Enhanced Semiconductor Carrier Generation Via Microscale Radiative Transfer; MPC - An Electric Power Finance Instrument Policy; Interrelated Innovations in Emerging Energy Technologies.

by
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Submitted to the Department of Electrical Engineering and Computer Science and the
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in Partial Fulfiliment of the Requirements for the Degrees of
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Abstract

This thesis is about a potential new energy technology MTPV and a related potential new energy policy MPC. MTPV is an electronic device concept for the conversion of heat or light to electricity using existing and emerging microelectronic technology. MPC is a financial instrument based energy policy which could both foster the emergence of new energy technologies such as MTPV and could also provide a framework for transitions between existing and emerging energy technologies including MTPV.

The MTPV (Microscale Thermophotovoltaic) device concept relies upon the hypothesized phenomenon of Enhanced Semiconductor Carrier Generation Via Microscale Thermal Radiative Transfer. Should this phenomenon exist, it would suggest the possible feasibility of MTPVs as a new class of electronic devices for solid state energy conversion and the possible feasibility of a larger new class of related devices based on more extensive utilization of microelectronic technology than is currently employed in solid state energy conversion. This thesis reviews each of the foregoing and proposes an experimental procedure to test the hypothesis of Enhanced Semiconductor Carrier Generation Via Microscale Thermal Radiative Transfer.

Innovation in energy technologies can arise from policy innovation as well as technological innovation. In energy, the two are often extensively intertwined. Such has been the case in the Electric Utility Industry as it has moved toward restructuring. MPC (Mortgage Backed Hybrid Power Purchase Contract) is a financial instrument based policy innovation which could aid in energy transitions such as the one occurring in Electric Power. It could also serve as a vehicle to facilitate the emergence of new technologies such as Photovoltaics, a broad field of which MTPV can be considered a part. This thesis formulates and reviews the MPC concept particularly in the context of Photovoltaics and the Electricity Sector; identifies MPC stakeholders and analyzes their interests; and reviews details of implementation to assess MPC policy feasibility.

To my wife Marianne,

our children John, Mary, Anne, and Stephen,

our parents,

and to my late best friend, my tenth grade teacher, Dr. James McLellan.

ACKNOWLEDGMENTS

My first thanks go to my Thesis Advisors and TPP Advisor Professor Clif Fonstad, Professor Ernest Cravalho, and Dr. Richard Tabors. Without the former two the MTPV device concept described herein would not have been developed and without Dr. Tabors the MPC instrument concept described herein would not have been developed. I hold enduring gratitude for the special roles each of them have played in this thesis and in my graduate education to date

Special thanks also goes to Prof. de Neufville and his staff, Francis Chin, Hugh Saussy, Mac Whale, Prof. Steve Senturia, Prof. David Turnbull, Dr. Gary Cheatham, Dr. Al Graff, Richard Pirelli, Libby Shaw, and the many others too numerous to mention who have helped in various ways. Partial financial support for Chapters 2,7,8 and 9 came from the U.S. Department of Energy for which I am grateful.

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NOMENCLATURE

A = unit, Angstrom = 10^-10 m
A = variable, Cross-sectional Area
A_c = lateral area of a flat plate capacitor
B = bandwidth (Hz)
C = Coulomb
c = speed of light in vacuum = 3*10^8 m/s
cm = centimeter, length
d_c = distance between two plates of a parallel plate capacitor
Eg = semiconductor energy gap
F = Farad
h = Planck's constant = 6.63*10^-34 J*s
J = Joule, energy
k = Boltzman's constant = 1.38*10^-23 joule/K
k_e = Boltzman's constant = 8.62*10^-5 eV/K
L = resistor length
m = meter, length
micron= 10^-6 m
mil = 10^-3 inch = 25.4 microns
n = electron carrier concentration (cm^-3)
ni = intrinsic carrier concentration (cm^-3)
nm = nanometer = 10^-9 m
p = hole carrier concentration (cm^-3)
Pf = photon flux (photons/sq.m/s)
q = electronic charge = 1.602*10^-19 C
R = Receiver Photoconductive Element resistance (ohms)
S = Microscale Spacing (gap) (meters, unless otherwise specified)
s = second, time

t(n) = carrier lifetime in seconds as a function of carrier concentration
Te = Temperature of Emitter (K)
Tr = Temperature of Receiver (K)
V = volt

ε_o = electrical permittivity of free space = 8.85*10^-5 F/m
λ = radiation wavelength (meters, unless otherwise specified)
μ_n = mobility, electron (sq.cm./Vs)
μ_p = mobility, hole (sq.cm./Vs)
ν = frequency (Hz)
ρ = resistivity (ohm-cm)
σ = conductivity (ohm-cm)^-1

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Chapter 1

Introduction

Can an electronic device be identified (designed, analyzed, and built) that could offer a new means for generating electricity by using the ability of modern microelectronic technology to order matter at the atomic level so as to order the "seething" [Fonstad, 94, p.17] electronic energy that exists at the atomic level, in order to convert it to useable energy? This is the Engineering question this thesis seeks to begin to answer.

Can a policy be identified (designed, analyzed, and implemented) that could promote the emergence of such new energy technologies while also serving as a means to buffer and stabilize existing energy technologies against the uncertainties posed by energy technology innovations? This is one of the primary Technology & Policy (T&P) questions this thesis begins to answer. The other primary T&P question is, "What are the relationships and interdependencies between the answers to the two foregoing questions?".

1.1 MTPV

Current microelectronic design and fabrication technology makes it possible to build structures and devices with dimensions smaller than the wavelengths of thermal radiation from sources exceeding 2000K. This may have important implications for non-isothermal electronic devices due to the very different behavior of thermal radiation at these length scales. Max Planck himself indicated that his now famous spectral density function for blackbody emission was subject to the constraint that the "the linear dimensions of all parts of space considered are large compared to the wavelengths of the rays considered". By moving beyond these dimensions substantially enhanced radiative heat transfer at sub wavelength spacings has been demonstrated experimentally by three groups and explained theoretically by three other groups.[ex. Cravalho 67]

The hypothesis of the current work is that this enhanced energy transfer would also promote band-gap crossings in an appropriately tuned semiconductor receiver thus increasing the carrier concentration in the semiconductor. If this is correct, then it appears likely that it would then be possible to utilize this enhanced carrier generation to create a new thermophotovoltaic device, proposed here, utilizing this microscale phenomenon, being called Microscale Thermophotovoltaics (MTPV). MTPV would use this enhanced microscale radiative coupling to create thermophotovoltaic devices with significantly increased power densities, potentially increased efficiencies, and potentially decreased costs.

1.2 MPC

Innovation in energy technologies can arise from policy innovation as well as technological innovation. In energy, the two are often extensively intertwined. Such has been the case in the Electric Utility Industry as it has moved toward restructuring. MPC (Mortgage Backed Hybrid Power Purchase Contract), proposed here, is a financial instrument based policy innovation which could aid in energy transitions such as the one occurring in Electric Power. It could also serve as a vehicle to facilitate the emergence of new technologies such as Photovoltaics, a broad field of which MTPV can be considered a part. Chapters 6-9 will formulate and review the MPC concept particularly in the context of Photovoltaics and the Electricity Sector; identify MPC stakeholders and analyze their interests; and review details of implementation to assess MPC policy feasibility.

1.3 MTPV and MPC

This thesis is about innovation in the Energy Sector. It is about an example of a potential innovation in Technology, MTPV, and an example of a potential innovation in Policy, MPC, and the relationship between the two.

If MTPV becomes an incremental improvement on Photovoltaics then MPC will serve it by facilitating the long amortization period, low interest rate finance that such high capital intensiveness technologies require. If MTPV were to lead to a significant breakthrough in energy technology then MPCs could be part of a Policy/Financial framework that could accommodate a more stable transition minimizing stranded asset losses. At the same time it is the very kind of disruptive technologies (as discussed in Chapter 6) that MTPV may exemplify, that may lead to the potential interest in MPCs in the Electricity Industry today.

As will be seen in the ensuing chapters, design is another common denominator between MTPV and MPC. Technology design in the MTPV experiment and Policy/Financial Design in the MPC instrument. It is the uncertainties and possibilities introduced by technological innovations that policy innovations must accommodate while at the same time facilitating them.

1.4 Overview of Chapters

Chapters 2 - 5 primarily focus on the Engineering issues of MTPV. While Chapters 6- 9 primarily focus on the Technology & Policy issues of MPCs particularly as they relate to Photovoltaics and the Electric Power Industry.

Accordingly, Chapter 2 very briefly reviews existing Thermophotovoltaic (TPV) technology which is the predecessor of MTPV. Chapter 3 then reviews Microscale Radiative Heat Transfer which constitutes the enhanced energy coupling in MTPV. Chapter 4 reviews and analyzes the MTPV concept itself. Chapter 5 then reviews an experimental design to test the hypothesis of Enhanced Semiconductor Carrier Generation Via Microscale Radiative Transfer which physical mechanism is the technical foundation for MTPV.

Chapter 6 assesses Photovoltaics as an Emerging Energy Technology. Photovoltaics are one of the technological contexts into which MTPV would fit. Fuel cells would be another but are not covered in this thesis. Photovoltaics also provide a prime example of the policy needs that MPCs may meet.

Chapter 7 reviews the need for MPC Policy in the Electric Power Industry which is itself the industry context into which grid connected Photovoltaics must fit. Chapter 8 then reviews the design of MPCs and Chapter 9 analyzes MPC stakeholders, their interests, and details of implementation. Chapter 10 provides brief conclusions.

CHAPTER 2

Thermophotovoltaics (TPV)

As a technology, and even more dramatically as an industry, Thermophotovoltaics (TPV) is in its infancy. The first working prototype, of which this author is aware, of a commercial TPV unit was successfully demonstrated in July of 1995. It is shown as Figure 2-1. Its maximum output is 82.7 watts. [Fraas, 95, p. 132] The first Conference in many years on TPV was the *The First NREL Conference on Thermophotovoltaic Generation of Electricity*, which was held in the summer of 1994. *The Second NREL Conference on Thermophotovoltaic Generation of Electricity* was held one year later in July 1995. The list of papers included in the proceedings from each of these conferences, shown as Figure 2-2 provides a most efficient overview of the work being done in the field.

While there is excellent work being done in the field Figure 2-2 shows the nascent nature of most of this work. Neither in these conferences nor in any other literature found to date does it seem that any work has been done to address the utilization of Microscale Radiative Transfer as a means for increasing the performance of TPVs. All work appears to be based on Planck's Law, as it should be when the radiating (higher temperature) surface ("the Emitter") is at macroscopic distances from the lower temperature photovoltaic cell receiving its energy.

As context for Microscale Thermophotovoltaics (MTPV) which is the subject of Chapters 3 - 5, this chapter will give a short overview of TPV by selecting an example of work being done in each component area.

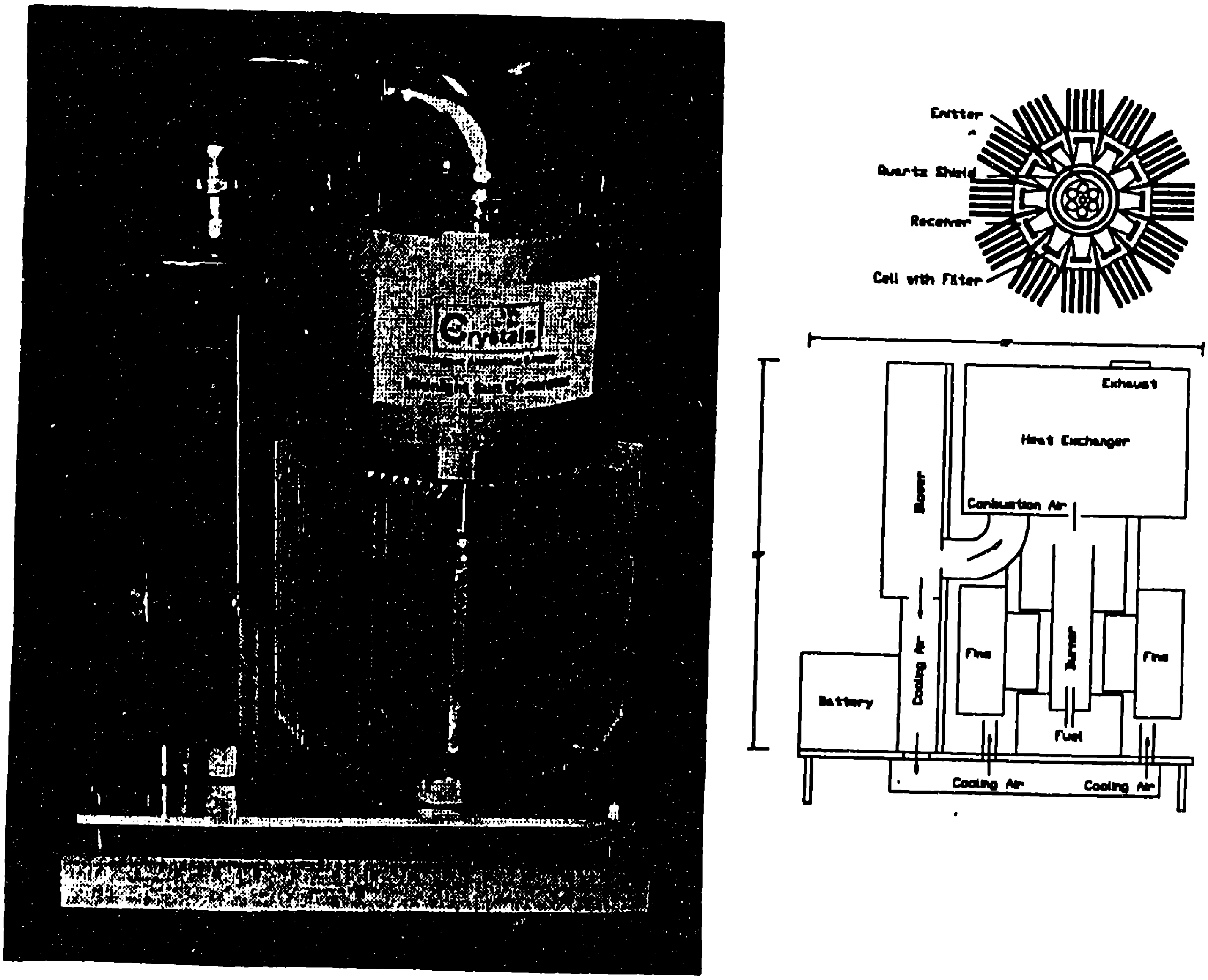

Figure 2-1 Prototype TPV Generator: Photograph and Schematic
(Source: Fraas, 96, pp. 133, 129 respectively)

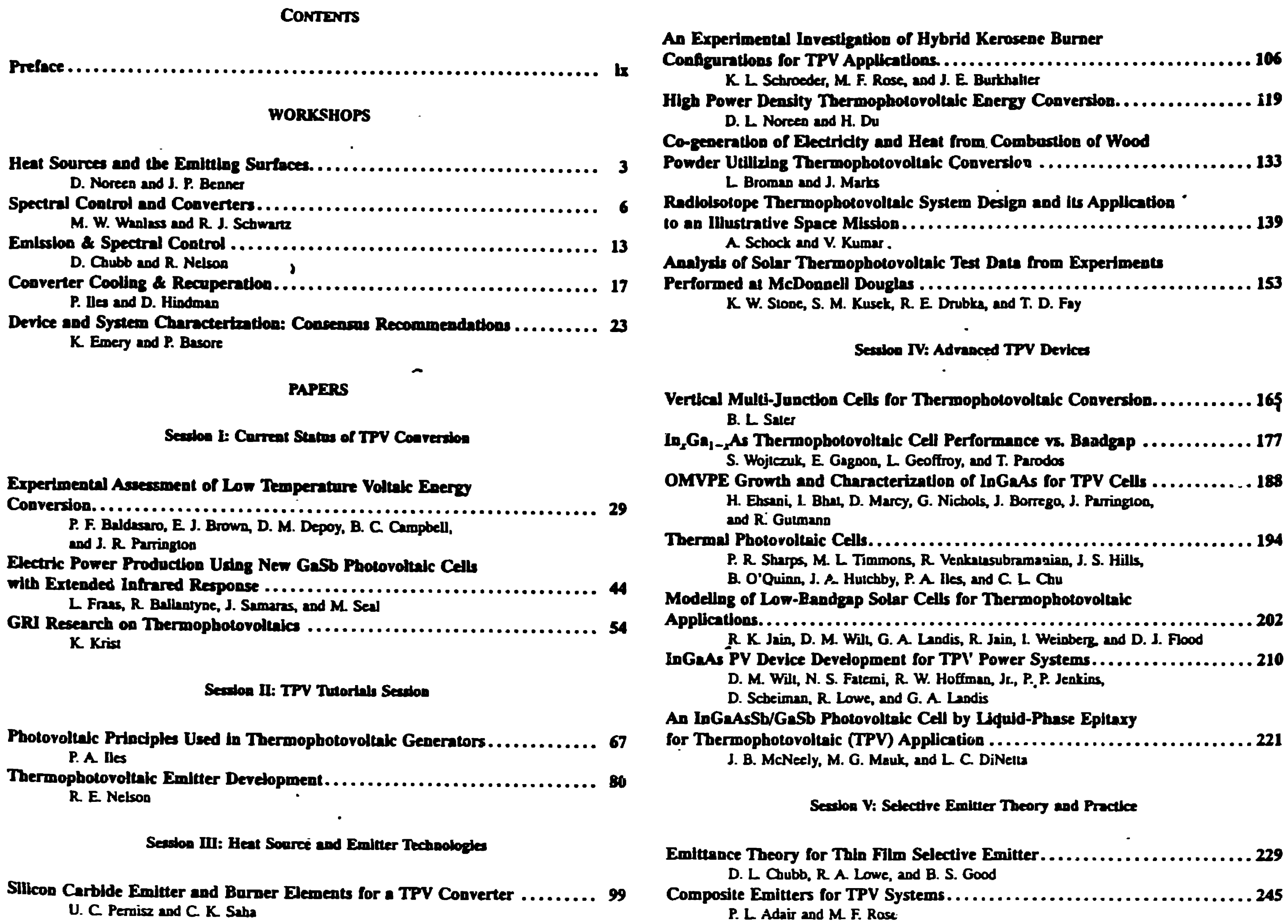

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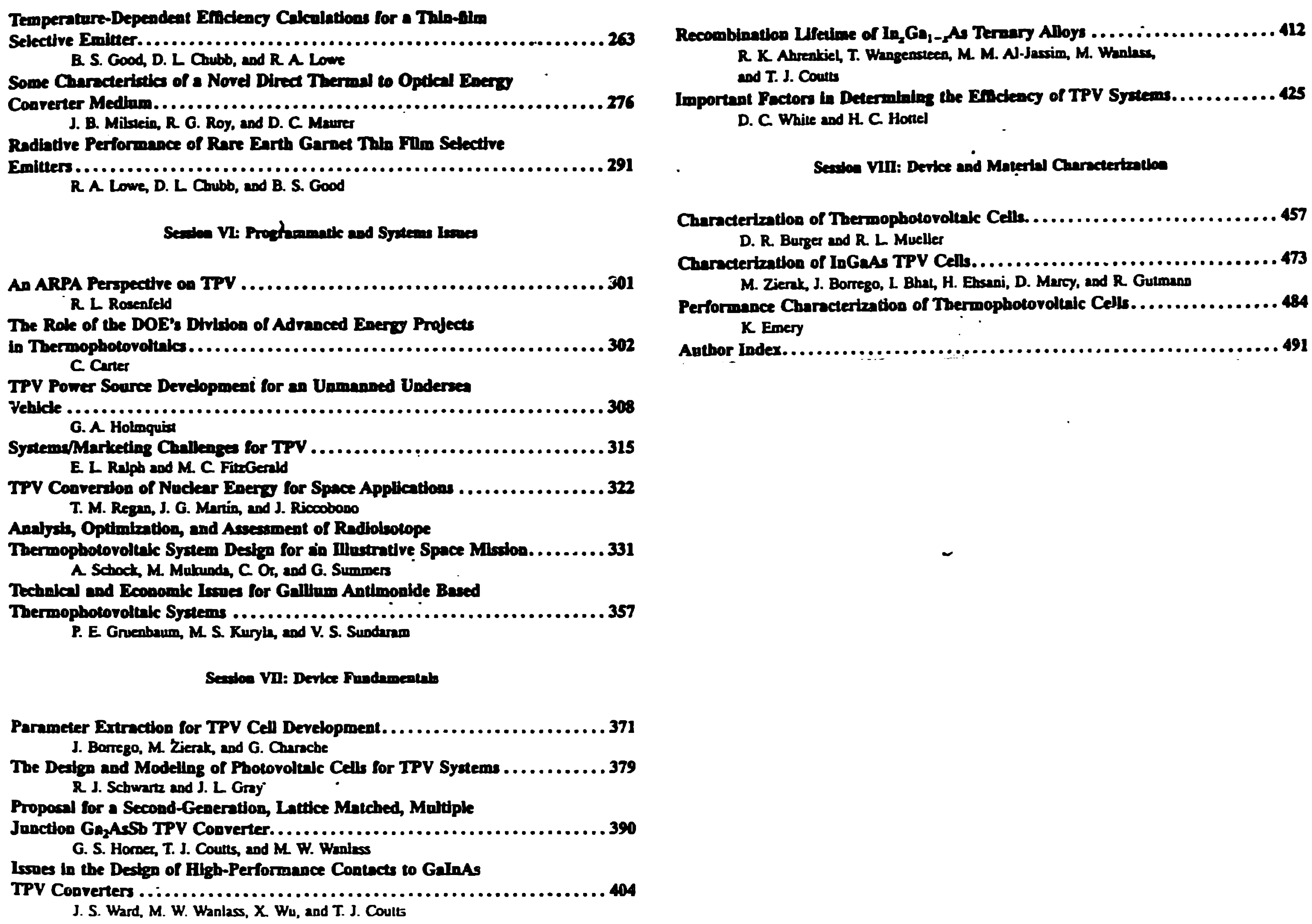
Figure 2-2 **Papers from First and Second (1994, 1995) NREL TPV Conferences**

1994 Conference (Source: Coutts & Benner, eds., 95, pp.v+vi)



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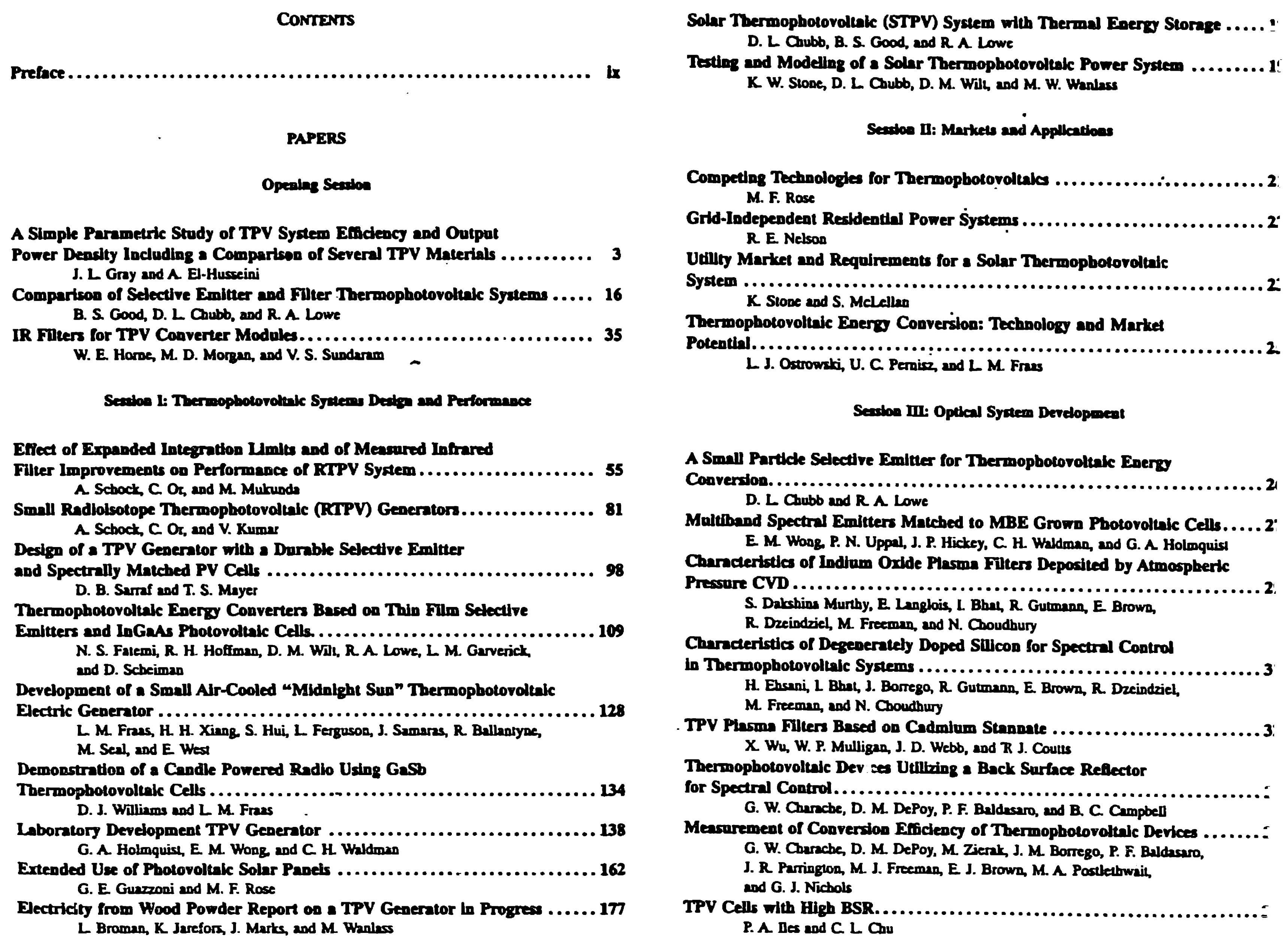
Session VIII: Device and Material Characterization

Fig.2-2(cont.) Papers from First and Second (1994, 1995) NREL TPV Conferences

1994 Conference (Source: Coutts & Benner, eds., 95, pp.vii+viii)



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1995 Conference (Source: Benner et.al., eds., 96, pp.v+vi)

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Session V: TPV Cells II

Session VI: Emitter Design and Testing

Fig.2-2(cont.) Papers from First and Second (1994, 1995) NREL TPV Conferences

1995 Conference (Source: Benner et.al., eds., 96, p.vii)

2.1 Background and Historical Development

Thermo-photovoltaics (TPV) have recently been re-emerging as a potentially viable utilization of Photovoltaic (PV) cell technology. Because TPV can convert any source of heat (ex. coal, oil, gas, or solar) into electricity, it may greatly broaden the application of PV technology. Since it need not rely on sunlight, it may become part of systems that are dispatchable and do not suffer from the limitations of intermittent sources as described in Chapter 6.

The concept of TPV was first proposed in the early 1960's. A number of cell and radiator combinations were developed on an experimental basis. [White et.al., 62; Kassakian, 67; Guazzoni, 75; Noreen, 95] The materials that must be used in fabricating the photocell component of a TPV system are different than those historically used for conventional PV. This difference in required materials is due to the large temperature difference between the hot source of a TPV system (1000K to 2000K) and the sun (5800K). As semiconductor materials technology has matured, particularly driven by optoelectronic and telecommunications applications, the materials required for TPV have become more widely available. This has lead to a recent and significant increase in TPV Research and Development as seen in Figure 2-2.

TPV can be easily compared to conventional Photovoltaics which are powered by radiation from the sun. The basic concept of TPV is to replace the sun as a radiation source with a heated radiating source (the Emitter) that is part of the same TPV system. Figure 2-1 depicts the basic elements of a TPV system. The radiation from the Emitter is often passed through a Filter(s) so that only useful radiation can reach the PV cell which converts the radiation into electricity. Another variation of TPVs are Solar Thermophotovoltaics (STPVs) wherein solar radiation is first passed through single or multiple junction PV cells which filter out the photons which they can absorb while transmitting through them the balance of the energy. This energy is then used as a heat source for a TPV Emitter. [Swanson, 80; Wurfel et.al., 80; Davies et.al., 94]

2.2 Emitter Technology

A growing body of work has focused on the use of Selective Emitter materials for improving TPV performance. These have often been fabricated from rare earth materials including ytterbia, erbia, and holmia. Figure 2.2-1 shows the Spectral Emissive Power of a blackbody vs. an Er-YAG SE emitter. The strategy is then to select a photocell bandgap so that the highest efficiency envelope of the photocell corresponds with the peak of the selective emitter.

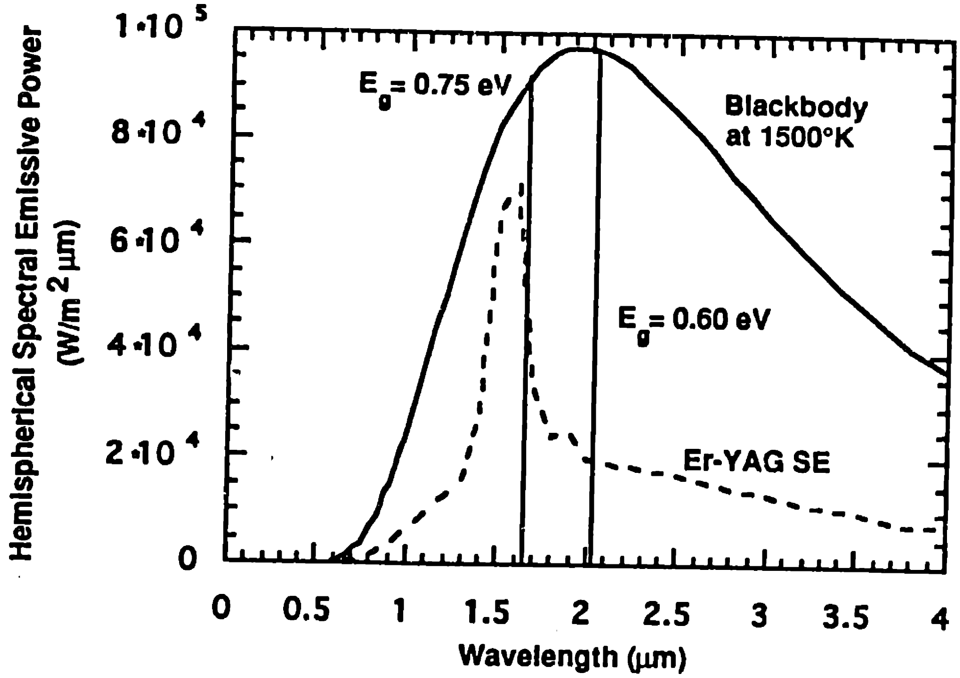


Figure 2.2-1 Hemispherical Spectral Emissive Power vs. Wavelength for a Blackbody and a Rare Earth Selective Emitter

(Source: Wilt, D.M. et.al., 95, p.215)

In addition to selective Emitters, work has also been done on high emittance materials such as SiC and on system functionality. The high emittance emitter is then used in conjunction with selective filters instead of using selective Emitters as described above. Figure 2.2-2 shows stackable SiC Emitters through which combustion gases pass. These are the units used in the generator shown in Figure 2-1.

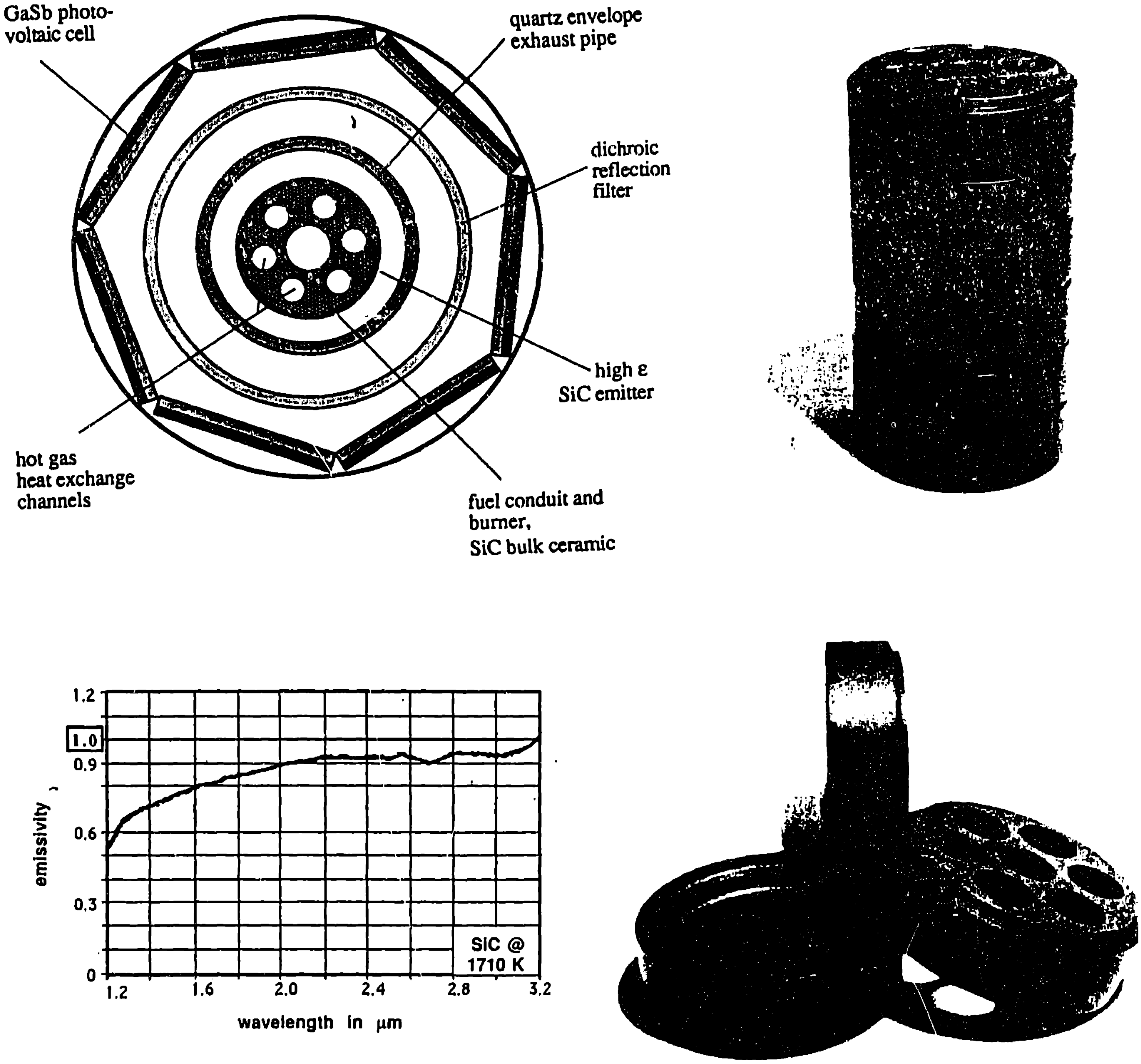


Figure 2.2-2 Stackable SiC Cores and their Emissivity at 1710K

(Source: Ostrowski et.al., 96)

2.3 Filter Technology

Many types of optical filters have been employed in TPV to tailor the radiation which reaches the photocell. The most common type of optical filters consist of alternating layers of deposited dielectric layers with different indices of refraction. By carefully adjusting the optical thicknesses of these layers to proper fractions of the wavelength of incident radiation, constructive or destructive interferences occurs yielding bandpass or bandrejection filters. Other optical filters include indium-tin oxide (ITO) filters and quartz envelopes which also serve to isolate photocells from combustion gases.

A recent filter development consists of a high density array of antenna elements formed by electron beam or masked ion beam lithography. If the elements are etched into a metal film than an inductive resonance is induced producing a bandpass filter. If metal elements are deposited on a dielectric substance then a capacitive resonance is established yielding a bandreject filter. Figure 2.3-1 shows a typical element pattern used. The cross shaped elements are placed on approximately 0.5 micron centers and the linewidth of the cross elements are on the order of 100's of Angstroms. The results of two examples of this still proprietary technology are also shown in Figure 2.3-1. By varying the size and spacing of elements the pass band can be moved to varying wavelengths which could make this approach useful for a wide variety of photocell types. [Horne, et.al., 96]

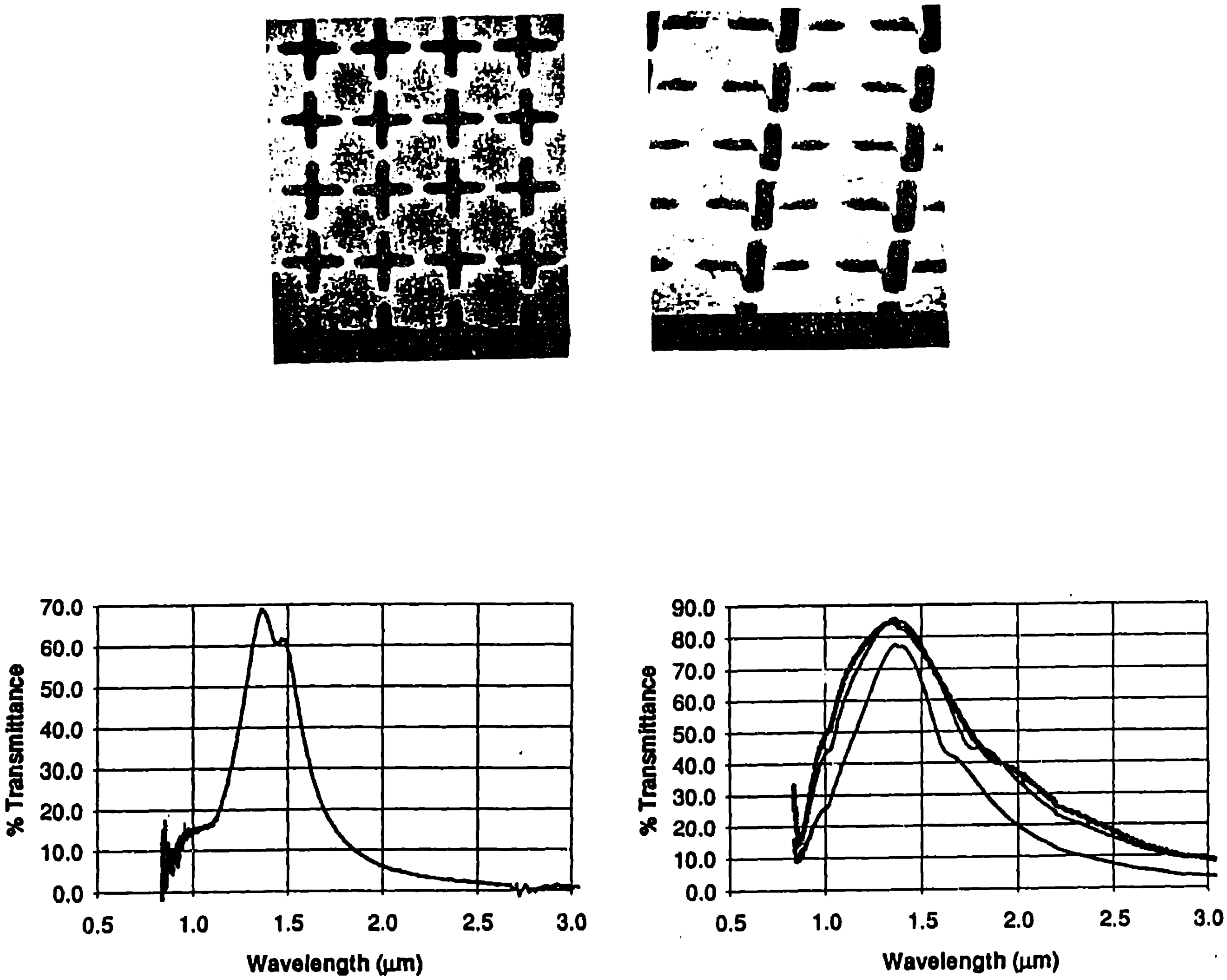


Figure 2.3-1 **Transmittance vs. Wavelength of two antenna array filters formed with a pattern similar to that shown in photo**

(Source: Horne et.al., 96, pp.46,48)

2.4 Receiver Technology

As seen in Figure 2-2, most TPV photocell work being done today is in InGaAs and in GaSb. Typical of the work in InGaAs are assessments of lattice matched and strained InGaAs photocells and the impact of varying energy gap and varying levels of strain defects on photocell performance. Figure 2.4-1 below shows the results of one such study. The stochiometry of different photocell materials were varied to achieve the bandgaps shown, with illumination from a 1273K blackbody yielding the photocell outputs and external quantum efficiencies shown. As predicted the lower bandgap cells have lower voltages due to both the lower bandgaps and due to increased dislocation defects due to greater lattice mismatch. [Wojtczuk et.al., 95]

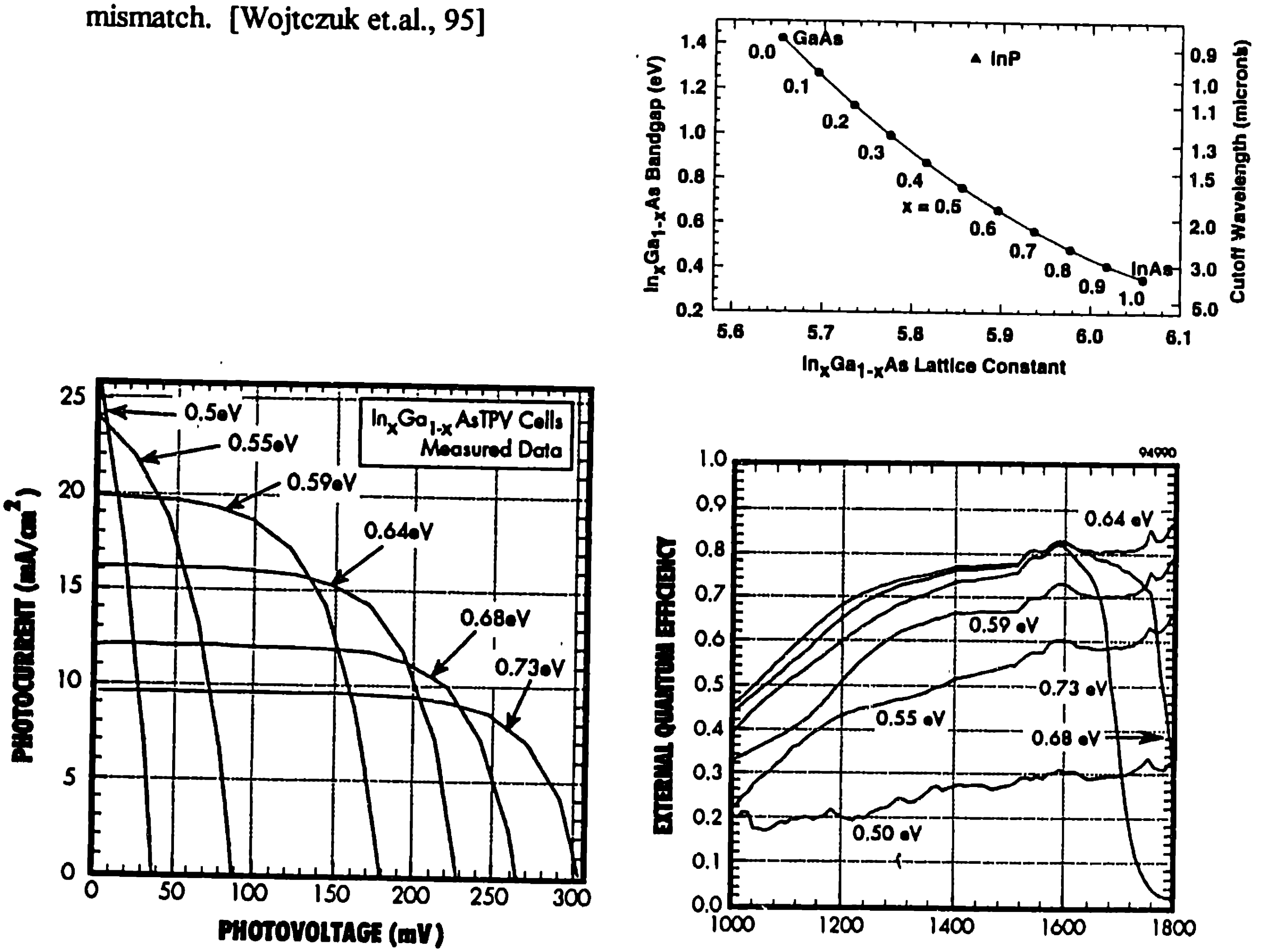


Figure 2.4-1 InGaAs Thermophotovoltaic Cells: Output vs. Bandgap

(Source: Wojtczuk et.al., 96, pp. 179,183,185)

CHAPTER 3

Microscale Radiative Heat Transfer

3.1 Radiative Heat Transfer - Macroscale

In a perfect vacuum, two opposing surfaces at different temperatures, not in physical contact exchange energy exclusively by thermal radiation. Using empirical arguments in 1879 Stefan showed that a surface emits radiation as the fourth power of its temperature. In 1884 Boltzman derived the same result using thermodynamic arguments, which result became known as the Stefan-Boltzman Law. In 1901 Planck derived the spectral characteristics of this thermal radiation based on assumptions which became the foundation for quantum theory. Equation 3-1 is Planck's Law where P is the energy per unit bandwidth for a blackbody at a specified temperature. [Cravalho et. al. 1995; Whale 1995] Figure 1 shows P as a function of wavelength for four different temperatures.

$$P(T,\lambda) := \frac{2\,\pi\cdot h\cdot c^{2}}{\lambda^{5}}\cdot\frac{1}{\exp\left(\frac{h\cdot c}{\lambda\cdot k\cdot T}\right)-1} \qquad (3\text{-}1)$$

Equation 3-2 then gives the Stefan-Boltzman Law by the integration of Planck's Law over all wavelengths, where TP is the total power emitted from a perfectly radiating surface known as a Black Body.

$$TP(T) := \int_0^\infty P(T,\lambda)\, d\lambda \qquad = \sigma \cdot T^4 \tag{3-2}$$

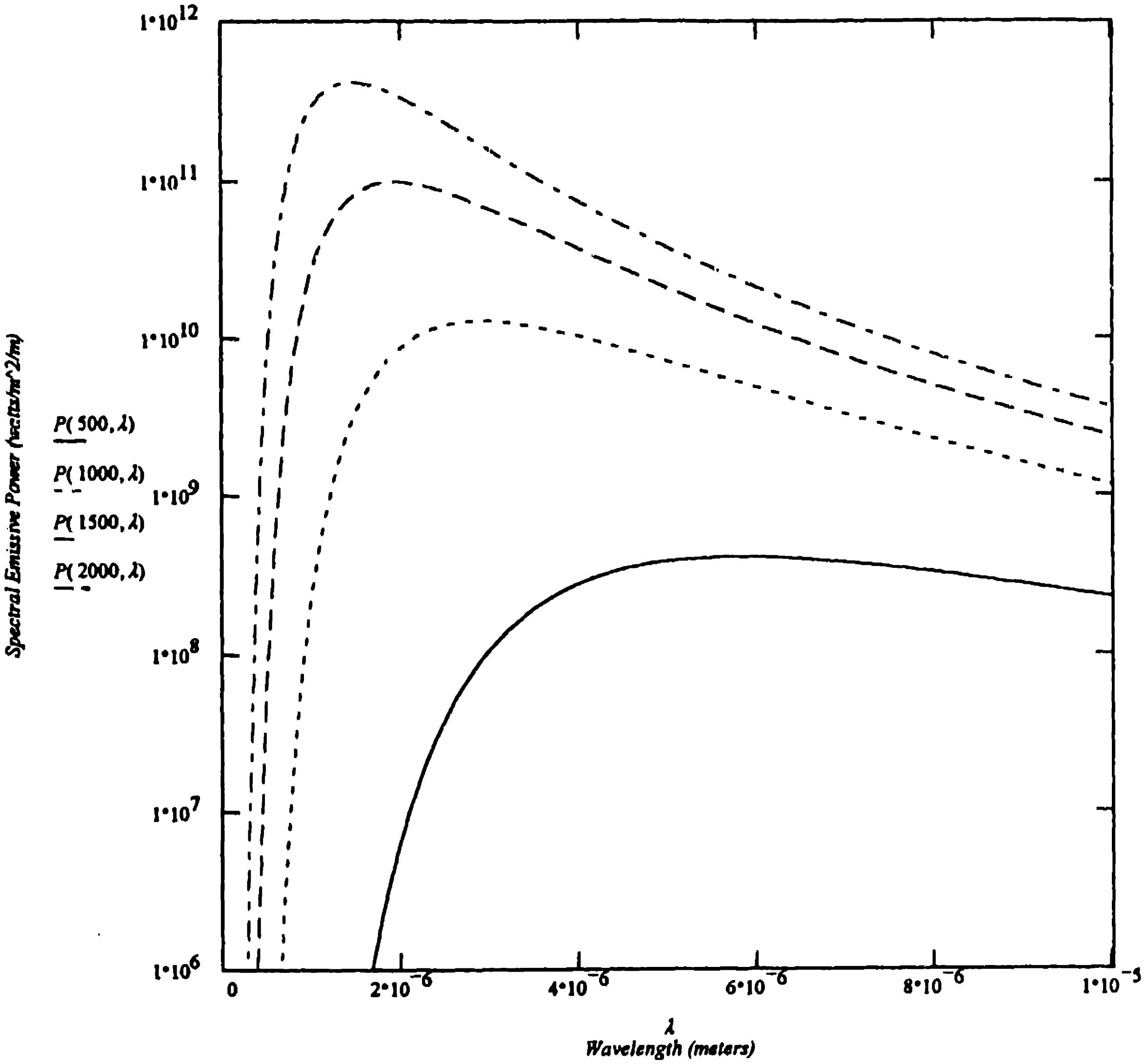
When two surfaces are separated by a distance which is large compared to the wavelengths of the radiation then these two equations determine the energy that will be exchanged.

3.2 Limitations to the Macroscale Formulation

The limitation that Planck's Law applies only when the distance between surfaces exchanging energy radiatively are separated by a distance larger than the wavelengths of the radiation was understood by Max Planck himself. At the beginning of his *The Theory of Heat Radiation* he states,

> "We are therefore obliged to introduce right at the start a certain restriction with respect to the size of the parts of space to be considered. Throughout the following discussion it will be assumed that the linear dimensions of all parts of space considered ... are large compared to the wave lengths of the rays considered."

This limitation did not begin to become of engineering importance until the 1960's when cryogenic multi-layer thermal insulation barriers were being developed for space exploration. It was at this time that experimental evidence began to be generated proving Planck's stated limitations on his macroscale formulation.



LEGEND:

Curve	Position in Figure	Temperature (K)
P(2000,)	Highest Curve	2000
P(1500,)		1500
P(1000,)		1000
P(500,)	Lowest Curve	500

Figure 3-1 Planck's Law - Emissive Power Spectral Density for a Black Body at Temperature T.

3.2.1 Experimental Evidence of Macroscale Limitations

The first known experimental results demonstrating the microscale radiative effect were published in 1967. [Cravalho, et. al., 1967] This work was done with dielectrics in the temperature range from 2K to 4K. A sample of these data are shown in Figure 3-2. This work suggested two modes of energy transfer and interaction, wave interference and radiation "tunneling". Wave interference accounts for the interference of traveling waves in the cavity. Radiation "tunneling" is not quantum mechanical electron tunneling but occurs when the surfaces are sufficiently close so that the fluctuating field from one surface directly couples with carriers in the other. Levin et. al. refers to this as "near field" interaction. [Levin et. al., 1981]

In 1969 and 1973 Hargreaves published results also indicating sharply increasing radiative heat transfer between closely spaced surfaces. Figure 3-3 shows a sample of these data. This work was done with metal films of chromium in the room temperature regime. [Hargreaves, 1969; Hargreaves, 1973]

In 1981 Kutateladze et. al. published similar results between copper surfaces over a wider range of temperatures (4.2K to 300K). This work demonstrated the microscale effect over the largest difference in temperature between the two surfaces (223K) which is of particular importance to the MTPV device concept discussed in the following chapter. Figure 3-4 illustrates their results which like the previous experimental results demonstrated significant increased radiative heat transfer at small spacing.

Each of these three Figures 3-2, 3-3, 3-4 exhibit the macroscale, Planckian radiative transfer to the right of the plots wherein the net heat flux is nearly independent of distance between surfaces. As the distance is decreased (moving toward the left) each plot exhibits sharply increasing net heat flux with strong dependence on spacing distance.

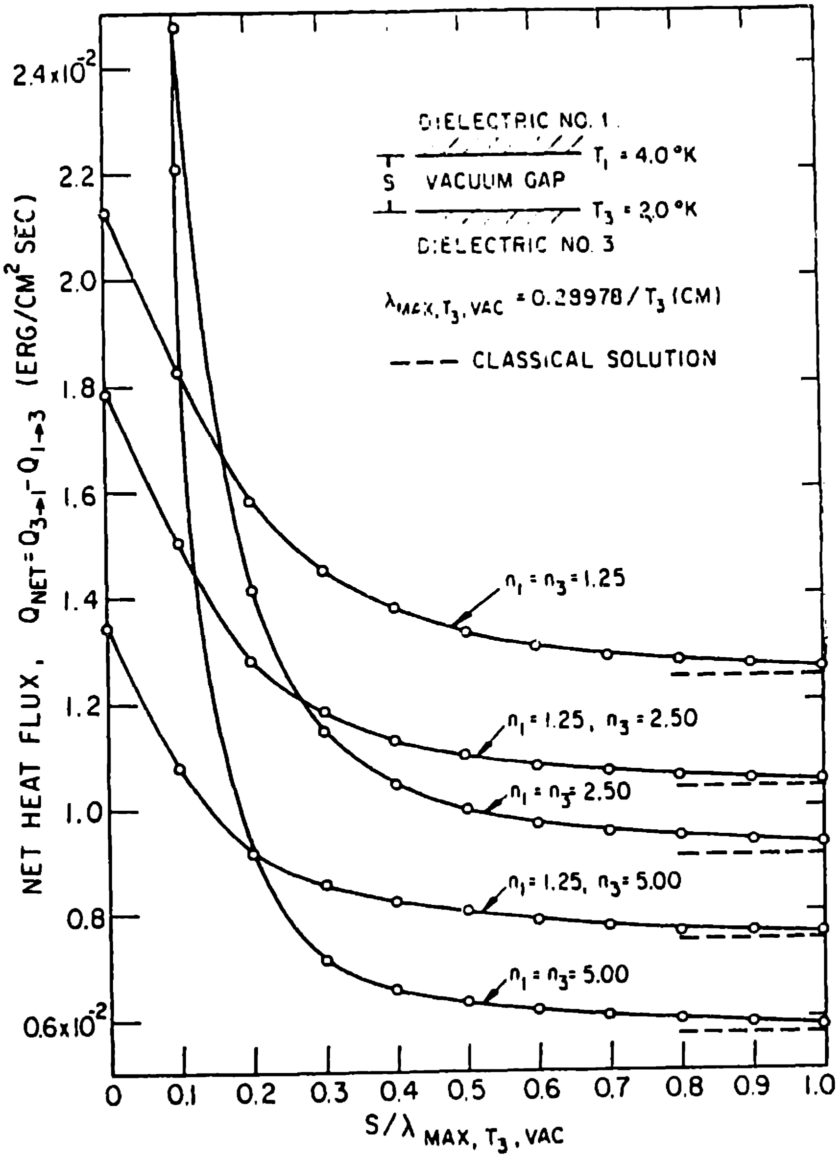


Figure 3-2 **Energy transfer between two dielectrics due to wave interference and radiation tunneling.**

(Source: [Cravalho, et. al., 1967], p.355, Figure 4.)

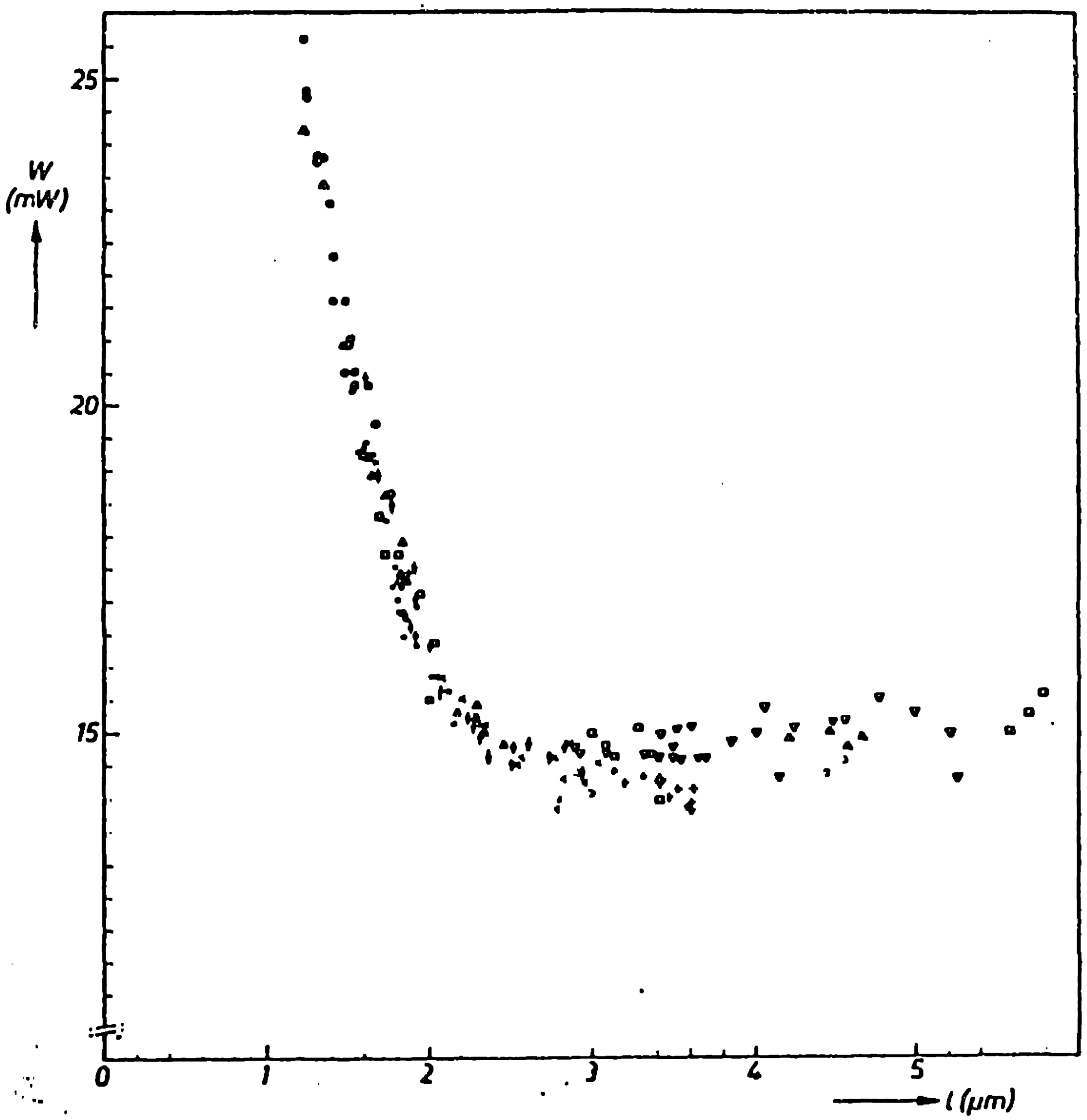


Figure 3-3 Provisional measurements of the radiative transfer W between parallel metal surfaces as a function of the spacing l. Mean temperature T=315K, Delta T = 17K.

(Source: [Hargreaves, 1973], p. 59, Figure 22.)

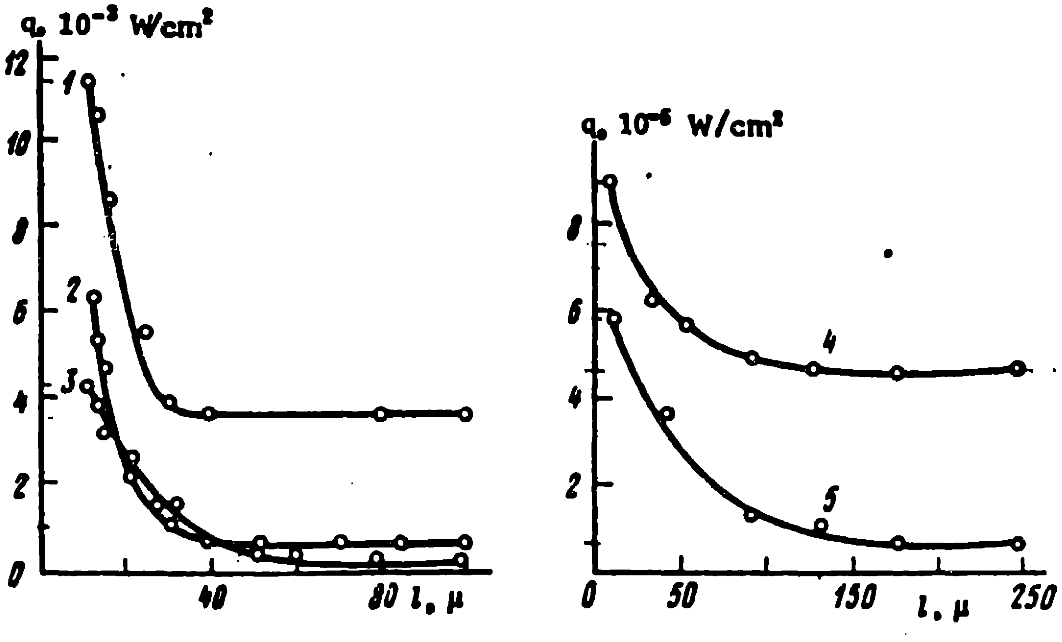


Figure 3-4 Thermal flux as function of distance between surfaces of copper disks at radiator temperatures of: 1) 300K; 2) 200K; 3) 150K; 4) 80K; 5) 46K. Receiver temperature (1-3) 77K and (4,5) 4.2K.

(Source: [Kutateladze, et. al., 1978], p.577, Figure 1.)

3.3 Microscale Analytical Formulations

Though for widely differing temperatures and materials, the experimental results reviewed in section 3.2 each shows marked deviation from Planck's Law as the macroscale spacing transitions to microscale spacing. Several efforts have sought to explain this microscale effect theoretically so as to quantify this phenomenon analytically and/or numerically. Polder and Van Hove showed microscale radiative transfer several orders of magnitude greater than macroscale transfer for small temperature differences between surfaces. [Polder et. al., 1971] While predicting lower radiative transfer enhancement than Polder and Van Hove, Levin, Polevoi, and Rytov also developed a model for microscale radiative transfer. It is based on earlier work of Rytov and uses the fluctuation dissipation theorem together with stochastic variables in Maxwell's Equations to derive a microscale power spectral density function. The results of this work are utilized in the following sections. [Levin et. al., 1981; Cravalho et. al., 1995; Whale, 1995]

3.3.1 Levin, Polevoi, Rytov (LPR) Power Spectral Density

LPR derived a modulation function which can then be applied to Plank's power spectral density function to obtain a microscale emissive power spectral density function. This modulation function is a function of S, the spacing between surfaces, and the wavelength, and accounts for both the interference and near field transfer mechanisms. This modulation function f(S) is given be Equations 3-3, 3-4 and 3-5 where floor(x) = the greatest integer less than or equal to x.

$$y(S) := \frac{2\cdot S}{\lambda} \qquad (3\text{-}3) \qquad\qquad m(S) := floor(y(S)) \qquad (3\text{-}4)$$

$$f(S,\lambda) := \frac{1}{2 \cdot y(S)} + \frac{m(S)}{y(S)} + \frac{m(S) \cdot (m(S)+1) \cdot (2 \cdot m(S)+1)}{6 \cdot y(S)^3} \qquad (3\text{-}5)$$

Figure 3-5 shows f(S) as a function of wavelength at three different spacings of 1 micron, 0.1 micron, and 0.01 micron = 10 nm. The microscale emissive power spectral density is then given by combining Equations 3-1 and 3-5 into equation 3-6. Figure 3-6 shows the resulting LPR emissive power spectral density function for emitting surface temperature of 1000K. This LPR formulation assumes that both surfaces are perfectly radiating (black body) metals.

$$TP(S,T,\lambda) := .75 \cdot f(S,\lambda) \cdot P(T,\lambda) \qquad (3\text{-}6)$$

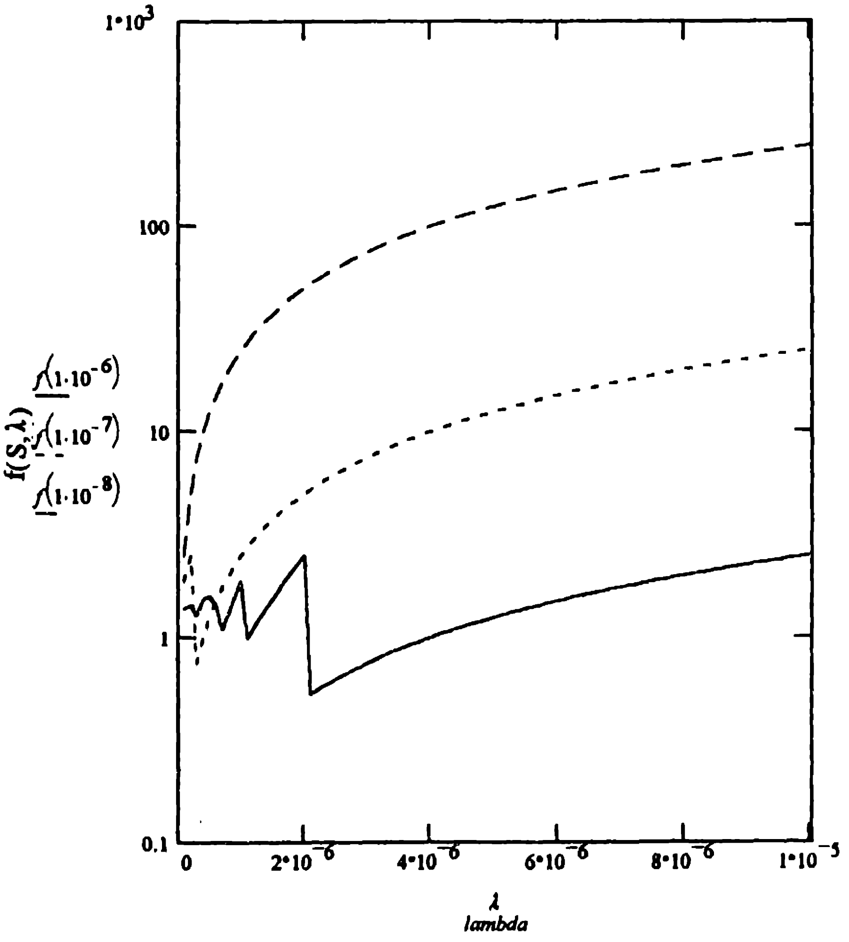


Figure 3-5 LPR Microscale Emissive Power Modulation Function

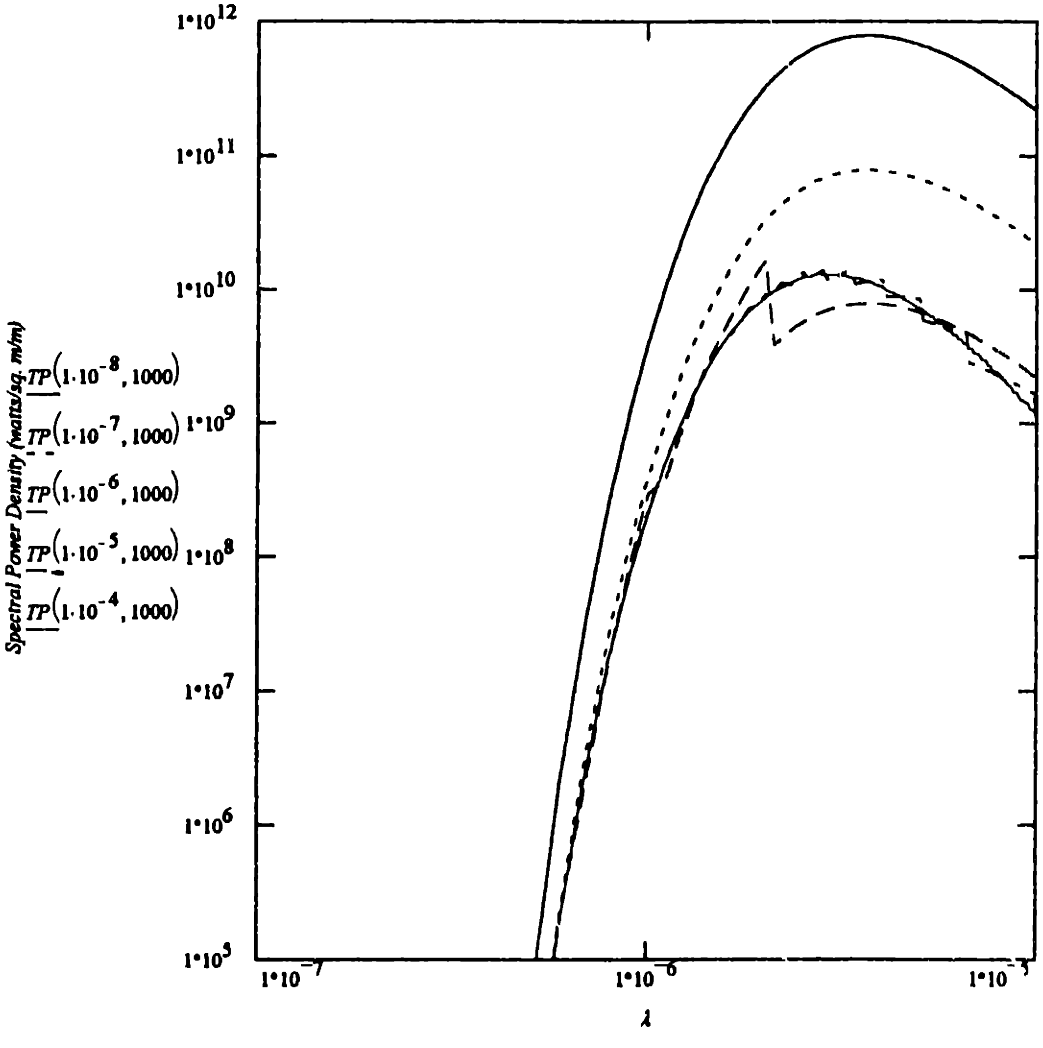


Figure 3-6 **LPR Microscale Emissive Power Spectral Density Function (T=1000K, Spacings: S=1E-4, 1E-5, 1E-6, 1E-7, 1E-8)**

3.3.2 LPR Integrated Power

Given Equation 3-6, the total microscale power emitted can be calculated by integrating over all wavelengths and is approximated by Equation 3-7. Figure 3-7 shows this integrated total power as a function of S for the indicated temperatures.

$$\mathrm{ITP}(S,T,\lambda) := \int_{10^{-7}}^{10^{-4}} \mathrm{TP}(S,T,\lambda)\, d\lambda \qquad (3\text{-}7)$$

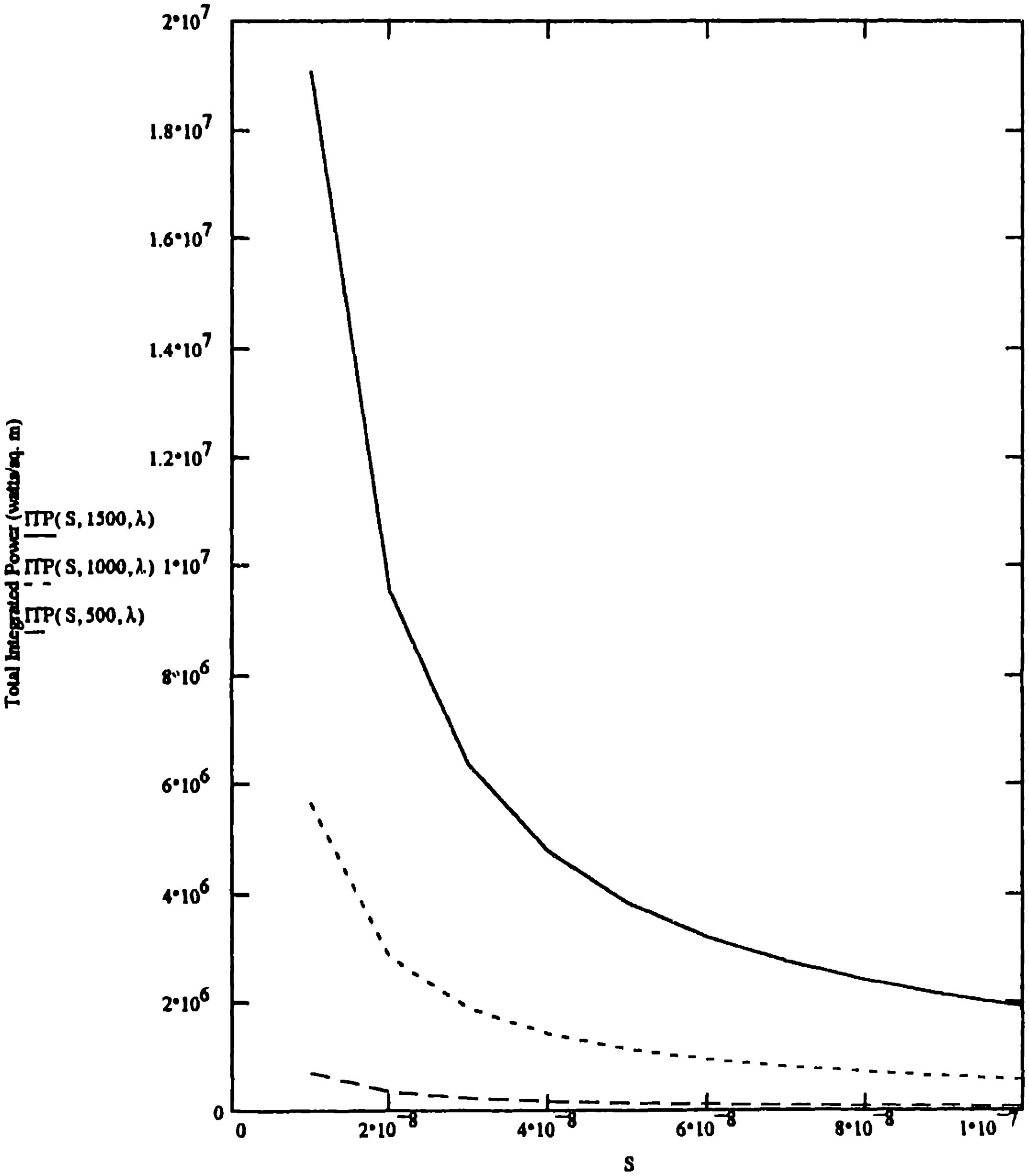


Figure 3-7 LPR Integrated Total Power as a Function of Microscale Spacing for Specified Temperatures (T = 500K, 1000K, 1500K)

3.3.3 Incremental Integrated Power

Given Equation 3-7 the incremental or additional power which is emitted due to moving the surfaces from S to S - 10 nm can be calculated by subtracting the ITP evaluated at the two different spacings as in Equation 3-8. This is shown in Figure 3-8.

$$\mathrm{IITP}(S,T,\lambda) := \mathrm{ITP}(S-10^{-8},T,\lambda) - \mathrm{ITP}(S,T,\lambda) \qquad (3\text{-}8)$$

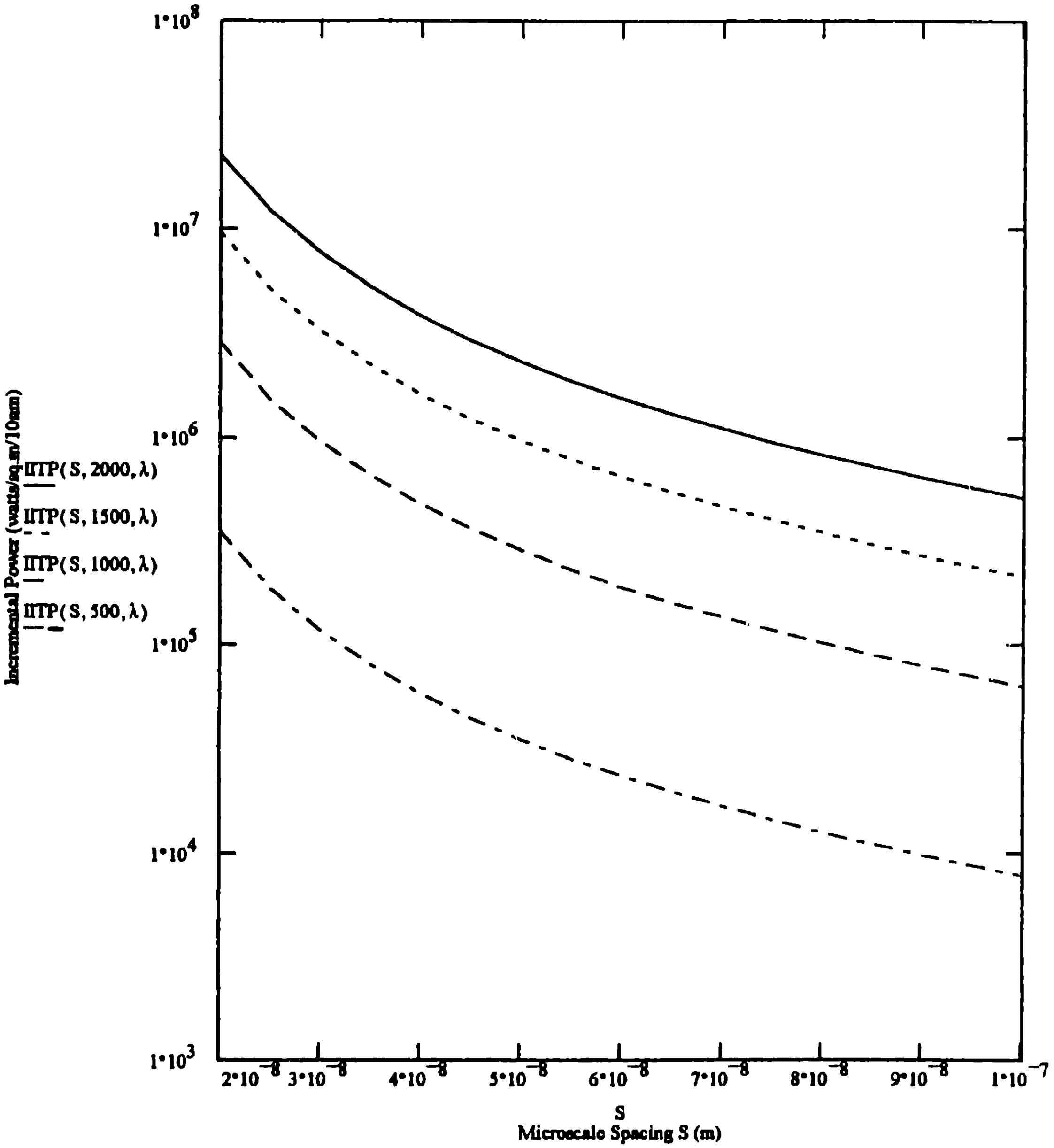


Figure 3-8 Incremental LPR Integrated Total Power for Spacing Increases of 10 Nanometer Increments (T = 500K, 1000K, 1500K, 2000K)

CHAPTER 4

Microscale Thermophotovoltaics (MTPV)

MTPV is a device concept which combines the fields described in Chapters 2 and 3 of Thermo-Photovoltaics and Microscale Radiative Heat Transfer respectively. The MTPV concept consists of using Microscale Radiative Energy Transfer as the means to electronically couple energy into a TPV cell with significantly increased power densities and possibly increased efficiencies. An MTPV would consist of a surface of higher temperature, the "Emitter" which would be brought into close "Microscale" proximity (1 - 0.01 microns) to the "Receiver". The Receiver would be a photovoltaic cell with its collection contacts either on its back surface or recessed from the front active surface. The very large increases in Radiative Transfer due to the Microscale effect, as reviewed in the prior chapter, would result in increased electrical output.

A fundamental question for the MTPV concept is whether or not all the energy transferred from Emitter to Receiver will promote energy gap crossings in the semiconductor as is the case with conventional Photovoltaics (PVs) and conventional Thermophotovoltaics (TPVs). It is hypothesized that although the direct coupling in the radiation tunneling mode is not equivalent to photons traveling through space, that this energy will promote enhanced carrier generation in the semiconductor as if it were quantized as photons. The analysis that follows in this chapter is based on that assumption. Chapter 5 reviews an experiment designed to test this fundamental hypothesis.

4.1 Electronic Noise

Having reviewed sequentially in the immediately preceding two chapters the fields of Thermophotovoltaics and Microscale Radiative Heat Transfer, it may seem obvious to combine them to form new electronic devices for power conversion. Prior to the MTPV concept, it appears that they had not been viewed in conjunction with one another and it was the pursuit of the domain of electronic noise that provided the first conduit between these two fields. This chapter shall therefore begin with a brief review of electronic noise both for its formative significance and because it continues to inform the development of the MTPV concept.

4.1.1 Developments of Noise in Energy Conversion

Noise in linear systems was examined theoretically by Nyquist and experimentally by Johnson in the late 1920's. [Nyquist, 1928; Johnson, 1928] Noise in nonlinear systems however has proven to be much more elusive and has been a subject of more recent theoretical research. [ex. Wyatt, 1984] In 1958 C.T.J. Alkemade at the University of Utrecht, Netherlands, gave a kinetic derivation for noise in a parallel plate diode. [Alkemade, 1958] Then in 1960 N.G. VanKampen, also of the University of Utrecht, used Alkemade's diode model together with the Master Equation to derive a statistical mechanic model of noise in a diode at constant temperature. [VanKampen, 1960]

At about the same time Richard Feynman (Cal. Tech.) in his Lectures on Physics described a pedagogical nonlinear system comprised of a ratchet and pawl in which the existence of a temperature gradient across the system enabled fluctuations at the higher temperature to be converted to useful work.[Feynman, 1964] He also mentions in passing the analogy between his ratchet and pawl and an electrical rectifier. In 1968 J.B. Gunn

(IBM Watson Research Center) constructed the equivalent of Feynman's ratchet and pawl with a circuit of a linear resistor and a diode. He theoretically concluded as did Feynman that when the temperature of nonlinear element becomes higher than that of the linear element that current flows in the high impedance direction through the diode. Surprised at his own conclusions Gunn experimentally verified his theory. [Gunn, 1968]

In 1974 the above works were synthesized in a paper by J.C. Yater in which he used Van Kampen's Master Equation approach with a nonlinear system at two different temperatures to demonstrate the results found by Feynman and Gunn. [Yater, 1974] In it he proposed the possibility of rectifying electronic noise for the conversion of heat to electricity limited by Second Law Carnot efficiency. In this paper he proposed the idea of putting large numbers of these rectifying circuits on opposing chips at different temperatures for the conversion of heat to electricity. He was later granted a U.S. Patent for this concept. [Yater, 1977] In 1982 M.S. Gupta (Univ. of Illinois) confirmed Yater's conclusion for modest bandwidth and temperature gradient based on a circuit model for noise in a nonlinear circuit.[Gupta, 1982] In addition to elevated lattice temperature, this work was extended to include nonequilibrium "hot" electrons with lower lattice temperatures which could be used with or without a thermal barrier [Yater 83 and 94] and which could be applied to MTPV as well.

4.1.2 Noise Power

The form of electronic noise considered here is thermal noise. Thermal noise is also known as white noise, Johnson noise, and Nyquist noise. The total noise power across a macroscale resistive element is independent of the size and resistance of the element. It is approximated by:

$$P = kTB \qquad (4.1\text{-}1)$$

where k is Boltzman's constant, T is the temperature, and B is the bandwidth (Hz) of the circuit in which the noise power is being calculated. At higher frequencies this formula must be adjusted by the Planck factor p(f,T) where f is frequency (Hz), given by Equation 4.1-2 and is shown in Figure 4.1-1.

$$p(f,T) := \frac{\frac{h \cdot f}{k \cdot T}}{e^{\frac{h \cdot f}{k \cdot T}} - 1} \qquad (4.1\text{-}2)$$

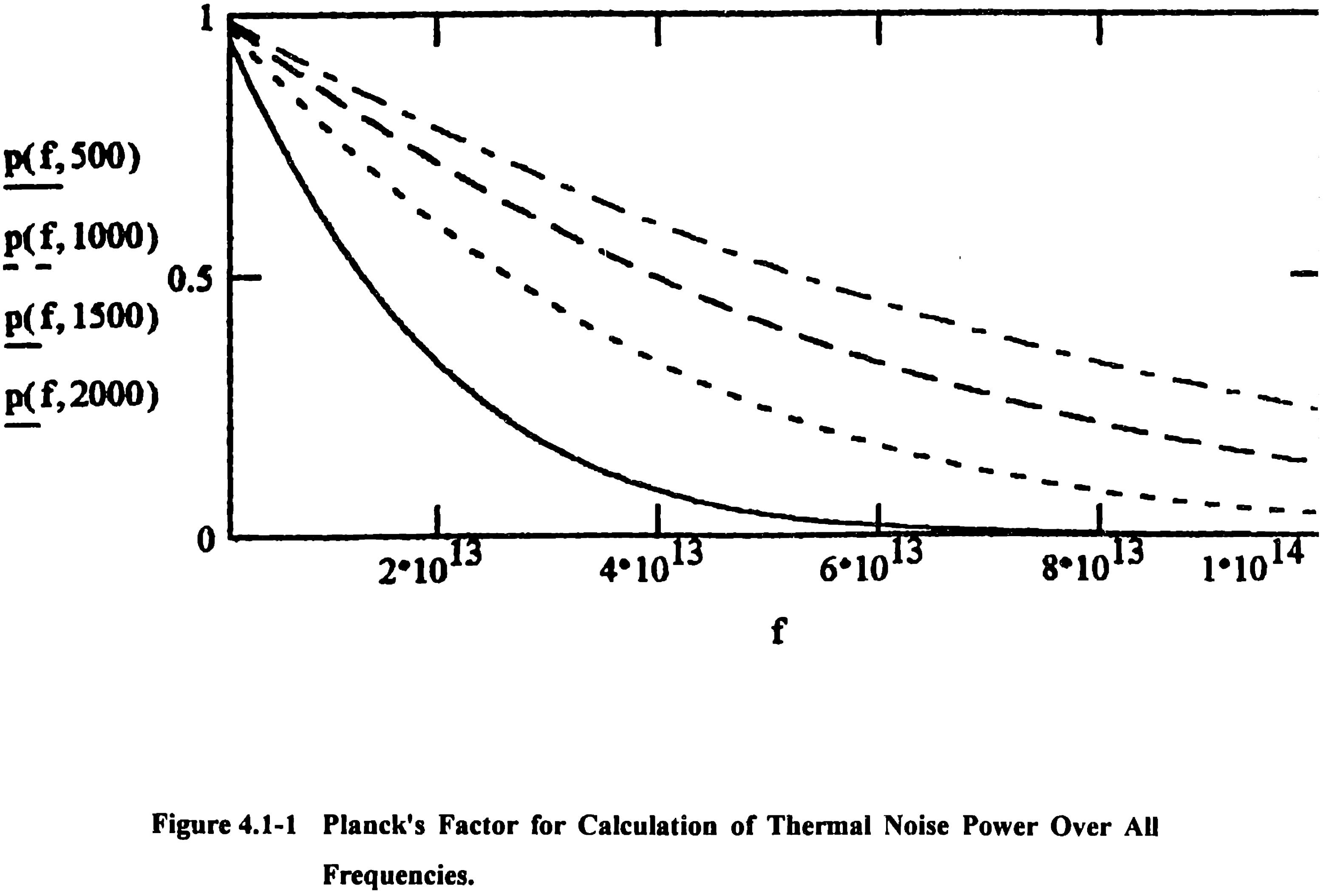


Figure 4.1-1 **Planck's Factor for Calculation of Thermal Noise Power Over All Frequencies.**

The total Noise Power (watts) between any two frequencies as a function of temperature NP(T,fmin, fmax) is given by Equation 4.1-3 where fmin is the minimum frequency and fmax is the maximum frequency. This is shown in Figure 4.1-2 as a function of temperature for values of fmax from 1E11 to 2E14.

$$\mathrm{NP}(T,\mathrm{fmin},\mathrm{fmax}) := \int_{\mathrm{fmin}}^{\mathrm{fmax}} k\cdot T\cdot p(f,T)\,df \tag{4.1-3}$$

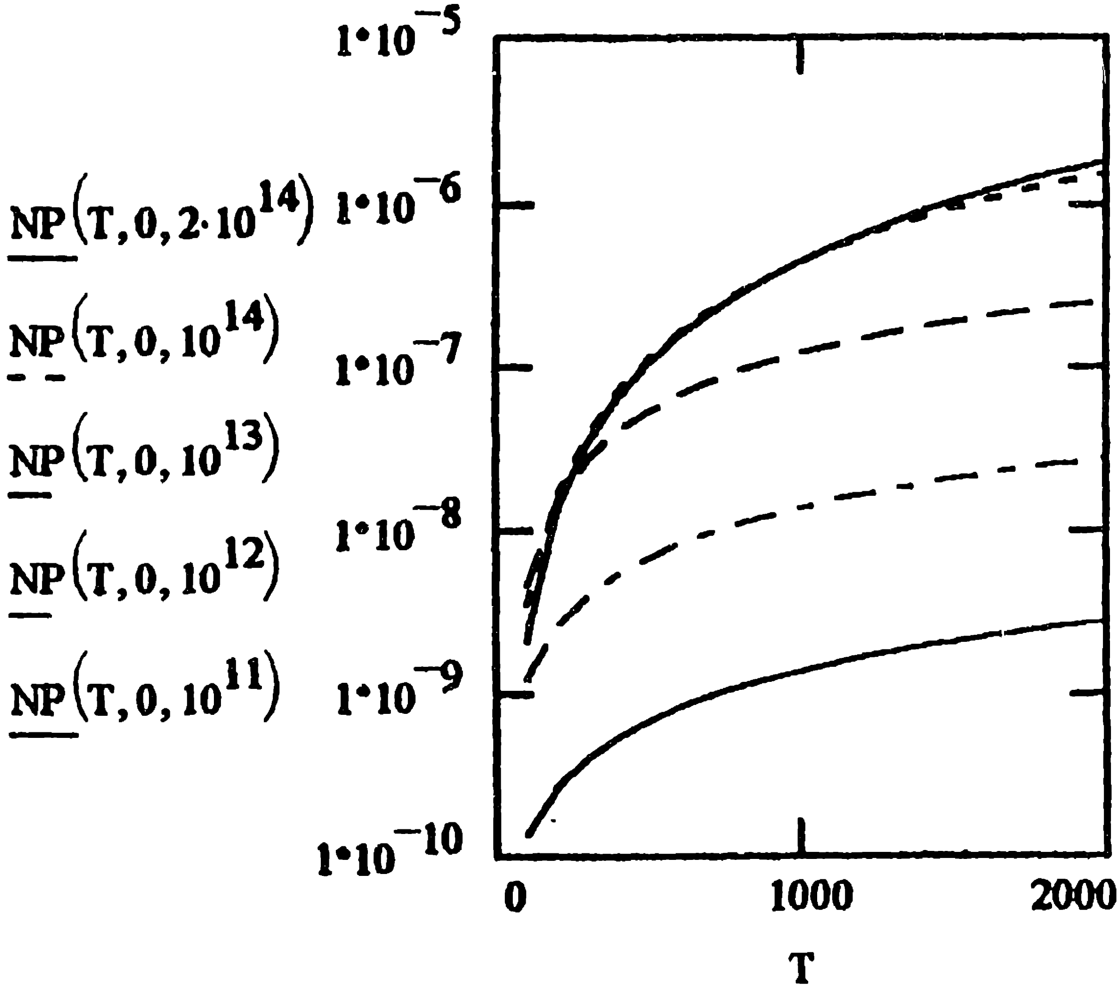


Figure 4.1-2 Total Noise Power NP(T, fmin, fmax) as a Function of Temperature for Maximum Frequencies, fmax(Hz) = 1E11, 1E12, 1E13, 1E14, 2E14.

One could imagine then a thought experiment wherein 2 point probes are placed on the surface of a homogeneous conductor or semiconductor. The material between them would comprise a resistor and would obey the above equations. The point probes could be moved closer and closer together and the above relationships would continue to hold. At a 1000K the noise power of each of these resistors would be 0.45 microwatts. If each resistor occupied one square micron then the total surface noise power that could be measured on this surface in a sq. cm. would be 45 watts. If the these surface resistor dimensions were reduced to 1 micron by 0.1 micron, the total surface noise power would be 450 watts/sq. cm. which is a factor of 79 greater than Planckian black body surface emission. It would seem logical then that two surfaces placed close enough together should exchange power greater than that predicted by Planck's Law and that this should manifest itself as increased heat transfer between two closely spaced surfaces. This reasoning leads to a search for anomalous heat transfer at close spacing which is the very domain of Microscale Radiative Heat Transfer as discussed in Chapter 2.

Xu et.al. used Nyquist's formula for thermal noise to derive an approximate expression for Microscale Radiative Heat Transfer. [Xu et.al. 94] Others have indicated the relationship between noise and black body radiation. One "source of noise ... is thermal noise, which is black body radiation in a single propagation mode." [Oliver 65, p.436] "It would be wrong to conclude ... that Nyquist's theorem represents the one-dimensional form of black-body radiation." [Van der Ziel 54, p.18] It is interesting to note from the discussion in the last paragraph that if resistors were 30 nm by 30 nm, the approximate size at which quantum dots begin to have limits on allowable energy states, which would perhaps limit their noise output, the noise power from such a surface of resistors would approximate the approximate 1E4 increase over blackbody emission predicted by Polder and Van Hove which is itself approximately 2 orders of magnitude greater than the LPR model reviewed in Chapter 2.

4.2 Electronic Materials

The ability to utilize the increased energy exchanged by surfaces in close proximity is a function of the Energy Gap of the Receiver material. Compound semiconductors enable a wide variety of Energy Gaps in single crystalline form. Figures 4.2-1 and 4.2-2 show Energy Gap (and corresponding Gap wavelength) as a function Lattice constants (distance between atoms in the lattice) all of which are dictated by the semiconductor stoichiometry as shown. Varying Energy Gap materials can be grown on one another provided the Lattice constants are matched. This provides for growth of materials vertically aligned in these Figures. [Fonstad 96]

More recent developments in growing pseudomorphic strained layers have further extended Energy Gap engineering possibilities. For example, InP with a Lattice Constant 5.87 angstroms can be used a substrate to grow lattice matched In(0.53)Ga(0.47)As which has an Energy Gap of 0.78eV. Through the use of Molecular Beam Epitaxy (MBE) layers of material can be grown as thin as from one to several atoms thick while maintaining tight stoichiometric control. It is therefore possible to continuously grow such thin layers while varying the stoichiometry such that nonvertical transitions can be made on Figures 4.2-1 and 4.2-2. Each subsequent group of several atomic layers is strained to accommodate the layer on which is it deposited. InGaAs can therefore be grown closer to pure InAs stoichiometry and Energy Gap while preserving the Lattice Constant of the original substrate thereby preserving single crystal structure. Because of the orthogonal strain induced by the in plain strain, ie. in plain compression therefore orthogonal tension, the smoothness of these pseudomorphic layers would need to investigated for application to MTPV. The very thin layers may have special relevance for MTPV since energy transfer mechanisms may occur much closer to the surface than in conventional Photovoltaics and Tandem, multi, or continuous varying junction approaches will therefore likely require this level of precise material control.

The Energy Gap engineering possibilities that now exist make it possible to consider MTPV devices over most values below 1.0 eV which is now considered in section 4.3.

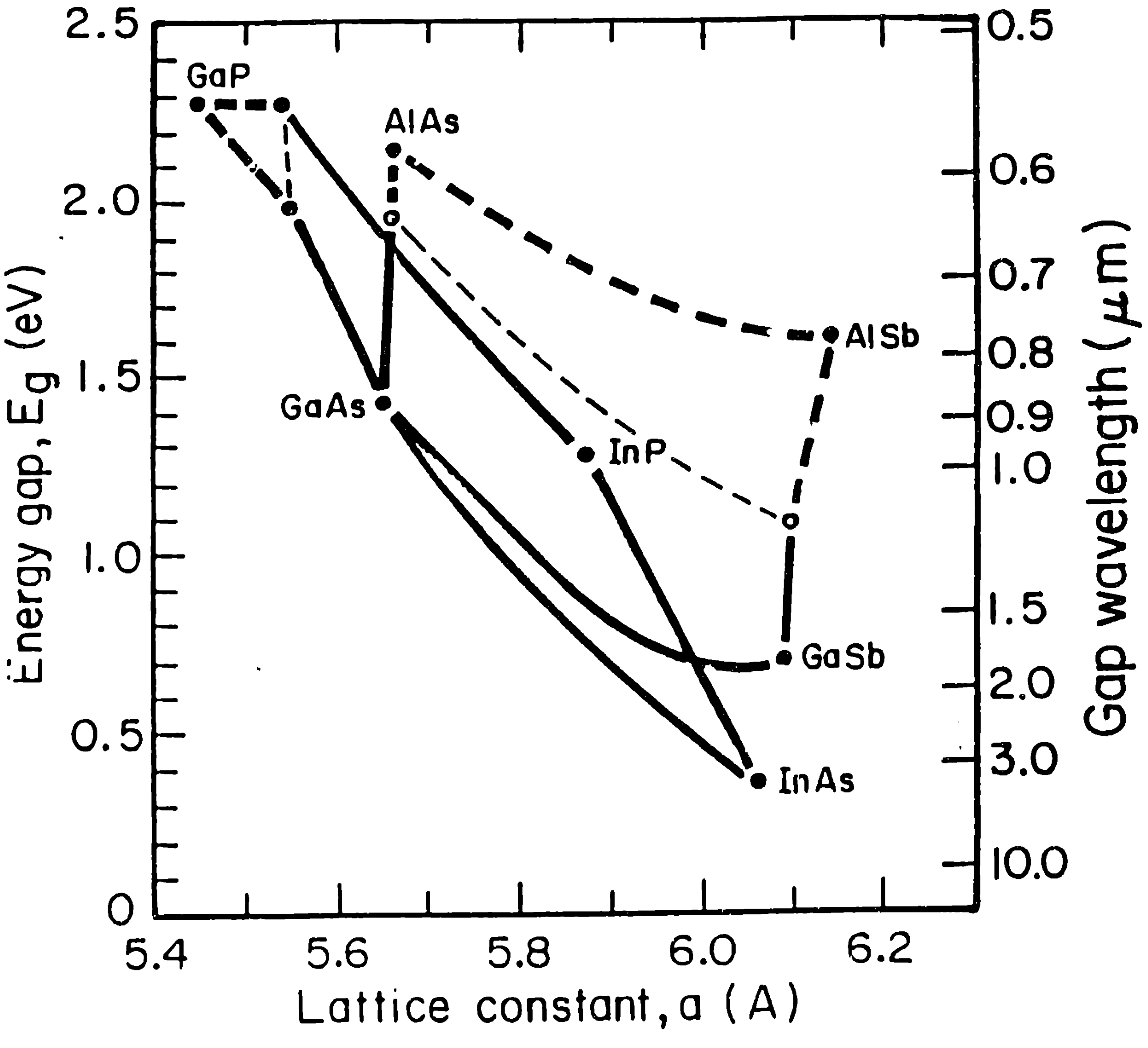


Figure 4.2-1 Energy Gap (eV) vs. Lattice Constant (A): InGaAsP, GaAlAsSb.
(Source: [Fonstad 96])

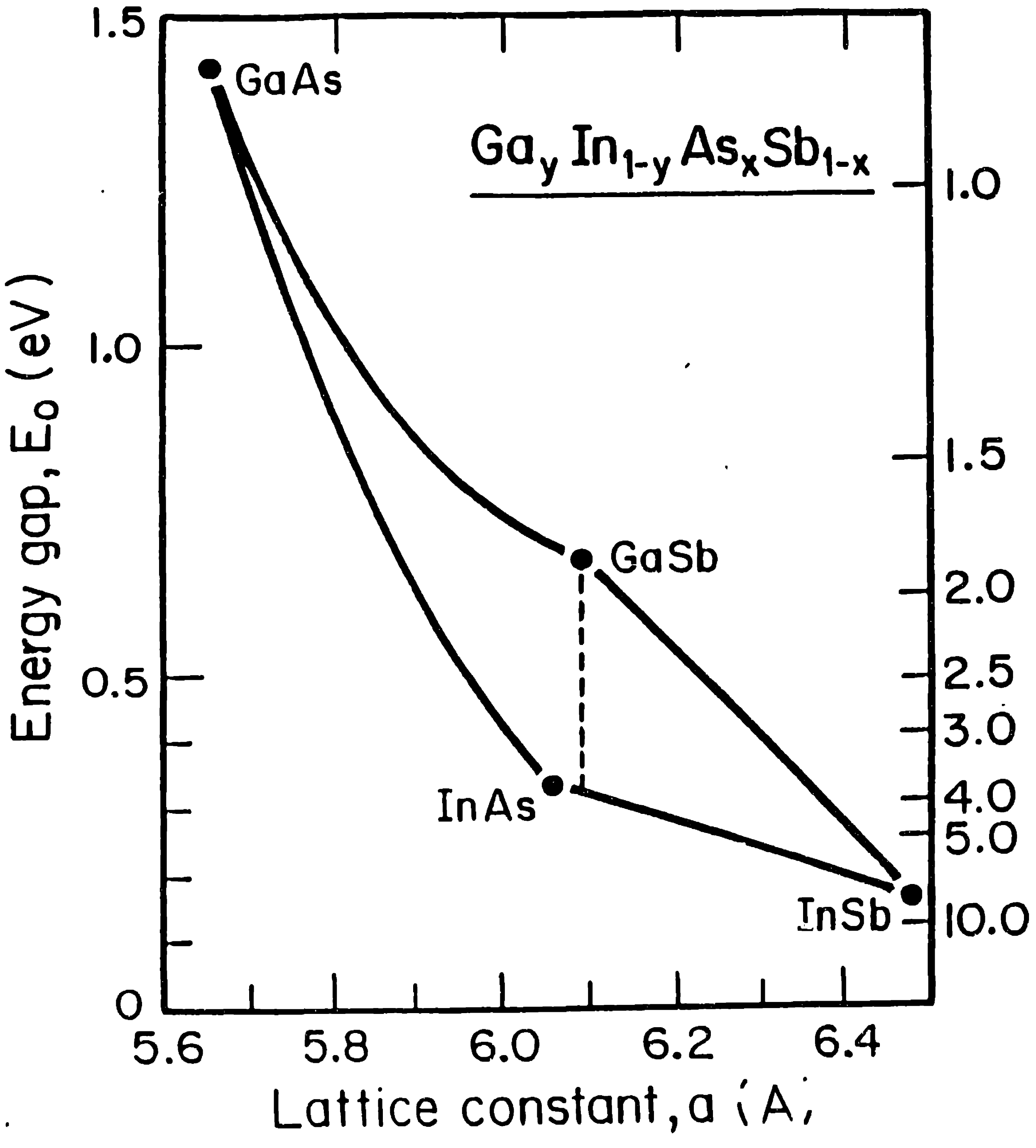


Figure 4.2-2 Energy Gap (eV) vs. Lattice Constant (A): Ga(y)In(1-y)As(x)Sb(1-x).

(Source: [Fonstad 96])

4.3 MTPV Quantum Efficiencies and Power

The following assumes that Microscale Radiative Energy is quantized like photons and uses the term photon both in its conventional sense and to refer to a quanta of Microscale Radiative Energy. Though a form of Tandem Cells are conceivable in MTPV similar to their use in conventional PV and TPV only single gap material is considered in this section. When a photon enters a semiconductor if its energy is less than the energy gap it cannot create an electron-hole pair and the carrier population is therefore not directly affected. If the photon is of equal or greater energy then that portion of the photon energy equal to the Energy Gap becomes available for conversion to useful power by the creation of an electron-hole pair. Any photon energy in excess of the Energy Gap is not utilized. Excess electrons and holes formed can be swept apart by the potential difference across the space charge region of a junction and the electrons can flow through an external circuit producding useful work. This section looks at the first part of this process and calculates the Quantum Efficiency for MTPV devices and the power available at the point at which the electron-hole pairs are created, given various levels of Microscale Radiative Energy Transfer. The subsequent effeciencies of converting the electron-hole pairs to dc output are not considered here and are the subject of Cravalho et.al. 96.

For a photon,

$$\lambda\nu=c \quad \nu=c/\lambda \quad . \qquad (4.3\text{-}1)$$

The energy of a photon (Ep) is given by

$$Ep=h\nu \quad Ep=hc/\lambda \quad . \qquad (4.3\text{-}2)$$

The wavelength of a photon with energy equal to the Energy Gap (Eg) of a semiconductor (Ep=Eg) is given by

$$\lambda Eg(Eg) := \frac{1.24}{Eg}\cdot 10^{-6} \quad (m) \quad . \qquad (4.3\text{-}3)$$

The Quantum Efficiency (QE) of the conversion of a single photon to a single electron-hole pair in a semiconductor of Energy Gap Eg is then given by

$$QE(\lambda, Eg) := \frac{\lambda\cdot Eg}{h\cdot c}\cdot 1.60\cdot 10^{-19} \quad . \qquad (4.3\text{-}4)$$

4.3.1 In Band Efficiency

The overall (Integrated) Quantum Efficiency of a semiconductor with Energy Gap (Eg) for a energy input with a Microscale Radiative Power Spectral Density Input (TP) can then be calculated in at least two ways. The total power of created electron-hole pairs (IQEP) can be compared to the total power received over the full spectrum (ITP) or it can be compared to the In Band power received. The In Band power (IBITP) being the total power received with photon energy in excess of the Energy Gap. IQEP is approximated by Equation 4.3-5.

$$IQEP(\lambda, Eg, S, T) = \int_{10^{-7}}^{\lambda Eg(Eg)} \frac{\lambda \cdot Eg \cdot 1.60 \cdot 10^{-19}}{h \cdot c} \cdot TP(S, T, \lambda)\, d\lambda \qquad . \qquad (4.3\text{-}5)$$

The total In Band power received can be approximated by

$$IBITP(Eg, S, T, \lambda) := \int_{10^{-7}}^{\lambda Eg(Eg)} TP(S, T, \lambda)\, d\lambda \qquad . \qquad (4.3\text{-}6)$$

The In Band Quantum Efficiency (IBIQE) is then given by

$$IBIQE(\lambda, Eg, S, T) := \frac{IQEP(\lambda, Eg, S, T)}{IBITP(Eg, S, T, \lambda)} \qquad . \qquad (4.3\text{-}7)$$

Figure 4.3-1 shows IBIQE at 1000K and 2000K at both micro and macroscale spacing.

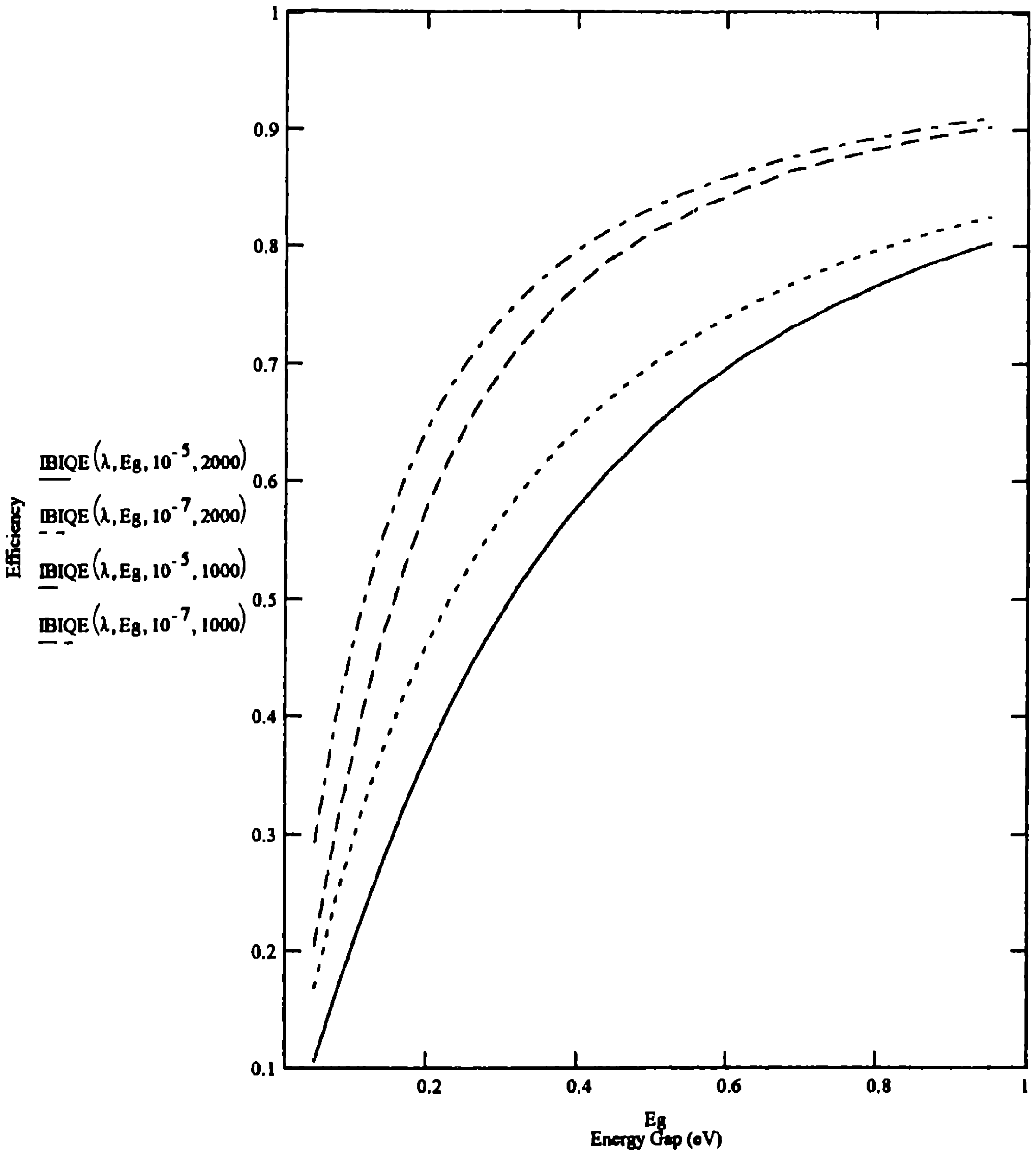


Figure 4.3-1 **In Band Quantum Efficiency vs. Energy Gap (eV) for 1000K and 2000K with Microscale Spacing 0.1 Micron and Spacing at 10 Micron.**

4.3.2 Full Spectrum Efficiency

The total power across the full spectrum received is approximated by

$$\mathrm{ITP}(S,T,\lambda) := \int_{10^{-7}}^{10^{-4}} \mathrm{TP}(S,T,\lambda)\, d\lambda \qquad . \qquad (4.3\text{-}8)$$

The Full Spectrum Efficiency is therefore given by

$$\mathrm{IQE}(\lambda,Eg,S,T) := \frac{\mathrm{IQEP}(\lambda,Eg,S,T)}{\mathrm{ITP}(S,T,\lambda)} \qquad . \qquad (4.3\text{-}9)$$

Figures 4.3-2 and 4.3-3 show Full Spectrum Efficiency at 1000K and 2000K for specified spacings.

4.3.3 Power Available

The power available in electron-hole pairs formed (IQEP) is given by Equation 4.3-5. Figures 4.3-4, 4.3-5, and 4.3-6 shows IQEP for various combinations of temperature and spacing.

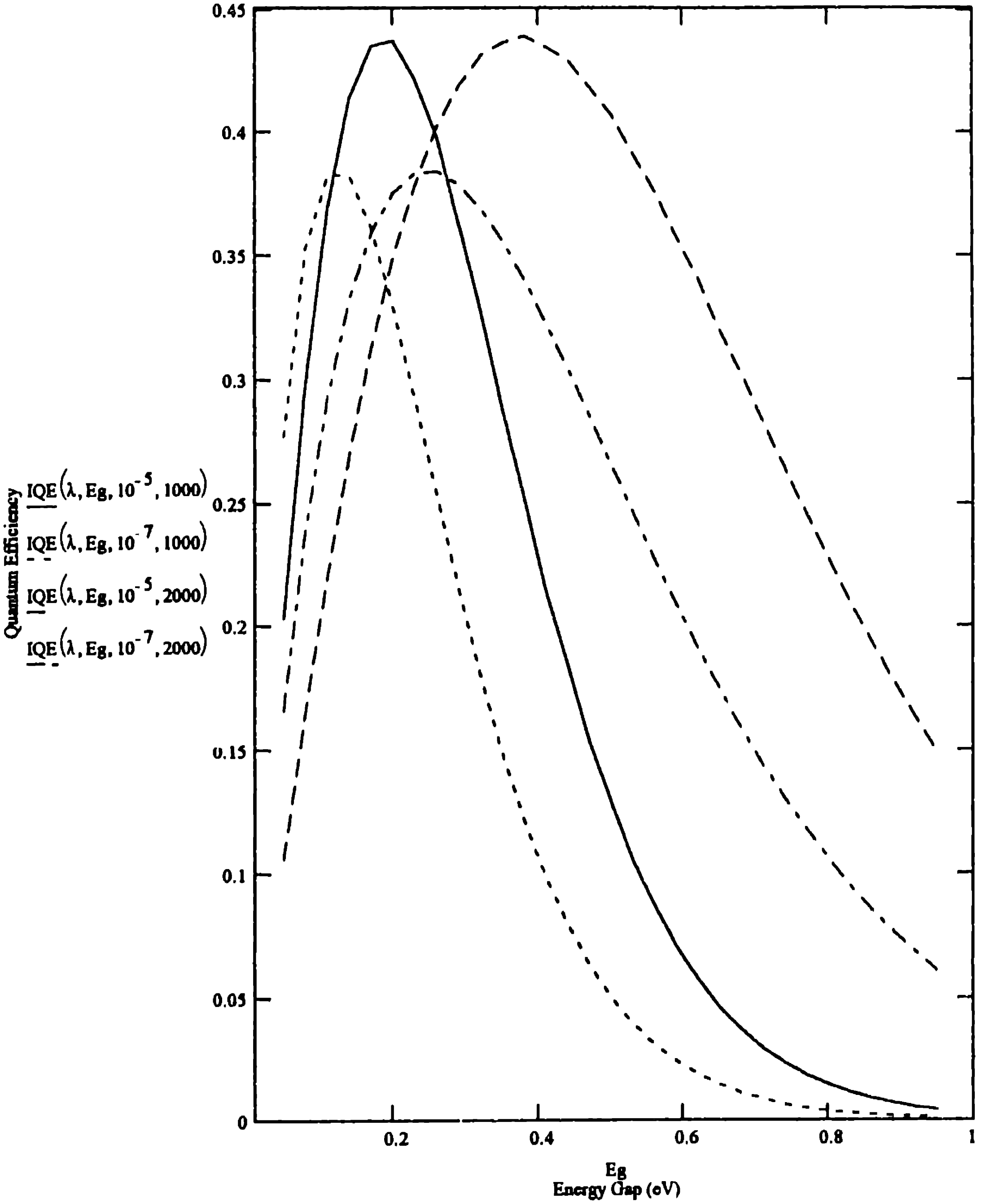


Figure 4.3-2 Full Spectrum Quantum Efficiency vs. Energy Gap at 1000K and 2000K for Microscale Spacing 0.1 Micron and Spacing at 10 Micron.

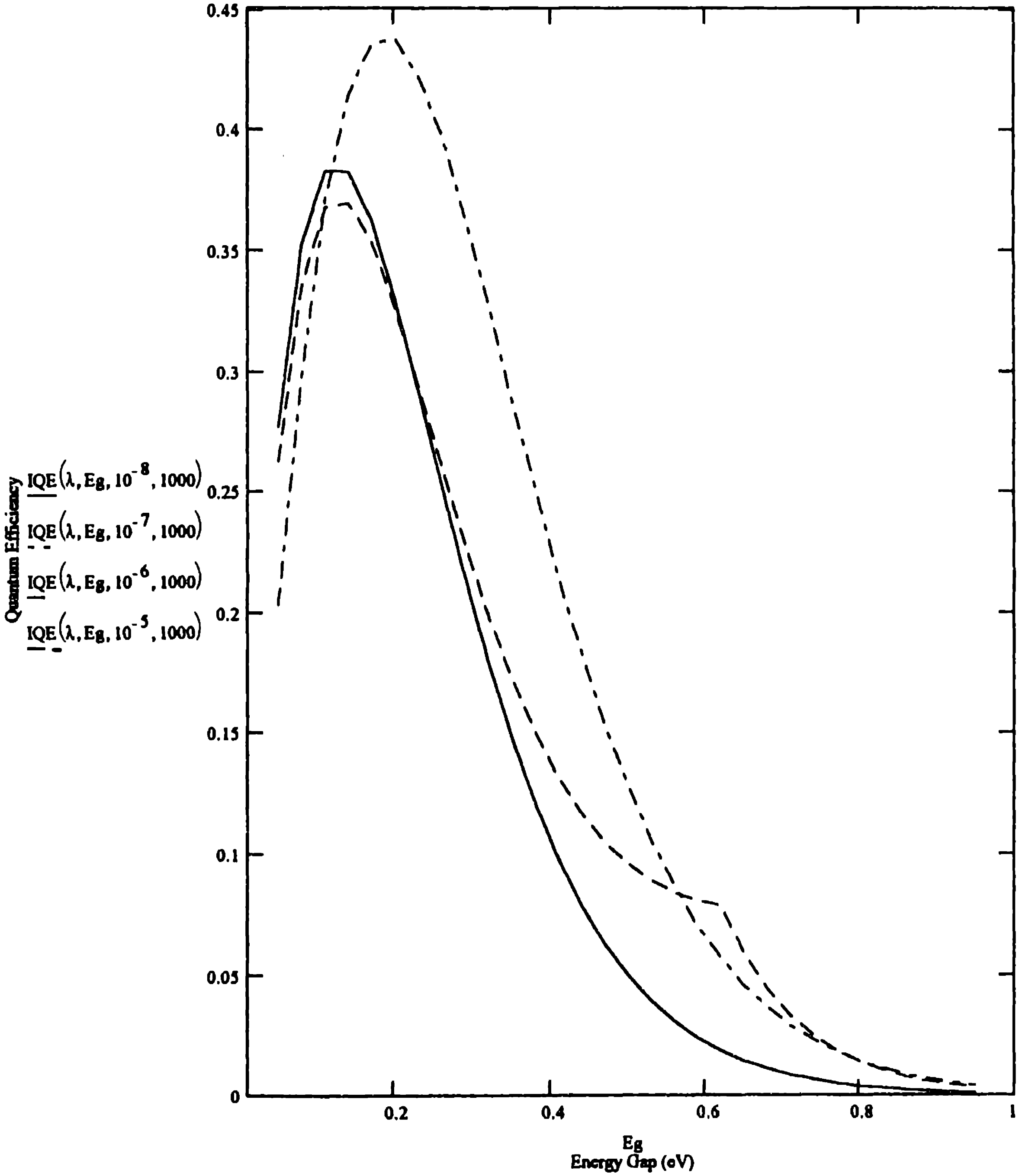


Figure 4.3-3 Full Spectrum Quantum Efficiency vs. Energy Gap at 1000K Spacings S = 10 nanometer, 100 nm, 1 micron, 10 micron

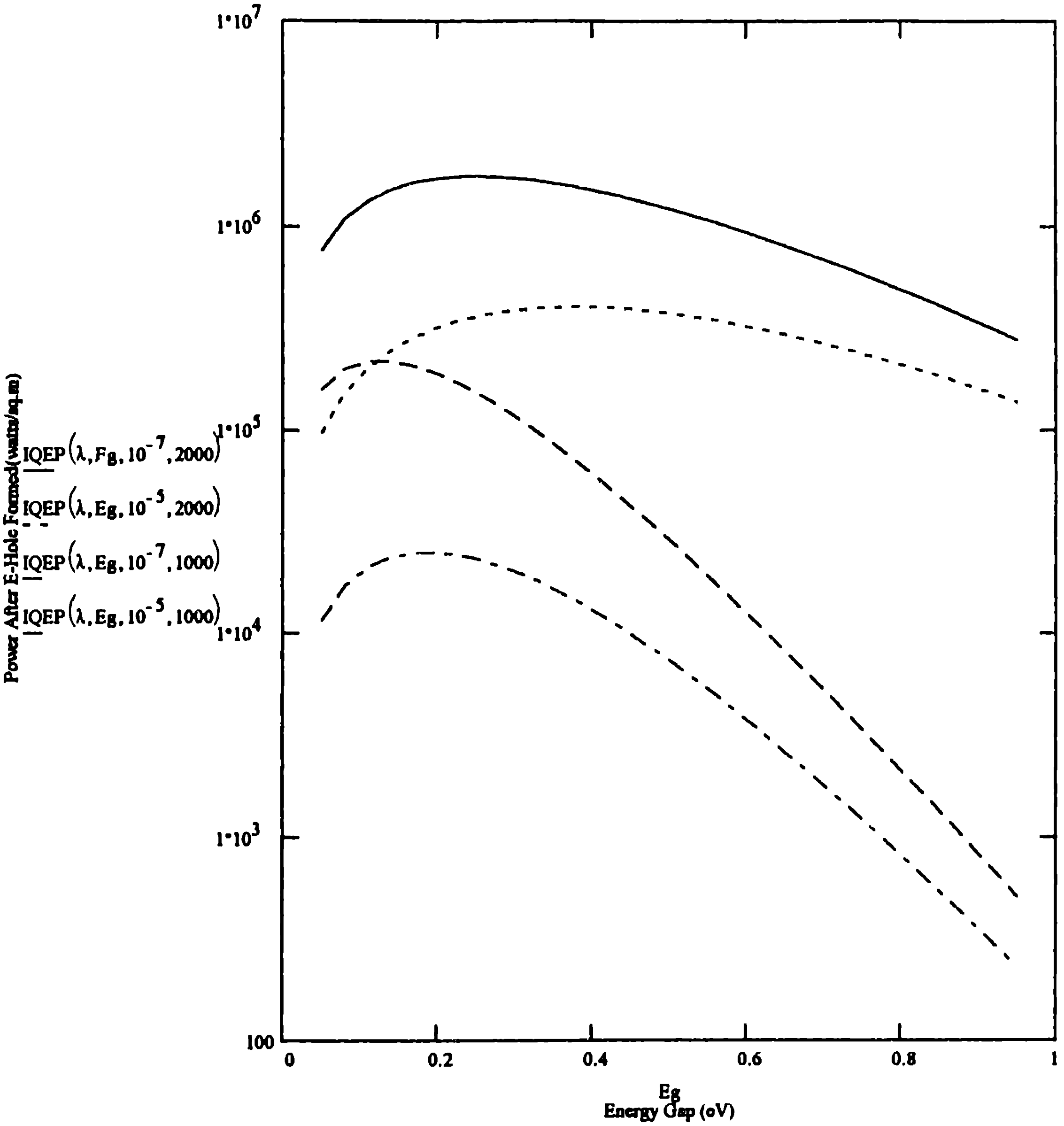


Figure 4.3-4 Power Available After Electron-Hole Pair Formation vs. Energy Gap (eV) for Combinations of Temperature and Spacing

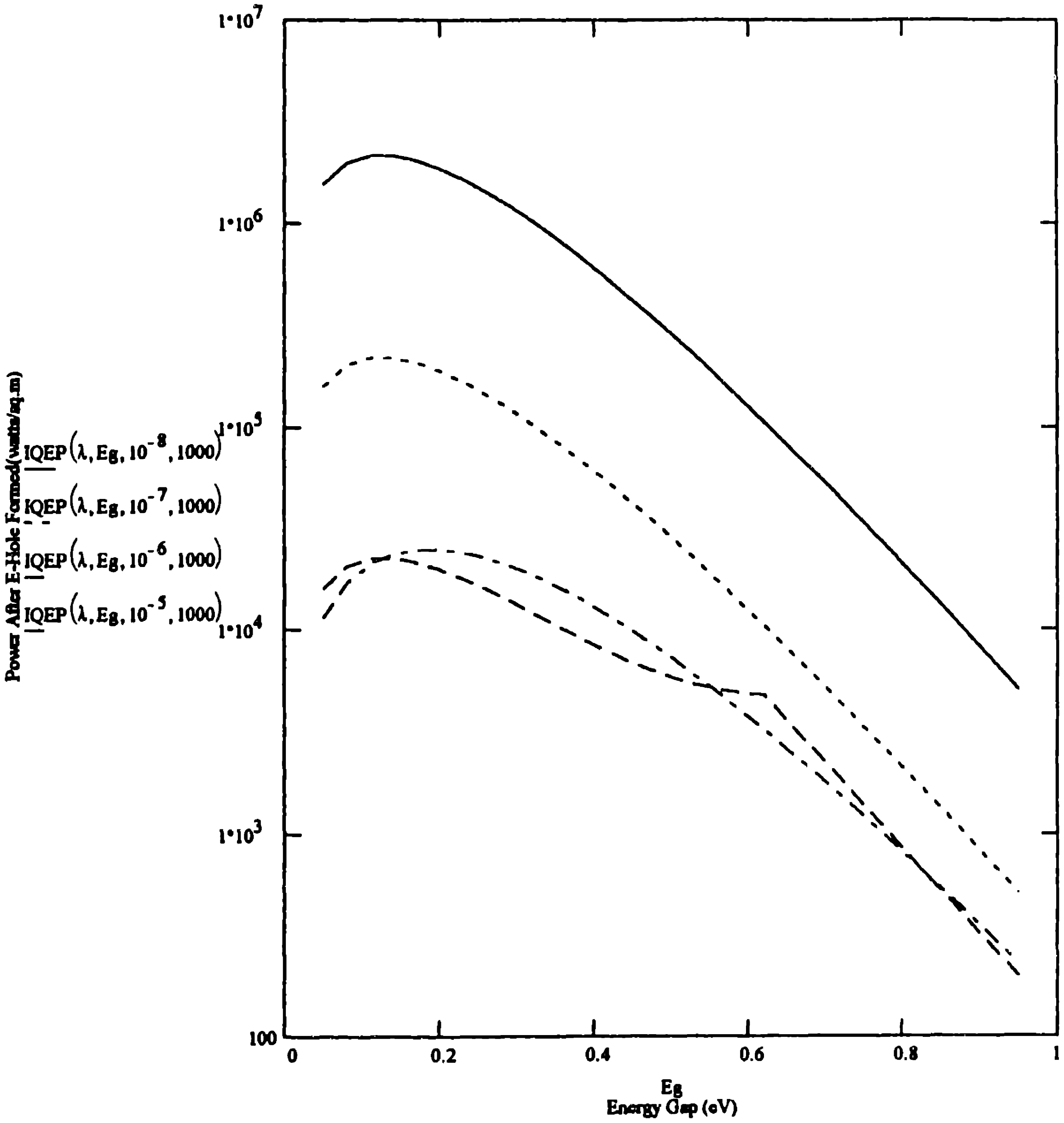


Figure 4.3-5 Power Available After Electron-Hole Pair Formation vs. Energy Gap (eV) at 1000K for Spacings S = 10 nm, 0.1 micron, 1 micron , 10 micron

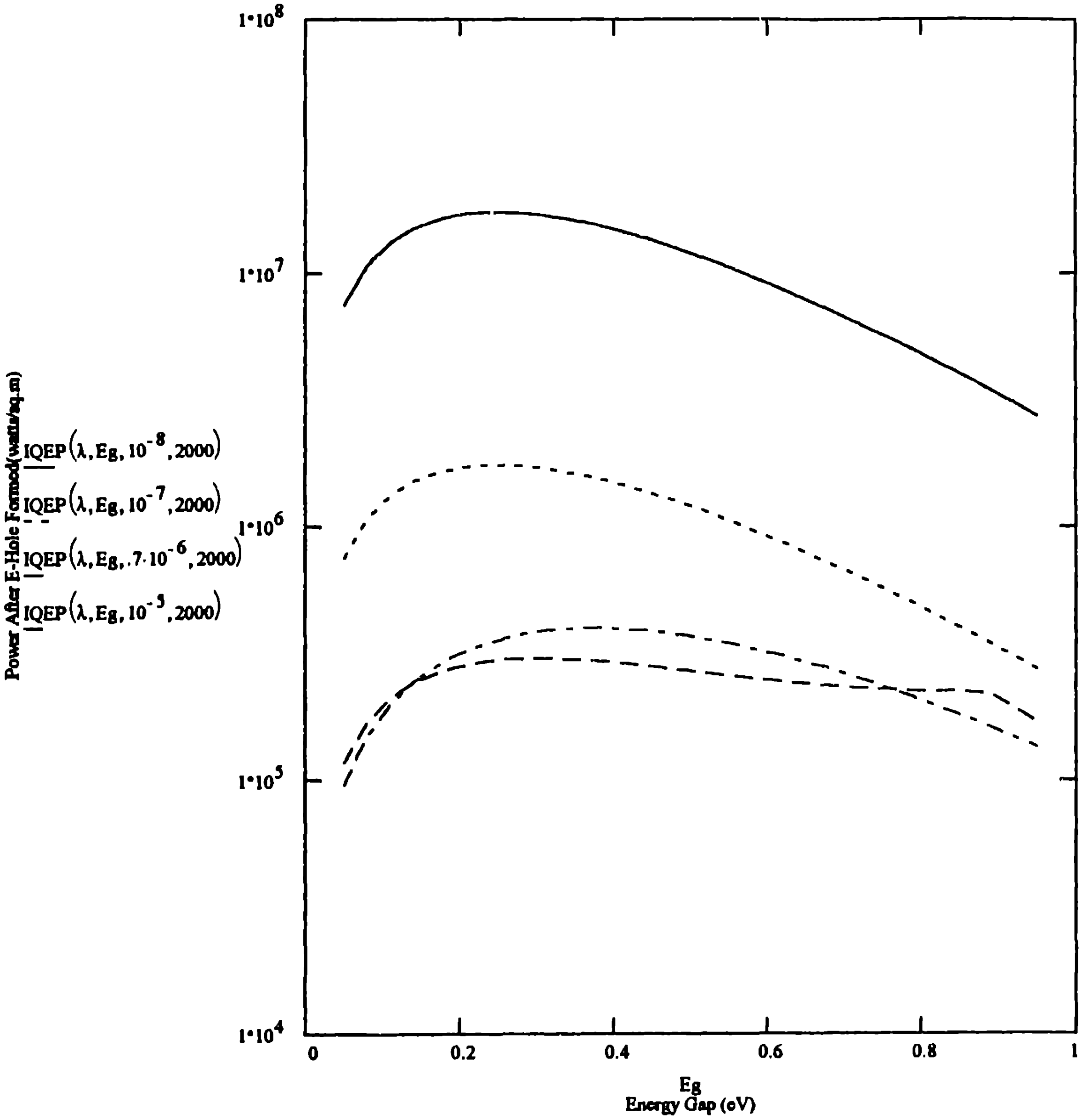


Figure 4.3-6 Power Available After Electron-Hole Pair Formation vs. Energy Gap (eV) at 2000K for Spacings S = 10 nm, 0.1 micron, 1 micron , 10 micron

4.4 Potential Implications of MTPV

Relative to other energy technologies both MTPV and TPV share some common advantages and disadvantages. One of their advantages is the flexibility to operate on renewable energy resources such as solar energy or on nonrenewable resources such as fossil fuels or nuclear power. Both also have the advantage of being deployable in large or small scale applications. Both have the disadvantage relative to for example conventional nonconcentrating Photovoltaics in that they require active cooling.

Relative to TPV, MTPV also has some distinct advantages and disadvantages. Starting with the disadvantages, MTPVs will have micropositioning system components TPVs do not require. Micropositioning technology however appears to be sufficiently developed for at least a first generation of MTPVs. MTPVs will also have large temperature gradients across a vacuum with microscopic dimensions which do not appear to exist in other existing devices. Because of the microscopic spacing required between the Emitter and Receiver any thermally induced geometrical deformations of their surfaces could be problematic. Because of the high power densities in MTPV the lateral dimensions of these surfaces may be kept very small relative to their thicknesses and this fact coupled with the 10 nm and less roughnesses of surfaces which can be produced today suggest that there is a good chance that this problem will be manageable. Finally MTPV will not be able to take advantage of much of the filter technology developed for TPV. MTPV may however have very powerful filtering techniques available to it which are discussed in Section 4.4.1 and which are not available in TPV.

MTPV also has several advantages relative to TPV. Power density is the most obvious with potential watts/sq.cm. of active chip area one to several orders of magnitude larger than TPV as seen in Chapter 3. This power density increase could lead to compactness and possibly reduced specific power (watts output/mass). These attributes could be particularly valuable for deep space probes and for mobile terrestrial applications. For solar conversion applications, MTPV could reduce the cell cost component of overall system cost by reducing the area of cells required. This reduction would be offset by increased micropositioning costs and by potential increased costs due the potential need for higher power density cooling. Therefore increased power density alone will not alone necessarily provide an advantage for MTPV relative to TPV in solar energy conversion with regards to initial system cost. This will likely require improved efficiencies which is currently an open question as the section above shows. Section 4.4.1 below indicates how subsequent generations of MTPVs may yield significant improvements in efficiency.

Modularity is another distinct advantage of MTPV which also derives from elevated power densities. In concentrating solar systems, the active Emitter/Receiver Chip area could be extremely small relative to the area of incident solar radiation being collected. Conventional concentrating Photovoltaic cells have been designed for 1000x concentration (1 kWatt/sq.m = 0.1watt/sq.cm.; @1000x = 100watt/sq.cm.) the major limit is cell heating as the cell is directly illuminated by the concentrated solar radiation. In TPV with the Emitter at 2000K the power density is already nearly this (91.7 watt/sq.cm.) without any Microscale effect. With MTPV at ex. 100x Planckian, it would take an Emitter/Receiver chip pair with an active area of 2cm x 2cm to absorb all the solar radiation from 39 sq. meters (38.5 kWatts; ex. a 7 meter diameter parabolic concentrating reflector such as the one in Figure 6.2-1). If the Polder and Van Hove model applies then this chip area could be reduced by another two orders of magnitude.

Even at an MTPV chip size of 2cm. by 2cm. (comparable to the size of Intel's Pentium microprocessor) as the chip technology improved and the efficiency of the MTPV chip pair increased, the old chip pair could be taken out and the new chip pair put in its place potentially without any other system changes. (For example since the cooling capacity would have been sized for the original efficiency it would be larger than necessary for the new increased efficiency chip set. This presumes that the power out bus and power conditioning circuitry could handle the increased electrical power output. Given the increasing microelectronic integration and decreasing cost of power conditioning capacity initial sizing to accommodate this would appear to be a reasonable presumption.)

Because of the increased power density and corresponding decrease in cell area, though initial solar conversion system costs may not be reduced without efficiency gains, the cost of upgrading an existing system should be substantially reduced. This should enable much more sophisticated microelectronic cells than would be possible with TPV or conventional concentrating PVs.

4.4.1 MTPV as Window into Microelectronic Energy Conversion

Figure 4.4-1 shows channels etched orthogonally into the surface of a silicon wafer. Figure 4.4-2 shows the spectral emittance from four variations of this modulated silicon surface. Increased spectral emittance by surface roughening is well known. The structure on these curves (ie. the peaks at particular wavelengths) exist at the macroscale where these measurements were made. [Hesketh, et.al., 86] It appears likely therefore that these effects seen at the Macroscale should also manifest themselves at the Microscale. That is to say that this spectral modulation should become a function of lateral position in the Microscale regime. Similarly if instead of being etched, lines were doped into the surface of the wafer, this should have a similar effect. If the samples (both etched and doped) were infinite in the lateral direction parallel with the channels, then the spectral density function should vary as a function of position perpendicular to the channels but not parallel to the channels.

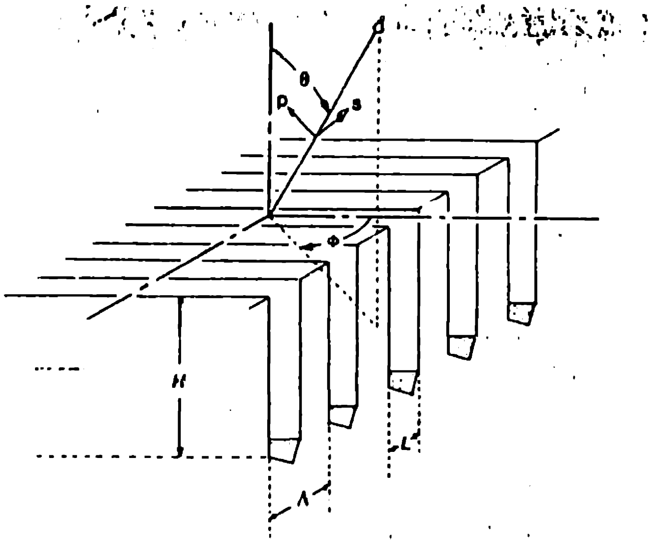


Figure 4.4-1 Etched Silicon Wafer Surface for Fig. 4.4-1 Measurements.

(Source: Hesketh et.al. 86, p.550)

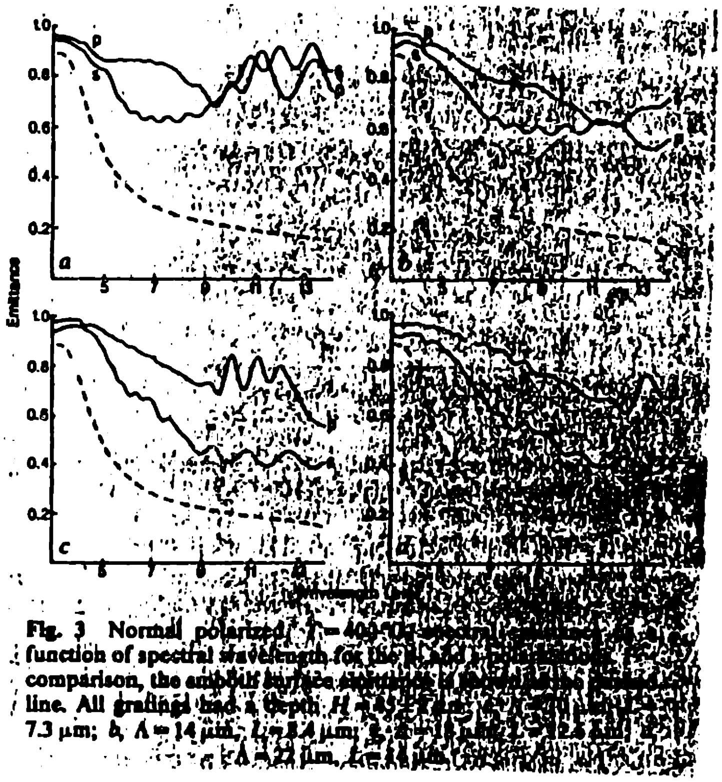


Figure 4.4-2 Spectral Emittance for 4 Configurations of Fig. 4.4-1.

(Source: Hesketh 86, p.550)

If instead of channels a grid were formed either by etching or doping then there would likely be spectral modulation as a function of position in both lateral dimensions. This would likely become even more pronounced if on a flat smooth surface an array of quantum dots was created inside of which only discrete energy levels can exist. It seems likely that spectral composition would then change significantly while moving laterally in both dimensions at Microscale spacing distances. It appears that all of these questions are open for answers and they represent an as yet unexplored domain of science and technology. The spatial variation of spectral composition may be able to be used to increase the efficiency of an MTPV device. In addition to Microscale spacing the MTPV Emitter/Receiver surfaces would themselves become microeletronic devices with micro receivers matched to the spectrum emitted from the micro Emitter region opposite it. This configuration could be referred to as Microscale Microelectronic Selective Emitters/Receivers and may be referred to more generally as Microeletronic Energy Conversion (MEC).

There may then be a natural progression from one dimension, MTPV, ie. controlling the distance between two surfaces, to three dimensions wherein in addition to the Microscale spacing, the properties of the surfaces as a function of the two lateral dimensions are also controlled. Further additional dimensions could be added perpendicular to the surfaces as the spectral composition of Microscale Radiative Energy may change as a function of depth from the surface which may be able to be utilized in some way ex. as it is in conventional tandem PV cells. In summary if x and y are in the plane of the Emitter and Receiver chip surfaces and z is perpendicular to them, then the degrees of freedom are: z between the chips (including z=0), z within one or both chips, x and y within one or both chips, and x and y of one chip relative to the other.

It appears that little work has been done to date to explore the potential of using the microelectronic ability to configure matter at the atomic level in order to harness the "seething" electronic activity which exists continually at this atomic level, and which manifests itself as Electronic Noise and as both Macroscale and Microscale Thermal

Radiation. [Fonstad, 94, p.17] This absence of work in this domain is of course no guarantee of success. The primary work in this domain done to date of which this author is aware is by J.C.Yater [Yater ex. 77 and 94] but it is not clear to this author precisely how this work relates to MTPV and MEC described herein. Also related to a limited extent is the work by Horne on microfabricated selective filters discussed in Section 2.3. [Horne et.al., 96]

Indeed much of this section 4.4.1 is speculative. But what is not speculative is the work reviewed in Chapters 2 and 3 on TPVs and Microscale Radiative Transfer which together leave the MTPV concept as a scientific and technological question that is both well founded and experimentally accessible (as described in Chapter 5) and therefore worthy of pursuit. As such, MTPV could then become a window through which to see, or an entree from which to begin to assess, the potential of the more general domain of Microelectronic Energy Conversion.

CHAPTER 5

Experimental Design for Microscale Radiative Carrier Enhancement

This chapter presents the preliminary design for an experiment to demonstrate Enhanced Semiconductor Carrier Generation Via Microscale Radiative Transfer. If MTPVs are to become feasible energy conversion devices, microscale radiative transfer must be capable of generating excess carriers as is the case with macroscale radiative transfer. If this is the case then the substantial increase in energy transfer at the microscale could then likely be utilized for similarly high power density devices. This experiment focuses on the enhanced carrier generation by measuring photoconductivity modulation by changing the spacing between two surfaces at microscale dimensions.

5.1 System Design

A semiconductor photoconductor patterned into a serpentine resistor at a lower temperature Tr will be brought into close proximity with an opposing surface parallel to it and at an elevated temperature Te. The spacing between the two surfaces S will then be oscillated between preselected minimum and maximum values. If this range of S values is in the microscale regime then the energy transferred, and therefore the excess carriers generated, and therefore the resistance of the photoconductor resistor R, should all oscillate with the oscillations in S. On the contrary, if macroscale radiative transfer were the controlling energy transfer mechanism then R would not be a function of S. An output of R as a function of S would therefore a) serve as further experimental evidence of microscale radiative transfer and b) demonstrate that this energy transfer mechanism can be used to generate excess carriers.

The experimental apparatus must then satisfy a number of requirements. It must have an energy gap tuned to the microscale radiation. It must be done in a vacuum to minimize heat transfer through conduction and convection and to minimize atmospheric interaction with high temperature surfaces. The vacuum will also reduce the gap contamination probability. The Emitter and Receiver surfaces must be sufficiently flat and smooth to allow them to be oscillated relative to one another with spacing down to at least 0.1 micron and ideally down to 0.01 micron (=10 nanometers = 100 Angstroms). Lack of smoothness or flatness could render it impossible to have a spacing value with meaning at these values of S. This parallelism must be maintainable during oscillations and the apparatus must be capable of causing the oscillations.

The smaller the Emitter and Receiver surfaces the lower the probability of contamination being present between them. Smaller lateral dimensions also make the experiment less sensitive to surface anomalies thereby allowing smaller S values before surface contact. This becomes especially critical due to the extreme thermal cycling both the surfaces (and especially the Emitter) will undergo. The Emitter will likely cycle between 300K and 1000K (though higher would be desirable) and the Receiver will likely cycle between 77K and 300K. Another secondary advantage of small size, that could facilitate much greater experimental efficiency, is that it increases the ability to move from one Receiver to another on the same chip without breaking the vacuum for each set of measurements on a specific Receiver.

The minimum limit on the Emitter and Receiver designs is that the Receiver resistance R should be maintained above several hundred ohms throughout all measurement regimes. This is described further in Section 5.2 below. The minimum size is also set by the practical consideration of the photolithographic line width achievable which is a function of the processing equipment available. Line widths down to 100A and below have been achieved but 1 micron line widths are readily achievable and is the assumed minimum line width for design of this experiment.

Microelectronic processing is carried out in cleanrooms of varying quality. The class of a cleanroom is determined by the quantity and size of particles allowed in the air of the cleanroom. These classes are shown below in Table 5.1-1. For this experiment, it would be ideal to both process the chip sets and to place them in the bell jar and seal it before leaving the cleanroom. Similarly, it would be ideal to break the vacuum only in the clean room. The fact that these precautions may not be feasible is another reason for the small emitter size and for putting multiple individual Receivers on a single Receiver chip.

Fabrication of the Emitter/Receiver chip set must be achievable with readily available microfabrication equipment. The fabrication will require 4 individual masks: Mask R-1, Mask R-2, Mask E-1, and Mask E-2 all of which are described below.

	Measured particle size (μm)				
Class	*0.1*	*0.2*	*0.3*	*0.5*	*5.0*
1	35	7.5	3	1	NA
10	350	75	30	10	NA
100	NA	750	300	100	NA
1000	NA	NA	NA	1000	7
10 000	NA	NA	NA	10 000	70
100 000	NA	NA	NA	100 000	700

Table 5.1-1 Cleanroom Standards: Class limits in particles per cubic foot of size equal to or greater than particle sizes shown (microns)

(Source: Whyte, 91, p. 34)

5.2 Receiver

5.2.1 Semiconductor Material Selection

A semiconductor of suitable energy gap must first be chosen. InAs has an energy gap of 3.5 eV which as shown in the prior three chapters is an energy gap useful for the 500K to 2000K emitter temperature range. InAs is the material used for this experimental design for the above reason and because of the practical, logistical consideration that it can be grown on available Molecular Beam Epitaxy (MBE) equipment at MIT. InAs can be grown on insulating GaAs which is readily available. Due to lattice mismatch dislocations will exist in the InAs lattice but the InAs quality should be adequate for this experiment since it is modulation of its photoconductivity and not its absolute value that are necessary to measure.

5.2.2 Receiver Chip Layout and Topography Design

The resistance R = R(S) of a Receiver will be a function of the microscale radiative transfer carrier generation rate, the carrier lifetime in the InAs, the temperature of the InAs which will determine the background intrinsic concentration, and the doping level of the InAs.

In Auger recombination the, the excess energy released upon recombination is transferred to majority carriers. This process is very fast compared to other recombination mechanisms and thus conservative values for carrier lifetime are obtained when based on Auger recombination. These lifetimes are a strong function of carrier concentration as would be expected from the increased interaction probability at higher injection levels. Figure 5.2.2-1 shows carrier lifetimes as a function of carrier concentration for InAs. In the regime of interest for this experiment the lifetime as a function of carrier concentration t(n) can be represented by the linear approximation

$$t(n) := \frac{4.9 \cdot 10^{26}}{n^2} \qquad (5.2.2\text{-}1)$$

and is shown as Figure 5.2.2-2. The microscale radiative photon flux Pf is given by

Photon Flux(Pf) = IQEP/Eg $$\mathrm{Pf}(\lambda, \mathrm{Eg}, \mathrm{S}, \mathrm{T}) := \frac{\mathrm{IQEP}(\lambda, \mathrm{Eg}, \mathrm{S}, \mathrm{T})}{\mathrm{Eg} \cdot 1.6 \cdot 10^{-19}}$$ "Photons/sq.m/sec (5.2.2-2)

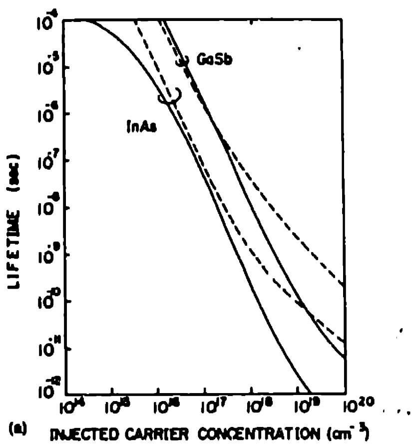


Figure 5.2.2-1 **Carrier Lifetime vs. Injected Carrier Concentration**

(Source: Sugimura, 80, p.4408)

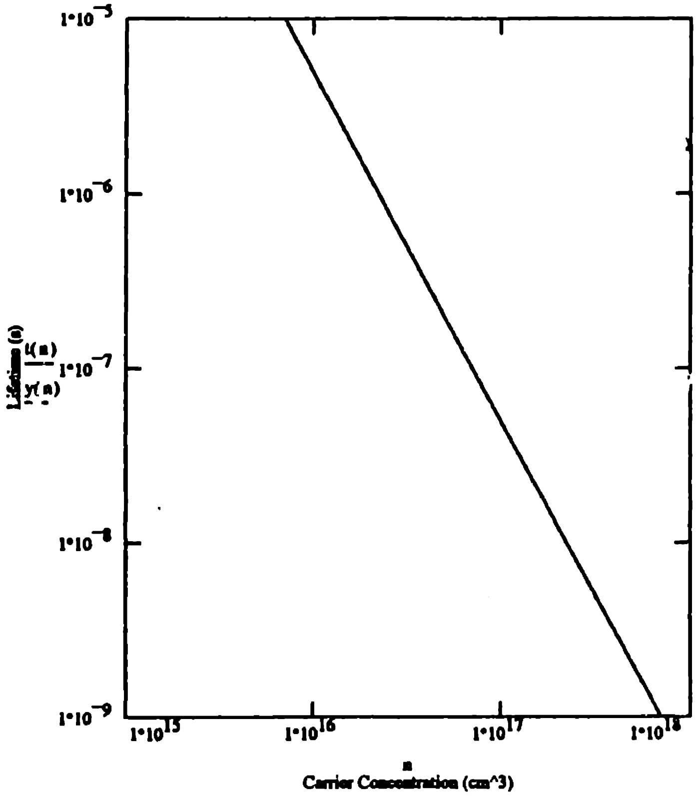


Figure 5.2.2-2 **Linear Approximation of Carrier Lifetime vs. Carrier Concentration in Range of Interest in Figure 5.2.2-1**

Making the approximation a)that the entire flux is absorbed in the 1 micron thick InAs film, b) that generated carriers are evenly distributed throughout the 1 micron film, and c)that the intrinsic carrier concentration and the doping concentration are much less than the microscale radiative generated carriers, the carrier concentration is then given by

$$n(\lambda,Eg,S,T) := \left(4.9\cdot 10^{26}\cdot Pf(\lambda,Eg,S,T)\right)^{\frac{1}{3}} \quad \text{carriers/cm\^{}3} \qquad (5.2.2\text{-}3)$$

Figure 5.2.2-3 shows the carrier population (concentration) at various values of S as a function of the Emitter temperature. The three horizontal lines show the intrinsic carrier concentration (ni) for Receiver temperatures of 300K, 350K, and 400K. These values are given by equation 5.2.2-4 which is an approximation for InAs between the temperatures of 350K to 900K. [Landolt & Bornstein, 87, p.120]

$$ni(Tr) := 2.14\cdot 10^{15}\cdot Tr^{\frac{3}{2}}\cdot e^{\left(-\frac{0.47}{2\cdot k_e\cdot Tr}\right)} \qquad (5.2.2\text{-}4)$$

The conductivity of the semiconductor is given by

$$\sigma := q\cdot\mu_n\cdot n + q\cdot\mu_p\cdot p \quad =1/\rho \qquad \text{(ohm-cm)\^{}-1} \qquad (5.2.2\text{-}5)$$

Using values for $\mu_n$of 2*10^4 sq.cm/Vs and for $\mu_p$of 200 sq.cm/Vs it is clear that Equation 5.2.2-5 can be approximated by the first half $\sigma := q\cdot\mu_n\cdot n$. If the Emitter temperature were 2000K and S were 10 nm, the carrier concentration would be 5.2*10^17 and the conductivity would be 1670 (ohm-cm)^-1. On the other extreme if the Emitter temperature were only 300K and S were macroscopic (ex. 100 microns) then the microscale radiative carrier concentration would be 1.3*10^15 and the conductivity would be 4.2 (ohm-cm)^-1. Using this bracket of values the Receiver resistor length can be determined and therefore the overall lateral dimensions of the active area of the Receiver which will therefore also be the active area of the Emitter. R is given by

$$R := \frac{\rho \cdot L}{A} \qquad (5.2.2\text{-}6)$$

where L is the length and A is the cross-sectional area of the resistor. Assuming the cross-section is 1 micron thick by 1 micron wide, for the maximum design conductivity of 1670 (ohm-cm)^-1 and for L = 50 microns, R=300 ohms. The maximum design conductivity of 4.2 (ohm-cm)^-1 would yield R=0.12 mega-ohms. Both these values are readily measurable and therefore L=50 microns will be used. With 1 micron spacing between the 1 micron wide InAs linewidths, the serpentine pattern would fit within an area approximately 10 microns by 10 microns.

Four discrete metallic capacitors would be formed around the resistor. They will each form parallel plate capacitors with the Emitter. The capacitance is given by

$$C := \frac{\varepsilon_o \cdot A_c}{d_c} \qquad (5.2.2\text{-}7)$$

The Hewlett Packard Precision LCR & Resistance Meter HP 0.01 femtofarads to 999.999 microfarads. If the Receiver capacitor plates are 100 micron x 100 micron then at a distance of 40 mils (0.04 inches), the capacitance would be 0.09 femtofarads and would increase to 0.9 femtofarads as d was decreased to 4 mils equals 101 microns. This plate area would thus provide a capacitance window for navigating the two surfaces for alignment and spacing S.

The capacitor plates could be even with but could not exceed the thickness of the InAs in order to prevent physical interference. The Receiver chip could have as many individual Receivers on it as the chip package pin out would allow. Each individual Receiver would require 6 leads (2 for the resistor and 1 for each of the four capacitors). The InAs would either be widened or doped more highly so that the only the active area of the resistor would control R.

The InAs will form leads of higher conductivity by doping or by larger width so that they will dominate R but so that the serpentine portion will dominate R.

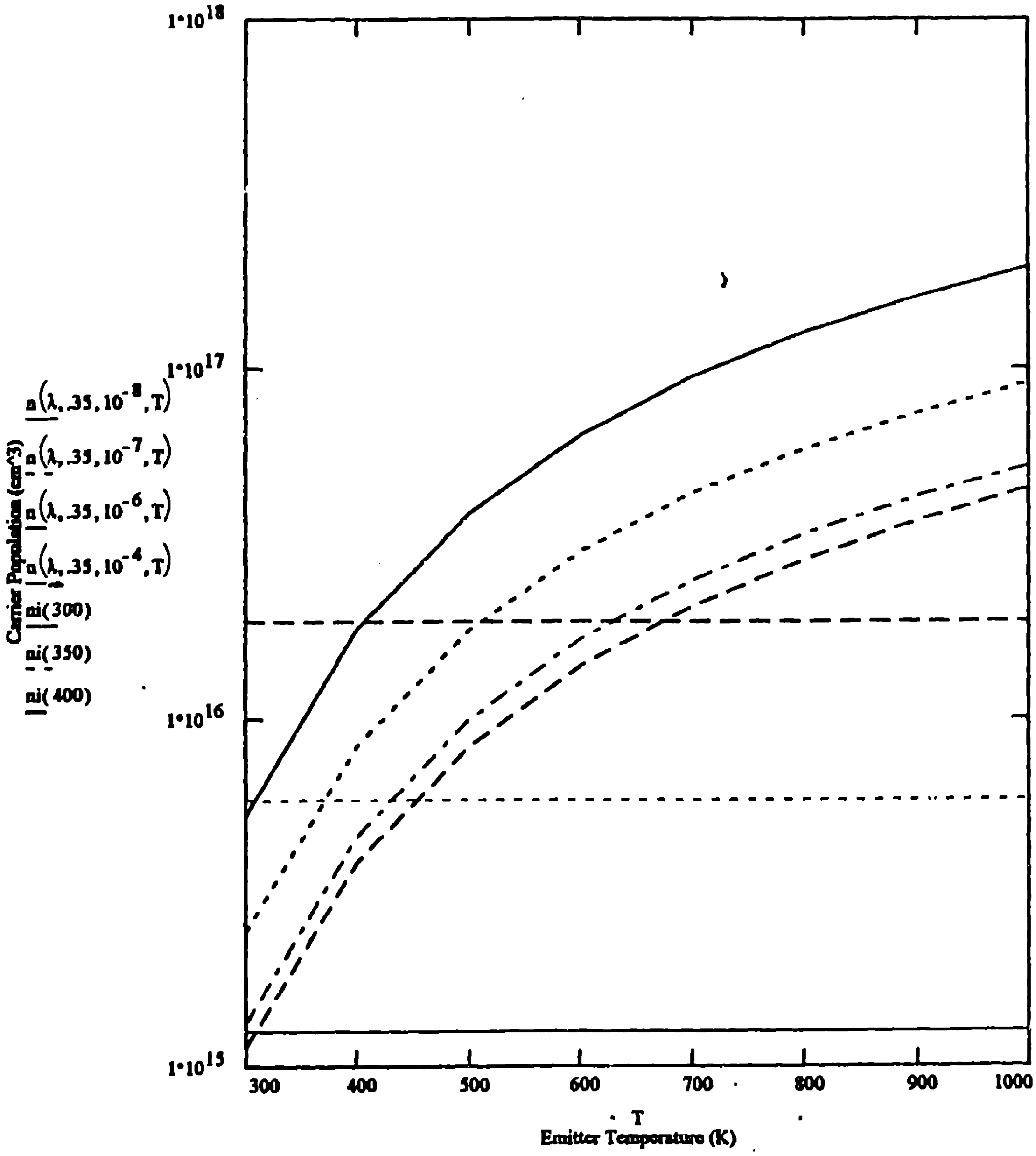


Figure 5.2.2-3 Carrier Concentration vs. Emitter Temperature

5.2.3 Receiver Chip Fabrication

The following is an outline of the Receiver Chip Processing Sequence.

1) Grow approximately 1.0 micron of InAs on an insulating GaAs substrate by MBE
2) Spin Resist
3) Pattern Resist with Mask R-1, Receiver Resistor Mask
4) Develop Resist leaving resist only over desired InAs
5) Etch InAs
6) Remove the Resist and Measure the InAs thickness
7) Spin Resist
8) Pattern Resist with Mask R-2, the Metalization Mask
9) Develop Resist leaving resist only where no metal is desired
10) Deposit Metal (to the thickness of the InAs)
11) Metal Lift-off, Remove Resist thereby also removing metal everywhere it is not needed thereby leaving behind Interconnects and alignment caps. (Confirm that this does not leave above plane burrs.)

5.3 Emitter

5.3.1 Emitter Material Selection

The material of Emitter should be of high emissivity. It appears that this will apply in the interference regime of the Microscale Radiative Transfer, in the Radiation Tunneling regime other material properties may dominate. Only the emissivity is considered here. As will be seen however the Emitter design reviewed herein can be easily modified for a very large variety of Emitter surface materials.

The emissivity of SiC is shown in Figure 5.3.1-1. SiC wafers therefore provide one alternative as the Emitter material. SiC wafers up to 1.375 inches are currently commercially available. The smoothness of these wafers is however currently much less than Si which would make it undesirable for this experiment. Building the Emitter structure out of Si is very feasible but the active surface could not be Si due to its spectral emittance which is low in the required wavelength range as shown in Figure 5.3.1-2. The approach should then be to build the Emitter structure out of Si and then deposit a high emittance material such as Silicon Nitride, which is widely and routinely used in microfabrication, on the Si structure to serve as the active surface of the Emitter. Values of spectral emittance of Silicon Nitride are shown in Figure 5.3.1-3.

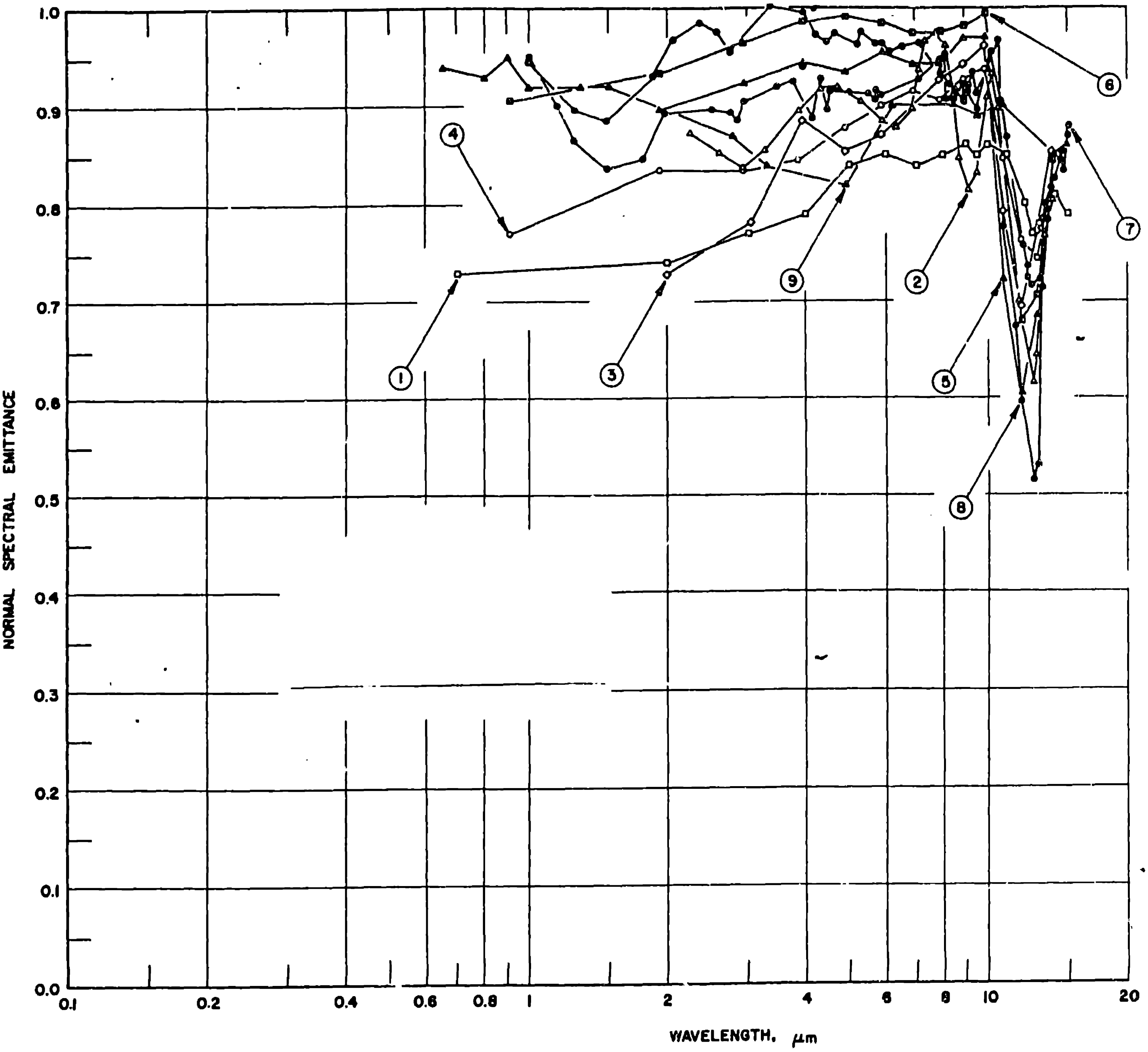


Figure 5.3.1-1 **Normal Spectral Emittance of Silicon Monocarbide**

(Source: TPRC, 72, Figure 295)

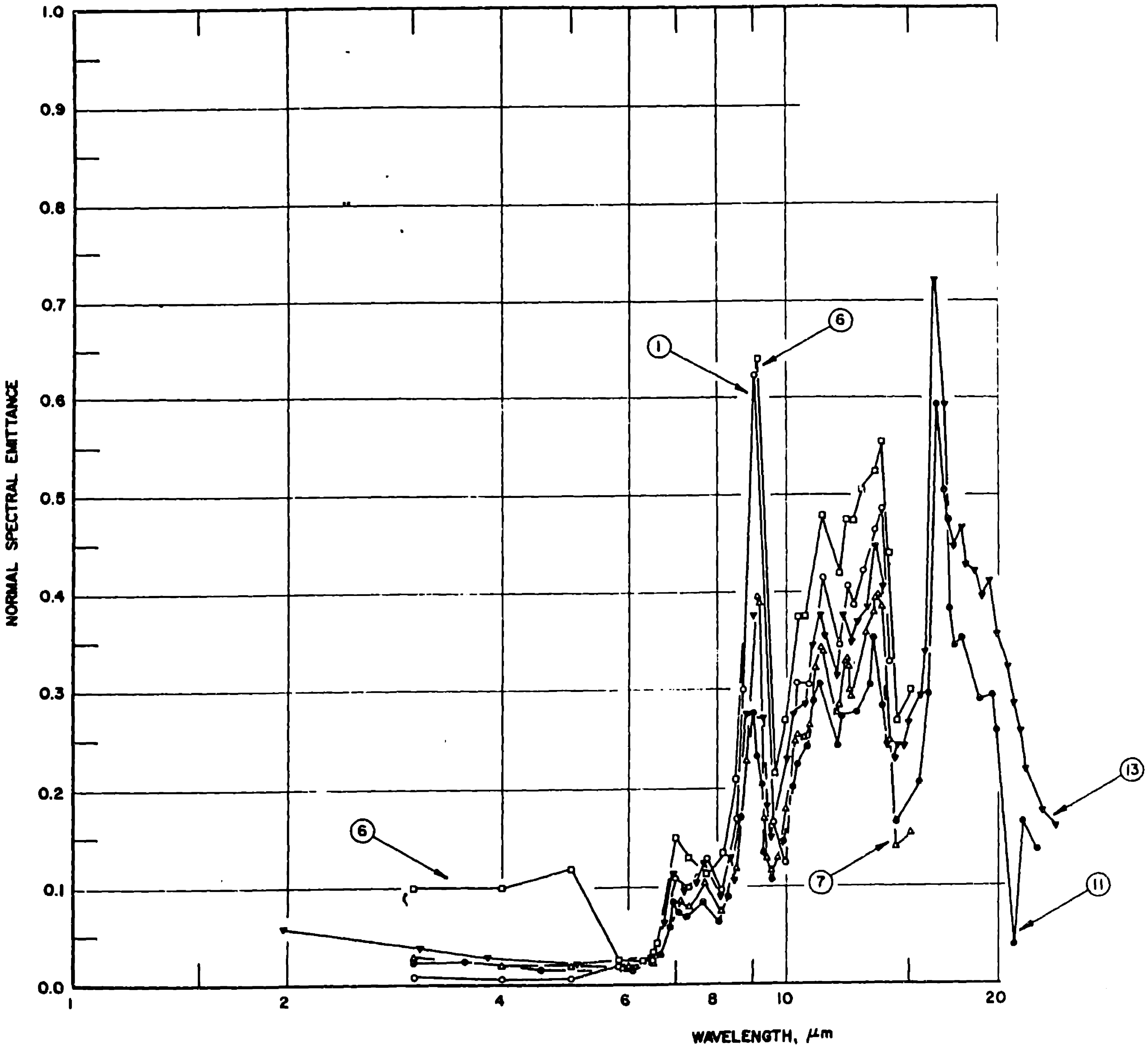


Figure 5.3.1-2 Normal Spectral Emittance of Silicon

(Source: TPRC, 72, Figure 35)

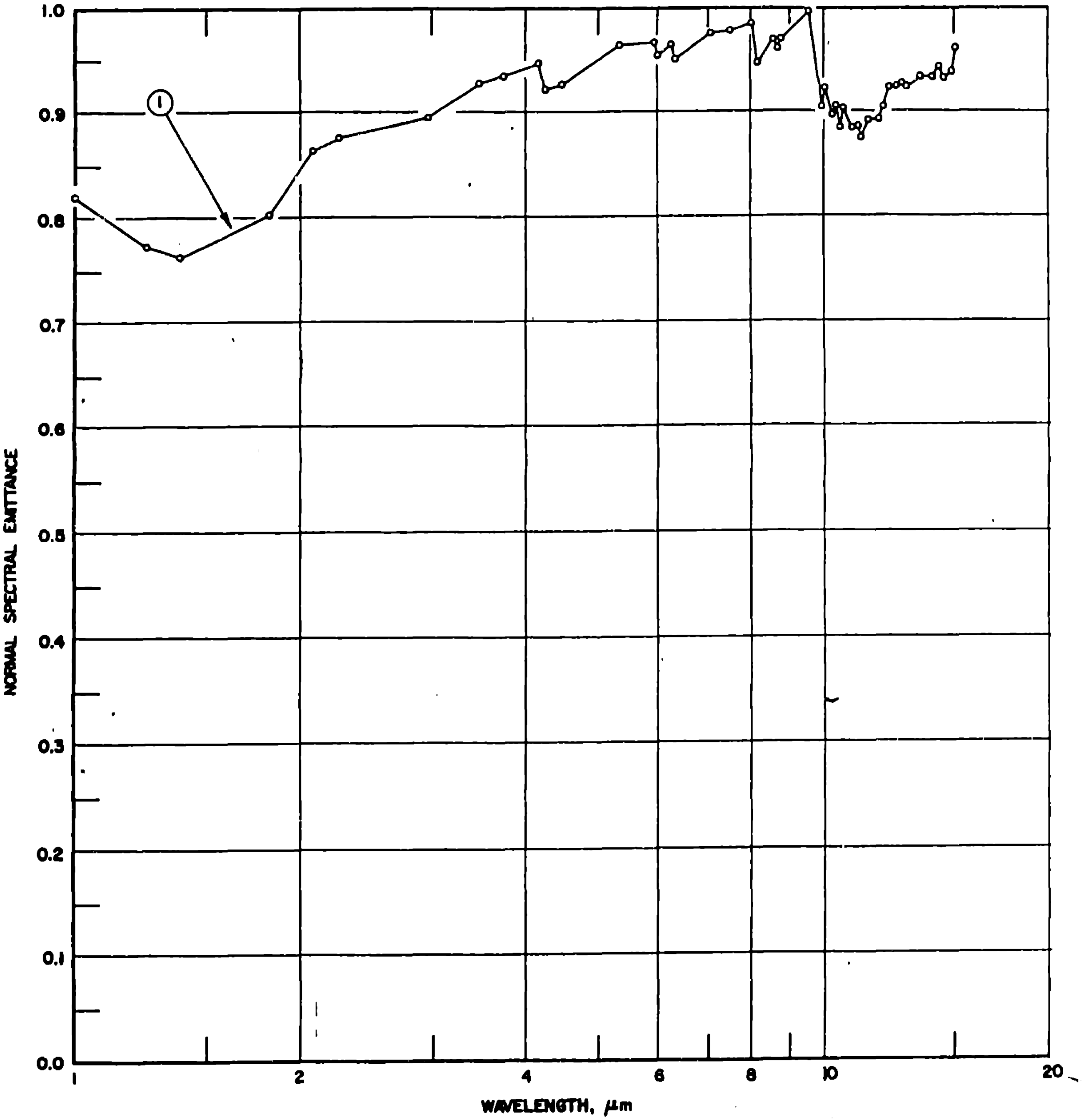


Figure 5.3.1-3 **Normal Spectral Emittance of Silicon Nitride**

(Source: TPRC, 72, Figure 393)

5.3.2 Emitter Chip Layout and Topography Design

The Silicon Nitride radiator surface would be deposited on a mesa which would protrude from the surface by 10 microns. The mesa would be 20 microns by 20 microns. This would provide 5 microns of lateral alignment error between the Emitter radiator and the active area of the Receiver. Five micron misalignment with the 100 x 100 micron discrete capacitor plates on the Receiver would be readily detectable by capacitance measurement. The total lateral area of the Emitter would be 250 x 250 microns with the outside 4 corners aligning precisely with the outside four corners of the Receiver capacitor plates. The Emitter would itself be one capacitor plate which would serve as the opposing plate for all four discrete Receiver capacitor plates. For this reason the Si wafer would be procured with high doping for the conductive path for this plate would be through the wafer, through the brazing material , and through the Emitter support structure.

5.3.3 Emitter Chip Fabrication

The following is an outline of the Emitter Chip Processing Sequence.

1) Spin Resist
2) Pattern Resist with Mask E-1, the Emitter capacitor plate Mask
3) Anisotropically etch 250 x 250 micron Emitter capacitor plates, approx. 500 microns deep leaving the capacitor plates as mesas
4) Deposit Silicon Nitride, 1.8-2.0 microns thick
5) Spin Resist on Silicon Wafer
6) Pattern Resist with Mask E-2, the Radiator (Silicon Nitride) Mask
7) Develop Resist (Only Silicon Nitride Radiators are covered)
8) Remove Silicon Nitride except where resist is present
9) Strip Resist
10) Anisotropically selective etch the Silicon everywhere except under the Nitride, 10 microns deep, thereby establishing Radiator Mesa
11) Remove Resist thereby leaving behind the 20 x 20 micron radiator mesas sitting in the middle of the 250 x 250 Emitter capacitance plate mesas

12) Cut into individual Emitter dies, approximately 2 x 2 millimeters (2000 x 2000 microns) which will be bonded to the end of the Emitter heater and support.

The Si wafer used for the Emitter would be polished on both sides. On one side the Emitter mesa as described would be formed. The opposite side would then need to be fastened by some means to a support structure which would also heat the Emitter. Many alternative designs are conceivable. The method for this design is to braze the Emitter onto the end of the Emitter support and heater which would be machined out of a common, readily available and easily machinable metal such as Cu. Various films of brazing alloys of gold, palladium, and nickel exist which exhibit low vapor pressures in 1 microtorr vacuum and which have melting temperatures well in excess of 1000K. These materials come in 2-3 mil thick films which would be placed between the Emitter and the Emitter support and then placed into a vacuum furnace for brazing. [Marek, 96]

5.4 Positioning Control

Parallelism adjustment is essential if two surfaces are to be ex. 0.1 microns apart. To be within 10% of parallel from one end of a surface to the other this requires adjusting the position of one end relative to the other by 0.01 microns. This is another impetus for small active areas. The larger the active area the greater the precision in tilt rotation to achieve a given end to end parallelism adjustment and the greater the deviation from parallelism from a given angular deviation from normal. For example, for a limit of S=10 nm, and parallelism with 2.5% allowable deviation, with the 10 x 10 micron Receiver active area, the angular adjustment required (x) must satisfy the condition

$$10 \text{ micron} * \sin(x) = 0.25\text{nm} \qquad (5.4\text{-}1)$$

Therefore sin(x) = 2.5*10^-5, x = 5.0 arcseconds = 25 microradians. Piezoelectric controlled leveling stages are currently available which are specified to have angular resolution of less than 0.7 microradians.

This same stage, the New Focus Model # 8095, on which the Receiver would be mounted, has lateral resolution specified at less than 0.03 microns which is more than sufficient for the +/- 1 micron lateral resolution needed for this experiment. Total lateral travel is 3 millimeters (3000 microns). If the 250 x 250 micron Receivers are placed on ex. 500 micron centers (to allow ample space for lead routing), this lateral travel would allow 36 individual Receivers to be placed on a Receiver chip and to be tested without breaking vacuum. This would require a 216 pin chip holder which is readily available.

The Emitter would be mounted to the bottom of the Emitter support/heater which would be mounted to the bottom of a single axis piezo electric linear translator. These are readily available with resolutions down to 1A and below. These can be oscillated over micron displacements up to several kilohertz. One kilohertz would be adequate for this experiment. These can be moved by precise amounts. Since the first derivative of the parallel plate capacitance goes as the inverse square of the distance between the plates, these precise increments of displacement executed by the linear piezo will be used to determine the distance between the plates. Small electrical contact points could be added if required, though this would require additional processing. Each of the four alignment capacitors would be utilized for lateral alignment of the active areas of the Emitter and Receiver, to determine parallelism, and to determine S.

Once alignment and parallelism were established the Emitter would be oscillated relative to the Receiver below it. For example for Te = 1000K, a 200 nm oscillation between S=0.8 micron and S=0.6 micron would modulate R by 8.7%.

5.5 Temperature Control

While the removal of heat from the Receiver could prove to be the fundamental limit on the power density of MTPV devices, particularly at temperatures nearing 2000K, since this experiment will not exceed 1000K, it does not appear that heat removal will be a limiting constraint. When approaching S=10nm, with Emitter at 1000K the highest microscale radiative transfer predicted in the LPR model used in Chapter 3 is 600 watts/sq.

cm., and this would begin to push the limits of heat removal technology. This would occur only in the unlikely worst case scenario wherein all power both below and above the bandgap were absorbed by the Receiver and thermalized. Experimental results have been reported in Si of heat removal rates of 790 watts/sq. cm with a temperature differential between the substrate and the coolant water of 71K. [Tuckerman and Pease, 81] Liquid nitrogen cooling (77K) would be used for this experiment providing over three times this differential. In addition the 20 x 20 micron Emitter chip silicon nitride radiator is the only area of the entire 2000 micron x 2000 micron Emitter chip that will be able to exchange microscale radiation. This is 0.01% of the balance of area which would also have lower emittance. It would still be important to perform a full thermal analysis of this experimental design, both microscale and macroscale though this is beyond the scope of this current thesis.

Though in vacuum, air molecules are still present though in greatly decreased concentrations. Free Molecular Thermal Conduction was evaluated for a 1 microtorr vacuum. [Edwards et.al., 76] For Emitter temperature of 1000K and Receiver temperature of 77K, this thermal conduction would be 1.21*10^-5 watts/sq.cm. which would be a small fraction of the energy exchange radiatively due to the very high temperatures.

The Emitter temperature would be maintained either by a 3,350 micron diameter High Temperature, High Vacuum Substrate Heater or by a fiber optic illuminator, optically coupled by a mirror into the metal Emitter support structure. Though any 60 hertz interference from the former could be filtered out the optical coupling would not require this and would eliminate any harmonics or magnetic effects on the Receiver output due to the heat source. A thermocouple would be placed as close as possible to the Emitter end of the Emitter support structure to provide feedback to the optical or electrical heat source.

CHAPTER 6

Photovoltaics (PV) - Assessment of an Emerging Energy Technology: A Need for MPC Policy, A Context for MTPV Technology.

Grounded in much of the same materials science, and a limited but growing amount of the microelectronic technology, as the semiconductor integrated circuit industry, the conversion of sunlight to electricity by photovoltaic (PV) devices offers substantial potential to provide environmentally sound, cost-effective electric power to users in both industrialized and developing nations. In applications where no electric grid exists, stand alone photovoltaic systems are competitive with fossil fuel based alternatives today. This together with consumer products have been the niche markets where PV has first been commercialized on a widespread basis. Because of the current, apparent, abundance of fossil fuel resources the emergence of PV must be driven, at least in the short term, on the basis of performance and cost.

In some ways this approximately $1 billion (1994) PV industry has already begun to emerge as a market force particularly in these stand-alone, off-grid applications. But even here this is only a very small portion of the potential market. In the case of grid-connected PV, which promises to be the vehicle by which PV technology and prices would be dramatically enhanced, thereby accelerating its growth in all areas, PV has not yet emerged and has occurred primarily in demonstration projects only. Enabling technological and industry precursors appear poised to change this dramatically. Some potential barriers still exist.

6.1 PV Technology Background and Overview

6.1.1 PV, Energy Transitions, and Emerging Technologies

"2001-2010: The New Competitive Era: ... On another front, alternate, decentralized energy sources (long talked about, but always in the future) become economically feasible with new materials and related technologies, thus over time substantially reducing the fuel demands" for conventional energy sources. [Stokke et. al. p.83] So goes one of the scenarios contemplated by Norway's Statoil. Being a major supplier of conventional energy sources, such forecasts are serious business.

The now famous success of Royal Dutch Shell's use of Scenarios Based Planning to anticipate the oil shock of 1973 has highlighted the importance of this strategic planning tool. Yet as critical as it is , it has turned out to be "extraordinarily difficult to achieve in a corporate setting." [Stokke p.74] "There is a reluctance on the part of management to squarely confront the central, long-term challenge facing the firm: namely, the challenge of emerging technologies." [Rappa, 95]

In the energy industry, it is particularly easy to avoid confronting the challenge of emerging technologies. After all "technological forecasters only a few years ago ... envisioned the world of today ... as one where solar cells and nuclear fusion would provide megawatts of pollution-free electricity ... when in fact ... solar electricity still remains too expensive for all but a handful of applications." [Brody Tech.Rev. p.39] With such unreliable predictions from the past, it is understandable, in some cases, why assessments of emerging technologies do not assume the central role they often should. These considerations underscore the importance of the study of emerging technology assessment in general and its relevance to the emerging technology of solar electricity in particular.

Solar electricity is produced by Photovoltaic (PV) cells which convert sunlight directly into electricity. Photovoltaics (PVs) have not been exempt from symptomatic problems that plague technology assessments. Proponents of PV have been "likely to overestimate the size of the market in the near term." Antagonists have been "likely to underestimate the size of the market in the long term." Market consultants have 'ably provided estimates to confirm their clients expectations". [Rappa, 95] The goal of this chapter is to navigate around the numerous pitfalls, such as these three, which hinder the assessment of emerging technologies; and to offer a balanced, reasoned view of where PV technology has been, where it is today, and what the forces and variables are that will determine which of a number of possible trajectories it is likely to follow in the future. This will serve as a technological context into which MTPV may fit as an improvement on PV technology. It will also serve to illustrate a need which MPCs could help to meet.

6.1.1.1 Alternative Technologies, Dynamic Simulation, and Disruptive Technologies

Building on the work by Fisher and Pry on a substitution model of technological change, Marchetti and Nakicenovic developed a logistic substitution model to study (more than two) competing energy technologies. They found that the energy technologies of wood, coal, oil, gas, nuclear, and solar and fusion could be modelled as "just different technologies competing for a market". The results from their model show the contributions of the various energy sources as fractions of the total market. Because they did this work in 1979 they used a "completely hypothetical model" for solar and high temperature fusion which they combined into a single parameter. To do a full study of the emergence of PV, an accurate model of PV solar would need to be constructed. This would be most informative as the various PV price/technology combinations could then be modelled. In addition to their work, Homer developed a system dynamics simulation model to study the addition to their work, Homer developed a system dynamics simulation model to study the diffusion of medical technologies. Because like many medical technologies, PV has "intrinsic uncertainties that involve more than the rate of adoption", this model would also be well suited for modelling the emergence of PV technology.

The foregoing presumes the steady (though often nonlinear) evolution of existing technologies. However it is important to briefly note the possibility of, as Foster called them "technological discontinuities" which could occur due to breakthrough discoveries. It would be useful to construct a dynamic simulation to model the impact of such a breakthrough.

In a full assessment of the emergence of PV, such "hard uncertainty" [Hauptman and Pope-ps.195+208], and plans to cope with it, would have to be given serious consideration. As Hauptman and Pope point out, the quantitative models discussed above are often inadequate either because of the complexity of using and understanding them or because it is not possible to capture all the interactions and considerations that must enter executive decision making. At a minimum, in a full assessment of the emergence of PV, their model of information processing for technology forecasting by an "adaptive" executive would need to used in conjunction with the quantitative models discussed above to assess the impact of such breakthroughs on the PV technology.

Another model of technological emergence is illustrated below as Figure 6.1-1.

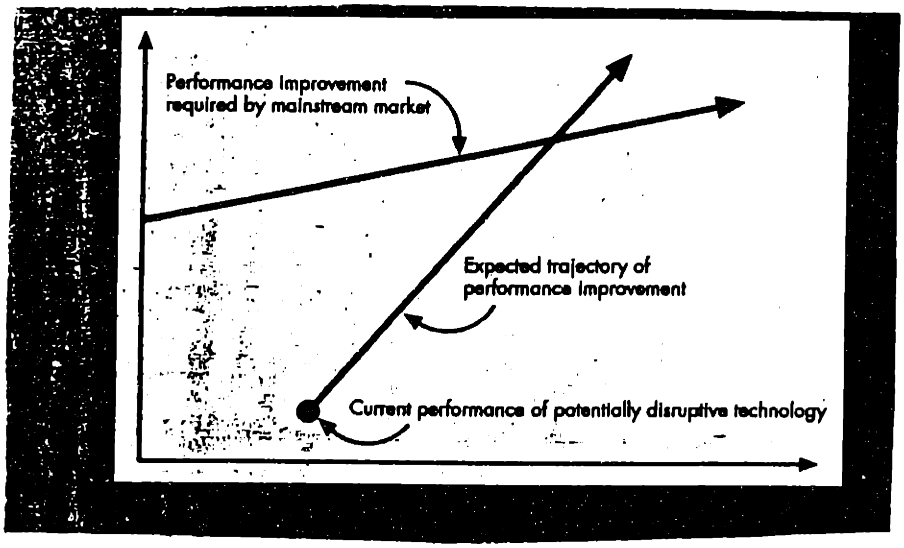


Figure 6.1-1 Performance vs. Time of a Disruptive Technology
(Source: Bower and Christiansen 95, p.49)

In February 1995 Bower and Christiansen published in the Harvard Business Review an article entitled "Disruptive Technologies: Catching the Wave." In it they write, "One of the most consistent patterns in business is failure of leading companies to stay at the top of their industries when technologies or markets change." As depicted in Figure 6.1-1, these technologies start out with inferior performance (combined technical/economic performance). They penetrate niche markets because of unique characteristics. They continue to improve and eventually overtake existing technologies in more major markets.

It appears there are at least three categories of disruptive technologies in Electrical Energy Technologies: 1) Prevalent fossil fueled technologies, of which the combined cycle gas fired turbine has already demonstrated its role as a disruptive technology in the Electric Power Industry; 2) Known but still emerging technologies such as PV; 3) Unknown technologies such as what MTPV could perhaps lead to, ie. unexpected breakthroughs. The context for PV and this thesis overall is characterized by this process of changing dominant energy technologies.

6.1.2 PV Overview

Photovoltaic (PV) devices are an almost pollution free means of converting sunlight directly into electricity. Over the last decade these devices have become commonplace in calculators and wrist watches. These thin pieces of semiconductors, the same materials from which computer "chips" are made, can be assembled into large arrays covering entire rooftops or even larger areas, and can produce useable quantities of electricity.

The industry has been growing rapidly, annual shipments increasing from 1 to 58 megawatts from 1978 to 1992. [Ahmed 94] The total revenue of the industry was approximately $1 billion in 1994. Despite increasing conversion efficiencies and decreasing costs, PV devices are still too expensive to compete with electricity produced by traditional means. This is expected to change as efficiencies continue to climb and costs continue to fall. Policy innovations such as MPC and technological innovations such as MTPV may hasten this change.

The key exception today is stand alone systems. These are typically small systems that have PV modules (panels) integrated with a battery storage system. These stand alone systems therefore do not rely on connection to a conventional electrical transmission and distribution system (the "grid") in order to deliver electricity upon demand.

Where the grid is not available, stand alone PV have now become competitive with diesel electric generators on a cost basis alone without considering environmental externalities which would greatly favor PV. PV therefore holds great and immediate potential for rural electrification in developing nations as evidenced by the fact that PV sales into this market have been increasing at 30% per annum. [Sutherland-95] This has become the biggest market for PV today displacing the still growing markets for specialty applications to provide reliable electric power to remote, off grid sites. These applications include powering satellite and microwave telecommunications sites, Coast Guard buoys, and more recently, temporary highway construction signs as well as remote vacation homes.

With over two billion people in the world currently without electric power the potential market for these stand alone PV systems is enormous. Given its size, PV has barely begun to emerge into this market. The biggest barrier is naturally that these people also tend to be the poorest in the world. There are a number of innovative efforts underway to unlock this large market but which are beyond the scope of this thesis. These efforts will be greatly aided by decreasing costs and improving technologies.

But the big driver of cost will be the emergence of a new scale of PV application, large grid connected PV facilities. A new 100 megawatt PV project recently announced by Enron, a major U.S. gas and IPP firm would bring PV to new levels of economies of scale and will bring the PV industry to new levels of maturity and integration. If it is successfully developed as planned it would deliver electricity at $.055/kWh, roughly comparable to prevailing wholesale prices in many U.S. markets but still slightly higher than prevailing wholesale prices at the project location in Nevada. The reduced panel costs implied by this would benefit both grid connected as well as stand alone applications.

6.1.3 The Solar Resource

Solar energy is the world's largest energy resource. For example, "In less than 40 minutes, the United States receives more energy in the form of sunlight than it does from the fossil fuels it burns in a year."[Johansson et. al. p.213] This is potentially high quality energy since its source, the sun radiates at approximately 5,800K. The Second Law of Thermodynamics therefore could allow conversion efficiencies could reach as high as 91%. Current day devices do not approach this efficiency though this not a fundamental limit.

Table 6.1-1 shows the total solar energy received annually at a number of locations globally. Solar energy that impinges on a surface at or close to the surface of the earth contains two types of light, direct and indirect (diffuse). Direct sunlight emanates from the sun's surface and proceeds in an essentially straight path to the surface. Indirect sunlight is scattered by the atmosphere, clouds, and reflected off objects onto a particular surface. It is, for example, the sunlight we see after the sun has disappeared over the horizon.

The total energy shown in the first two columns of Table 6.1-1 include both direct and indirect sunlight. This is energy that can be converted to electricity by the flat panel technologies (crystalline, poly, and thin film/amorphous). The third column shows only direct energy. Only direct energy can be used by concentrator cells since they rely on the incoming direction of the sunlight. Two axis tracking keeps the panels or concentrators oriented toward the sun during all hours of the day. Fixed orientation insolation is naturally less since the effective area of the panel is only its full size for the brief period of the day when the suns path is orthogonal to the surface. Each of these PV technologies is described in Section 6.2.1

Location	Total, two-axis tracking	Total, fixed at latitude	Direct, two-axis tracking
Albuquerque, New Mexico	3,450	2,530	2,630
Phoenix, Arizona	3,390	2,510	2,520
Almeria, Spain	3,307	2,422	2,582
Zaragoza, Spain	3,293	2,437	2,552
Denver, Colorado	3,100	2,280	2,340
Sacramento, California	2,990	2,190	2,150
San Diego, California	2,720	2,110	1,860
Honolulu, Hawaii	2,580	2,000	1,610
Madrid, Spain	2,549	1,782	1,887
Austin, Texas	2,500	1,910	1,640
Omaha, Nebraska	2,490	1,850	1,680
Nice, France	2,405	1,745	1,790
Brasilia, Brazil	2,397	1,877	1,649
Miami, Florida	2,380	1,870	1,420
Messina, Italy	2,354	1,742	1,706
Rome, Italy	2,288	1,677	1,664
Athens, Greece	2,268	1,678	1,622
Nashville, Tennessee	2,100	1,650	1,280
Pisa, Italy	2,099	1,547	1,492
Washington, DC	2,080	1,610	1,310
Boston, Massachusetts	1,920	1,470	1,170
Manaus, Brazil	1,776	1,430	1,128
Pittsburgh, Pennsylvania	1,760	1,390	990
Seattle, Washington	1,740	1,340	1,020
Stuttgart, Germany	1,729	1,276	1,167
Zürich, Switzerland	1,653	1,220	1,089
Hamburg, Germany	1,497	1,083	977

a. Source for U.S. locations, [14, 15].

Table 6.1-1 Average annual solar radiation resources available to three types of collector (kWh/sq.m) (Source: Johansson et.al. 93, p.374)

6.1.4 Direct Conversion of Solar Radiation to Electricity

Figure 6.1-2 figuratively illustrates the principals by which a PV cell converts sunlight to electricity. This occurs by the presence of two physical entities: a semi-conductor energy band gap and a junction. The band gap in a semiconductor material is a range of energies at which electrons in the material cannot exist. Most electrons in a semiconductor exist below this energy. In order for these electrons to absorb energy, the energy must be of sufficient quantity to excite the electron across the range of forbidden energies. Since light exists as photons of quantized energy, only some photons from sunlight contain sufficient energy to excite electrons across the band gap of the semiconductor from which the solar cell is made. This is why solar cells cannot convert all wavelengths (energies) of sunlight into electricity.

Once an electron has absorbed an electron and has been promoted across the band gap into the conduction band, the junction can spatially separate this electron from the hole (vacancy) from where the electron originated. These electrons can then flow through an external circuit in the form of dc power.

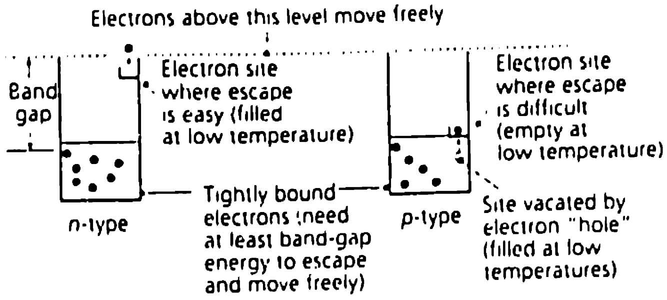


FIGURE A-1: n-type and p-type materials insulated from each other.

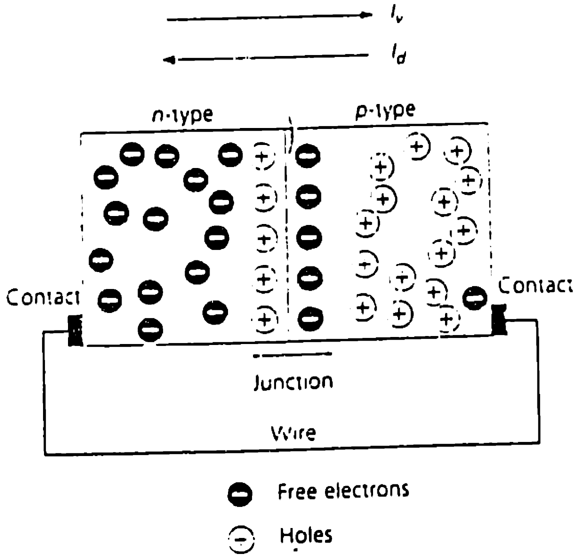


FIGURE A-2: A photovoltaic junction in the dark.

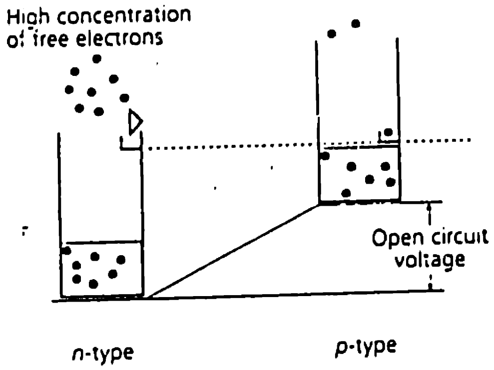


FIGURE A-3: n-type and p-type materials connected at a junction.

Figure 6.1-2 Figurative Operation of Photovoltaic Cell.

(Source: Johansson et.al. 93, p.330)

6.2 PV Technology and Applications

Because of the enormous magnitude of the solar resource as described above, PV holds the promise to promise almost unlimited electricity with virtually no degradation of the environment. Additionally, due to the small, modular nature of PV, it can be deployed very rapidly, and can be configured to produce any level of desired output. This versatility is exemplified by the large variations in applications some of which were described above.

6.2.1 PV Cell Types

PV cells can be grouped into three broad categories. They are 1) flat panel crystalline and polycrystalline, 2) flat panel, thin film amorphous, and 3) single crystalline, concentrator cells. They differ in material and/or processing and/or in configuration.

1) Flat panel crystalline and polycrystalline have been to date the most widely used form of PV for electrical power generation. Crystalline materials are those whose atoms are positioned in an orderly periodic pattern or lattice. They are usually grown from a large reservoir of molten semiconductor starting with a small crystalline seed which initiates the lattice ordering which then perpetuates itself through the entire ingot as it is grown. The diameter of these ingots have grown steadily over time with 8 to 12 inch diameter ingots being commonly grown today. This is an example PV's progress has been facilitated by the enormous progress in the semiconductor industry. These large ingots are then cut into thin wafers, approximately 0.3 mm, doped to form the junction, and then metallized to form a carrier collecting grid. Many of these individual cells are then assembled into flat modules which can then be mounted for use.

Polycrystalline PV cells are very similar to crystalline cells except in two primary ways. As the name suggests they are comprised of many pieces of crystalline material, typically .5 to 4 cm. across, which are cast or extruded into large blocks of sheets. The casting process is much simpler and less expensive than the crystal growth and the grain boundaries do not affect the efficiency of cells excessively. In the other approach to poly crystalline growth the molten semiconductor (typically silicon) is extruded through a die into long thin sheets or "ribbons" greatly minimizing required cutting. Once cut these sheets are then processed and mounted onto flat panel modules similar to the crystalline cells. (This "ribbon technology" as it is called was developed by Mobil Solar which recently ceased operations and was subsequently bought by a German firm.)

2) The amorphous, thin film PV cells are the most common sort found in wrist watches and calculators. Amorphous indicates the random atomic ordering, noncrystalline nature of the material. These thin films are deposited on flat surfaces such as glass and have even been deposited on flexible flat surfaces. They are consequently both much less expensive but also less efficient than the crystalline and poly cells.

3) The single crystalline, concentrator cells are most often made from GaAs though other materials have been investigated including Si. These cells are optimized for low series resistance and high current carrying capacity as they convert concentrated sunlight (typically 5x to 1000x) to dc. Most concentrator cells require active cooling as their efficiency degrades with increasing temperature. Other than the fact that the sunlight is concentrated before hitting the cell these concentrator PV cells operate analogously to the crystalline and poly flat plate modules. Table 6.2-1 summarizes the current and theoretical maximum efficiencies for various types of PV cells.

	Field experience (modules)[a]	Prototype modules	Experimental cells[b]	Theoretical limit
FLAT PLATE				
Crystalline Silicon	10–12[c]	17.8[d]	24.2[e]	30–33[f]
Polycrystalline Silicon	8–9[c]		18.2[g]	
Single-junction a-Si	3–5[c]	5[h]	6[b]	27–28[i]
Multi-junction a-Si	6[h]	8[h]	10[h]	
Mechanically stacked a-Si and CIS			15.6[h]	42[i]
CIS		11.1[j]	14.8[j]	23.5[k]
CdTe		10.0[j]	15.8[j]	27–29[k]
CONCENTRATORS				
GaAs		22[l]	28[l]	
GaAs on GaSb			34[m]	

Table 6.2-1 Photovoltaic Cell Efficiencies (Source: Johansson et.al. 93, p.301)

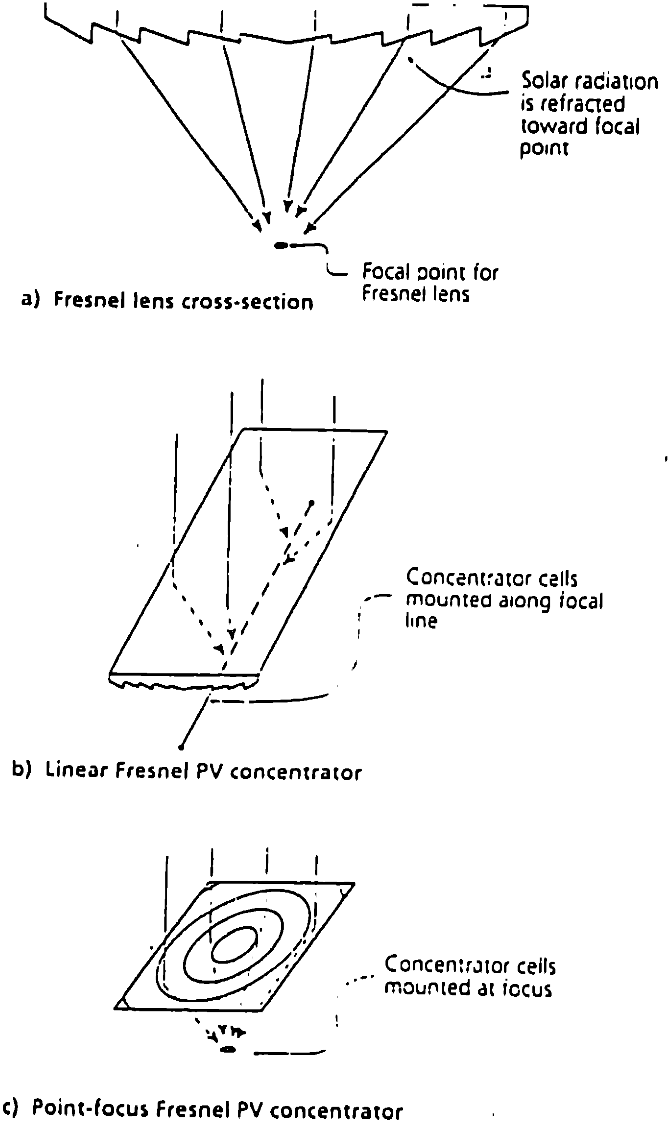
6.2.2 PV Systems and Compatibility with Existing Technological Infrastructure

Most PV systems can be characterized by two features, one characteristic from each of the two following pairs: stand alone vs. grid connected and concentrator vs. flat panel. The distinction between flat panel and concentrator systems are shown in Figures 2 a+b. Flat panel systems are flat. Both direct and diffuse sunlight hit the PV module directly. The semiconductor materials that comprise the PV cells cover almost the entire flat area of the module. In the concentrator systems, only direct sunlight can be used.

The sunlight is focused or reflected onto a small, highly specialized PV cells. Two primary methods exist to concentrate sunlight: fresnel lenses or reflective surfaces. Variations on each are shown in Figure 6.2-1. Concentrating systems benefit from the reduced cell areas required which are approximately inversely proportional to the level of concentration. As discussed in Section 4.4 MTPV could provide further cell area reductions.

The primary existing technological infrastructure directly affecting PVs emergence is the electrical grid. In grid connected systems the PVs are connected to a distribution grid through an invertor and power regulator. No electrical storage is therefore required. As mentioned prior, stand alone systems do not require connection to an electrical grid as they contain electrical storage typically in the form of batteries. Experimental systems have been developed and operated which electrolytically convert the electricity to hydrogen which is stored. Upon electrical demand unmet by the PV output the hydrogen is converted to electricity by fuel cells.

Where the grid is pre-existing connecting to the grid is much less expensive than providing for storage so although in the future storage may become an option for grid connected systems, in the near term, storage will generally not be provided for grid connected systems. PV is a "nondispatchable" power source. In other words it cannot be turned on at anytime. There must be daylight or PV modules cannot generate electricity.



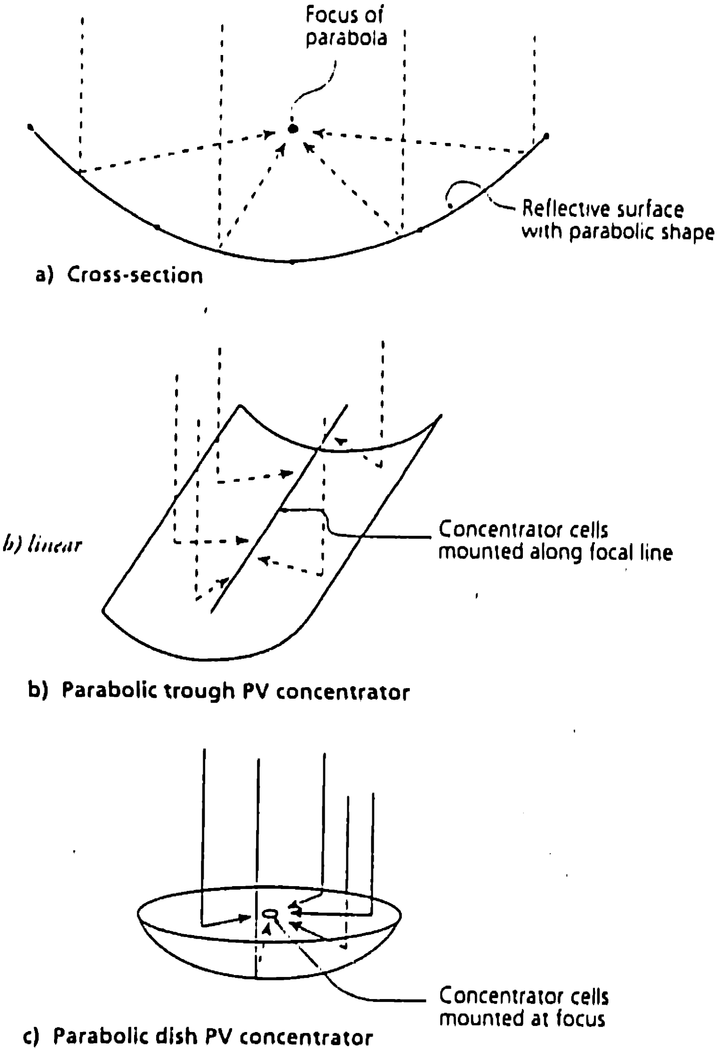
a) Fresnel lens cross-section

b) Linear Fresnel PV concentrator

c) Point-focus Fresnel PV concentrator

'GURE : Fresnel concentrator design concept: a) cross section showing optical principle; b) linear
nel lens; and c) point-focus Fresnel lens.

(Johan.-ps.363,364)



a) Cross-section

b) Parabolic trough PV concentrator

c) Parabolic dish PV concentrator

FIGURE : Reflective parabolic-concentrator design concept: a) cross section showing optic principles; b) linear parabolic trough; and c) point-focus parabolic dish.

Figure 6.2-1 Concentrating Systems (Source: Johansson et.al. pp. 363,364)

The grid connected power system is expected to deliver power whenever there is demand. This "intermittent" nature of the PV power source therefore limits its contribution to a grid to approximately 20% of the grid's capacity before grid performance degradation becomes problematic, though this can vary greatly from grid to grid. To go beyond 20% electricity storage technology will be required, thereby adding to the cost of PV generated electricity. The penetration of PV electricity onto grids is negligible today. The 20% limit is therefore in effect no limit at all. At 94 world PV production level of 61 megawatts [Maycock-94, p.155], it would take, literally thousands of years to approach this 20% limit. The highly nonlinear growth in PV that seems likely will narrow this gap by orders of magnitude. It seems unlikely that it will become a practical limit in less than 10 years.

In the past there was a concern that grid connected PV was not feasible because it would degrade the overall grid performance. This concern was that quality of the electricity on the grid (frequency, phase, voltage levels) would suffer if PV was installed at various places on the grid. Modelling and actual trial installations have shown that this does not appear to be a problem.

In one demonstration project, Massachusetts Electric installed PV modules on 40 individual single family homes in Gardner, Massachusetts. The modules were connected to each homes electrical system individually and each home maintained its individual connection to the grid. After almost a decade of monitoring, grid degradation has not been a problem. More recently Germany installed grid connected panels on 2,000 homes. Other studies have confirmed that PV installations can actually improve a grids performance if they are located at places of transmission and distribution constraints on the grid.

Existing technological infrastructure is therefore not a limit to PV growth in the stand alone and grid connected applications. The third phase of PV's expansion will require the enabling technology of cost effective electricity storage. This enabling technology does not yet exist although it is a subject of active research. These storage technologies include hydrogen storage, electrolytic generation of hydrogen, advanced batteries, fuel cells, advanced composite material flywheels, and superconducting electromagnetic storage units. It is likely that at least some of these technologies will have matured by the time PV growth will require them.

6.2.3 Users and Settings of Use

Users of PV can be as diverse as its applications. A number of users and settings of use have been described above. They range from individual homeowners such as in the Gardner project to large commercial installations. Once installed, particularly in the grid connected case, very little user interface is required. It essentially becomes part of homes and buildings electrical system comparable to wiring in the walls and the electrical panel fuse box in the basement.

Electrical utility firms are a growing user of PV. A few of them have been instrumental in a number of the larger demonstration projects that have been developed. Interest in PV by the electrical utility industry can still be divided into three groups: those very interested, those mildly interested, and those interested only enough to be able to justify why they are not involved. As PV technology has improved and as it has become increasingly difficult to obtain permits to build new power plants, interest has been steadily shifting toward the latter two groups. This interest is exemplified by the recent growth in the number of "Photovoltaics for Utilities" state working groups. Fourteen states now have such working groups. These groups exist to bring all the stake holders together on a regular basis to share information on the emergence of PV. These include regulators, utilities, and PV industries.

Two other examples of utility interest include 1) the recent formation of a utility consortium which has committed to purchase 50 megawatts of PV modules over the next six years. It is not clear whether or not this is a legally binding commitment. It does appear to be assisting PV firms in acquiring capital to expand production facilities. 2) Last year Pacific Gas and Electric installed a .5 megawatt PV plant at one of its substations in California's San Joaquin Valley.

Another important PV user and setting for PV use, though very different from the electrical utilities, is seen in providing electricity to those who currently have none. Much has been written about the intangible, societal benefits of PV such as private (individual) ownership of energy production equipment, lack of emissions, positive influence of decentralized technology on democratic decentralized political processes, etc. Rural electrification provides a concrete example of how PV is positively impacting people's lives by providing power where transmission and distribution systems are not currently available.

As mentioned above, when stand alone PV system costs are amortized over 4-5 years they become more cost-effective than diesel generators. This has lead to a rapidly growing number of rural electrification installations in industrialized and developing nations.

In Norway there are reported to be 50,000 PV powered country homes. [Beardsley-94] In Colombia over 17,000 small systems are in use. In Mexico, over 1,000 single-module home lighting kits have been installed by the Mexican utility CFE in association with the local Siemens Solar Industries distributor. The Dutch government and Royal Dutch Shell's subsidiary R&S Renewable Energy Systems BV have worked with the Indonesian government which plans to install 2,000 PV systems as part of its rural electrification plan.[Johansson ps. 507-509]

In the Dominican Republic, 2,000 homes have PV systems all acquired by homeowners through a revolving credit fund.[Flavin-94-p.158]

6.2.4 Approaches to Technical Barriers

Two basic technological strategies are being pursued to make PV cost-effective. The flat panel strategy seeks to produce large areas of low cost PV cells while keeping efficiencies as high as possible. The concentrator cell strategy, by focusing (concentrating) the sunlight onto a small area of relatively expensive (per unit area) PV cell while approaching theoretical limits of efficiency.

Two examples of the flat panel approach follow. 1)United Solar Systems of Troy, Michigan a joint venture of Canon of Japan and Energy Conversion Devices. It has developed a three layer, thin film, tandem cell and is building a plant in Newport News, Virginia with a production capacity of 10 megawatt per year. [Beardsley-94] 2)Texas Instruments has been developing a PV panel made of tiny beads of Silicon which it calls a "Spherical" PV cell. Both of these developments promise to produce power below the benchmark of $.05/kWh. The timing of achieving this cost point is not clear.

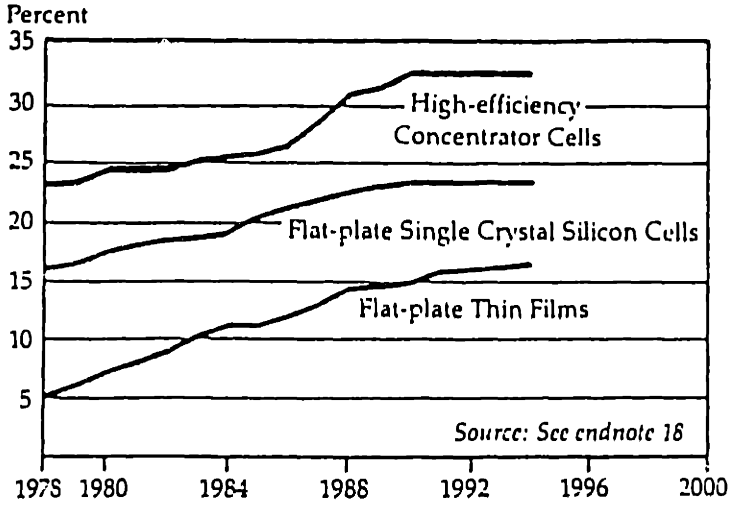
Though lagging the flat panels in current utilization, the concentrator approach has two important long term advantages. 1) It will benefit more directly by computer chip technology as each PV cell can be much more sophisticated than in the flat panel case. 2) The concentrating reflectors will become permanent infrastructure. Just as the chip fabs now achieve new levels of performance in each new chip design, PV concentrator cells may go through similar generations. When a new generation emerges it will likely be possible to simply replace the old PV cell ("power chip") with the new one without altering the reflectors which will be 100 to 1000 times the size of the cell. As discussed in Section 4.4 MTPV could extend this ratio further.

6.3 PV Commercialization and Electricity Costs

6.3.1 Technological Trajectory

Figure 6.3-1 illustrates the steady progress that has been made in PV technology. This efficiency progress coupled with the growing market for PVs shown and the increasing economies of scale they have facilitated have contributed to the substantial price declines shown.

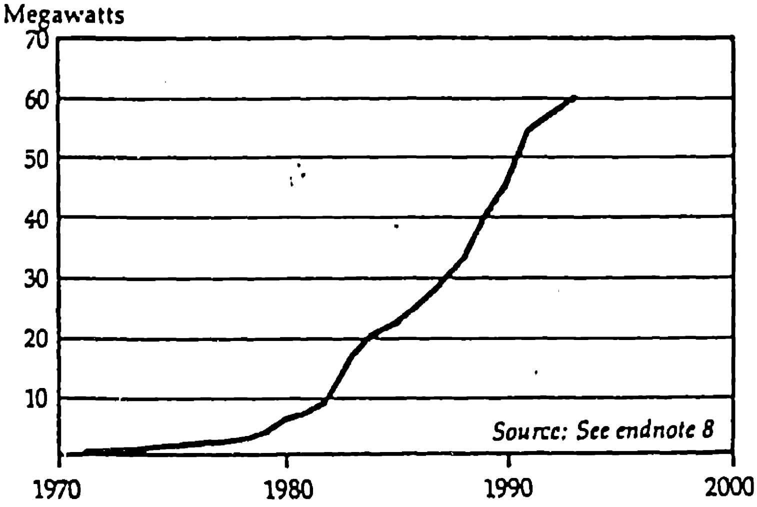
Figure 6.3-2 below illustrates some of the increasing utilization of microelectronics technology to continue the trend of improving PV technology performance. As further example Varonides,93 and Corkish,93 are examples of innovations in basic PV technology with the utilization of superlattices and quantum wells as new means towards further PV improvements. Solar TPV is another potential vehicle for increasing solar electric conversion and MTPV may provide provide the means for extending this trend much further still.



Source: See endnote 18

FIGURE *. Laboratory Photovoltaic Cell Efficiencies, 1978 Through February 1994*

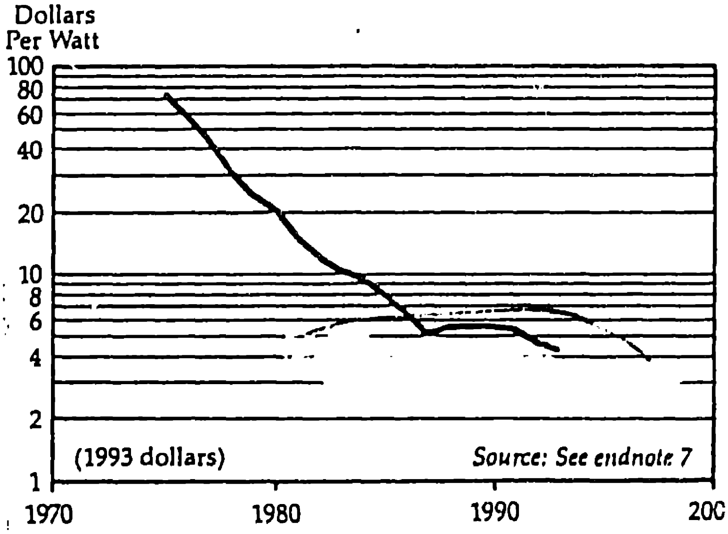
FIGURE 4 (Flavin-p.157)



Source: See endnote 8

FIGURE *World Photovoltaic Shipments, 1970–93*

FIGURE 5 (Flavin-p.156)



Source: See endnote 7

FIGURE *. World Price for Photovoltaic Modules, 1975–93*

Figure 6.3-1 Efficiencies, Worldwide Annual Shipments, and Module Costs for Photovoltaics (Source: Flavin 94, p.162)

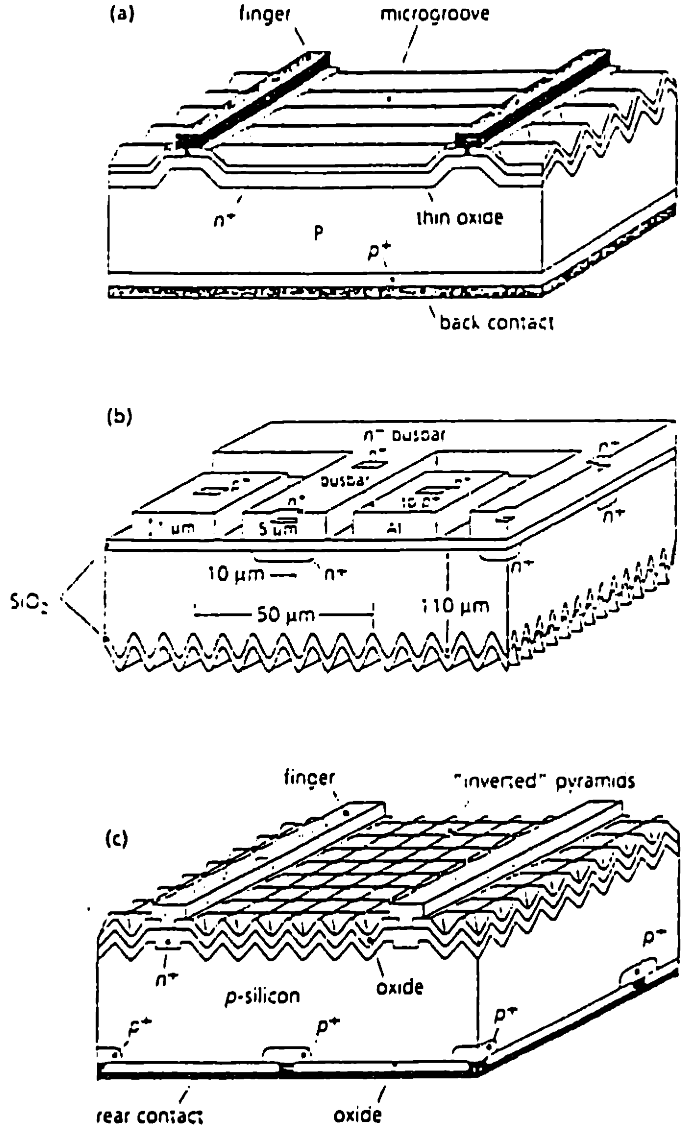


FIGURE : Several high-efficiency silicon solar cells have been demonstrated recently. They include passivated-emitter cells (a), the first silicon cells to give 20 percent energy conversion efficiency by using oxide surface passivation, reduced contact area, and optimized junction diffusion [19] (the antireflection coating is not shown); point-contact cells (b) with microelectronics-quality oxide passivation, contacts on the nonilluminated surface and minimal diffused and contact areas [22] (the cell is inverted to show illumination striking from below); and (c) 23 to 24 percent efficient PERL (passivated emitter, rear locally diffused) cells that incorporate features of cells (a) and (b) [23].

Figure 6.3-2 Microelectronic Fabrication Applications to Photovoltaics

(Source: Johansson et.al. 93, p.343)

These developments illuminate a more general trend in PV's technological trajectory. At the MIT Technology Supply Chain Symposium last year, Dr. Mary L. Good, Undersecretary, U.S. Department of Commerce, described her Department's Advanced Technology Program (ATP) which has great relevance to PV technology. The program is designed to pull technology out of basic research domains and laboratories and to move it into development contexts where it can contribute to new products and hence new markets.

She cited an example which is highly analogous to PV technology today. Her example was in the domain of chemistry. Much industry R+D today is driven by engineering/production process concerns. This therefore never penetrates and draws upon the enormous scientific progress that has been made in chemistry at the molecular and atomic level. Their ATP program has been trying to bridge this gap as they foresee this untapped atomic and molecular level knowledge will become a rich source of chemical technology innovation.

Similar atomic and molecular level knowledge also exists in the field of solid state physics, which is a large part of the body of knowledge underlying semiconductors and microelectronics, and therefore PVs as well. This connection to the atomic and molecular level for PV technology is still in its nascent stages. It is highly likely that enormous progress in PV technology such as possibly MTPV, will result as this connection becomes more solidly established.

It highly unlikely however that such a connection could benefit the technologies that compete with PV including such renewable technologies such as wind power. They are on or near a plateau of technological progress, ie. "their machines of tomorrow will be much like their machines of today". [McGowan 95] PV on the other hand is still on a very steep portion of its learning curve and does not appear anywhere close to such a plateau.

6.3.2 PV Economics and Costs

The economics of photovoltaics depend heavily on several key factors. First is the solar resource at the specific location where a PV installation is to be located. As shown on Table 6.1-1, the solar resource (kWh/sq. meter/year) can vary by over a factor of 2 from one location to another. It is dependent on both latitude and cloud cover. Cost per kWh is approximately proportional to the inverse of the solar resource.

Second and perhaps most importantly is the cost of the PV modules themselves. Both the specific technical approach and its conversion efficiency are captured in module cost. As described above module costs have been falling for all three types of PV and are expected to continue to do so. Module costs can be expressed as $/watt-peak ($/watt-p). This is the cost of purchasing a panel(s) or proportion thereof that would put out 1 watt of electricity at peak sunlight. Specific standards have evolved to define peak sunlight and these are used to rate modules output and therefore cost/watt-peak. The third cost component is the balance of system cost which for a grid connected system are estimated at 15% of total system cost. [Ahmed-94]

Since PVs are capital intensive, almost all costs are paid at time zero. PV economics are therefore very sensitive to the interest rate and to the amortization period used. Figure 9.1-1 illustrates this sensitivity.

The cost of the electricity is one portion of the economic calculus. The other portion is the value of the electricity for the specific application. As discussed above this can vary greatly particularly with regards to distance of a site from a grid. Statistical data on solar illumination as a function of time of day can be used to determine the marginal value of the PV electricity which can often be at a premium since peak grid loads often coincide with peak PV output (such as AC loading on hot summer afternoons). [Buresch 85]

Year	Module Cost ($/watt-p)	Electricity Cost ($/kWh)
1970	400	14.6
1980	80	2.9
1994	8	.29
	6	.22
	4	.15
1996 Enron	1.75(?)	.05
	1(?)	.03
unplanned breakthrough	.1(??)	.004

Table 6.3-1 Typical PV Module Cost and Electricity Costs (High Insolation)

From the early 60's when PV was developed primarily for space applications and up until the present time, Table 6.3-1 shows that PV has been expensive relative to the grid. But judging from the steady growth of the industry, primarily to date, by cultivating niche markets alone, it seems likely that significant downward trend in PV module costs will continue. Since Enron's seemingly aggressive claims additional information has begun to corroborate them. The New York Power Authority recently received comparable bids. Others however, such as the World Energy Council forecast "business-as-usual" as implying little growth in the PV industry. The planners at Royal Dutch Shell, recently characterized such "business-as-usual scenarios to be deeply and fundamentally flawed". [Beardsley 94]

Critically assessing cost trajectories, though it may be the driving force determining whether or not a particular technology successfully emerges, is often a more intransigent problem than assessing purely technical issues. [Rappa 95] "The fact is that it is difficult to determine costs to use" in analyzing systems and technologies. [de Neufville 90, p.263] Technical feasibility, the steps required, the probability of success, are things that can reside within the mind of single individual. Many individuals may possess this knowledge or insight into it, which one can attempt to assess through various means of extracting expert opinion. Cost is more nebulous. Elements of cost reside throughout a firm in accounting, manufacturing, marketing, engineering, finance, etc. Even when in production it is not always easy to know costs but uncertainties are much greater when estimating prior to a technology having ever been manufactured.

6.3.3 Research Community and Industry Structure

6.3.3.1 Research Community - Growth, Decline, Resurgence

One of the preeminent research oriented conferences for PV is sponsored annually by the Institute for Electrical and Electronic Engineers (IEEE) and is referred to as the IEEE Photovoltaic Specialists Conference (PVSC). In 1993 it had over 600 attendees. They included representatives from all firms and institutions at the forefront of the PV industry. Though there is some international representation this is quite limited given that the U.S. accounts for just over one third of total annual PV production. This is probably because both Europe and Japan each host a comparable PV conference annually. In addition to PVSC there also a large, annual, less research oriented conference known as SOLTECH. One thousand people attended SOLTECH 95 which was held in April 95 in San Antonio, TX.

As with any new and emerging technology R+D funding plays a large role in the pace of PV development. In the U.S. for example, at least for the last 15 years, this funding has proven to be highly politicized. As the following figures illustrate, this funding tracked the political dispositions of incumbent parties. Federal funding for PV R+D went as follows: 1981 - \$155M; 1989 - \$36M; 1990 - \$25M; 1993 - \$64M (1981 \$). [Cardell-94-p.12] Despite these disparities, PV R+D in the U.S. has progressed steadily as evidence by the volume of published research in IEEE PVSC-93. Many states in the U.S. also have active PV projects and/or programs. Other countries with active PV efforts include: Algeria, Brazil, China, India, Venezuela, Colombia, Mexico, Thailand, Honduras, Pakistan, Indonesia, South Africa, India, Austria, Germany, Italy, Japan, Switzerland, Spain, [Johansson-93- ps. 507-509, 496-502] Wales, Australia, and the Dominican Republic.

6.3.3.2 Industry

"The period of pre-commercial development can last for several decades..." [Rappa 95, Overhead Slide #3, Mechanisms for Technological Emergence Lecture] This statement accurately describes PV technology.

The PV industry has been growing steadily since 1978 as shown above. Recent trends, such as the fact that currently all U.S. PV manufacturers are operating at full capacity, indicate that this trend will continue and will probably accelerate. At the end of 1994, Enron, a large Houston-based natural gas firm and IPP developer, acquired from Amoco Corp., 50% ownership of its subsidiary Solarex. In November, preceding this acquisition, Enron, the largest natural gas firm in the U.S. announced that it would build a $150M, 100 Megawatt (supply for approx. 20,000 homes), PV electric generating plant in southern Nevada. Earlier in 94, 88 electric utilities formed a consortium which committed to buy $500M of PV panels over the next 5 years.[Southerland- 95] The scale of these developments reflects the movement of the PV industry from small scale batch production to continuous and lower cost manufacturing processes.

It is interesting to note that as firms such as Enron and British Petroleum expand their PV production plans in North America, two other petroleum firms, Mobil and Exxon recently closed and sold respectively, their PV businesses. Even if PV does emerge as a major electricity source, this does not necessarily mean that Mobil or Exxon have made the wrong move. Nothing will preclude them from reentering the field through the purchase of a PV firm. It may appear at that time the purchase price would be greater than if they had developed (or retained) their own firms but the reality may be that greater earnings may have occurred as a result of the greater focus on their core businesses at the time they spun off their PV subsidiaries will more than compensate for premium they'll pay for an operating PV firm when the industry is larger and more mature.

This view is reinforced by the specialized nature of PV technology itself and how very different it is from petroleum industry functions such as oil and gas exploration and crude oil refinery operation. PV technologies are also highly diverse and it is not possible to know now which one or ones will become dominant in the future. It therefore would have been very easy for Mobil or Exxon to have invested heavily to develop a technology that would not have prevailed. The difficult challenge for them will be when and on what terms to re-enter the field in the event that it becomes a major electricity source.

In light of these divesting moves adopted by these major firms it is most interesting then to explore the very contrary moves by Enron. It appears that they are very carefully structuring their positions to address some of the very issues that Mobil and Exxon likely saw as reasons for exiting the industry such as uncertainty in future dominant technology and core focus. It could turn out that all of them made the best decisions for their firms, for the reasons set forth above, despite the opposite paths chosen.

6.3.3.2 Industry Maturation

At $1 billion of revenue with a world output of 60 megawatts of PV modules the industry is still an infant industry relative to the size of the electrical generating business overall. Each year electric utilities install 60,000 megawatts of generating capacity. If PV technology continues to emerge and PV electricity begins to compete on a cost basis with the existing generation technologies it is likely to grow by orders of magnitude.

The large Enron project constitutes both a new level of economies of scale and a new level of vertical integration. This is contrary to the fact that as technologies mature the market structure typically "evolves from one with a high degree of vertical integration toward a greater degree of specialization". [Rappa 95] It seems likely that this will be a transitionary phase for PVs. The structure of the Enron PV arrangement achieves two things that only such vertical integration can do at this point in time but that market mechanisms will eventually provide. Once the market provides them then it seems likely that PV will also follow the trend mentioned above.

These two key functions of the Enron deal are a) the new level of economies of scale in both manufacturing and finance and b) elimination of variables that have hindered the industry to date. The major such variable is who will buy the PV modules a company wishes to produce. This translates into, who will buy the electricity that will be produced by the PV modules a company wishes to produce and how much will they pay. This is the key role that MPCs may be able to play for PV. Drawing on its experience of developing gas fired power projects in the past, Enron will have in hand before the PV project starts, power purchase contracts (or guarantees of the same), that will eliminate the variables of who will buy its panels, who will buy the electricity they produce, and what will they pay. As described in Chapters 7 -9 the MPCs may be a key role in reducing the necessity of large scale vertical integration that few companies such as Enron can currently bring to bear on PV commercialization by eliminating the variables of who will buy the modules, who will buy the electricity from them, and what will they pay.

In another dimension of the industry, though the analogy is not precise, the PV industry of today relative to its future potential, can be likened to the semiconductor industry of 15 to 20 years ago. The analogy highlights two areas from which the PV industry will benefit greatly as it matures. These two were discussed at the MIT Technology Supply Chain Symposium cited earlier.

Dr. Craig Barret, Executive Vice President & Chief Operating Officer of the Intel Corporation discussed the impressive rise over the last 15 years of the most successful PC companies who have little to no involvement with developing and producing the technology and products that comprise PCs. This trend starting with Compaq, then Gateway, then Dell culminated in 1995 with Packard Bell (which is least involved in the technology) topping all other firms in PC sales for the first quarter of 1995. His assertion was that, "Differentiation without a difference is not the key to success." Through standardization the technology of all four of these companies is the same. His point is therefore that for one of these firms to try to distinguish itself on its technology would be a failing effort.

But in the PV industry, firms still pride (and promote) themselves on their technology. The Compaq-Gateway-Dell-Packard Bell, ie. the <u>non</u> technology-differentiating, packager of others' technologies, does not yet exist in the PV industry. When it does emerge it will become another source of the accelerating market penetration and decreasing costs that will continue to characterize the PV industry.

The second area was cited by Dr. William L. George, Corporate Vice President of Motorola. In discussing his experiences with Sematech (and Semi-sematech), of which he was the Exec. VP and COO for three years, he underscored the importance of industry co-operation particularly in light of international competition where strategic industrial planning is more highly centralized and co-ordinated. One of the keys to the horizontal co-operation in the U.S. was clear definitions of core competencies and agreement to not try to collaborate in areas that were core competencies.

In the U.S., for example, the Solar Energy Industries Association (SEIA). It functions in a manner similar to way the Semiconductor Industries Association (SIA) did before 1987 when the Sematech collaboration was formed. Though Sematech was no panacea it appears to have helped to reverse the declining market share of the U.S. semiconductor industry.

There are many areas in PV that would be conducive to collaboration such as structural enclosures for the PV cells, PV cell output performance regulation, and invertor regulator development for grid connected applications. Unfortunately the industry has not matured enough to be able to separate these from its core competencies thus making collaboration difficult at this time. As the larger scale projects begin to come on line this is likely to change. As it does, it will facilitate a new level of technological collaborative efforts, that will further strengthen PVs against its competing, more mature technologies all of which have already benefited from this level of technological collaboration to the extent that they can. Because they are less technologically driven, the traditional energy sources have less to gain in the first place than the semiconductors and PV industries.

6.3.3.4 Government Role - Technology Push to Technology Pull

Whereas until now the governments role has been one technology push primarily through R+D funding, it appears this is shifting toward a technology pull model. ie. The establishment of market demand which then pulls the technology forward.

One example is the government as customer. The Department of Defense (DoD) has a Photovoltaics Review Committee. A tri-service organization formed in 1985 by the Office of the Secretary of Defense and comprised of representatives from the Air Force, Army, Marines, Navy and U.S. Coast Guard. It is the focal point for introducing and integrating PV technology into DoD applications. It co-ordinated approximately $15 million PV system acquisitions in 1994. [Whitely 94] Another, even more important role in this technology pull is the government as guarantor of power purchase contracts as in the Enron project described above at the Solar Enterprise Zone.

Probably the largest policy issue shaping the future of PV technology is how environmental pollution (ie. externalities) will (or will not) be factored into energy pricing. With no externalities imputed to existing fossil and nuclear based electrical generation, one estimate of PV penetration into this market is 5% by 2020. If the costs of externalities were included then this estimate of PV penetration rises to 80 - 90% by 2020. [Jackson 82-p.874]

Because PV has no emissions it constitutes a benign source of power compared to the fossil and nuclear based thermal technologies in widespread use today. PVs have two primary environmental impacts. They consume space. If these are roof mounted systems, this impact is minimized as no additional space is required. Higher efficiencies minimize the area required as it is inversely proportional to the efficiency. The initial processing and production of the PV cells also generates hazardous gaseous and liquid wastes. Large steps have been made to minimize these and to develop adequate treatment procedures. Another example is the U.S. National Renewable Lab's (NREL's) recent development of Methods are to recycle PV once they are taken out of service although they typically have lifetimes that exceed 20 years.

Another externality that favors PV is "energy security". The geo-political consequences of protecting the current energy infrastructure is substantial. It is estimated that 1/3 to 1/2 of the U.S. Dept. of Defense budget (approx. $256B in fiscal year 96) is used to protect existing fossil based, non-renewable, energy interests.[R.Tabors TPP126 3/20/95] This fact illustrates the magnitude of some of the transitions that will accompany the emergence of PVs and other Emerging Electrical Energy Technologies.

6.4 PV Prospects

It is not yet clear which of the 3 primary PV alternatives will prove to be most effective: amorphous thin films, poly and single crystalline flat plates, or high efficiency concentrator cells. They each may find and fill their own markets. Each of them could gain efficiency from multi-junction versions. The potential impact of solar TPV and MTPV is also not known at this time.

Although basic microelectronic technology is being driven currently primarily by the computer chip market, much of this technology also benefits PV cells as well. This is likely to become increasingly true as PV cell designs become increasingly sophisticated. This increasing sophistication is likely to be coupled with declining prices as seen in the microelectronics industry. As discussed in Section 4.4 this could become accentuated by potential developments in MTPV.

These technology improvements are coupled with the growing markets, decreasing costs, environmental sustainability, improving manufacturing economies of scale, and maturing of the PV industry. Though the exact timing of various levels of market penetration are impossible to predict, these trends suggest that there is a high probability that growth in the PV industry will continue to accelerate and that there is a significant probability that PV technology is in the early stages of successfully emerging from its long gestation period to become a major source of electrical power. As Chapters 2-5 reviewed a particular technological innovation that may contribute to this emergence, Chapters 7-9 will explore MPC, a financial instrument policy innovation which could also contribute to PV's emergence in grid connected applications within the fast changing Electricity Industry.

Chapter 7

The Context for MPC Policy: Transitions to a Restructured Electricity Industry

Though many questions remain as to the details of what a restructured electricity industry will look like, two things appear certain at this time. One is that it will become competitive (at least in Generation) and the second is that it will be based on Spot Markets. One of the criticisms of a restructured electricity industry built around Spot Markets is its inability to facilitate long-term decisions, long-term planning, and long-term investments. [Schweppe, Caramanis, Tabors, Bohn, 1988, p.127][Joskow and Schmalensee, 1983] *The primary goal of Chapters 7-9 is to offer evidence that longer-term perspectives and activities such as long-term System Planning need not be sacrificed in order to gain the benefits offered by Spot Markets in electricity.* This evidence will be in the form of the description of a new financial and legal instrument that could facilitate long-term planning within the context of a Spot Market while at the same time taking advantage of its inherent benefits. Figure 6.1-1 depicts the Market and Physical System parameters as a function of time, which are required for the grid to function.[Fernando et. al., 1995, p.17] While important work is being done regarding how the physical system can be held together as the Market side evolves [Ilic. et.al., 1995], Chapters 7-9 will focus on an instrument to integrate together the two ends of the Market time domain.

At the current point in the restructuring process there is indeed an intense, probably myopic, though probably necessary, industry focus on the short-term. However, though some would date the beginning of this restructuring to the enactment of PURPA in 1978, it is only in the last 12 to 24 months that the certainty of the full impact restructuring will have has begun to be fully and widely recognized. Regardless of the date of the beginning of this restructuring, and in spite of the enormous change it is currently creating, it appears that restructuring of the electricity sector is still in its nascent stages. It is from this vantage point that one can understand that the current short-term focus is a function of the "start-up" pains of a transformed industry and not necessarily an inherent reality of an electricity industry built on Spot Markets.

The fact that long-term needs exist is certain. Many investments throughout the industry, from Transmission Line upgrades or expansions to Emission Control Equipment retrofits, are long-term in nature and therefore require assumptions about the long-term. As restructuring proceeds forward new vehicles for meeting these long-term needs will likely evolve. The challenge will be to find incentives that also lie in the long-term which can be coupled with these needs of the long-term in order to produce solutions to these needs. Chapters 7-9 are about one concept which may be able to play this role of matching long-term incentives with long-term needs.

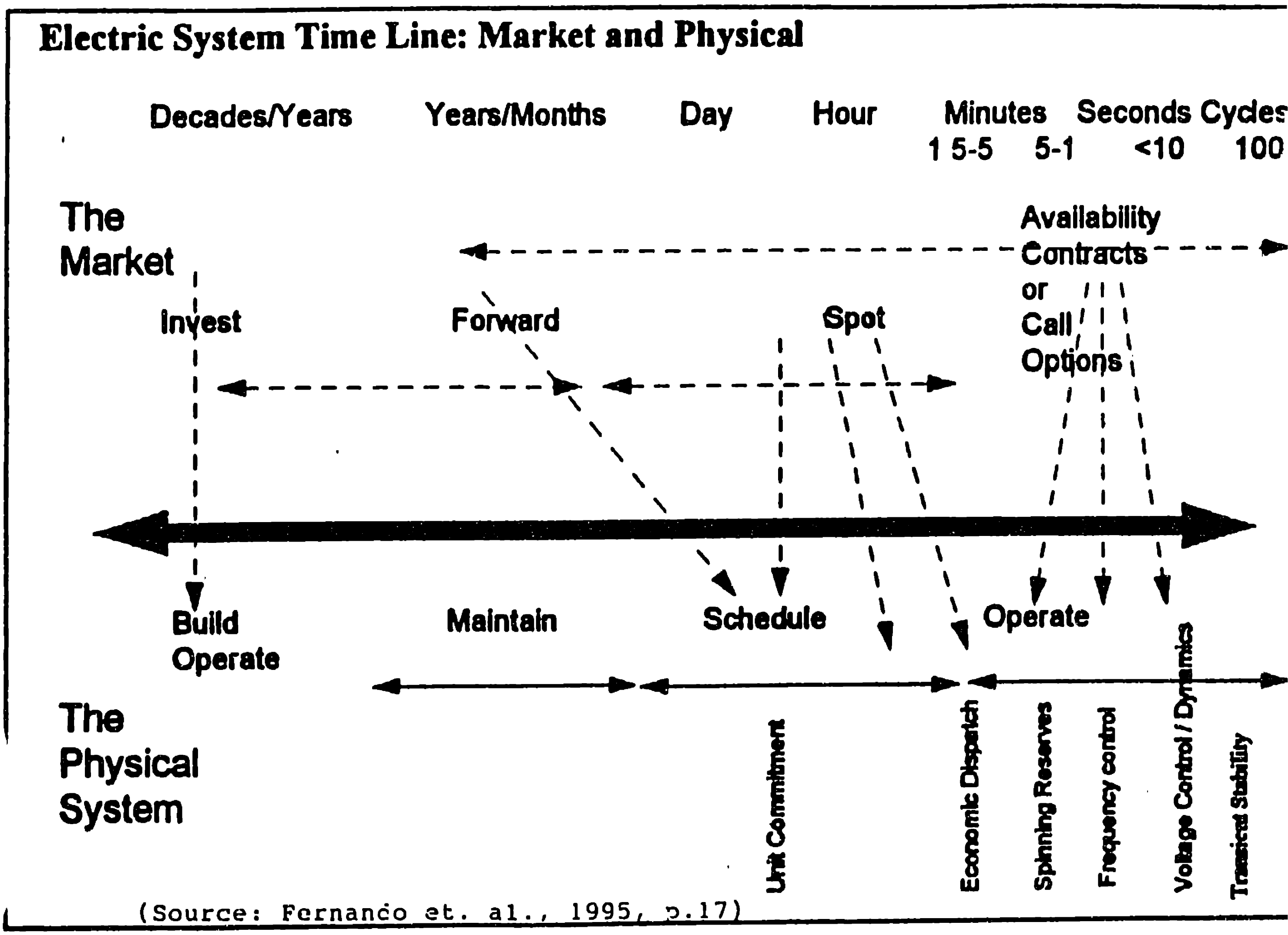


Figure 7.1-1 Electric System Time Line: Market and Physical
(Source: Fernando et.al. 95, p.17)

As the restructuring of the Electric Utility Industry progresses many new financial and contractual arrangements and instruments implementing these arrangements will emerge.[McGee, 1995] Already this has begun. For example by April 1996 the New York Mercantile Exchange had begun trading futures contracts in electricity. Some of the instruments that have been and are emerging include futures, options, swaps, and derivatives. A common feature of these instruments is their short-term nature. Three years for example is considered "long-term" by the participants in these forward markets.[Taylor, 1995]

Long-term contracts (15 to 30 years) have become rare at best and appear to be totally absent from the Electric Utility Industry. This is not without good reason. Two powerful forces seem to explain this phenomenon. First is the painful experience most utilities have had with IPP power purchase contracts. Second is the pervasive overall uncertainty which currently engulfs the Electric Utility Industry.

Particularly in light of this uncertainty how then are long-term investment decisions in Electricity Generation, Transmission, and Distribution to be made? The purpose of Chapters 7-9 is to explore a concept for an instrument that may have potential to play a role in answering this question, the Mortgage-Backed-Hybrid-Power-Purchase-Contract (MPC).

7.1 Capital Formation for Long-Term Investments such as Photovoltaics

Since PURPA, long-term, take or pay contracts have traditionally been the instruments which anchored financing for new generation capacity built by Non-Utility Generators (NUGs). With the unbundling occurring in the U.S. Electric Utility Industry, whether this unbundling follows a Bilateral or Poolco model, it is likely that these contracts will be uncommon. These physical delivery contracts will likely be replaced by financial instruments that will not insure physical delivery for specified prices but will instead protect against the risks of price shifts and price fluctuations. These "contracts for differences" will therefore serve the investment risk mitigation function, formerly performed by conventional power purchase contracts.[Hogan and Ruff 1994; Tenenbaum et. al., 1992]

7.1.1 Prior to Restructuring

NUGs (also known as Independent Power Producers (IPPs)) typically capitalized new Generation capacity through Project Finance. Project Finance differs from other forms of finance in that the "Project" itself becomes the primary collateral for debt financing of the project. In Project Finance there are two primary forms of risk on which the ratings of the Bonds issued are based. These forms of risk are technical risk and market risk. Technical risk is based on the probability that the project will function properly on a technical basis. Market risk is based on whether or not the electricity generated will be sold and whether or not it will be sold at adequate price levels.[Standard & Poors, 1994]

Project Finance originated in the 1930's in the oil and gas industry. At this time the market risk was assumed by the entity providing the capital. But by the 1980's the market risk for IPPs debt financings were typically covered by 20 to 30 year power purchase contracts.[EIA, 1994, p.61] These were typically signed with an Electric Utility Company which were required by PURPA, subsequent FERC implementations of PURPA, and subsequent court rulings, to purchase this IPP power. These power purchase contracts usually covered most or all of the power output from the subject project. Since the Electric

Utilities were a regulated monopoly they could be assured that rate payers would pay rates that would cover the electricity costs in these long-term contracts.

7.1.2 A Restructured Electricity Industry

In a restructured Electricity Industry, where there will be competition in Generation it is not clear who if anyone will be signing long-term power purchase contracts. Several candidates do exist.

2.1.2.1 Electric Utilities

In a restructured Electric Industry the term "Electric Utility" will need to be more clearly defined. It is likely that existing utilities will be unbundled into separate operational companies: Gencos - generating companies; Transcos - Transmission companies; Discos - Distribution companies. It would be the Gencos that might be candidates to sign long-term power purchase contracts. This however seems very unlikely. [Hagar, 1989] The disinclination of the Utilities today illustrate this unlikeliness. This disinclination exists due to several factors including: a)pervasive uncertainty, b) excess capacity, c) inability to enforce,[EEI, 1996] d) prospector mentality (oil and gas industry). [Tucker 1995] Indicative of this is the prevalent thinking by users and generators as well. Proctor and Gamble, the consumer products company, for example, has no interest in singing any energy contracts beyond one year.[Smith 1995]

At least one exception in the case of Eastern Utilities exists wherein heavy oil derivative instruments are being used to sign 10 year supply contracts.[Fox 1995] This firm is also signing similar term contracts with their industrial customers. Is this indicative of progressive planning and of the smartest players? It demonstrates a recognition of the importance of longer-term and a focus on it. This is difficult to do when the herd is focused on (riveted to) short-term/immediate term corporate profits and/or survival. If investments and approaches with the longer-term view are ultimately better economically for society, then those who will have aligned their corporate interests with best economic interests will be likely to ultimately benefit handsomely. What makes free market economies work is they generally force a coincidence between what is best in firm level decisions and what is best economically.

7.1.2.2 Special (well capitalized) Aggregators

These could be another candidate for signing long-term contracts. However this would imply a willingness to take the long-term risk associated with long-term purchase contract should electricity prices continue to decline. Given the possible and perhaps likely probability of this decline it is unlikely that these Aggregators will serve this role.

7.1.2.3 Virtual Long-Term Power Purchase Agreements

These could in concept be formed by combining various forward contracts. This also appears infeasible at this time given the short-term nature of these instruments currently being traded wherein three years is on the long end.[Taylor ,1995] Generally declining prices and general over capacity indicate little need to build new and thus little need for long-term arrangements. These financial instruments ultimately rely on someone who thinks electricity prices will go up in the long-term and is therefore willing to take a position accordingly. The current climate does not suggest this is likely. It would require high premiums to compensate for this perceived risk.

7.1.2.4 Merchant Power

The Merchant Power business is a growing new area of the Electricity Industry. Merchant power is distinct from traditional Utility and IPP power in that electricity buying, building, and selling is done on the Spot Market. Though it appears this equity intensive activity will become a major force in electricity, it also is focused on short-term horizons and would be an unlikely buyer of long-term fixed price power contracts. (Once they exist however, they would be likely candidates to be active traders in them.) [Canonica, 1995, p.6]

7.1.2.5 End Users

Up until this time, the End User, the Consumer, has rarely been the signer of long-term power purchase contracts with the exception of large industrial customers. This has left the end user without the benefits of such contracts, i.e. price increase protection (which has indeed been unneeded of late). While the end user has not been positioned to benefit from these contracts, he has been positioned to absorb the downsides of such arrangements. It seems likely that end users will pay for a significant portion of the stranded assets partly created by these long-term contracts and by long-term investment decisions.

In the absence of long-term contracts it is unlikely that Bond Markets, i.e. debt markets will be the source of capital for investment in the Electricity Industry to nearly the extent it has been previously. Investment will therefore be in the form of equity which requires a higher rate of return than do rated debt instruments. Equity is more risky and therefore costs more. Ultimately the customer will pay this higher cost. That is the lower the cost of finance, the lower the cost of electricity. Who is taking the long-term risk and who will receive the long-term benefits from this risk? Is there an instrument that could be designed wherein the customer could benefit from the lower electricity costs implied by lower rate Bond Market financing?

Rate making provided a virtual guarantee that costs of investments could be recovered from electricity customers who would pay rates which would pay for capital investments made by utilities. Is there an instrument which would provide a vehicle for creating this linkage in a restructured electricity industry. If so it would facilitate long-term capital investments by enabling the signing of long-term power purchase contracts and thereby establish some certainties which could facilitate long-term planning. The MPC instrument policy described in Chapters 8&9 may have potential to partially serve these functions. As discussed in Chapter 6, it is such long-term arrangements that enable the long-term amortization periods which are crucial for high capital cost, low fuel cost technologies such as PV.

Chapter 8

Mortgage-Backed-Hybrid-Power-Purchase-Contracts (MPCs)

8.1 MPC Overview

An MPC would be a long-term power purchase contract that would be affixed to the particular building which would consume the power delivered under the contract. Because the MPC would be securitized by a mortgage on said building, multiple MPCs could be bundled into an instrument which could then cover the market risk of a Bond Market offering in a manner commensurate with a high rating owing to the security provided by the mortgage instrument.

Pricing signals that give market incentives for customers to control their behavior in a way that optimizes the overall economic efficiency of the system are one of the major benefits provided by a Spot Electricity market. The MPC would preserve this benefit by its hybrid nature. "Hybrid" is used to describe this instrument because it could be designed to yield benefits that are a hybrid between the long-term and the short-term. By being a long-term instrument MPCs would facilitate long-term planning. At the same time however they could preserve the short-term benefits that the spot market provides. One particular "design" version of the MPC that could capture the benefits of the spot market follows. (The term "design" is used to indicate that in fact a myriad of designs could be imagined which would incorporate the basic MPC concept. "Design" of financial instruments follows the growing terminology of "financial engineering" and "financial technology", all of which will play an important part in shaping a new Electricity Industry.[Weinberger and Tufano, 1995, p.35])

If the spot price for an approaching hour was likely to be higher than the prespecified price in the MPC then if the User could shift his load so that he would not have to use his entire allocation for that particular hour, the unused portion of his allocation could be sold to the spot market and the difference in price or "contract profit" could be split in some prespecified way. This would be specified in the MPC contract and would probably have a User/Producer split contract profit in a range between 90/10 and 50/50. In this way the User would always have an incentive to reduce demand when the spot price exceeded the contract price. When the spot price was less than the contract price the user would pay the contract price. In this condition it would become a take or pay contract though the unused balance would naturally be sold for the spot price. Though take or pay it would be implemented as a contract for differences.

8.1.1 Definitions and Concepts

Allocation - an amount assigned in the contract for some particular time period, ex. a specified number of kWh for a particular hour subject to the max./min. constraints described below.

Provider/Producer - refers to the party providing the electricity under the MPC.

Most often this would be in the form of a contract for differences modified as described above instead of an actual physical delivery contract.

Maximum Power - This is the maximum instantaneous power allowed under the MPC. It could vary from hour to hour. It could also be implemented as a series of Power Levels. For example an MPC could allow exceeding Level i for 1 minute, Level j for 2 minutes, and Level k for 3 minutes during a particular level. Any power during that minute in excess of these levels would be charged at the spot rate.

Several details would have to be specified. a) Do these levels overlap or not? Either could generally be the case in a MPC, but one or the other would have to specified. b) Allocation of time intervals: i.e. Assume Max. Power Levels i and j where i >j. Assume these are hourly maximums and that each is equal to 1 minute. Suppose i is used up by P>i for exactly 1 minute in a given hour. Then assume i>P>j for two minutes in the hour. What will decide which these minutes will be covered by the one minute P>j covered by the contract and which will pay the spot price. Several alternatives exist. a) First minute first or b)user decides at end hour in retrospect or c)generator decides at end of the hour.
c) Suppose P>i does not occur, but for two minutes P>j occurs. Can the P>i allocation be used for the second P>j minute?

There exist many such details that would need to be specified. Once specified, it would be easily implemented in software. It is likely that "typical" conventions or "standards" for many of these simple details would evolve.

Minimum Power - i.e. minimum kW for a particular time interval, time of day, day of year, entire contract duration or some combination of the above.

Maximum Energy - i.e. maximum kWh for particular time interval.

Minimum Energy - i.e. minimum kWh for particular time interval.

Max/Min: Energy,Power - hourly, daily, monthly, yearly, time intervals ex.3-6pm etc, could have different interval max/mins for different hourly, daily, monthly, yearly

Time - Though a spot market could in concept be an instantaneous market, i.e. market prices set and markets cleared on an ongoing, instantaneous basis, as a practical matter, spot markets will likely be implemented on an hourly or half-hourly basis. In

Chapters 8 and 9 the assumption is that the spot market will function on an hourly basis. MPC concepts described herein could however be extended to whatever time interval a particular spot market was utilizing.

8.2 Securitization Options

The virtual monopoly as electricity supplier, over a given geographical area coupled with the ability to set rates to recover capital investments, provided security for debt obligations issued by electric utilities. With both of these absent in a restructured electricity industry, from where will this security be derived?

One option would be to not make long-term investments but focus only on shorter-term investments, i.e. put a premium on short amortization investments. Another would be to not use the Bond Markets for debt finance which have historically been the primary source. This is prevalent at this time. Herein lies a potentially major challenge to a restructured electricity industry. *What if long-term investments and long-term planning provide the greatest economic efficiency for society but these cannot occur due to shorter-term financial imperatives at the firm level?* For MPCs to play a role here they must offer securitization comparable to that which was present when Electric Utilities had the monopoly power that guaranteed that customers would create the revenues to meet their debt obligations.

While the name MPC utilizes "mortgage", the basic MPC concept could be implemented by at least two other means. One would in fact be closely aligned with mortgages and the other would function independently from them. These are both mentioned here before describing the mortgage based MPC securitization which would likely be the most common implementation.

The first kind, closely related to mortgages, would be similar to property taxes and municipal betterments. In both cases these obligations are affixed to a particular parcel of land or building and are senior to any mortgages on said property. Since the mortgage is subordinate to these, as a practical matter most mortgage instruments today have provisions for payment of these senior obligations. This often extends to escrow payments made coincident with mortgage payments in order to satisfy these obligations. The MPC could be structured like property taxes or a municipal lien. This might be most practical if a Municipal Aggregator as opposed to a Private Aggregator was the local electricity supplier. This is due to the fact that these obligations generally exist at the state and/or local level. It is for this reason that although this form would provide underwritable quality security it would likely not become the most common means for securing MPCs.

The other alternative to mortgage security would be unsecured personal guarantees which can in fact function as a form of security.[Adler, 1992] In this case individuals would sign the power contract. As in the case of credit card debt such guarantees can be bundled and traded themselves as securities. This would not however be underwritable to as high a level as a mortgage backed contract would be because of the lack of a specific physical asset securing the obligation.

8.2.1 Mortgages

A mortgage is a legal encumbrance on a specific parcel of property. Generally mortgages secure performance under a promissory note which is an agreement signed by a borrower to repay funds advanced. Mortagages can also be used to secure the performance of contractual obligations. The value in the underlying property on which the mortgage is placed is placed at risk if the contractual obligation is not met just as it is in a conventional mortgage.

In the late 1970's and early 1980's the secondary market for mortgage securities was developed. This was facilitated by two federal programs known as Fannie Mae and Freddie Mac which were established to standardize mortgage securities thus facilitating their ability to be traded on a commercial basis. The term "secondary" thus indicating that although the primary transaction is between the lender and the borrower the lender can then immediately perform a second transaction wherein the mortgage can be transferred or sold to a third party. These secondary transactions constitute the secondary mortgage market. Since the mortgages were standardized they could easily be bundled and sold in large denominations to institutional investors. This enabled the formation of capital to give these mortgages in the first place when the original issuer of the mortgage (often a local bank) did not have sufficient capital for the mortgage. While the secondary market for mortgages was originally developed for residential home mortgages it has also been extended to mortgages on commercial properties as well.

It is this standardization, and the large scale that it could facilitate, that could make mortgages useful for the securing of long-term power purchase contracts for the specific mortgaged properties. This is discussed further in subsequent sections.

Because of the diversity in the properties where electricity is consumed, there would be the same diversity in MPCs. The largest long-term power purchase contracts signed directly with users would likely be with large corporate clients with multiple properties. Such a contract could be secured by the corporate guarantee and not affixed to any specific property. Any bond issuance or portion thereof could then have a maximum rating equal to that of the corporation. Such large corporate contracts could also be mortgage secured on one or multiple properties. If this underwriting met secondary market standards it could then likely be bundled into highly rated, easily tradable securities. The other end of the size spectrum for MPCs would be individual residential dwellings would could similarly benefit from standardization facilitated bundling.

Another variation of mortgage based MPCs would lie in how they were affixed to the primary property mortgages and/or to the property itself. There could for example be a separate mortgage the sole purpose of which would be to secure the power contract for the property. This could be in first position in front of the primary mortgage securing the loan on the property. It could also be subordinate to the primary mortgage i.e. in second position although this would result in a lower rating for a bond issuance backed by these second mortgages relative to one backed by a bundle of power mortgages ahead of the primaries. Secondary mortgage market regulations could be altered to allow for priority power mortgages provided they met predetermined parameters. Particularly in the case of priority MPCs these could become permanently affixed to the property for the term of the power contract by virtue of the mortgage being re-endorsed should the ownership of the property change during the term of the power contract. This is one way in which MPC terms could vary from 3 to 30 years, though the middle of this range would probably become the most common for a variety of reasons including mortgage refinance rates.

8.3 MPCs and Financial Markets

8.3.1 MPC Buyouts and Mortgage Refinance

MPCs would add another parameter to the mortgage refinance decision process. It is common that when interest rates are declining, properties with fixed rate mortgages will be refinanced to lower prevailing rates.[White, 1992] In the case of primary mortgages the calculus on the timing of refinance includes expectations on whether or not interest rates will fall further and if so by how much. Analogously, the question of whether or not to buy out MPCs would involve expectations of the future prices of electricity. It would become common for users to ask, "Should we pay off the MPC or carry it over?" and "Are we allowed to carry it over?". If the MPC were incorporated into the primary mortgage then prevailing electricity rates relative to the property's MPC specified electricity rate would have to be considered. If prevailing electricity rates were substantially lower then the buyout cost would be higher and would have to be weighed against the savings from the lower interest rate. If prevailing energy prices were higher than the MPC electricity rate then there could be a credit or payment for early termination.

The preceding assumes that buyouts or early terminations are not prohibited in the original MPC. It is likely that they would not be prohibited. The MPC could however specify the terms of a buyout. It is most likely however that at any given time there would be market driven terms for these buyouts. The MPC would simply enable the buyout upon mutual consent. If the MPC however were to be secured by a separate mortgage apart from the primary mortgage, (as described above) then the primary mortgage refinance question could then be decoupled from MPC buyout considerations.

It is also possible that MPCs could be implemented in a way that would make them mobile as opposed to being affixed to a specific property. In this MPC design, the underlying power purchase contract could be moved by the user from one property to another property without any change to the terms of the power contract. The change would simply be in the mortgage which would secure the contract. Standardized appraisal procedures facilitated by the secondary mortgage markets could facilitate this. The MPC would specify conditions of security as opposed to the specific property that would serve as the underlying collateral. This form of mobile MPC would also lend itself to decoupling MPC buyout considerations from primary mortgage refinance decisions.

8.3.2 Secondary Market for MPCs, i.e. MPC Tradability?

In the existing secondary mortgage market one of the disincentives to buying mortgage backed securities is that although for fixed rate loans the interest rate paid on capital is fixed, there is no protection against refinance. When interest rates decline sufficiently borrowers typically refinance the mortgage thereby paying it off. Therefore although the rate may have been guaranteed for 15 to 30 years there is no guarantee that the instrument will remain outstanding for the full term. Since MPCs could and would likely be non-terminatable (or if terminatable, terminatable at a cost) they could offer the benefits of long-term fixed rate returns like the secondary mortgage market but without its risk of early repayment. The fixed return on the MPCs could derive from the fixed rate of return on the capital which would have been raised on the MPC initially. The short-term fluctuations and long-term trends in the spot price could be decoupled and move separately from this fixed return. This could then facilitate either trading MPCs directly or in derivative form.

8.3.3 MPC Derivatives

Strips are a form of derivatives wherein specific facets of one group of instruments become the basis for a new "derivative" instrument. If an MPC bundle was of the variety wherein they were part of the primary mortgage, then the MPC strip could be separated from the primary mortgage and sold as a separate MPC Derivative Instrument. This derivative could also provide the benefit of guaranteed rate without the early termination risk. Because of the security of repayment for electricity provided, these instruments may be able to fill part of the demand for very stable, institutional grade, i.e. nearly guaranteed returns that were provided by many electric utilities in the regulated environment. The MPC market would not likely exceed approximately one tenth the size of the secondary mortgage market.

8.4 User Security/Provider Security

One of the issues that arises in analyzing the feasibility of a secondary market in MPCs is that whereas the user's obligation to pay under its power purchase contract portion of the MPC is secured by the security portion of the MPC, how is that the generator's ability to deliver is insured. In the case of a conventional mortgage, money lent against the note which the mortgage secures is provided at the time of the origination of the loan. The supplier therefore has delivered on all its obligations at time = 0. For the mortgages to be traded in secondary markets only the user's (borrower's) obligation need be secured which is done by the mortgage itself. In the case of an MPC at time =0 only the users obligation to pay is secured by the mortgage itself. Since the mortgage itself does not secure the providers obligation to provide under the contract, what does this imply about the feasibility of a secondary market in MPCs?

Many variations are imaginable. With no feasible guarantee it is unlikely that a secondary market would develop. However, the user's willingness to guarantee his obligation in the first place would likely have to be based on the fact that he would be assured of the provider performing under his obligations. One solution would be the underlying value of the corporation signing the contract. This can change over time however. This same issue of guaranteeing performance by the provider also arises in thinking about whether or not the provider could sell his rights under the MPC to third or subsequent parties. This would not be possible if the performance guarantee was based on the original providers corporate guarantee. For both of these reasons, the most likely solution would probably be in the form of an insurance instrument that would guarantee the providers performance. Standards could then evolve which would enable this insurance to be affixed to and therefore moveable with the MPC bundle.

An MPC bundle would likely have an average duration remaining on the contract, an "average" electricity price(or some other more accurate measure of electricity price, which is briefly discussed below), a measure of the secureness of the securities underlying the MPC, and the financial size of the issuance. The financial size might be expressed as the average annual revenue from all the individual MPCs included in the bundle. A daily financial update might therefore report that , "Fifteen year duration, $0.048/kWh, A-rated, $10 million dollar MPC bundles sold yesterday for a discount of d (if electricity prices were generally lower)which is up (or down) from last weeks close of d'; or for a premium p (if electricity prices were generally higher) which is up or down from last weeks close of p'."

There are many variations on how the electricity price of an MPC bundle would be computed and expressed. The simplest version might be a time weighting of the electricity prices on the MPCs in the bundle. This time weighting would then need to be discounted back to the present. This simple time weighting would work only where the electricity price was constant throughout the day which would be unlikely even under a baseload only MPC. Expressing the electricity price of an MPC bundle might then be best done with reference to a standard daily price schedule. An oversimplified example being that the price from 7:00 AM to 9:00 PM is x and the price for balance of day is .5x. Beyond this approach, the most likely scenario may be that with modern computers each of the 1,000s of MPCs that would likely be in a bundle could each be analyzed individually relative to the specific interests of the purchaser of the MPC bundle. Simplifying expressions such as those above would simply be convenient ways of tracking the general trend of the market in MPCs.

8.5 Implementation Details

The secondary mortgage market regulatory agencies constitute policy infrastructure that could be used to implement MPCs on a widespread basis in a manner that could then have relevance for the electricity industry. It may be possible for Fannie Mae and Freddie

Mac for example to amend their policy to accommodate MPCs without any legislative initiative. This could occur by structuring the primary mortgages to be subordinate to the relatively small mortgage obligation which would secure the long-term electricity concept. Even assuming that the necessary secondary mortgage market changes could be made without legislative change, as with any policy change it could be subject to political forces.

8.5.1 Political Support for an MPC Policy

In thinking about the practicalities of implementing the policy changes required to accommodate MPCs it is necessary to consider the stakeholders that could be affected by or involved in MPCs and the political forces they may imply. Many are considered in further detail throughout Chapters 8 and 9 but several are briefly enumerated here.

IPPs - Facilitate Project Finance - Would favor smaller less capitalized firms who could not access equity markets as easily as they have learned to enter bond markets facilitated by Utility backed power purchase contracts.

Electric Utilities - Could facilitate traditional focus on hardware.

Insurance companies - New lines of business. By providing delivery insurance their policies could become the underpinning of markets trading in bundles of MPCs.

Financial Industry - This is growing force in the politics of electric power. Support for MPCs would seem likely in that they would rely heavily on this industry.

Environmental Lobby - MPCs could be of particular relevance to grid connected Renewable Energy Technologies as described below in Chapter 9.

Investment Banking Firms that specialize in the Bond Market would likely be very interested MPCs as they could increase the portion of Bond Market debt vs. equity in new generation projects which they up until recently enjoyed with NUGs which were financed extensively through the Bond Markets.

Mortgage Brokers - Another service to sell.

Mortgage Companies - Just as they originate but then sell off the paper and then only administer the mortgage they could play a similar role in MPCs wherein they would collect monthly electricity payments under the MPC just as they collect monthly payments under primary mortgages .

8.5.2 MPCs and Bond Rating Agencies

Moody's Investors Service recently stated that, "Intense competition in the generation sector today threatens the value of utility assets, which have historically provided fundamental protection for holders of fixed income securities." [Canonica, 1995, pp.10-11] For this reason bond rating agencies would likely view favorably securitized future revenues which MPC would facilitate. In addition, should global warming continue to increase as an issue, rating agencies may want some percentage of generating portfolio to be from non-carbon producing technologies which could favor nuclear or renewables though a cap on the portion of this percentage that is nuclear may occur due to its unresolved disposal and proliferation issues. The remainder of the non-carbon quota would then have to be renewables which MPC could facilitate.

8.5.3 Start Up

Though one of things that is appealing about MPCs is that it could utilize the standardization in mortgage practices that are facilitated by the secondary mortgage market to become widely used instruments, there is no reason MPCs would or should start this way. Experimentation would be entirely feasible. Small pilot programs could be designed with private capital sources so that variations on the myriad of design details could be tried in several different MPC designs before any regulatory changes would be needed. One simplest method for a first experiment could be to involve only one individual electric utility company, or a single Genco with one individual secondary mortgage market financial institution. This could also take the form a major Environmental Foundation providing a portion of the capital, or being the first bond buyers of an MPC backed offering for a Renewable generation source such as PV.

Chapter 9

MPC Impacts on Stakeholders' Interests

9.1 Benefits of MPCs

9.1.1 Long-Term Planning and Bond Market Finance

MPCs would facilitate Long-Term planning because loads covered by MPCs could be known for the long-term period of the MPC. These loads could be known with some assurance because of the secured guarantee the MPCs would provide. This same guarantee of long-term load would also facilitate Bond Market finance for the Electricity Industry and for those technologies that require long amortization periods such as Photovoltaics.

As described in Chapters 7&8, capital formation for the Electricity Industry through debt financing via the Bond Markets have been a major source of new capital. This capital flowed a) directly to Electric Utilities and b) to IPPs. In the case of the IPPs the guarantees underwriting the project finance bonds were power purchase contracts with Utilities. When the Utilities floated their own bonds the security was the equity in the utilities and their revenue flows which were implicitly guaranteed by their customers by virtue of the fact that they no where else to buy their power. MPCs would make this implicit agreement explicit. In so doing, this new clarity, may help to avoid in the future very difficult issues like the "customer transition charge" with which MIT is confronted today. [MIT Tech Talk, 3/3/96]

IPP firms have become experts at project finance and are currently seeking alternatives to the Utility backed long-term power purchase contracts that fueled their industry since PURPA. Though this micro-level securitization aggregation would be different than the conventional large scale, long-term power purchase contracts they obtained from a single source in the past, they would likely be early adopters of this financial technology and swift implementors of MPC bundles which would function as the now virtually defunct Utility backed long-term power purchase contract.

9.1.2 Potential Environmental Impact of MPCs

Because Utilities will no longer have the ability to pass costs onto their customers they must minimize long-term risk by minimizing the capital intensiveness of capital expenditures. Many Renewable Energy Technologies (RETs), which can be more environmentally beneficial, are however characterized by high capital costs and low or no fuel costs. This is in contrast to conventional fossil fuel combustion based electricity generation where a substantial portion of the final electricity cost is fuel. Short amortization periods greatly favor the less capital intensive, higher fuel cost technologies.

Figure 9.1-1 illustrates this dependence of electricity prices on amortization period and interest rates for two technologies of different capital intensiveness. To simplify, one technology is assumed to be 100% capital cost and the other is assumed to be 40% capital cost and 60% operating costs, which would be primarily fuel and O&M. The former is representative of wind and recently claimed PV prices and the latter is comparable to an oil fueled steam turbine.[Kemp, 1995] To focus on these relationships, Figure 9.1-1 assumes that at 25 year amortization and at a 6% interest rate that both technologies will yield electricity at $0.05/kWh. The interest is compounded monthly. It also assumes that the capital is fully paid for during the amortization period. In practice this requirement would be relaxed somewhat due to the fact that the equipment would have value beyond the amortization period though this would be highly discounted in debt markets due to the unsecured revenue streams.

The curves in Figure 9.1-1 were computed using the expression

$$R=P[r(1+r)^N]/[(1+r)^N-1] \tag{6.1-1}$$

which can also be written as $R=P[crf]$ where crf is the capital recovery factor. R is the constant payment which when made N times equals the present sum P. [de Neufville, 1990, p.208] Figure 9.1-1 does not factor in the value of dispatchability which would favor the 40/60 technology nor the marginal value of electricity which would favor the 100% capital technology. Table 9.1-1 below gives the costs for the electricity at the outer limits of the amortization period analyzed, 5 years and 25 years, for the 3 different interest rates. As expected if the interest rate is decreased to 4% the 100% capital technology becomes less expensive than the 40/60 technology from amortization periods between 18 and 25 years. The 40/60 technology then becomes less expensive for amortization periods less than 18 years.

Since MPCs could facilitate longer term amortization periods (ex. 15-25 years) they would "level the playing field" between these two groups of technologies. Interest in such mechanisms that could reduce barriers to RETs have been of growing interest.[Johnson, 1995; Hartford Courant, 1995] This "leveling" may greatly facilitate larger market share for renewables with beneficial environmental consequences due to their significantly reduced emissions relative to fossil fuel based electric generation.

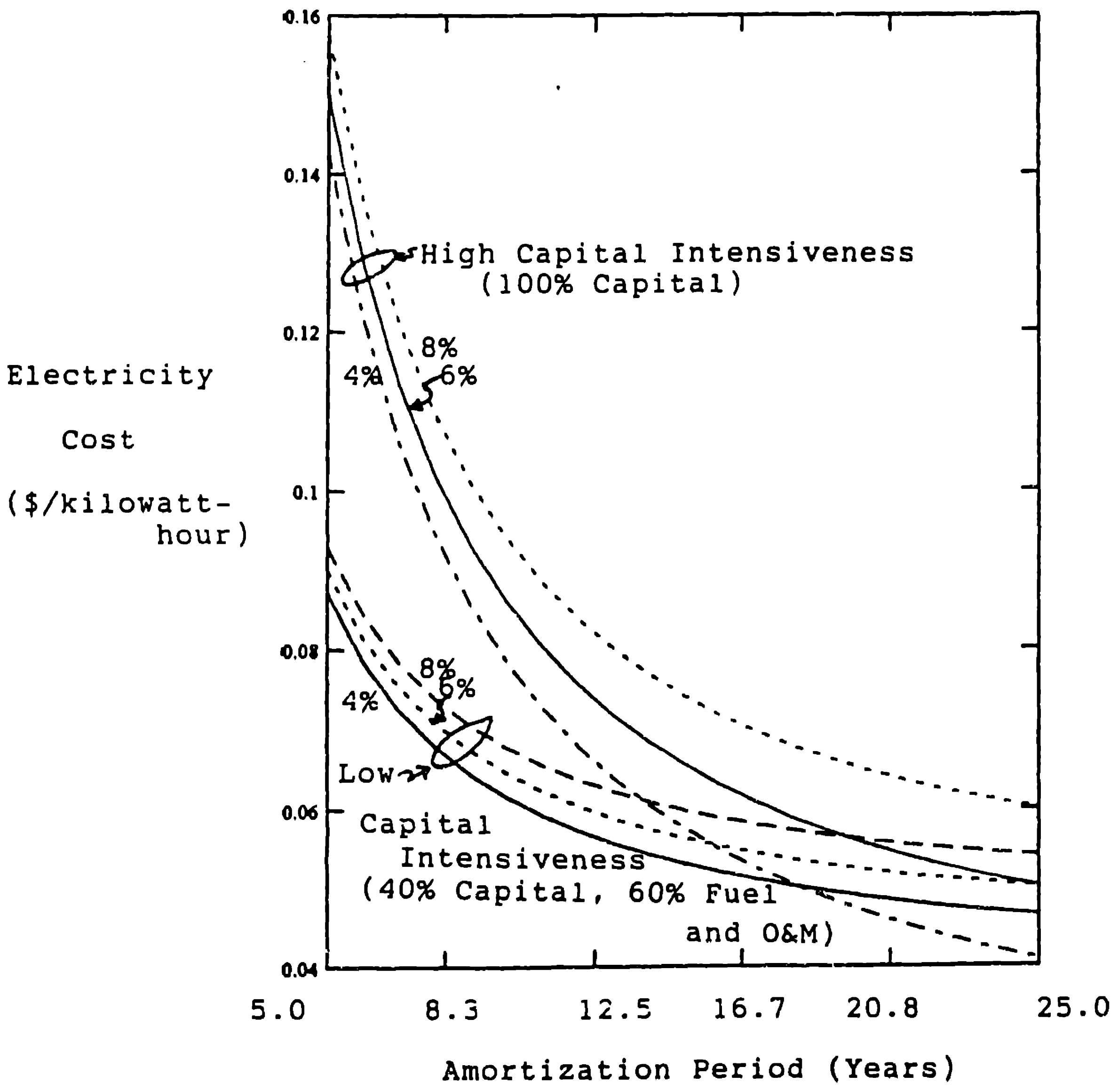


Figure 9.1-1 Effect of Financial Parameters of Amortization Period and Interest Rate on Electricity Costs As a Function of Capital Intensiveness of the Generation Technology.

Electricity Cost
($/kWh)

	Amortization Period			
	25 year		5 year	
	Technology		Technology	
Interest Rate	A	B	A	B
4%	.046	.041	.087	.143
6%	.05	.05	.09	.15
8%	.054	.06	.093	.157

Technology A: 40% Capital Cost, 60% Fuel and O&M
Technology B: 100% Capital Cost

Table 9.1-1 Electricity Costs for Two Technologies of Different Capital Intensiveness As a Function of the Financial Parameters of Amortization Period and Interest Rate.

Because long-term price commitments would be made in MPCs by the Provider, the Provider would need to be assured of its long-term costs. For fossil base generation this would necessitate a long-term fuel supply contract with pricing fixed to the same extent the electricity pricing is stipulated in the MPC. Long-term fixed price contracts have become uncommon in fossil fuels for many of the same reasons they have become uncommon in electricity as cited in Chapters 7&8. Because there is little to no fuel cost in RETs the cost of electricity for the life of the generating equipment (in excess of 25 years typically) can be well known at time=0. MPCs based on RETs would therefore not require suitably matched third party fuel contracts.

9.1.3 MPCs as a Form of Business Insurance

MPCs enable the participating parties to give up some up-side gain in order to eliminate some down-side risk. This is the function insurance provides. For the User in an MPC, they give the up-side gain that could be achieved should spot electricity prices go below their MPC pricing. At the same time they eliminate the down-side risk that their electricity will cost them more than their MPC pricing. For the Provider the exact opposite applies. Commodity markets are known for their self-reinforcing price volatility.[Dixit and Pindyck, 1995, pp. 114-115] This can wreak havoc on business plans and coping with this volatility can become a major sink for a firm's management and planning resources. MPC secured revenue would reduce this thereby facilitating more focus on core business functions. In the case of fossil fuel based generation under MPCs this greater focus on core business would also extend to the fossil fuel firm providing the fuel was under long-term contract wherein the contract would in effect be fixing the value of that fuel while its in the ground.

9.1.4 MPCs as a Form of Stranded Asset Insurance

The likely prospect of Stranded Assets in the Electric Utility Industry highlights the consequences unanticipated change can have on capital investments. In this example the unanticipated change came from many sources which include lower demand growth than the 7% forecasted; and higher efficiency, lower cost, and greater modularity in combined cycle gas turbine technology than anticipated. MPCs could function as stabilizers against unanticipated change.

MPCs would provide a more market based approach with less government involvement and therefore less political uncertainty in dealing with technological and market transitions and the displacements they can cause. To illustrate, consider the current Utility restructuring and compare it to what it would be had MPCs been widely implemented when those assets which are likely to become partially stranded were first constructed. It seems likely that customers will end up paying a lot even though they had no explicit long-term commitments. In the interim, it is very difficult for stakeholders to plan due to uncertainties of how stranded costs will be dealt with by regulators, legislators, and the courts whereas with MPCs all parties would have known their positions and could have done their planning accordingly. Commitments would have been explicit. With MPCs no economic entity, neither firm nor household nor stockholder position could be crippled by unanticipated changes, whereas this is not the case today.

9.1.4.1 T&D (Transmission and Distribution), MPCs and Stranded Assets

The recovery of today's stranded assets through transmission and distribution (since generation will be competitive it will be difficult to recover them here) does not appear to be a problem at this time for Transmission and Distribution will still likely be regulated monopolies. Unanticipated changes could however alter this also. If small scale generation ex. fuel cells, micro gas turbines or thermophotovoltaics were to become competitive with larger scale generation technologies then gas transmission and distribution systems would to a degree compete with electricity transmission and distribution. The degree of this competition would depend on gas congestion as well as new gas based technologies. [NGI, 1995] This subject merits careful further consideration but is beyond the scope of this thesis. It is noted here for two reasons. a) To motivate the role of MPCs for transmission and distribution as a hedge against the loss of their monopoly status as did generation. b) To illustrate the MPC's ability to avoid stranded assets due to unanticipated technological or market change.

9.1.4.2 Risk Allocation and Risk Distribution

The utilization of MPCs would not eliminate unanticipated change nor would it therefore eliminate stranded assets in a broader sense. It would however distribute stranded investments a) over many people and b)over time. Much of the difficulty of the current Electric Utility Stranded Asset debate is due to the fact that the risk was not distributed and therefore the potential losses could fall on a relatively small number of stakeholders and the impact could occur over a very short period of time. MPCs would in essence become an automatic, built-in mechanism for dealing with stranded investments. Consumers absorb stranded asset losses all the time due to technological innovation. It does not become a heated issue because of its distributed nature and because it is a perfectly logical consequence of technological innovation . One small example is that it is not objectionable that although a major appliance like a refrigerator may last 10 to 30 years, the fact that more efficient ones exist and that the owner could now buy, for the same real dollars, a higher efficiency model and pay less per month for refrigeration energy. Through an MPC a user would in effect be buying (becoming part owner of) a small portion of generation capacity that he would be obligated to use for 10 to 30 years just like he commits to a major appliance for a similar period.

In the language of Option Value Theory, when equipment is purchased the "option value" of not yet having committed to the expenditure is "killed". [Dixit and Pindyck, 1995] That is to say that once equipment is purchased it is no longer possible to reuse the same funds to buy alternate equipment. It would appear that summation over individual option values killed by users signing MPCs would be less than the option value killed by an individual firm when it builds the capacity to meet the demand equal to the sum of electric demands in the same group of MPCs. Though beyond the scope of this thesis, this would be an interesting way to quantify the advantage of using MPCs as a tool to manage risk.

Particularly in the case of larger projects, disaggregation of "ownership" may facilitate larger projects with larger economies of scale by reducing the risk traditionally associated with them. (Such economies of scale in traditional electricity generation have however given way to diseconomies of scale for very large plants and to the modularity of aero derivative gas turbines.)

MPCs could also be useful in directing risk and reward, stability and uncertainty to their most appropriate destinations. They could provide stability at the retail level. They could also provide for more stable albeit lower rate of return investments while leaving "big find" (oil), "big hit" investments in the speculative domain where such risk is explicit. [Tucker, 1995]

9.1.5 MPCs and Electric Utility Customer Retention

Should MPCs be implemented in the near term, it is possible that they could play a role in the strategies existing Electric Utilities adopt to adjust to restructuring. They could become a vehicle by which Utilities could reestablish or continue the current permanent and secure relationship they have with their customers by establishing a long-term, securitized contractual arrangement which an MPC would provide. [Saussy, 1995]

9.2 Impediments to and Potential Problems with MPCs

9.2.1 T&D and MPC "Critical Mass"

In a restructured Electric Industry it is likely that there will be disaggregation i.e. unbundling of Generation, Transmission, and Distribution. Whereas these functions are today commonly performed by a single corporate entity for a given service territory, it is likely that this will not continue to be the case. Even in this disaggregated form it is possible that MPCs would be executed for the provision of three services by a single provider firm. If however an MPC were executed for Generation only, its long-term nature would make it subject to changes in the transmission and distribution industries.

Such a generation-only-MPC would be predicated on the permanence (for the duration of the MPC, 10-25 years) of the transmission and distribution systems. Such an assumption seems of little risk today in most locations.

If however new on-site generation technologies become feasible and for example natural gas transmission and distribution (T&D) began to compete more directly with electricity then this permanence could become less guaranteed. An example of this is currently occurring on the western U.S. grid wherein it is becoming less expensive to service some rural customers with on-site PV than it is to build or maintain long distance distribution. In the language of System Dynamics, this is an example of a Negative Feedback Loop wherein the more the phenomenon occurs the more expensive the distribution becomes (i.e. as less people use it) and the phenomenon is made even more prevalent as increasing numbers disconnect thereby exacerbating the problem further. [O'Neil, 1995] Having an MPC between a Generator and a User will be of little value if there is no transportation network between the physical locations of generation and use. (This does not of course necessitate a physical connection between provider and user. This connection could be strictly financial. But somewhere there must exist the physical connection.)

Part of the solution could be to tie T&D into all MPCs. This is only a partial answer and raises a more fundamental aspect of MPCs which applies to Generation as well as to T&D. For MPCs to be feasible it will likely be necessary that a sufficient portion of the revenue for the given service, whether it be Generation or T&D, be secured by MPCs. They may therefore require a certain critical mass in order to be effective. Evaluating this critical mass would become the role of the insurance companies discussed in Section 8.4 which would issue MPC provider performance insurance similar to the way mortgage insurance and system performance insurance are issued today.

9.2.2 MPCs and Environmental Policy Change

For a Generator to enter into an MPC it would need to be reasonably sure of its long-term costs, i.e. for the duration of the MPC. As discussed above this would necessitate for example a long-term fuel contract matched to the Generator's MPC energy obligations. However, how could the Generator be protected against Environmental Regulatory changes? If for example a federal tax on carbon dioxide emissions were levied, how would the Generator recover these extra costs assuming for example that 100% of his capacity was obligated under MPCs?

Several solutions are conceivable though they each have their drawbacks. 1) If the MPC enabling regulations discussed above required legislative action then the legislation could also provide for immunity from future environmental emissions legislation. However, a) this would not address state initiatives, b) it seems unlikely that legislative action would be required for MPCs, and c) this would likely be politically unsatisfactory to environmental interests.

2) Another solution may be to have a provision in MPCs that allows the pass through of any such environmental costs thereby increasing the set price(s) in the MPC. This would expose MPC instrument holders to some risk on their return that they would not have in for example a Treasury bond. The MPC market, or the market for MPC backed bonds would factor this risk into their pricing. This risk would appear to be very low since it seems unlikely that the increased payments under the MPC due to the new environmental legislation would be very substantial relative to the underlying asset value behind the MPC. The exact amount of risk would depend on the exact structure of the specific bundle of MPCs in question. It would appear then that this would not be a serious impediment to the use of MPCs as long as the Environmental Regulation provision was included in them.

9.2.3 User Demand for MPCs?

What Users would sign MPCs and why? More specifically, why would a User sign a long-term commitment for electricity instead of just buying from the spot market?

Many factors play a role.

The largest factor may be Users' electricity price expectations. If they believe prices will be going steadily down during the term of the MPC and further down than may be reflected in the MPC then they would not be MPC signers. If they thought prices would be steadily rising and wanted to hedge against this and an MPC allowed them to lock in a prevailing price then they would likely be MPC signers. Most Users will lie between these two polarities either out of uncertainty or disinterest in the electricity market. Market research by a utility on a sample group of customers would begin to gage where on this spectrum current sentiment lies.

Though beyond the scope of this thesis it would be interesting, as part of a market research effort to answer the present question, to conduct a Multi-Attribute-Utility-Analysis (MAUA) on how electricity customers value various aspects of electricity. For example for a residential customer it seems likely that the difference in Utility between paying $150/month for electricity vs. paying $100/month for the same x kWh would be greater than the difference in utility between paying $50/month vs. paying $100/month for the same x kW. If this were the case than this risk aversion could induce MPC signers.

Because MPCs could be a means for expressing environmentally based preferences over generation technologies, targeted market research on an environmentally interested group with a RET based MPC might also be another first step to generate meaningful data on the present question.

The most significant argument that may favor MPCs is the fact that in the long-term, rates of return on equity capital are higher than on highly rated debt instruments. Without long-term contracts there is more business risk for generators and "more business risk" means "more equity" is required.[Canonica, 1995, p.6] This would therefore imply higher electricity prices in the long run due to the higher cost of equity. Whether or not this long-term pricing signal will have any bearing on whether or not individual users will sign MPCs is unclear. It will probably depend on whether or not the emerging competitive generation industry will utilize MPCs (should they become available) to secure competitive advantage through lower prices due to lower capital costs of bond financing.

From the practical perspective of what Users will and will not do, all of the above considerations would become secondary if the secondary mortgage regulations were amended to include a requirement for a permanent electricity source for the duration of the mortgage as discussed above. MPCs or their equivalents would then become standard practice built right into the boiler plates of the secondary mortgage markets.

9.3 Changing Paradigms in Electricity

The question of whether or not long-term contracts implemented as MPCs have a role to play in a restructured electricity industry may ultimately call into question the nature of electricity relative to the nature of other commodities which typically do not have MPC equivalents. Though electricity, as a product that is bought and sold, has existed for over a century, it is just now that it is becoming a commodity traded on spot markets like many other commodities. Much recognition has been given to the facets of electricity that distinguish it from other commodities such as storage difficulty and unique aspects of its transmission and distribution. This chapter attempts to review properties and paradigms of electricity that may influence whether or not MPCs or some similar long-term instruments may be feasible and/or desirable in the electricity industry.

9.3.1 Spatial and Temporal Consumption Patterns

The physical locations where electricity will be consumed are very well defined. They are typically the locations of buildings which locations are not functions of time. Though the location is not a function of time the level of consumption at a specific location is a function of time. It is among other things for example a function of prevailing meteorological conditions (is it a hot or cold day), of the specific day in the week (is a weekday or weekend), and as spot markets in electricity become increasingly prevalent consumption will increasingly be a function of the spot price of electricity.

This consumption as a function of time for a given location is however is relatively well known, relatively well behaved, and relatively periodic. It is therefore possible to define with high probability the level of power that will be consumed at a given location over a given range in time.

This consumption function behavior adds to making it both feasible to use MPCs and also logical to use MPCs. The consumption is fixed to a known location which location is also mortgaged or mortgageable. The mortgage is continually in place and the consumption of electricity is likewise fixed to that place though varying in quantity over time. In the case of another commodity such as copper for example it is possible to know neither the exact location nor the time of the end consumption (or installation) on a longer-term basis.

9.3.2 Electricity Supply as Permanent Infrastructure

The relationship of electricity to the buildings in which it is inevitably consumed may change with restructuring. Historically Electric Utilities have had an obligation to serve. As long as a building was physically connected to the grid it was assured of being supplied with abundant, reasonably priced electricity. In a restructured Electricity Industry it is unlikely that anyone will have an obligation to serve any particular customer. Simply being connected to the grid will not be a guarantee that electricity will flow to the building today or say 20 years from now when the security of the mortgage on that building will still be secured by its assumed value.

A building is not a building without electricity. The secondary mortgage market routinely requires that a building be permanently provided with all the infrastructure systems necessary to make it function. Could electricity supply begin to fall into that category? Just as secondary mortgage regulations mandate a sanitation system that will last for the life of the mortgage, could the supply of electricity for the life of the mortgage become similarly viewed? Many arguments could be presented on both sides of this question. Perhaps as an insurance policy some small portion of electricity supply, ex. 20-40% would be prudently required on long-term basis.

9.3.3 Environmental Implications and Telecommunications

In striving to find the best form of a restructured Electricity Industry, analogies are often drawn with the Telecommunications Industry. In telecommunications demand is routinely aggregated without any long-term commitments. It is possible that electricity could similarly be aggregated without any type of long-term arrangements such as MPCs. There is at least one difference between electricity and telecommunications that may justify and encourage MPCs in the former without any equivalent in the latter. This difference is the environmental consequences of the specific technology used to provide the service.

In telecommunications there is relatively little difference in the environmental consequences of providing a unit of time of a given bandwidth over for example a fiber optic cable vs. a satellite link. Whereas the difference in the emissions for providing a given unit of electricity can vary greatly from one technology to another. Since MPCs facilitate lower emission technologies they may become a vehicle by which customers can exercise their environmental preferences in the electricity market.

Though in a restructured electricity industry there will likely be aggregators who market "green" ex. photovoltaic power, the quantity of such offerings will be very small with only the short-term arrangements prevalent in the restructured telecommunications industry. Though it is possible that electricity aggregators could offer green power, it would be unlikely that the lowest cost financing (which the renewables would need given their capital intensiveness) which is debt financing, would be possible without long-term, secured purchase contracts such as MPCs. Without this financing it is unlikely that very much green capacity would be brought on line. If a customer signs MPC they would be directly facilitating the creation of new green power. This would facilitate customer choice of long-term supply in a more direct way which does not currently exist.

Several versions of green MPCs follow.

a) Spot-Based-PVMPCs (Photovoltaic MPCs) could have the user taking all the PV output from a specified peak rated quantity of PV modules and then to use with spot market pass through or stipulated markup for the balance of power both buying when short and selling excess.

b) 100%-Green-PVMPCs could only call for delivery to the user of the kWhs from a specified peak output PV quantity. This would use the grid for storage when the instantaneous PV output exceeded the user demand (i.e. sell it to the spot market) and would then buy back the same number of kWhs when instantaneous user demand exceeded the PV output. Because the marginal value of PV power is likely to be higher than the marginal cost [Buresch, 1985], this version of MPC would likely yield a discount for the nonPV spot power.

c) 100%-Green-electron-PVMPC - This would rely solely on non-grid storage so that the "actual electrons" consumed were PV generated. "Actual electrons" would in most cases mean that for every kWh consumed there was a kWh produced by PV.

d) Another option or feature of any of these PVMPCs could be that the Generator would reserve the right to pay the user a fixed amount to terminate the contract. This could facilitate the Generator's selling of the modules into much higher margin international markets when feasible. This fee might have to be substantial. It could also be left out of the initial MPC but could be mutually agreed upon by the parties at the time it becomes relevant. This would leave no assurance for the Generator however. This level of flexibility would depend on the details of the financial and legal structure of the MPC and specifically how it was structured relative to the means for securitization and the underlying secondary market underwriting regulations some of which are discussed above.

9.3.4 Electricity as Other Commodities

In addition to being different from other commodities electricity may become increasingly viewed as other commodities.

"Air Squeezing" is the business of producing liquefied or compressed gases such as oxygen and nitrogen by compressing air. Approximately 75% of the cost of theses gases is in the cost of the electricity to run the motors which compress the air. [Tabors at MIT-TMP-LEES, 1995;(Richard do I have this correct?)] In one sense then is liquid nitrogen 75% electricity?

A more pervasive commodity which electricity may "become" is water. EUA (Eastern Utilities Associates) recently announced that it will be placing its "financial and technical support" behind the development of a $31.5 million desalinization plant which will supply water to a number of towns in southeastern Massachusetts which are in EUA's subsidiary's Eastern Edison Company's service territory.[Downing, 1995] This would suggest that due to a variety of factors including overcapacity, that the electricity supplying the plant will be at a low enough price that when combined with the improving technology and decreasing cost of desalinization technology that the water can be competitive with the rising prices of water from traditional sources.

Will this trend continue to more modular forms of water treatment technology wherein it could be placed in the individual buildings where the water will be consumed. On-site sources (like the ocean, ground water, rain water, or gray water) that may not have been suitable without treatment would then become potable. Should this become cost-effective, which it appears it has in the larger scale EUA example, then instead of water getting delivered to that building (by pipe or truck), electricity would get delivered. Electricity delivery itself would displace delivery of the non-electric commodity Securing long-term water supply would then be facilitated by long-term electricity supply which MPCs could facilitate.

9.3.5 MPCs and Shifting Paradigms in Electricity

The substitution of electricity for other commodities could increase the quantity of electricity consumed per service delivered. In the example cited the kWh consumed per gallon of water consumed would rise considerably (i.e. kWh/gallon desalination vs. kWh/gallon pumping from a reservoir). At first this may seem to run counter to the goals of Demand Side Management (DSM) which are to reduce the electricity consumed per service delivered. Whereas in this example the electricity consumed for a unit of service delivered is increased. If DSM is defined as producing a unit of service for as small an economic and environmental cost as possible then there would be no inconsistency. (Since there can be no social welfare function [Arrow, 1963], finding such a single measure which would quantify "economic and environmental cost" is the subject of much active research and depends on the utility functions of the individual stakeholders for the said "cost" which is being evaluated.] Should electricity continue to substitute for other commodities electricity consumption per capita could increase. Particularly in developed nations, increasing electricity consumption per capita is generally viewed as environmentally undesirable. If however the electricity is produced with minimal environmental consequences then this could facilitate increased electricity consumption without environmental detriment. Herein lies another potentially shifting paradigm in the Electricity Industry with possible implications for MPCs as follows.

Using more electricity can become environmentally sound if it is generated by technologies without emissions. Therefore RETs could become of benefit to Transcos and Discos by increasing their volumes without increased Generation emissions. (This could occur without expansion only where congestion does not limit volume either due to sufficient existing capacity or by increased utilization of existing capacity by new transmission technologies.) Therefore this may be an example of where competition for fossil generation may be exactly the technology that allows growth in transmission and distribution. Thus restructuring may not only lead to disaggregation of Generation, Transmission, Distribution, and Service/Marketing and the formation of them into separate operating units but may lead to diverging business priorities for future growth as well. MPCs may be a facilitator of as well as a beneficiary of these transitions. It may facilitate cleaner technologies as discussed which could benefit Transcos and Discos and could facilitate increased penetration into other commodities which may increase the desire for stability in energy prices increasing the demand for MPCs.

9.4 MPC Conclusions

"The forecast is always wrong!" [Schweppe, Caramanis, Tabors, Bohn, 1988, dedication] The Electric Utility Industry has been a rich and abundant source of proof for the validity of this postulate. Five examples follow.

1) For many years seven percent growth in electricity demand was a well accepted assumption in the Electric Utility Industry. Billions of dollars were invested based on its validity.

2) In 1988 when Spot Pricing of Electricity was first published it was a well accepted assumption that Spot Pricing for electricity would not occur, could not occur, and should not occur. The jeering received by the authors of this book more than once testified to the deep rooted nature of this assumption.[Tabors, 95a] Despite the conviction (backed up by many millions of dollars of investments that would a decade or more later become known as "stranded") by 1995 these two assumptions would become fully debased and clearly and dramatically wrong.

3) The continued dominance of the superiority of incumbent technologies and the ever increasing efficiencies from their economies of scale were well established. Emergence of aero derivative combined cycle gas turbines and diseconomies of scale proved them wrong. Could we be making similar assumptions today about incumbent technologies?

4) The Nega-watt and DSM proposals put forth by Amory Lovins were roundly criticized and then as in the three examples above went on to become an important contributor to slowing electricity consumption.

5) The possibility that DSM could slow down emission improvements by slowing down investments in new Generation capacity which typically have improved emissions relative to older technologies was unexpected. [Tabors and Monroe 1991]

However, hindsight is often 20/20. It is exceedingly more difficult to make forecasts than to diagnose them after the fact.

"The forecast is always wrong!" In another field of engineering endeavor, in Robotics there is a related expression. "There is always error." When a machine vision system determines a location, for example it always wrong to some level of precision. The application of this phrase to the electricity industry also applies to precision. In this sense it is easy to understand how the "Forecast is always wrong!". It is this inevitable imprecision that indeed gives this phrase the somewhat ironic attribute of always being correct.

But when systems that integrate markets and policies and technologies are involved it is often more than a matter of precision that generates error. It can be wholly new, and often unexpected developments that shake the very assumptions on which the forecasts were made and render them not only incorrect in precision but totally out of step with the eventual realities that materialize. Such is the story of the Electric Utility Industry which is currently undergoing its vast and fundamental restructuring.

The MPC concept presented herein may be one small part of the issues yet to be imagined which will emerge as restructuring proceeds. It is precisely because "The forecast is always wrong" that the stability of an instrument like an MPC may have some role to play.

Chapter 10

Conclusions

The energy sector is in a period of enormous uncertainty and change. The Electric Utility Industry is the most evident example to date. There is a finite probability that enormous additional change could impact the Energy Industry. The sources of this change could be from innovations or changes in both technology and/or policy which is defined broadly to include public, private, financial, and legal policy.

MTPV and MPC are each an example of a potential impetus to this energy sector change and each is as well a potential facilitator of it. Both MTPV and MPC can be pursued with small incremental steps first. This is recommended.

Policy can play critical roles in defining the meaning of a particular technology. Policy can also play a critical role in whether or not a particular technology emerges from small niche markets to become a dominant technology. MPC illustrates both. It could facilitate the possible expression of individual's wills, desires regarding the environment and energy. In so doing it could create a financial platform from which emerging energy technologies could compete with existing dominant technologies and perhaps become "disruptive". It can be policy that makes the technology disruptive, not just the technology itself.

By providing a vehicle for spreading the stakes of negotiations regarding energy technology further out in time (with added certainty) MPC could become part of a framework within which serious negotiations over energy technology's role in global environmental issues could occur. By introducing an increase in longer-term certainties MPC would also provide a framework for more stability to the transitions that can be caused by energy technology breakthroughs of which there is some finite probability that MTPV will be an example.

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