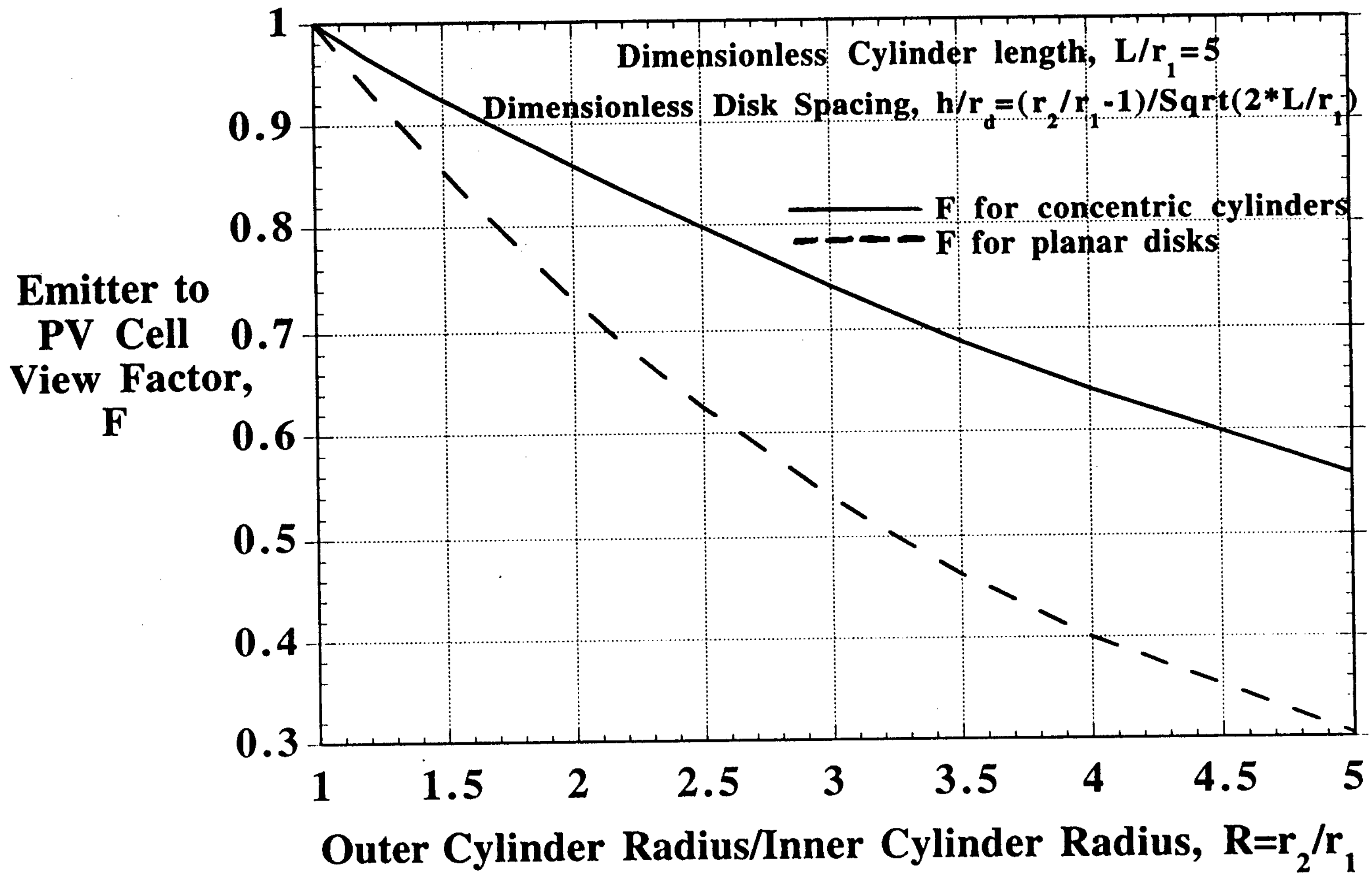
F_{CE} = PV CELL TO EMITTER VIEW FACTOR

F_{CC} = PV CELL SELF VIEW FACTOR

COMPARISON OF CYLINDRICAL AND PLANAR DISK TPV GEOMETRIES FOR EQUAL EMITTER AREAS AND EMITTER TO PV CELL SPACING



COMPARISON OF CYLINDRICAL AND PLANAR DISK TPV GEOMETRIES FOR EQUAL EMITTER AREAS AND EMITTER TO PV CELL SPACING



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CONCLUSIONS

POWER TECHNOLOGY DIVISION

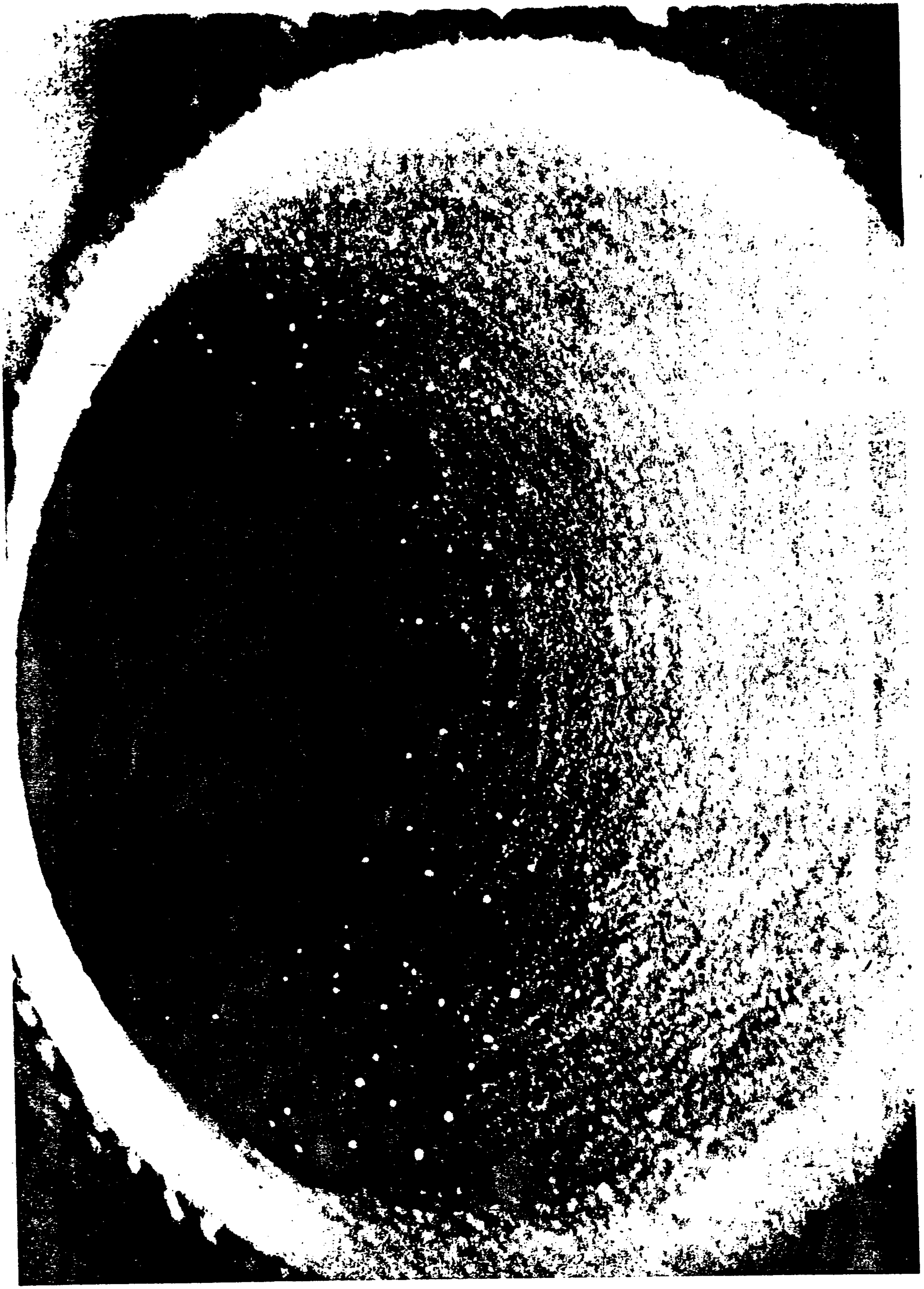
- IDEAL SELECTIVE EMITTER ($\varepsilon_E \rightarrow 0$ FOR $E < E_g$) REMOVES RADIATION LOSS DEPENDENCE ON VIEW FACTORS

- SPACING BETWEEN EMITTER AND PV CELLS MUST BE SMALL TO MINIMIZE RADIATION LOSS

  $\frac{h}{r_d} \leq .1$ FOR PLANAR DISKS TO YIELD $F_{EC} F_{CE} > .8$

  $\frac{r_2}{r_1} \leq 1.6, \frac{L}{r_1} > 5$ FOR CONCENTRIC CYLINDERS TO YIELD $F_{EC} F_{CE} + F_{CC} > .8$

- FOR MINIMUM RADIATION LOSS CYLINDRICAL GEOMETRY MORE ADVANTAGEOUS THAN PLANAR GEOMETRY



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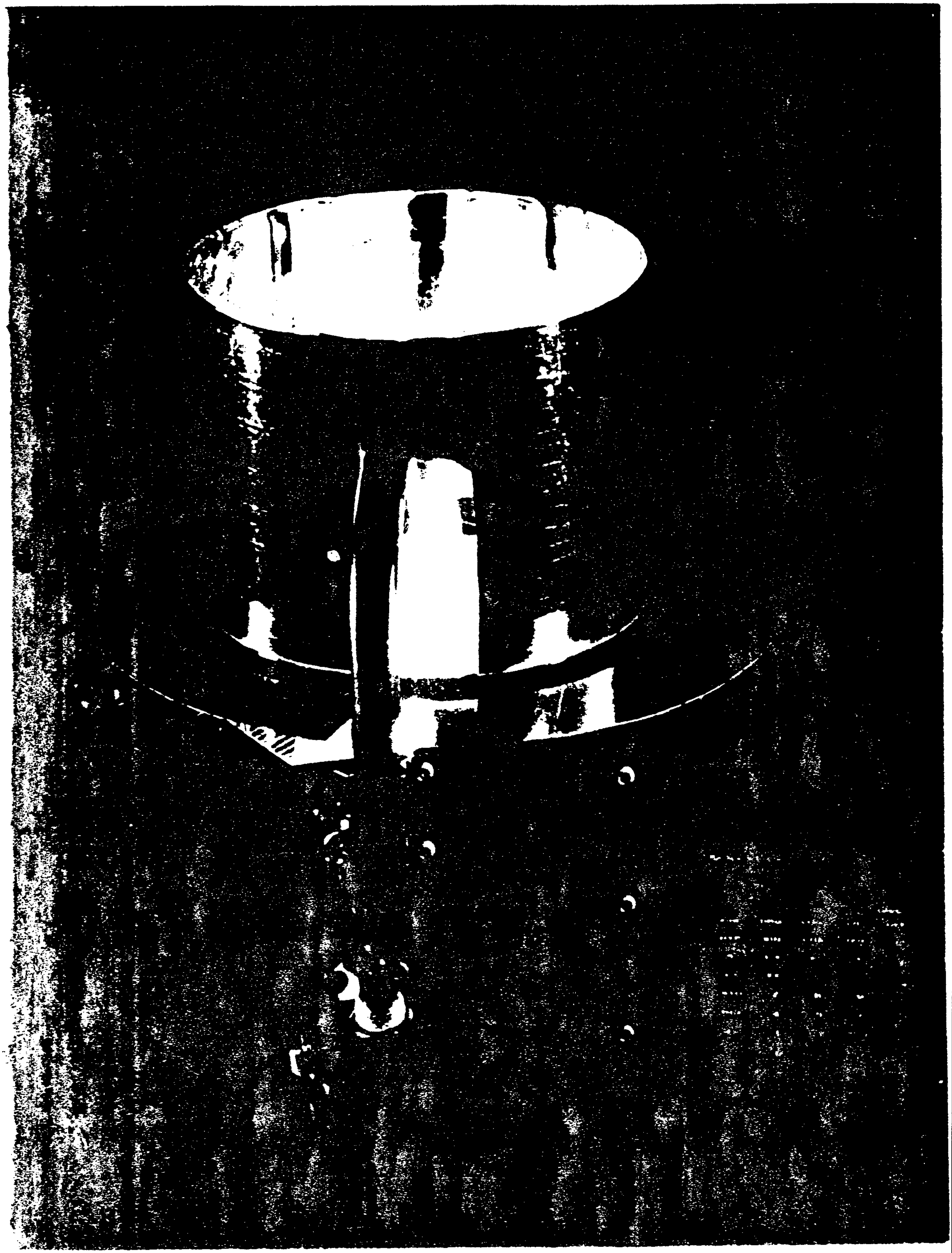
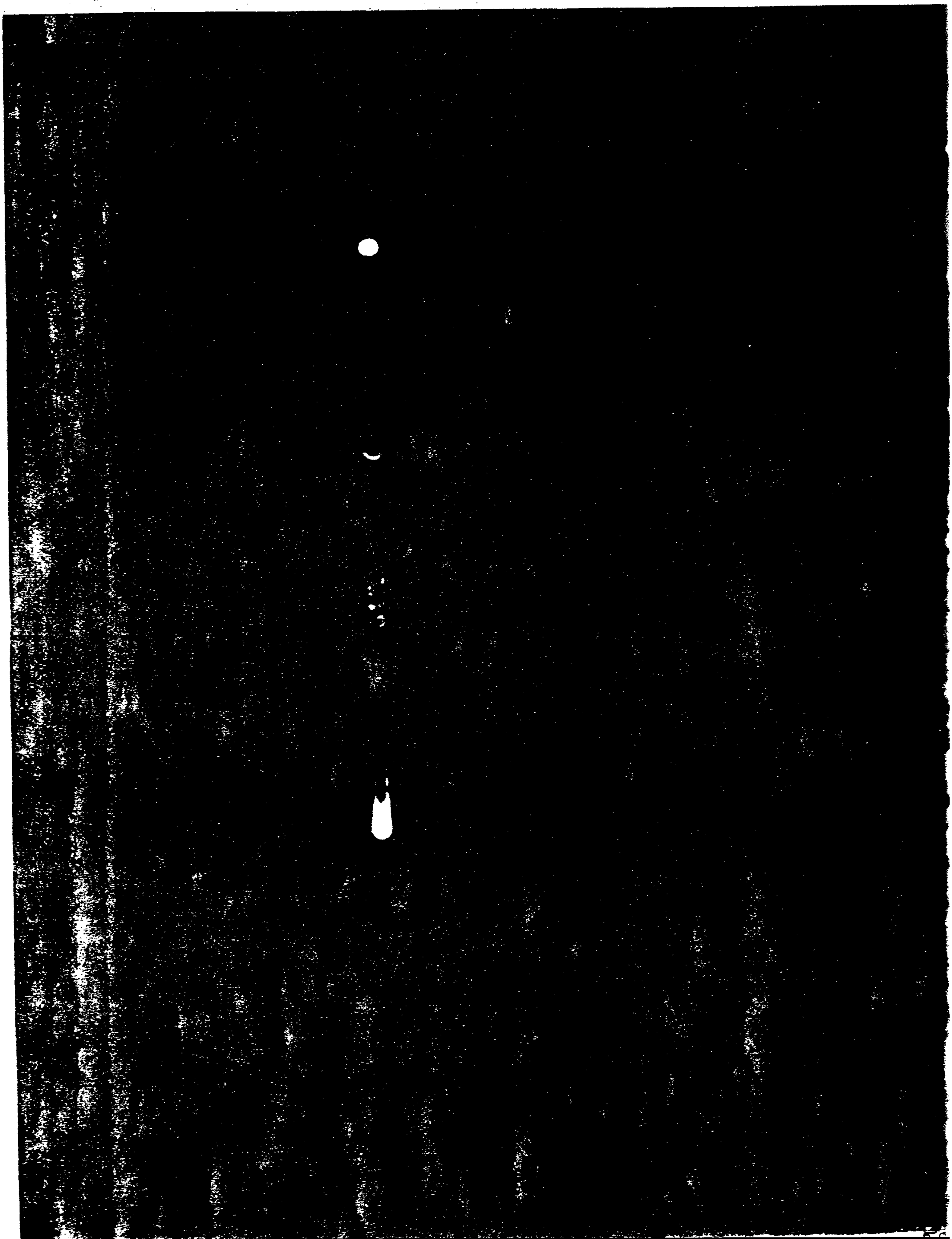
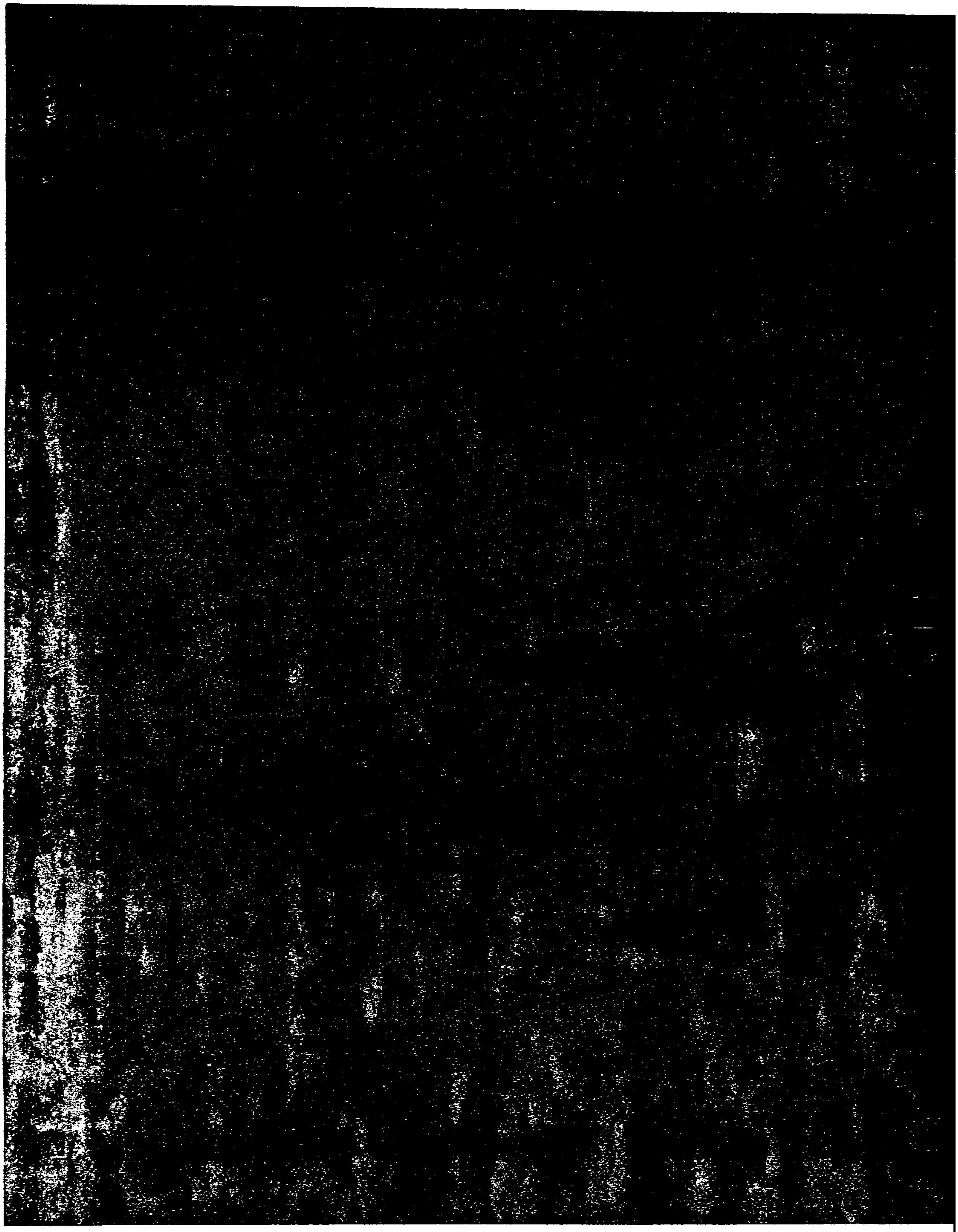
Quantum Group's Inward Firing Superemitting Ceramic Fiber Burners

Burner Type:	Powered Ceramic Fiber Burner, Inward Firing Design
Firing Capacity:	260,000 Btu/hr
Specific Fuel Input:	110,000 Btu/hr-ft^2 (based on burner surface area)
Materials:	Alumina Fibers coated with superemitters (Ytterbia, Holmia, Erbia, or Neodymia superemitters (narrow band emitters) are also available.







Space Power Institute

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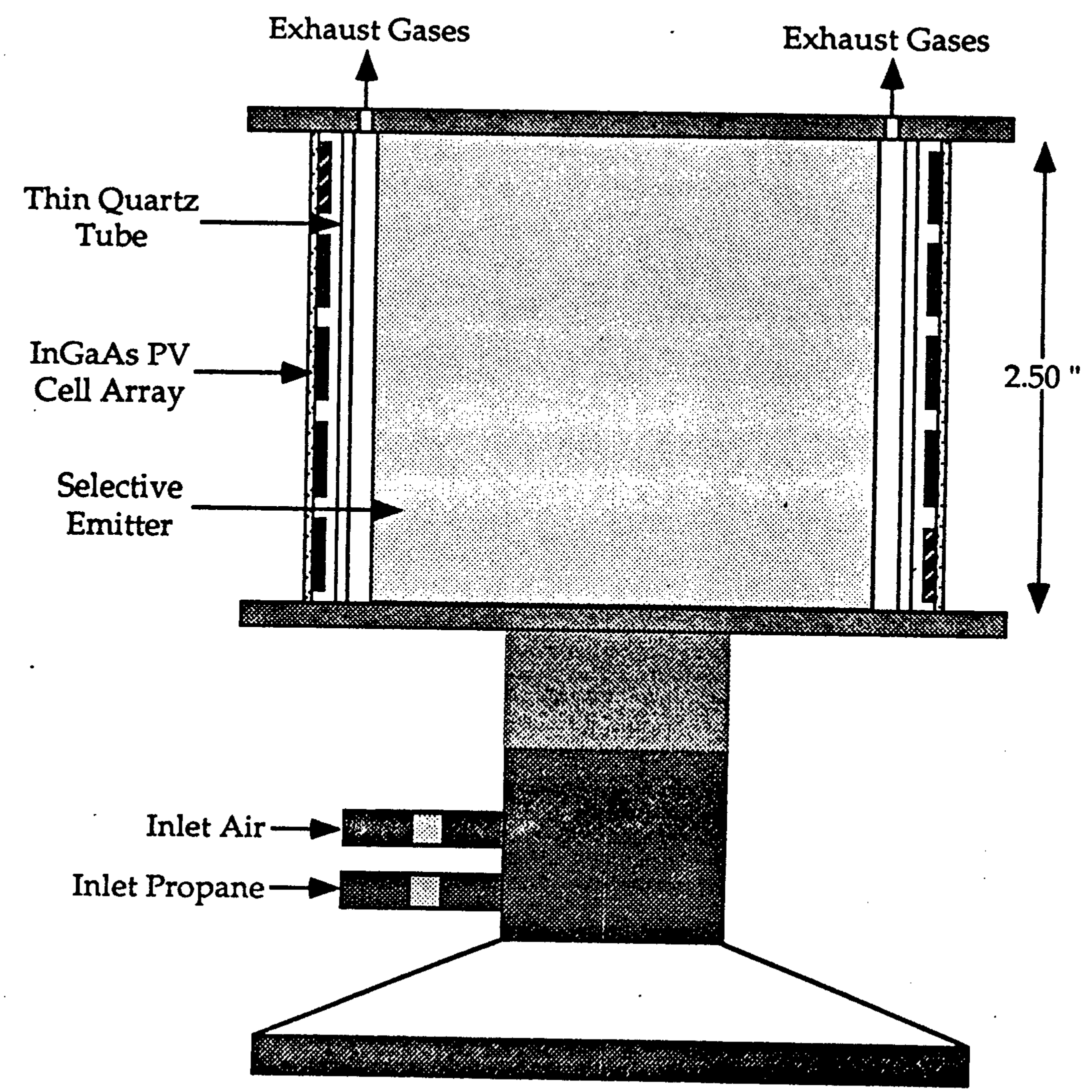
STATUS OF TPV RESEARCH AT SPACE POWER INSTITUTE

Space Power Institute is currently performing research on a thermophotovoltaic system to provide power to a soldier in the battlefield. The research is sponsored by the Army Research Office. The main issues that are being studied are emitter and burner issues. We are continuously looking to improve the strength of the composite emitters that were developed at Auburn University and quantify these improvements. We also have looked at how the emitter temperature affects the radiant output. We have defined our selective efficiency as the radiation centered between 1 and 2 μm in wavelength and determined that the efficiency of erbia increases with increasing temperature and reaches a plateau of around 29% after 1850K. Similarly, we looked at using erbia and thulia in the same composite emitter to increase the selective efficiency. We varied the ratio of the constituents and determined that as much as 42% selective efficiency can be attained. This particular emitter can be used to increase the photovoltaic cell electrical output power density while still maintaining a relatively high conversion efficiency. It should be noted however that only the radiation above the bandgap can be photoconverted. We have also investigated the radiant power to electrical power conversion efficiency of the composite emitters illuminating InGaAs photovoltaic cells. The cells were obtained under a cooperative agreement with NASA Lewis Research Center. We investigated three different cells with bandgaps of 0.75, 0.66, and 0.60 eV. We achieved a conversion efficiency of 16% with the 0.75 eV cell when illuminated by an erbia emitter. Conversion efficiencies of 8.4 and 5.7% were achieved with the 0.66 and 0.6 eV cells respectively, when illuminated by an erbia/thulia composite emitter.

Space Power is in the process of fabricating a prototype TPV system and developing a model for predicting TPV system performance. We investigated several different composite emitter geometries that could be used in the burner system for the TPV prototype. A cylindrical type system will be used to illuminate 100 cm^2 of lattice-matched 0.75 eV InGaAs photovoltaic cells. The photovoltaic cells were purchased from the Research Triangle Institute. The prototype will consist of a diffusion type burner with air and propane as the inlet fuels which will in turn heat a composite emitter. The radiant output of the composite emitter has to be uniform as both a function of height and azimuthal angle around the emitter. The emitter must also have a large radiating surface in a small volume. We found that a spoke shaped emitter satisfies these criteria.

TPV Prototype Power Generation Unit



Initial Form	Final Form
Structural materials: • Quartz fibers • Alumina fibers	Sinter-bonded structural fiber matrix
Precursor material: •Activated carbon fibers (1500m^2/g)	Rare earth oxide fibers mimicing the dimensions of the precursor material
Binder •Ashless cellulose	No binder material is present, however binder material amount controls porosity of final form

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QUANTUM GROUP INC.

DESCRIPTION OF QGI PHOTON ELECTRIC POWER (PEP™) GENERATORS

PEP™ - 10 We

Electric Power Supply for Military and Civilian Markets

- *Quiet*
- *No Moving Parts*
- *Low Maintenance*
- *PV Cooling System - Natural Draft/Forced Air Cooling*
- *Emitter - Ytterbia*
- *Outward Photon Collection System*
- *Combustion System - Atmospheric Type Burner*
- *Fuel - Natural Gas, Methane, Propane*
- *Power Output - From 2 to 10 We*

5/9/96

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QUANTUM GROUP INC.

SUPEREMITTER™ PRODUCTS

FELTS

Description:	Fiber mat made of discontinuous fibers of 7 - 10μm diameter and aspect ratio of ~30 to 1.
Composition:	Yb_2O_3
Dimension:	18 inch x 16 inch
Thickness:	1.4mm and 1 mm
Temperature limit:	~ 2400°C

COATINGS

Description:	Fast drying coatings for fabrication of selective emitters
Composition:	Single and mixed rare-earth oxides including Yb_2O_3, Er_2O_3, Ho_2O_3, Nd_2O_3
Solvents:	Flammable organic solvents
Oxide Content:	Approximately 1-10 weight % of oxides after organic pyrolysis
Temperature limit:	~ 2250-2400°C

ADHESIVES

Description:	Fast drying selective emitter adhesive to join selective emitter ceramics
Available Compositions:	Single and mixed rare-earth oxides including Yb_2O_3, Er_2O_3, Ho_2O_3, Nd_2O_3
Solvents:	Flammable organic solvents or water
Oxide Content:	Approximately 10-20 weight % of oxides after pyrolysis
Temperature limit:	~ 2250-2400°C

MANTLES

Description:	Selective emitter mantles that give off specific emissive wavelengths in incandescence
Compositions:	Single and mixed rare-earth oxides including Yb_2O_3, Er_2O_3, Ho_2O_3, Nd_2O_3
Characteristics:	Easy and fast forming of superemitter structure
Temperature limit:	~ 2250-2400°C

FOAMS

Description:	Open-cell ceramic foams
Composition:	Yb_2O_3
Temperature limit:	~ 2400°C

5/9/96

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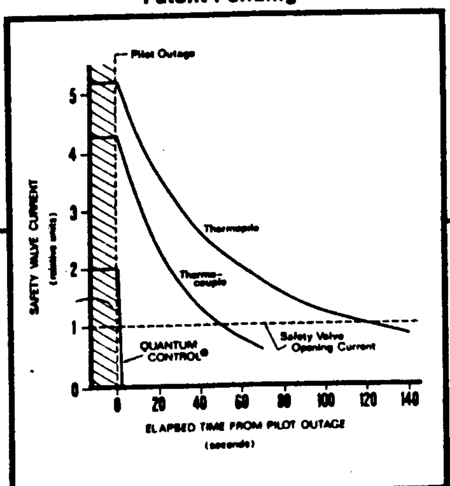
Specifications

The design of Models QC11 - (N, MF, MX, L, LA) are certified by the American Gas Association Laboratories.

Electrical:	Self powered. Will operate with standard 10 or 22 ohm latching magnet.
Pilot:	Special emissive pilot.
Ignition System:	Heated element, spark or manual ignition.
Valve:	Any standard valve with appropriate latching magnet.
Fuel gas:	Natural gas, liquified petroleum gas, manufactured gas, mixed gas, and LP gas-air mixtures.
Ambient Temperature Range:	- 20 degrees F to 125 degrees F.

Patent Pending



Quantum Control® response time compared to typical response of other self-powered systems. The Quantum Control® is 50 to 100 times faster.

QUANTUM GROUP INC.

11211 Sorrento Valley Rd., Suite D
San Diego, CA 92121
(619) 457-3048

O.E.M. inquiries invited.

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QUANTUM GROUP INC.

11211 Sorrento Valley Rd., Suite D
San Diego, CA 92121

Quantum Control®

Totally
new concept:
Today's low cost
answer
for
superfast
gas safety shutoff!

Quantum Control® The Low Cost, Superfast, Gas Shutoff System

The story is familiar. The pilot light goes out and gas begins to escape. Suddenly, explosion and fire become real threats.

The best solution? A fast, reliable safety shutoff system.

Now, Superfast Shutoff with Quantum Control®

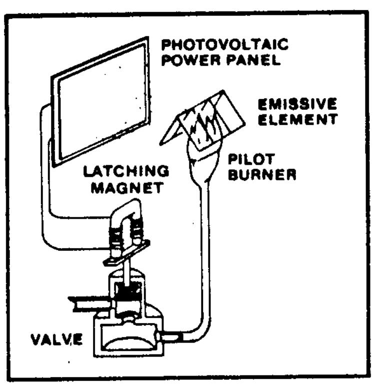
Quantum Control® delivers virtually instant, reliable gas shutoff! How fast? In less time than you can snap your fingers.

Quantum Control® has been clocked. On pilot outage, Quantum Control® shuts down gas flow in about one second. This is more than 50 to 100 times faster than other self-powered systems in use today!

Think what this means to you in terms of increased safety and reduced liability!

Quantum Control® The New Choice

Until now, your options in pilot safety systems were limited—fast response meant high cost, low cost meant accepting slow response. Today, the Quantum Control® gives you a new choice—a fast safety shutoff system at low cost!



The Quantum Control® system consists of an emissive screen, pilot burner, and photovoltaic power panel which connects to a standard gas control valve. The pilot flame heats the emissive screen which, in turn, radiates light energy to the photovoltaic elements. The photovoltaic elements convert the radiation to electricity which holds open the electromagnetic safety valve. Pilot outage quickly cools the screen, shutting down the appliance.

Self-Powered and Fail-Safe

No outside power is required—Quantum Control® is powered by the flame! No flame—no power to hold the gas valve open. It's that simple. It's fail-safe. Quantum Control® gives you the protection you want.

Extremely Reliable

Reliable Design:

The Quantum Control® System has no moving parts. The power produced by the Quantum Control® power panel holds open the gas safety shutoff valve. The instant the pilot flame goes out the flow of electricity stops and the electromagnet lets go. A spring snaps the valve closed. The Quantum Control® power panel and special pilot burner require no complex electronic circuitry. This simplicity gives reliability you can count on.

Reliable Construction:

Quantum Control® is reliable because it's so simple. With no moving parts, breakdown is virtually nonexistent. And if any service does become necessary, a trained service man can do the job in minutes using ordinary tools.

Highly Adaptable

Quantum Control® can be easily adapted to virtually any gas appliance. Our customer service representatives and engineers can assist with your customization needs.

Experienced Customer Service Staff

Customer services include consultation, development, custom design, and modifications for both your application and/or hardware requirements. Depending on your need, customer services are performed by our staff of experienced engineers, technicians, and system designers.

Lowest Cost

The Quantum Control® is so simple in design and so basic in construction that it's very inexpensive—inexpensive to install, inexpensive to use, inexpensive to maintain, and inexpensive to buy. It's the lowest costing fast shutoff system on the market today. When compared with the price of competitive safety shutoff systems, the Quantum Control® yields both tremendous safety and savings.

Quantum Control is manufactured and distributed by:
QUANTUM GROUP INC
11211 Sorrento Valley Rd., Suite D
San Diego, CA 92121
(619) 457-3048

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WORKING GROUP PRESENTATIONS

WORKING GROUP 1
PRESENTATION

GROUP 1

Customer Requirements, Specific MIssion Needs, State of the Art

Membership

* Henry Brandhorst, (AU) Chair
** Peter Adair, (AU) Recorder
Guido Guazzoni, US Army
John Szentes, Caterpillar
Ed Horne, EDTEK
Al Schock, Orbital Sciences
Al Newhouse, Newhouse Consulting
Malachy McAlonan, Teledyne-Brown

Linda Garverick, Essential Research
Harvey Serreze, Spire Corp.
Steve Flammang, Tecstar, Inc.
G. H. B. Schaffer, Quantum Group
Don Hindman, Babcock and Wilcox
Norbert Elsner, High Z Tech.
Jack Kruger, ARO

ARMY* REQUIREMENTS

- Battery Charger Station (300-500W)
  - » Less than $1000
  - » 5-10 batteries at same time
  - » Small unit which will be on the front line
  - » Unit using liquid fuel or gaseous fuel
  - » 10-15 lbs. in weight

*Navy, Marines, Air Force

ARMY REQUIREMENTS

- Unit which uses PV array for solar during day and TPV at night
  - » 20-30 Watts
  - » Replace hand-cranked generator
  - » Cell responsive to solar
- Replace 5590 battery
  - » 10% efficient
  - » Supply 5 W continuous / 50 W peak

ARMY REQUIREMENTS

- 5590 Battery cont.
  - » Can be immersed in water w/ rechargeable battery
  - » 5590 costs $56, would pay $250 for TPV
  - » Fuel cell and TE are main competition
- Shower/Laundry equipment (Cogeneration)
- Radiant heating

ARMY REQUIREMENTS

- "Soldier of the next century"
  - » Man portable
  - » Low IR
- APU's
- UPS

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CUSTOMERS FOR TPV

- Yachts/Sailboats/Motor Boats (50kW)
- Recreational Vehicles
- Commercial Trucking
- Small Motors
  - » Lawnmowers (2kW)
  - » Snowmobiles (10kW)
- DOD

ATTRIBUTES OF TPV

- Simple Design
- Low Noise/Vibration
- Potentially capable of using wider range o fuels (use of logistic fuels)
- Repair/Replacement Simple
- Turnkey Operation
- Potential Low Maintenance
- Dormancy Tolerance

ATTRIBUTES OF TPV

- Dual Use (Cogeneration)
- Power Leveling
- Portability
- Specific Power
- Thermal Signature
- Safety (Hydrogen, Lithium Batteries)
- Low EMI (DC Directly)
- EPA

MARKETABLE TPV ITEMS

- Recuperators
- Burners
- Filters
- Cells
- Electric Power Control
- Emitters
- Fuel Atomization

DESIGN ISSUES

- Deaerated Water
- Ignition System
- Emitter Strength/Lifetime
- Cell Heating/Lifetime
- Fogging
- MILSPEC Tolerance
- Liquid Fuels
- Nonuniform Heating

COMPETING TECHNOLOGIES
TEG

- ADVANTAGES
  - » Higher efficiency
  - » Higher power density
- DISADVANTAGES
  - » Reliability
  - » Lower maturity
  - » Higher operating temperature
  - » Higher cost

COMPETING TECHNOLOGIES
FUEL CELL

- ADVANTAGES
  - » Direct use of logistic fuels
  - » Potential multi-fuel
  - » Reformer for fuel cell
  - » Simplicity
  - » Safer than hydrogen
  - » Exploit waste heat
  - » Turn down capability
- DISADVANTAGES
  - » Lower efficiency
  - » Thermal signature
  - » Less mature

COMPETING TECHNOLOGIES SOLAR PV/BATTERIES

- ADVANTAGES
  - More efficienct (but solar is free)
  - Lower weight
  - Continuous (No cycling)
- DISADVANTAGES
  - Fuel needed
  - Less mature

COMPETING TECHNOLOGIES STIRLING

- ADVANTAGES
  - » No vibration
  - » Higher power density?
  - » Potentially more reliable
  - » DC vs. AC?
- DISADVANTAGES
  - » Less mature
  - » Perhaps more costly
  - » Less scaleable

COMPETING TECHNOLOGIES
MOTOR/GENERATOR

- ADVANTAGES
  - » No vibration
  - » Longer maintenance interval
  - » Small portable size (<1kW)
- DISADVANTAGES
  - » More expensive
  - » Less mature

COMPETING TECHNOLOGIES BATTERIES

- ADVANTAGES
  - » Longer life
  - » Potentially higher power density
  - » More safely acceptable
  - » Cold climates?
  - » Wide turndown
- DISADVANTAGES
  - » Less mature
  - » Thermal signature
  - » More costly
  - » Batteries widely available

COMPETING TECHNOLOGIES SMALL TURBINES

- ADVANTAGES
  - » No moving parts
  - » No noise (signature)
- DISADVANTAGES
  - » TPV's MAIN COMPETITION

TPV VALIDATION

- BUILD DEMOS
  - » 500 to 2 kW (Complete system)
  - » Cogeneration
- Consortia for demos (system driven)
  - » NICE^3
- Demonstrate efficiency

TPV CONCERN

- CONCERN - TPV community has many disparate entrepreneurs/organizations
  - » Separation promotes weakness and lack of focus
  - » No demos
- APPROACH - Offer substantial funds ($10M) to validate consortia to deliver a DOD acceptable product within 4 yrs.

COST GOALS

- TPV cost goal 35 cents/W
- HONDA generator
  - » 2 kW @ $1500 = 75 cents/W
  - » 5 kW @ $1000 = 20 cents/W

COST OF TPV*

- Cells+
- Emitters
- Filters
- Recuperators

*In order of cost

+Will entrepreneurs invest in all of the cell options or will 1 cell type "win out"?

SUMMARY

- System level demonstrations necessary
  - 500 -2000 W electric power output
  - Many possible applications at these levels (civil and DOD)
  - Consortium approach proposed
- Limiting factors and technology choices not clear
- Elements of TPV systems may be separately marketable
- Comparisons against competing technologies allowed cost goals and clarification of TPV attributes
- Markets not limited to U.S.

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Requirements – What applications, what priority?

- Carried by individual soldier.
- Need model of soldier
- Need to understand what is the best size to develop.
- Soldier input: physiology, capacity, signature, etc.

Specific Requirements

- Package specs for mission
  - Energy
    - 100 Whr/kg (beat a battery)
  - Power
    - 20 W/kg
  - Weight
  - Time
  - Environment (Mil Spec)
- Primary TPV converter specs
  - Power density
  - Efficiency
  - Cost
- Logistic specs
  - Type of fuel
  - Weight to be replenished

Specific Requirements (Continued)

- Convenience of operation
  - Startup issues. Flip a switch.
  - Operational issues
  - Heat rejection: comfort. Especially on man-portable.
  - Air required
  - Thermal signature
  - Modular structure, repairability.
- Ruggedization

System

- Packaging and geometry
- Systems Models
  - Geometry
    - Uniformity of emitter temperature
    - Flow paths for fuel and air
    - Radiation paths
      - End effects in cavity
      - Reflectors in cavity
  - Weight
  - Power density
  - Thermal integration
  - Fidelity
  - Tradeoffs of power density vs efficiency, etc.
  - Temperature limits on materials

System (Continued)

- Matching of cell, filter and emitter
  - More energy in PV band.
- Materials
  - Materials compatibility
  - Thermal cycling.
- Radioisotope sources are an issue of perception of safety.
- Component research issues are not enablers. (not total consensus)
- Scaling laws
- Controls

Burner

- Fuel versatility, multi-fuel
- Fuel injector
  - Liquid fuel: atomization, especially diesel fuel
  - Low power and low fuel flows
  - Throttleability
- Recuperator
  - High temperature operation
- Coupling to emitter
  - Uniformity of irradiance on cells
- Orientation independence
- Difficult to model, intuitive
- Startup
  - Cold environment
  - Ignition system

Photovoltaic

- Cell cost
  - Materials (not exotic)
  - Processing
  - Volume, cost models
- Cooling system
- Coatings - For protection and spectral control
- Spectral control within cell
- Manufacturing technology
- Tolerance to nonuniformities
- Interconnections
  - Integrated
  - Avoid arcing
- Fault tolerance
- Multiple designs
  - Need standard designs
  - CAD/CAM systems

Filter

- Diffractive
- Cooling
- Performance: losses, efficiency, sharp cutoff
- Cost
- Thermal sensitivity
- Integration with PV Cell

Emitter

- Affect of high temperature on materials
  - Change in grain size
  - Wear and replacement of emitters.
  - Vapor pressure
- Multi-emitter
- Support structure
- Attachment at end

Research community

- Need to know application
- Not enough experience building systems.
- Need for collaboration
- Standards for evaluating TPV components. Difficult to do because of coupling of components and many system choices.
  - Standards for black body (temperature as parameter)
  - Standards for selective emitters (wavelength as parameter)
- Need to standardize terminology. For example, understanding of combustion efficiency terminology.
- Lack of funds

Limiting factors and constraints

- Funding
- Temperature (vapor pressure)
- Cost
- Efficiency of cells
  - Within 70% of theoretical for GaSb
  - Less certain for InGaAs and others
- Efficiency of photon collection from emitter to PV cell
- Recuperator
- Contamination of optical surfaces
- Spectral control

Attributes of TPV

- Quiet
- Intrinsically light weight
- Capable of using logistic fuel directly
- Multifuel capable
- No moving parts in main power stream.
- Cogeneration compatible.
  - Convenient for incidental electric generation on heating systems
- Tolerates low temperatures better than fuel cells.
- High temperature (negative)
- Moderate efficiency (good at this size on logistic fuel)

Integrated Systems (Highest priority)

- Different Sizes
  - 5-10 watts
  - 150 watts
  - 500 watts
- Different Fuels
- Different Approaches

7/25/96

Components (Lower priority)

- Diesel burner and recuperator in assembly with emitter. (Thermal cavity)
- Recuperator (debatable as a research issue)
- Optical cavity
  - Photocell
    - Better cooling
  - Filter
  - Emitter

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Commercial versus military

- Military has more choices (cost)
- Military has more demands (environment)

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WORKING GROUP 3
PRESENTATION

Prospector VIII

TPV - Update on DoD, Academic, & Commercial Research

Durham, North Carolina
July 14-17, 1996

Working Group 3

- Dennis Flood (NASA Lewis), Chairman
- Cal Johnson (Auburn Univ), Recorder

- Tim Coutts (NREL)
- Dan Krommenhoek (Lockheed Martin)
- Bill Berry (Notre Dame)
- Frank Vicente (Lockheed Martin)
- Eric Barringer (Babcock & Wilcox)
- James Avery (JX Crystals)
- Phillip Jenkins (Essential Research)
- Edward West (Western Washington U)
- Dick Paur (ARO)
- Eric Clark (NASA Lewis)
- Bill Biter (Sensortex)
- Fred Becker (Thermopower)
- David Wilt (NASA Lewis)
- Mark Goldstein (Quantum Group)
- Zheng Chen (Auburn Univ)

Introduction

- Set requirements
- Why TPV?
- Limitations
    - Army Priorities
    - Breakthroughs
    - Commercial Markets
        - Strategy
        - Near-term Issues
        - Long-term Issues
            - Recommendations
            - Timeframe
            - Surge Capability
                - Summary

Requirements

- For BA5590 replacement, TPV must be capable of the following:
  - Instant "recharge" (i.e. refueling)
  - Fully integrated unit
  - 50 Watt peak
  - Low thermal signature
  - Use in closed spaces
  - Operational capability (water tight)
  - $<$ 5 W "continuous"
  - Use in $>$ 100 different devices
    - Transmit: 35 W (20% of time)
    - Receive: 3 W (80% of time)
  - "Outer skin" temp $<$ 120 F
  - Load Leveling

What is attractive about TPV?

- High energy density compared to batteries (wrt BA5590)
- "Infinite" shelf life (wrt BA5590)
- Multi-fuel capability (possibly)
- "Simple" system (reliable, robust)
- Modular in construction
- Environmentally benign
- TPV life-cycle cost
  - Compared to batteries, in general, life-cycle cost is low
- High efficiency not required to compete w/batteries
- Low noise

Limitations

- No long-term experience/installed capacity
- Load management
- Component vender infrastructure lacking
- Peak efficiency lower than conventional generator sets
- Start-up response
- Thermal fatigue and/or creep of ceramics

Army Need (Priorities)

- BA5590 replacement (300,000 units/yr needed)
- Portable generator sets (5,000 units/yr needed) @ up to 500 W
- APUs (10 KW or less) (1,000 units/yr needed)
- Multi-KW gensets (100 or more KW desired) (1,000 units/yr)

<u>Bottom Line</u>: TPV community would be happiest with development of portable generator sets and APUs

- BA5590 is a very difficult technical problem
- BA5590 requires a unique solution
- Portable gensets represent more attractive path
- Portable generators offer greater spin-off potential

Break-throughs Required

- No tech breakthroughs required for system demonstration

Commercial Markets

- Batteries: 20 billion primary batteries sold world-wide per year (Eveready sells only 30% of those)
- Recreation Vehicle: Large, lucrative market. Is there a military parallel to this market?
- Marine market may be larger than RV market for TPV
- Portable generators: Large market, but cost-driven
- Bottom Line: Commercial market should become more viable as technology matures and manufacturing base is established for Army applications

Strategy

- Need a near-term "success," whether military or commercial
- Use the Army's priorities to identify target application
  - Focus on portable generator sets (up to 500 W)
- Meet the Army's declared policies on primary portable power sources/generators
- Optimize mass, life-cycle cost, and efficiency of the TPV system to meet/exceed requirement for selected military application
- Efficiency: Issue is the way that efficiency is measured, whether at peak power, average operating conditions, etc.
- Consider leveraging Army investment with funds from other branches

Near-Term Issues

Definition: Engineering to make a working system (technology demo)

- System design/modeling
- Spectral control
- Cavity design
- Emissive system
- Combustion (liquid fuel)
- Thermal management

Questions: Can we freeze the design? Should we compete designs?

Army should set requirements (already in DARPA BAA)

Bottom Line: Fund system demonstrations

Long-term Issues

Definition: Cost-effective product to meet customer requirements

- Thermal management
- Cost
- Lifetime
- Packaging (weight, size, robustness, durability, etc)
- User interface
-
-

Questions To Be Addressed

- Should we freeze a design, a set of designs?
    - Fund a "technology demonstration" at a system level or an engineering protoype level
    - Specify specific target: 150 W or 500 W
    - Multiple sets of competing subsystems
- Should we compete designs? Probably "yes, 3 or 4 of them."
- There is enough tech out there to draw together a couple (or three) systems)? How long will it take ? "Four years is not too long" - ARO.
- <u>Consensus</u>: Army should be prepared to fund system studies
- <u>Funding</u>: $10M to field engineering prototype (This figure was determined independently by two different companies, in a 3-4 year time-frame)

Recommendations

- Establish "Two-Phase" Program
  - Technology Demonstration
  - Preproduction (Engineering) Prototype
- Technology Demonstration to address near-term system issues
  - <u>Bottom Line</u>: $4-5 M/yr for 3 years is "optimum" program (yields 3-4 technology demonstration units)
  - <u>Affordable Program</u>: $2-3 M/yr for 3 years yields two systems (This is about 10% of the $22 M Army budget for BA5590's, which may be realistic)
- Engineering Prototype to address long-term issues to meet customer requirements
  - Army should define application and requirements
  - Require additional +/- 18-month period

Other Recommendations

- Establish a Consortium of DoD, industry, academic institutions
- Consider cost-sharing in engineering prototype phase
- Mechanism for information exchange
- Mechanism to pool resources
- Need to promulgate "same language" to discuss TPV technologies, data banks, etc
- Need to promote TPV to other organizations

Timeframe To Prototype Product

- Any Fuel System: 5 yrs maximum
- Gaseous Fuel System: 4 years maximum
  - 30-36 months to technology demo (at a cost of $15 M for 3 awards)
    - "Technology demo" w/specs of < 2 cubic ft, < 25 lbs
  - 15-24 months to "preproduction' device/phase ($10 M for 2 awards)
  - "Surge capability " can be done: 2X cost for a 1-year reduction (~ $50 M for a product in 4 years)

Summary

- Substantial discussion on BA5590 replacement: Concluded not near-term TPV application
- Substantial discussion of need for up to 500 W power source
  - Solution to BA5590 problem
  - Replacement for engine generator set
  - Represents a mission-enabling technology
  - Recommended < 500 W power source be developed through technology demonstration
  - Identified strategy, cost constraints, timeframes

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