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Thermoradiative Conversion for Space Power Systems

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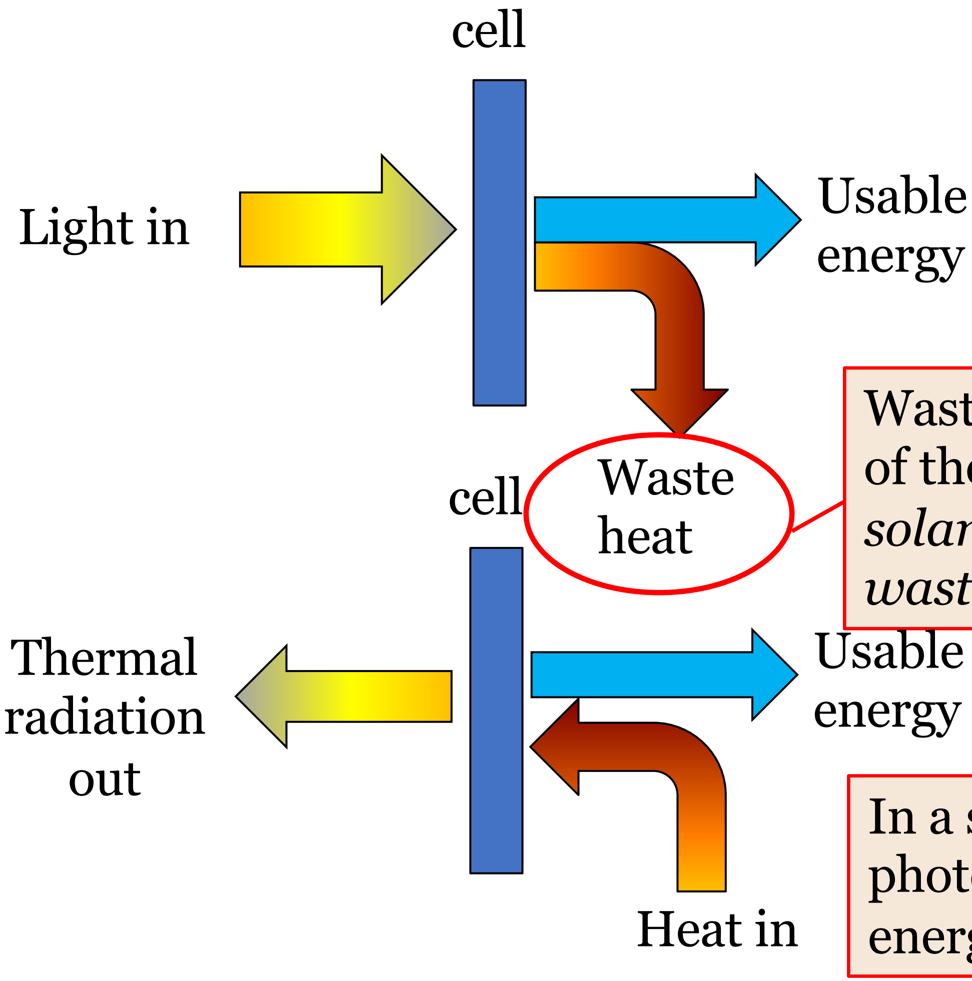
What is a Thermoradiative cell?

And why should we care?

- A thermoradiative cell is a new method for converting heat energy into electrical power
  - First detailed by Strandberg in 2015 and by Santhanam and Fan in 2016 (based on concepts elucidated by Byrnes, Blanchard, and Capasso)
  - Operationally similar to a photovoltaic cell, but thermodynamically exactly backwards
- No moving parts
- Think of it as a panel that acts like a **thermal radiator that generates power**

Photovoltaic Cell vs Thermoradiative Cell


cell

Light in

Usable energy

Waste heat

cell

Thermal radiation out

Usable energy

Heat in

Photovoltaic Cell

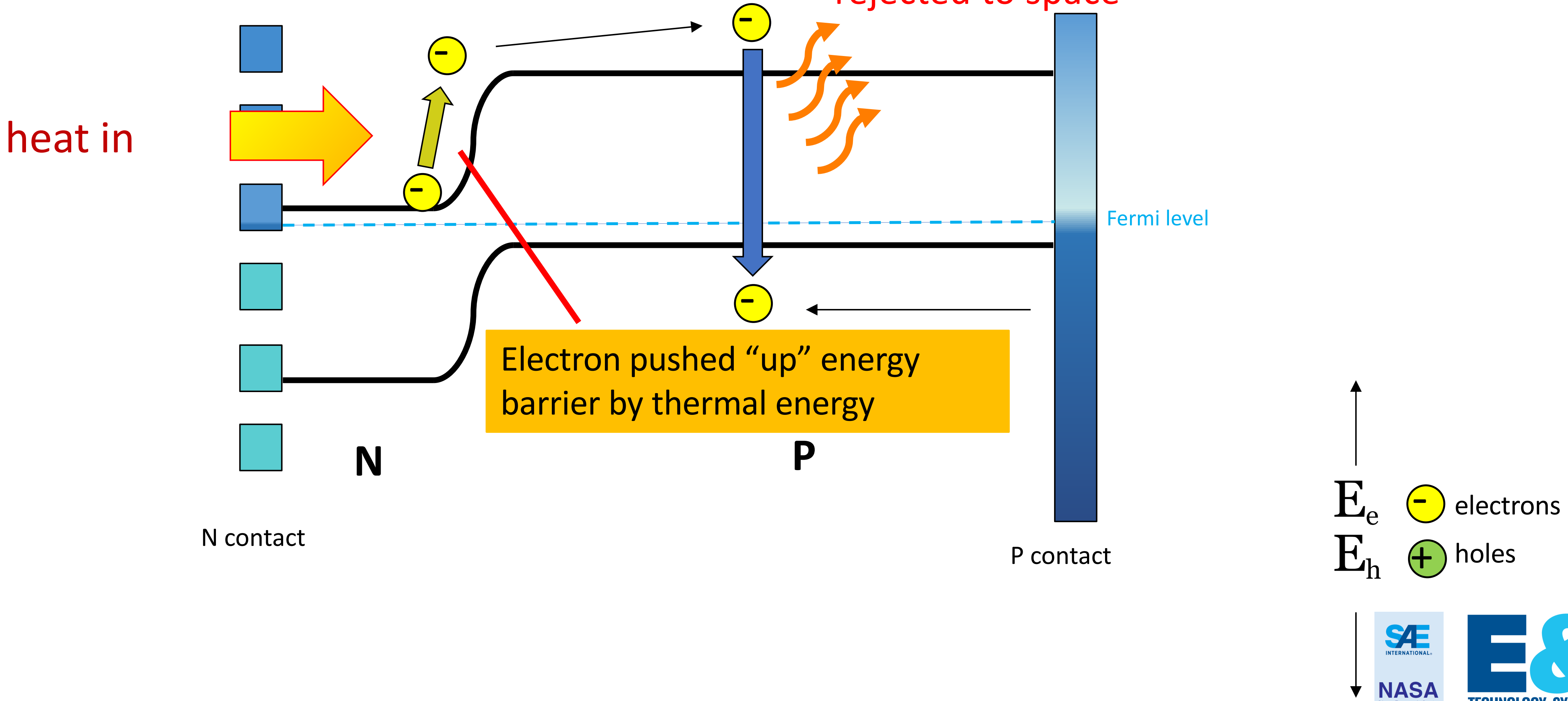
Waste heat is an unavoidable consequence of the second law of thermodynamics: *a solar cell cannot work unless there is waste heat rejection*

Thermoradiative Cell

In a solar cell, waste heat comes from the photogenerated carriers sliding down energy barrier created by the p-n junction.

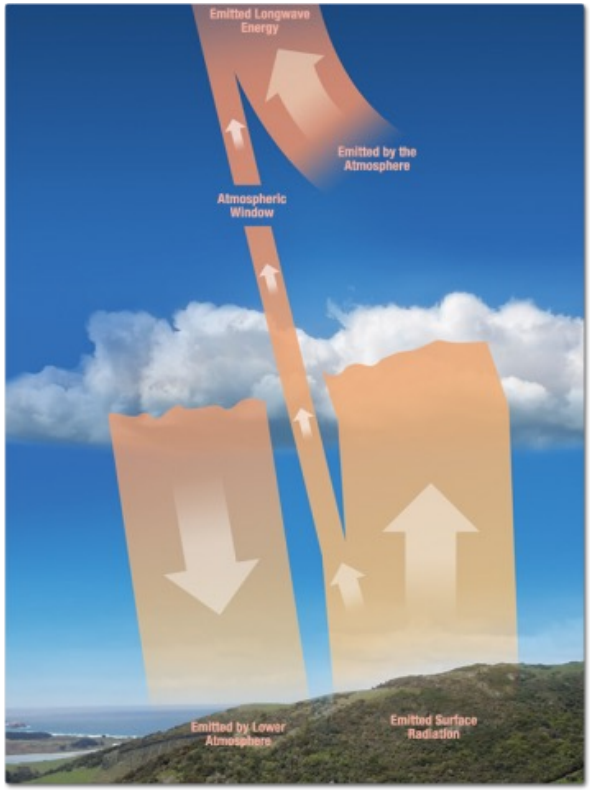
Net current flow

Deep space (~10 K)



Terrestrial Applications?

- Thermoradiative conversion could, in principle, be used for energy conversion for any thermal source.
- The original proposals were for terrestrial applications. However, the Earth's atmosphere is not IR transparent, and so effective temperature of the heat sink is at best 200K (for a clear night sky with low humidity), and in most applications much higher.
- This results in a downward infrared flux which cancels out part of the upward radiation driving the cell current
    - Earth also has a surface environment in which convective cooling competes with radiative cooling for heat transfer.



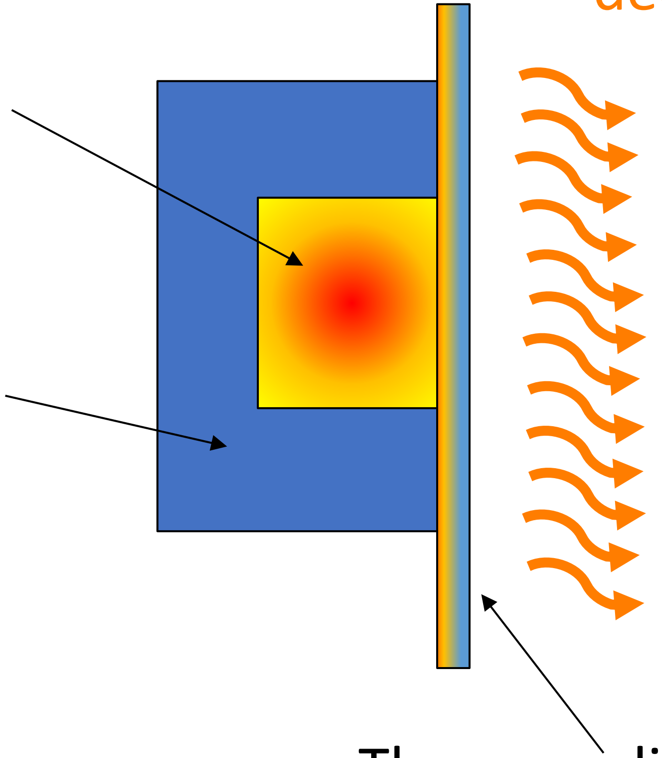
Upwelling and downwelling IR flux in Earth's atmosphere

NASA image

Space Applications

- In-space applications are well suited for this technology, since with no atmosphere the cell radiates to the heat sink of deep space. Heat source would be a radioisotope (*e.g.*, Pu-238) or nuclear reactor.
  - Temperature of deep space is often quoted at 4K, but inside the solar system, actual effective temperature ~10-12K
  - However, in practice the difference here is unimportant, since even 12K is << operating temperature of a realistic heat source, and can be ignored
- Planetary bodies with atmospheres (Venus, Mars, Titan) not ideal.
  - Atmospheric convection will be significant heat loss.
  - Infrared opacity of the atmospheres means that the cold side temperature will be the atmospheric temperature, not the temperature of deep space.
- For bodies with no atmosphere (*e.g.*, moon), radiating surface must be in the dark & shielded from other sources of infrared, such as the Earth, and the hot lunar surface.

Conceptual operation of thermoradiative cell in space



Radiation to deep space

Radioisotope heat source

insulation

Thermoradiative panel

(serves as both the converter and the radiator)

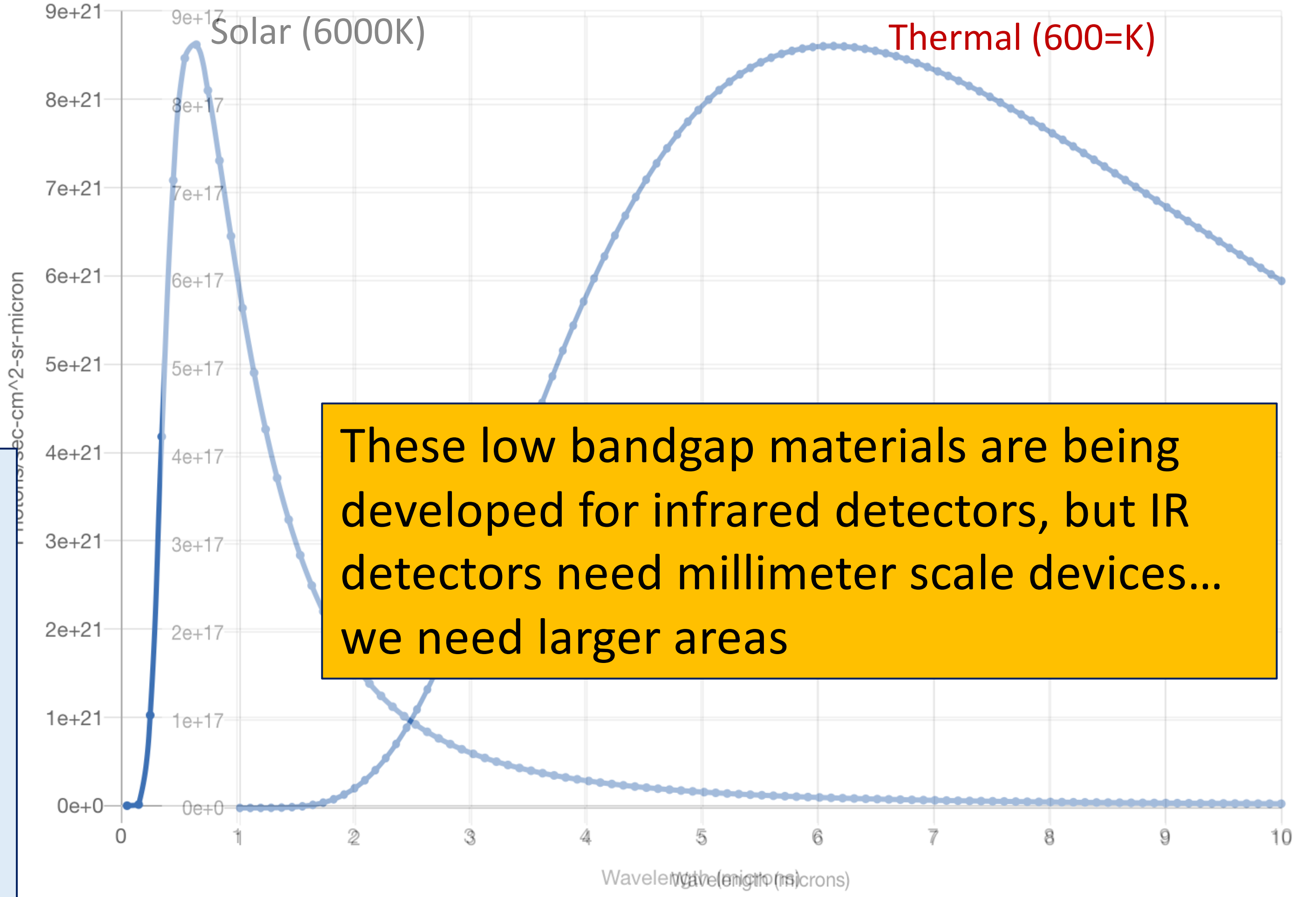
Deep space: ~10 K

*The effective temperature of deep space is only 4K if you are outside the galaxy. Inside the solar system zodiacal light makes the effective temperature more like 10-12K

PV cells compared to Thermoradiative Cells

- Solar cells need to be made from semiconductors with bandgap comparable to the peak output of the solar spectrum
  - Solar peak is ~0.5 to 1 micron, so optimum bandgap is order of 1-2 eV

- Thermoradiative cells need semiconductor bandgap comparable to the wavelength of the thermal spectrum
  - Thermal peak for ~600K emission is around ~6 micron, so optimum bandgap is ~ 0.1-0.2 eV
    - (back of the envelope)
  - Thus: **Narrow bandgap semiconductors**



These low bandgap materials are being developed for infrared detectors, but IR detectors need millimeter scale devices… we need larger areas

Carnot Efficiency

- As with all heat engines (including solar cells), a thermoradiative cell is limited to a maximum possible efficiency by the Carnot efficiency limit,
- $\eta_{carnot} = (1 - T_c/T_h)$
- where T_h is the (absolute) operating temperature of the cell and T_c is the (absolute) temperature of the heat sink,
- However, in the real world, cells are not likely to approach the Carnot efficiency limit.

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Power as a function of temperature

- Since the number of photons in the blackbody spectrum is proportional to temperature cubed, and the voltage at the maximum power point is directly proportional to temperature, the **total power output is proportional to T^4.**

Thus, although the efficiency has only a small temperature dependence*, the power output depends strongly on temperature.

*assuming that the environmental temperature is much less than the device temperature

Simplified calculation of Max power point

for the simplified calculation, we assume that $T_{external} << T_{cell}$, so the external environment can be ignored

Power $\sim VI_o e^{-(E_b+V)/kT}$

Solve for maximum power

- ${}^{d}/_{dV}\, VI_o e^{-(E_b+V)/kT} = 0$

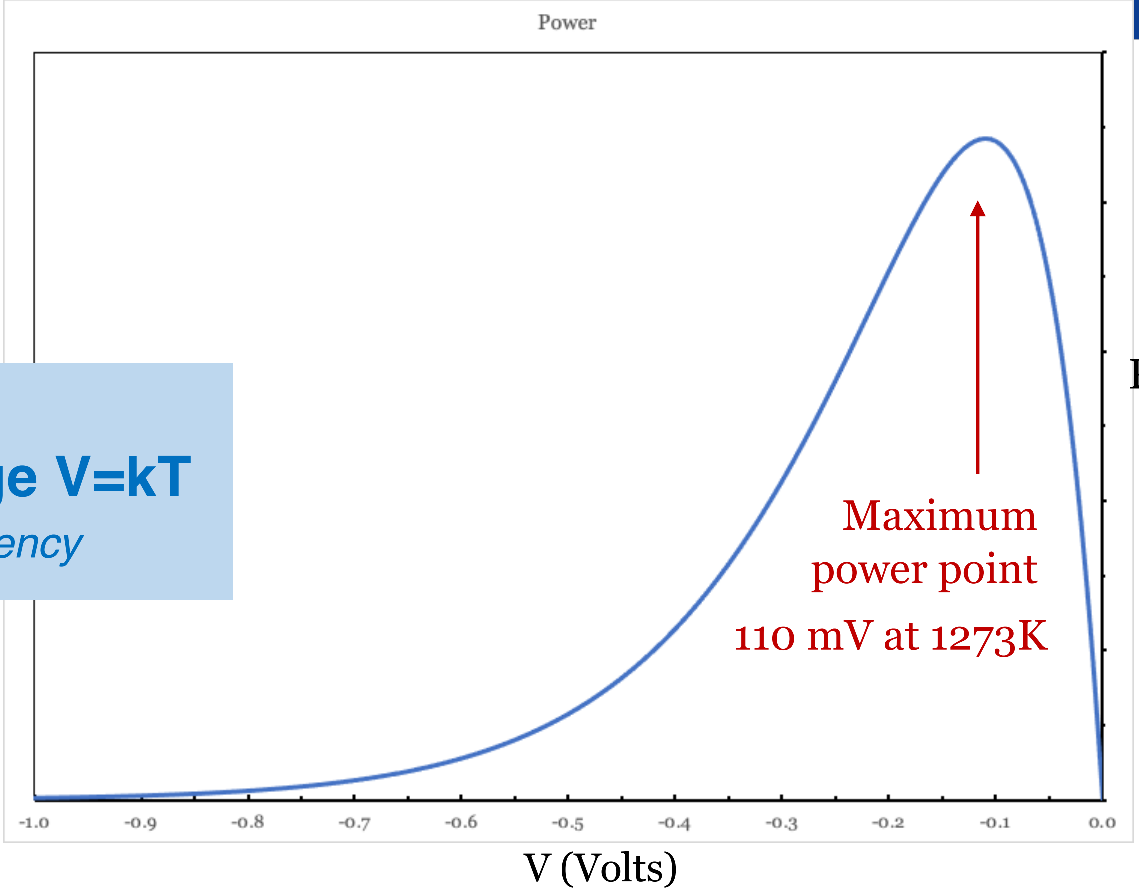
Analytical solution:

maximum power is at bias voltage V=kT

– *Note that maximum power point is **not** maximum efficiency*

These are low voltage devices!

25 mV for room temperature (20°C)
100 mV for 900°C



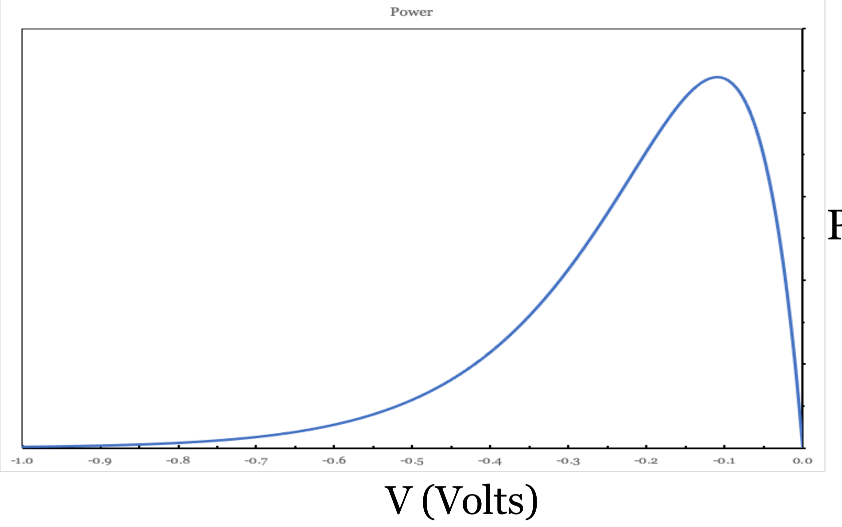
Maximum power point

110 mV at 1273K

Output power as a function of bias voltage for idealized thermoradiative diode at 1000°C
(background temperature assumed negligible)

Idealized calculation of highest possible efficiency at Maximum power point

- ➢ Power is current times voltage
- ➢ Power produced is equal to I times bias voltage
- ➢ Voltage lost is equal to I times bandgap plus 3kT/q
    - $-E_g/q$ is bandgap voltage
- ➢ Efficiency = power produced divided by total power
    - ➢ $\eta = IV_b / I(V_b+E_g+3kT) = V_b/(V_b+E_g+3kT)$



Output power as a function of bias voltage for ideal thermoradiative diode at 1000°C

At maximum power point, bias voltage $V_b = kT$

$$\eta = (kT)/(kT+E_g+3kT)$$

But bandgap must be ≥ 0, so highest efficiency (at maximum power bias) is

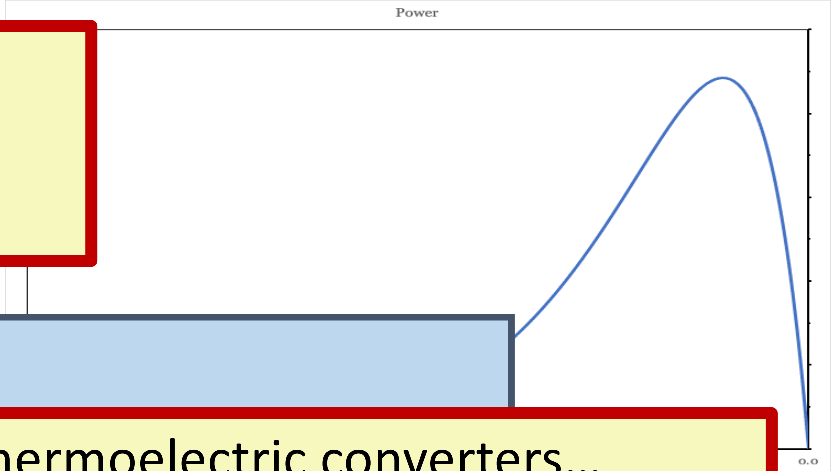
➢ $\boldsymbol{\eta \leq V_b/(V_b+3kt) = 1/4}$

Idealized calculation of highest possible efficiency at Maximum power point

Efficiency at max power point is

≤25%

- Many assumptions in this approximation



At maximum power point, bias voltage V_b = kT

$\eta = (kT)/(kT+$

But bandgap must be ≥ 0, so highest eff

➢ $\eta \leq V_b/(V_b+3kt) = 1/4$

Higher than today's thermoelectric converters…

But can't compare real devices with a theoretical limit

- Real world devices never reach ideal efficiency

- The ideal efficiency can be higher than this if the diode is operated at a (negative) voltage greater than the maximum-power voltage

- However, power decreases exponentially as the diode goes to high negative voltages
- Due to non-ideal losses, real-world operating point will tend to be *less* than the ideal maximum-power voltage, rather than higher

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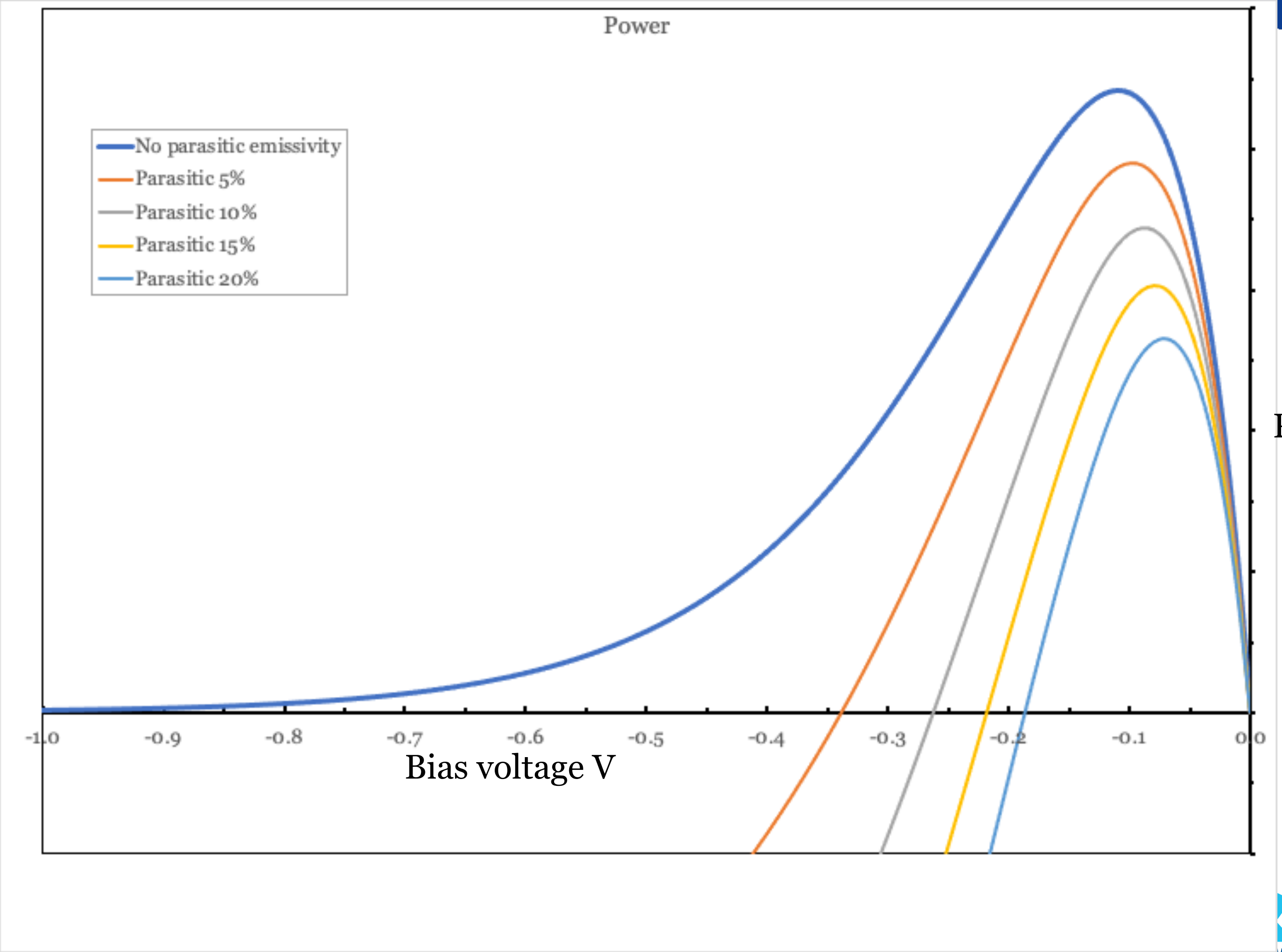
Increasing ideal power:
Spectral Selectivity

- Maximum conversion efficiency of 25% is due to photons of energy $>E_g$ carrying away thermal energy
  - Would like to emit only of photons of energy exactly equal to E_g
- Efficiency could be increased by a spectrally selective surface that transmits photons of bandgap wavelength ($\lambda = hc/E_g$) and reflects shorter wavelength photons back into the cell
  - In the real world, such a spectrally selective reflector would have some bandpass $\Delta\lambda$
  - For an ideal semiconductor, no photons of wavelength less than hc/E_g are emitted. In a non-ideal semiconductor, these photons are parasitic loss and should also be reflected
  - This could be implemented using a dielectric antireflective coating tuned to the bandgap wavelength
- Incorporating such an ideal antireflective coating, **theoretical energy conversion efficiency approaches the Carnot limit**
  - (98% for a 600K radiator and a 12 K sink temperature)
  - Parasitic losses will make this much smaller

Effect of parasitic emissivity at $\lambda<\lambda_c$

- Parasitic emissivity at energy greater than the bandgap energy generates thermophotovoltaic current that subtracts from the thermoradiative current
- This *reduces the power output* and shifts the maximum-power point to lower voltage



Comparison with other solid-state electrical generation

Other forms of solid-state heat engines are thermoelectric and thermophotovoltaic converters.

- Each takes heat energy in to produce electrical power with no moving parts.
- Each has advantages in different applications

For thermoelectric and thermophotovoltaic conversion, the waste heat radiator is on the **cold** side of the system.

  - High radiator temperature **decreases** efficiency

For thermoradiative cells, the radiator is the **hot** side of the system

  - High radiator temperature does not decrease efficiency

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Where are the most valuable applications for thermoradiative cells?

Power Systems in which radiator area is at a premium

- Since thermoradiative cells operate best at high temperature, radiators run hotter, and hence smaller radiators can be used.

Power Systems in which the heat source is low temperature

- Since the cold side of a thermoradiative system is the temperature of deep space (~10K), thermoradiative cells are efficient even at low temperatures*, since the Carnot efficiency loss ($\Delta\eta = T_c/T_h$) is small even at room temperature

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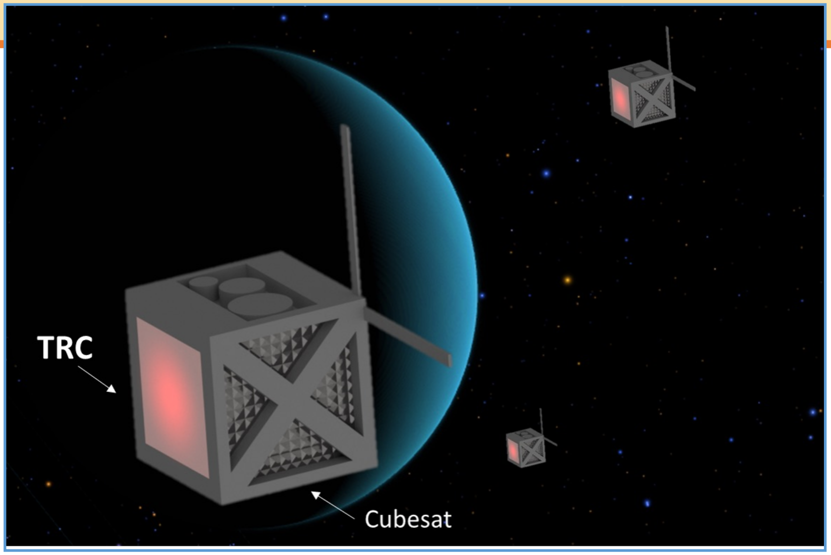
*note that although efficiency stays high the actual amount of power produced will be small at low temperatures, since the radiated power is proportional to T^4

NIAC Project

- We are now working on a NASA Innovative Advanced Concepts (NIAC) project to demonstrate this technology
- Principle investigator is **Dr. Steven Polly** of Rochester Institute of Technology
- Example mission case is to use a small radioisotope source to power a cubesat for outer planet exploration



Conclusions

- Thermoradiative cells represent a new type of semiconductor device for converting heat into electrical power
- A simplified analysis was presented, showing the performance near the maximum power point.
- A number of loss mechanisms were identified that lower efficiency below the theoretical maximum. Most critical of these is the effect of parasitic emissivity.
- Much work needs to be done in developing the low-bandgap semiconductors and the technology needed to put these into arrays.

Acknowledgement

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Research problems to be addressed

Demonstrating real-world devices

- So far, proof-of-concept devices have been fabricated by a number of groups, which demonstrates that the theory works, but only on very small area diodes, and high efficiency has yet to be demonstrated. We need to prove these devices can achieve high efficiency in the real world!

Real World Losses: Parasitic emissivity

- The ideal calculation of conversion efficiency assumes *all* of the thermal emissivity is due to band-to-band radiative recombination. This is unrealistic: there will be other emissivity. **The other sources of emissivity are the dominant factor in the losses of the cell.** We need to understand sources of parasitic emissivity and learn to minimize them.
- In particular, parasitic emissivity at photon energy greater than the bandgap can be re-absorbed by the diode, subtracting from the dark current.

Research problems to be addressed

Manufacturing large-area low-bandgap cells

- We have not yet demonstrated high conversion efficiency on thermoradiative cells. Existing work on low-bandgap materials is in very small area devices, with little or no research on large area devices.

Operating low-bandgap materials at high temperature

- We need to learn how to operate low-bandgap devices at high temperatures. To date little or no work has been done on developing materials characteristics and ohmic contacts for high-temperature operation.

Encapsulation

- Like solar cells, thermoradiative devices must be protected from the space environment. Since glass is opaque to light in the thermal infrared spectrum, new encapsulation techniques will be required.