Thermal Management and Engineering Economics in CPV Design

Phil Blumenfeld
Principal Mechanical Engineer
Emcore Corp.
Albuquerque NM

James Foresi, Yei Lang, John Nagyvary
Emcore Corp.

Installed CPV Field

- ***Emcore's 3rd Generation Solar Receiver Modules, Maui, HI, 2010***

CTJ Cell

- **The triple-junction solar cell is the motivator for Concentrating Solar Photovoltaic (CPV) technology**

CTJ Photovoltaic Cell – 10 mm x 10 mm

Triple-Junction Solar Cell for Terrestrial Applications

Part No. 615016

DATASHEET **SOLAR POWER**

Typical Current-Voltage Parameters at 50 W/cm², 25°C

Parameter	Value at 25°C, 50 W/cm²
Efficiency (%)	38.5

EMCORE's Concentrating Triple-Junction (CTJ) solar cells with n-on-p polarity are built on germanium substrates and incorporate a proprietary antireflective coating that provides low reflectance over a wavelength range of 0.3 to 1.8µm. These high-efficiency solar cells are characterized and optimized for terrestrial applications under concentrated incident illumination and high current densities.

Features and Charactersitics

- Series interconnected triple-junction solar cells monolithically integrated on germanium.
- Photovoltaic absorber materials and bandgap energies are 1.86eV InGaP, 1.40eV InGaAs, and 0.67eV Ge.
- Cells are optimized for operation at 25°C under ASTM G173-03 direct reference spectrum 50 W/cm^2.
- Weldable or solderable front and back contact metallization terminated in silver/ gold alloy.
- All cells are flash tested at concentration at 25°C.
- A variety of shipping options are available, including waffle packs, tape and reel, or processed wafers.

CPV: Some Fundamentals

- The triple-junction cell
  - has the 'world's highest' efficiency in conversion of sunlight to electrical power
  - The efficiency of the cells increases with higher solar concentration
    - But decreases with increasing temperature
  - Lenses or mirrors are used to focus and concentrate incident solar power
    - A structure or enclosure is required to establish a stable, clean focal space
  - It's necessary to track the sun on two axes to keep the spot on the cell
    - Thus moving parts and control systems are required
- Lenses, enclosures, trackers are a "cost of doing business" with CPV
  - It ends up being a challenging and competitive design space
    - against other solar technologies
    - against coal-fired electric plants
- Concentrated sunlight not converted to electricity is concentrated heat
  - This heat increases cell temperature
- Increased cell temperature means lower efficiency
  - Thus degrading the cost advantage for CPV
  - Details to follow

- *Thus thermal design for CPV must consider both performance and economy*

Dollars per Watt

- ***A convenient metric that captures both performance and economy***
  - **about which engineers and business people agree is:**

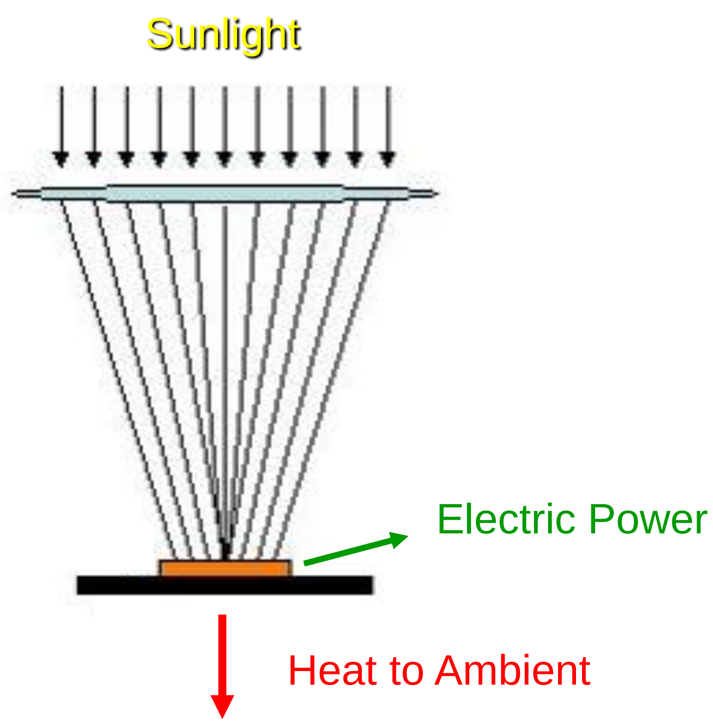
$ / W

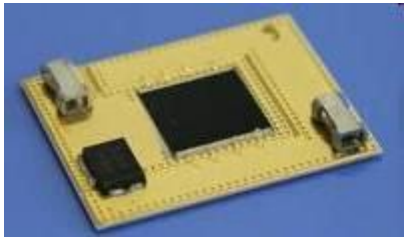
"dollars per watt"

- ***Uninstalled cost per watt of DC power conversion***
  - **at standard operating conditions**
  - **this evaluates the hardware design; excludes things like inverters**
- **We will work through an example of component redesign for improved $/W**
- ***First we'll look at system basics and a few designs***

Basic CPV Schematic

- *Concentration ratio = lens area / cell area*
  - *Earlier designs: 500x*
  - *Present Design > 1000x*

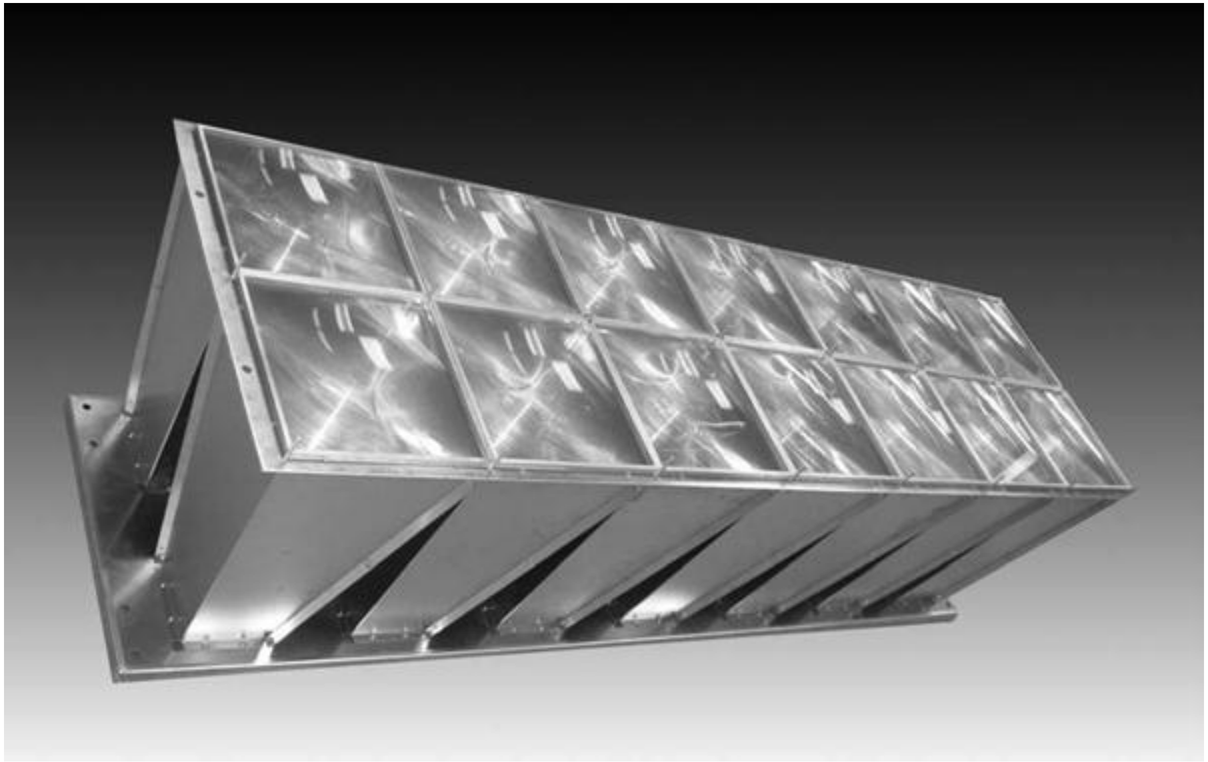




Cell area: 1 cm^2

CPV Module Development

- An early generation CPV module
  - Lens area: 0.05 m^2 per receiver
  - P_{elec} ~ 12 W per receiver
  - Heat rejected: 28 W per receiver from flat backplate

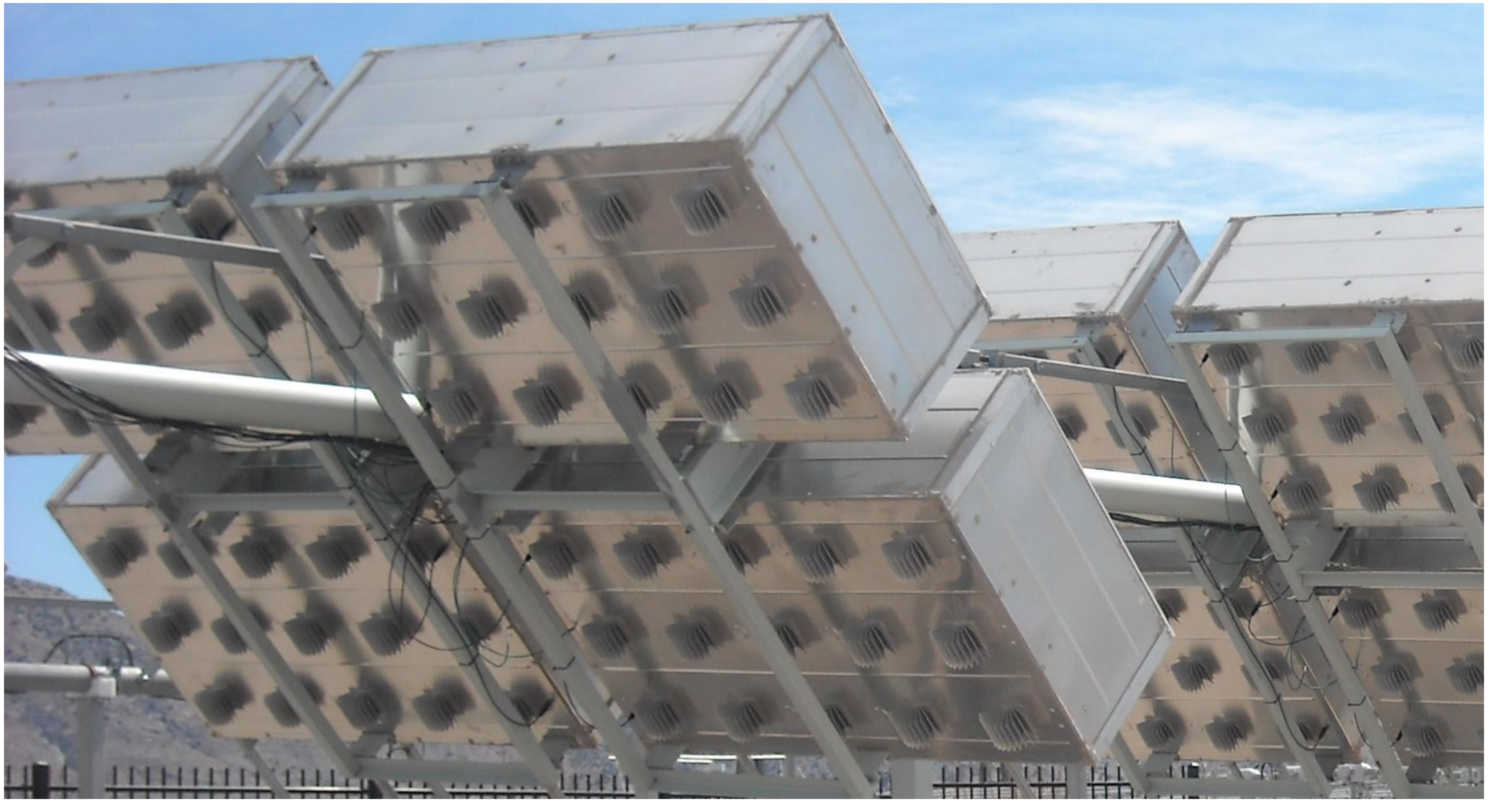


CPV Module Development

- A present generation CPV module
  - Lens area doubled: 0.10 m^2 per receiver
  - P_{elec} ~ 30 W per receiver
  - Heat rejected: 50 W per receiver from aluminum heat sinks

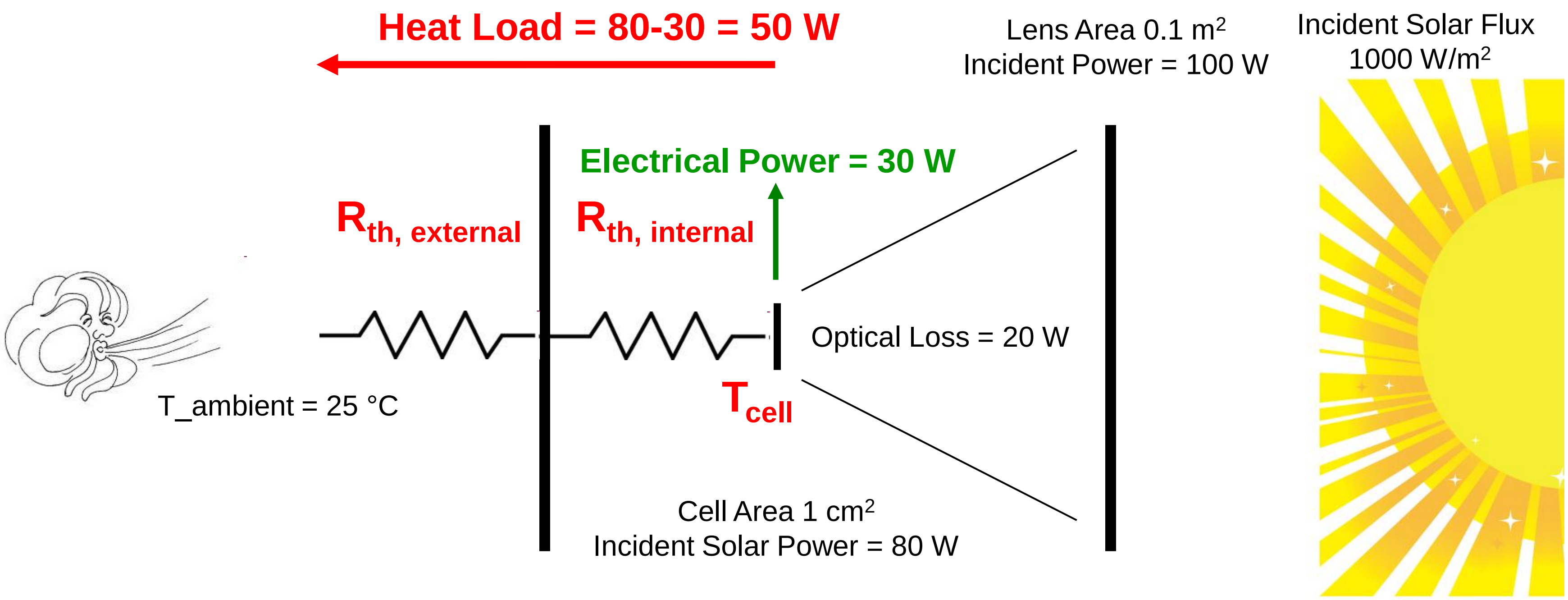
Present CPV Module Design

- **We will examine the engineering economy of this heat sink**
  - **Compared with previous design**
  - **How does the addition of a heat sink affect $/W?**
  - **Begin with a look at a simple thermal schematic**



CPV System Thermal Schematic

- **The parameters in red are our present concern**
  - **Consider some representative conditions**
  - **Rth: thermal resistance, °C/W_{th}, "how hot does it get as it carries heat?"**



Reducing the operating temperature of the cell increases conversion efficiency.

Frugality for a Low-cost Unit Product

- Consider marginal contribution of a receiver component to system cost.
  - Each receiver produces about 30 W of power
  - A design cost target might be 1.50 $/W
  - Each receiver is thus worth $40.50
- ***A $2.00 heat sink represents ~ 5% of unit cost.***

- Consider a PC that sells for $2000
- ***A $2.00 heat sink represents 0.1% of unit cost.***

- Consider an electric sports car that sells for $109,000
- ***A $2.00 heat sink is ~ free.***

- ***CPV designers have to be very frugal!***
  - Compared with thermal design for certain other high-ticket products

Temperature-dependent Economics

- **From Emcore's datasheet: power production increases by 0.2% for each °C reduction in temperature (-0.002 W/W/°C).**
- **That marginal increase in power provides a marginal increase in $/W**
- **Assume a System Design Baseline: $1.50/W**
- **How much is every °C "worth"?**
  - **Let ΔT = -1.0 °C. Baseline power is 30 W.**

$$\Delta\$ = \Delta\$/\Delta P * (\Delta P/P_{base} * 100)/\Delta T * P_{base}/100 * \Delta T$$

$$\Delta\$ = 1.50\ (\$/W)\ -0.002\ (W/W\text{-}°C) * 30\ (W) * -1.0\ (°C)$$

$$\Delta\$ = \$0.09$$

- ***Each degree C temperature reduction is worth 9 cents per receiver***
  - ***Assumes cost of components is equal***
  - ***Worth more if the design change can save $ at the same time***

Consider Design Changes

- Now that we know how much one degree is worth
- We can consider marginal (not insignificant) changes to the design
  - Use predictive modeling to estimate resulting change in cell temperature
  - Estimate marginal change in system cost associated with the design change
  - Calculate net change in $/W

- Let us consider:
  - Replace a flat aluminum plate, 6.4 mm thick, 0.33 m square -> m = 1.8 kg
    - This represents the backplane of a module without heat sinks.
  - Replace it with an engineered heat sink
    - Optimize the heat sink design for high performance and low mass
    - Keep manufacturing costs low
    - The following are some design considerations…

Heat Sink Design

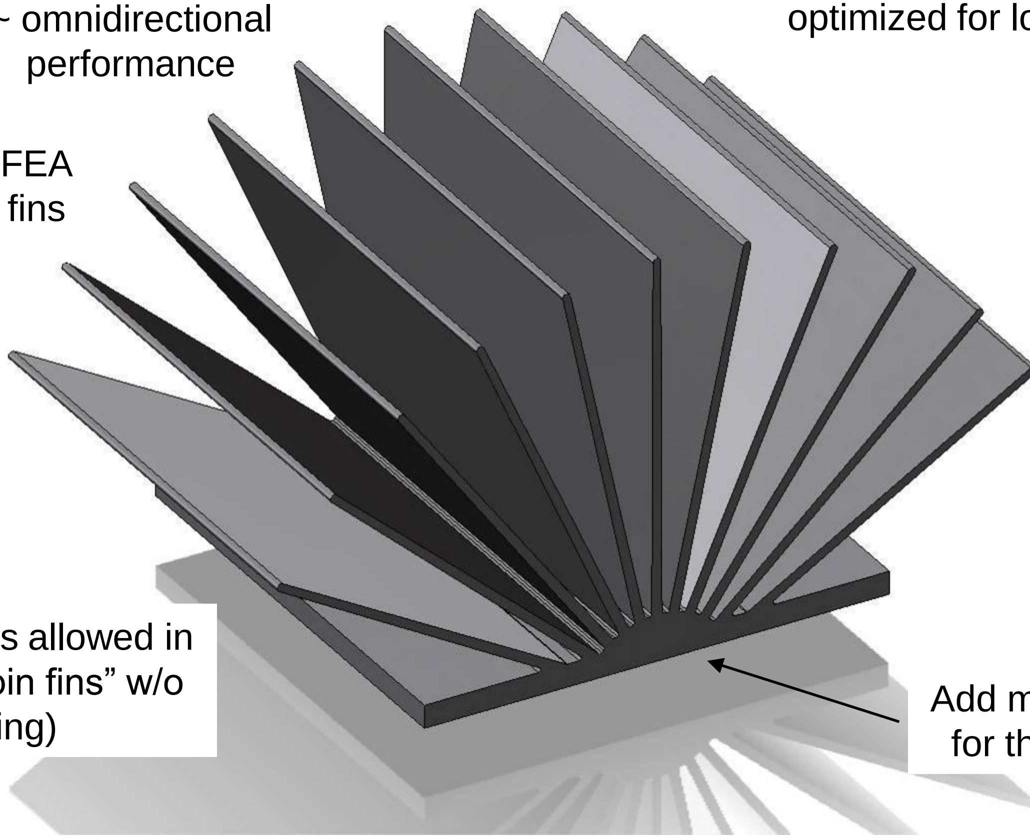
- **Heat Sink Design Principles**
  - **Create a lot of surface area (fins)**
  - **Extend the surface area out and away from stagnant boundary layers**
  - **Minimize the path length from the source to the surface area**
  - **Maximize the cross section of the same path**
  - **Set fin spacing for expected fluid conditions**
    - **Fins wider apart for natural convection; there are formal ways to optimize**
  - **Set fin orientation for expected angle of fluid incidence**
    - **i.e. wind direction relative to module**
- **Some design constraints unique to this product:**
  - **Passive heat sink is specified**
    - **Heat is rejected to ambient air without moving parts**
  - **Module orientation is constantly changing (tilt and roll)**
    - **Thus there is no one "up" direction to enhance natural convection**
    - **Arrange heat sink fins so that at least some of them will always point up**
  - **Outdoor utility application**
    - **Nothing fragile allowed**
    - **Has to survive the "hail test": 1" ice balls shot close range at 22 m/s (50 mph)**

Heat Sink Manufacturing

- What manufacturing process?
  - Heat sinks are typically die-cast or extruded
  - We determined that for a very low-cost component extrusion was best
- Extrusion alloy Al-6063 has high thermal conductivity
  - Compared with e.g. A360 die casting alloy
- In large quantities extrusion cost can approach that of the material.
  - Some detractions from this, mainly addition of holes and coatings

Heat Sink Design

- **Final heat sink design**



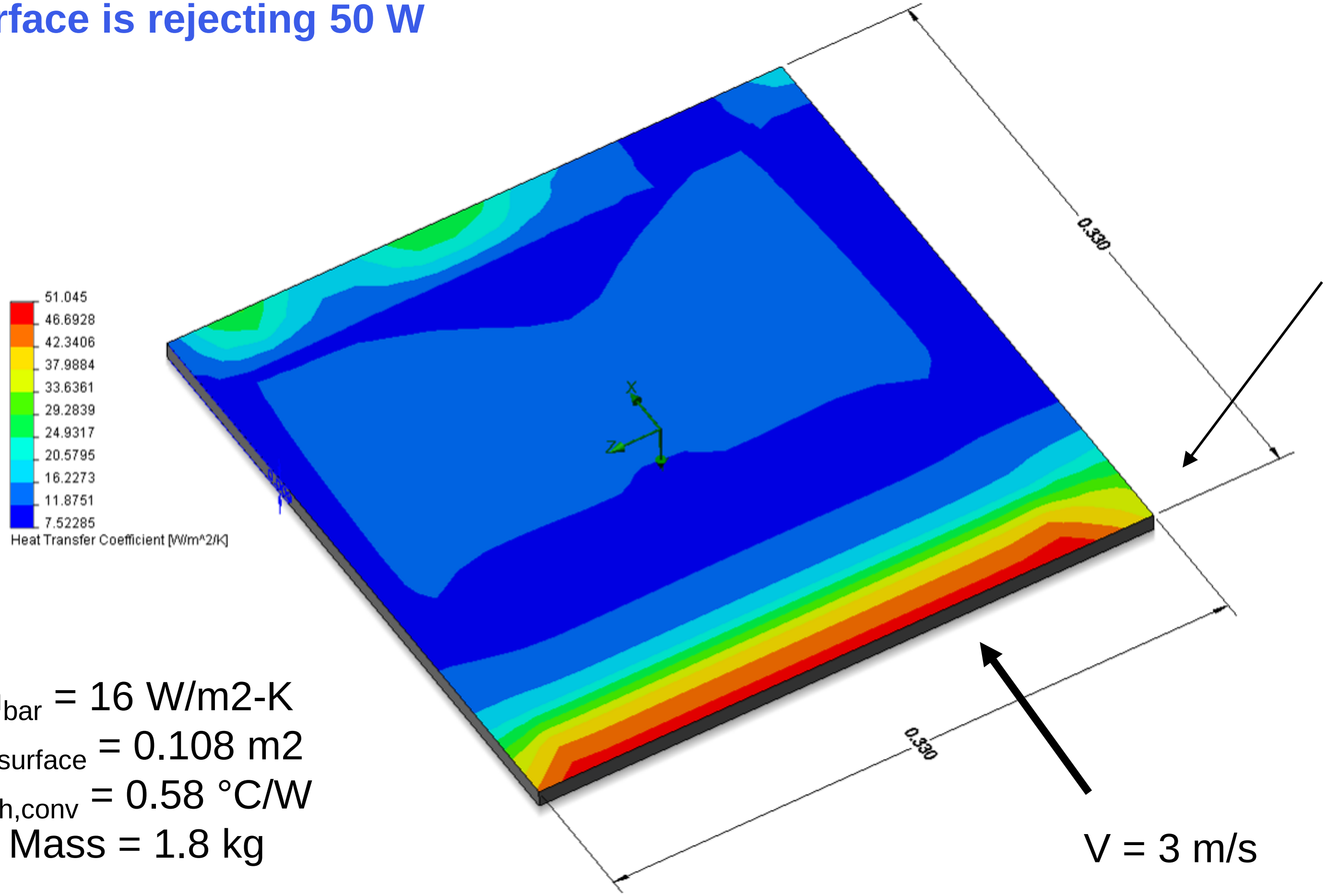
Heat Rejection Performance Comparison

- Characterize the competing designs by their convective thermal resistances
  - This is a simplification for present purposes
  - Define thermal resistance for convection:

- $R_{th, conv}$ (°C/W) = 1 / [h_{bar} (W/m^2-K) * $A_{surface}$ (m^2)]

  - h_{bar}, the average convection coefficient is a measure of the ‘quality’ of heat transfer from a solid surface to an adjacent fluid.
  - h_{bar} depends on a lot of things, including the geometry of the surface and the velocity of the fluid.
  - There are a variety of ways to estimate h_{bar} for any situation
  - In the present case I’ve used Computational Fluid Dynamics (CFD) software to simulate airflow past a flat surface and past a heat sink.
  - The software calculates h locally across all surfaces
    - The software also provides an average over selected surfaces; this average is h_{bar}.

- **Flat surface local and average heat transfer coefficients**
  - **Surface is rejecting 50 W**



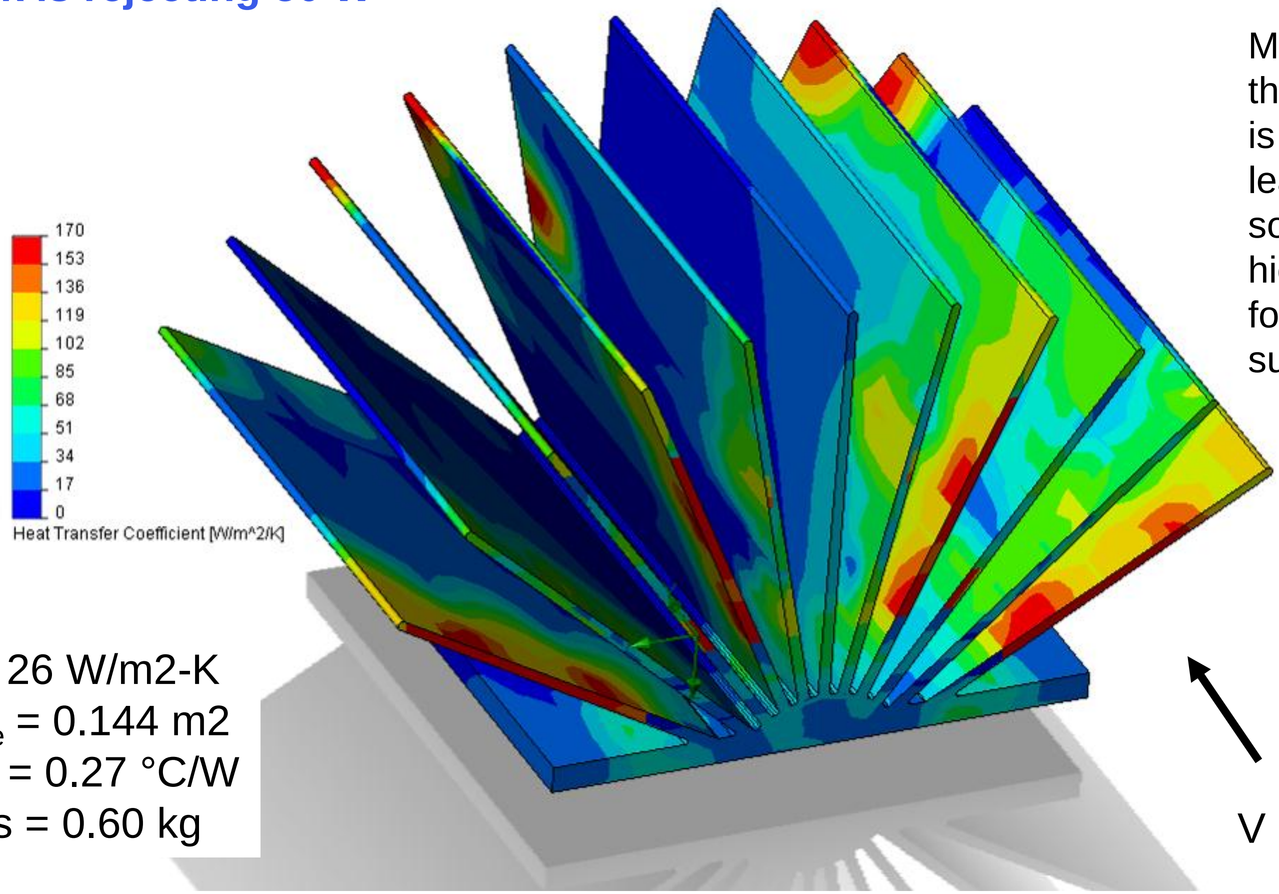
Note that h is highest near the leading edge. On a large plate with many receivers the average, h_{bar}, will be lower than for this single plate.

h_{bar} = 16 W/m2-K
$A_{surface}$ = 0.108 m2
$R_{th,conv}$ = 0.58 °C/W
Mass = 1.8 kg

V = 3 m/s

CFD Modeling

- **Heat sink local and average heat transfer coefficients**
  - **Heat sink is rejecting 50 W**



Much more of the material is near the leading edge, so h_{bar} is higher than for a flat surface.

h_{bar} = 26 W/m2-K
$A_{surface}$ = 0.144 m2
$R_{th,conv}$ = 0.27 °C/W
Mass = 0.60 kg

V = 3 m/s

Estimate the Change in $/W

- **Estimate reduction in cell temperature and increased power**
  - **ΔR_{th} = 0.27 °C/W – 0.58 °C/W = -0.31 °C/W**
  - **ΔT = -0.31 °C/W * 50 W = -15.5 °C**
  - **ΔP = -0.002 W/W/°C * 30 W * -15.5 °C = 0.93 W**
- **Estimate change in cost**
  - **Simply assume it's the change in cost of aluminum @ 2.53 $/kg**
  - **Δm = 0.6 kg – 1.8 kg = -1.2 kg**
  - **Δ$ = 2.53 $/kg * -1.2 kg = -$3.04**
- **Calculate change in $/W**
  - **New cost per receiver = $40.50 – $3.04 = $37.46**
  - **New power per receiver = 30 W + 0.93 W = 30.93 W**
  - **New $/W = 1.21 $/W**

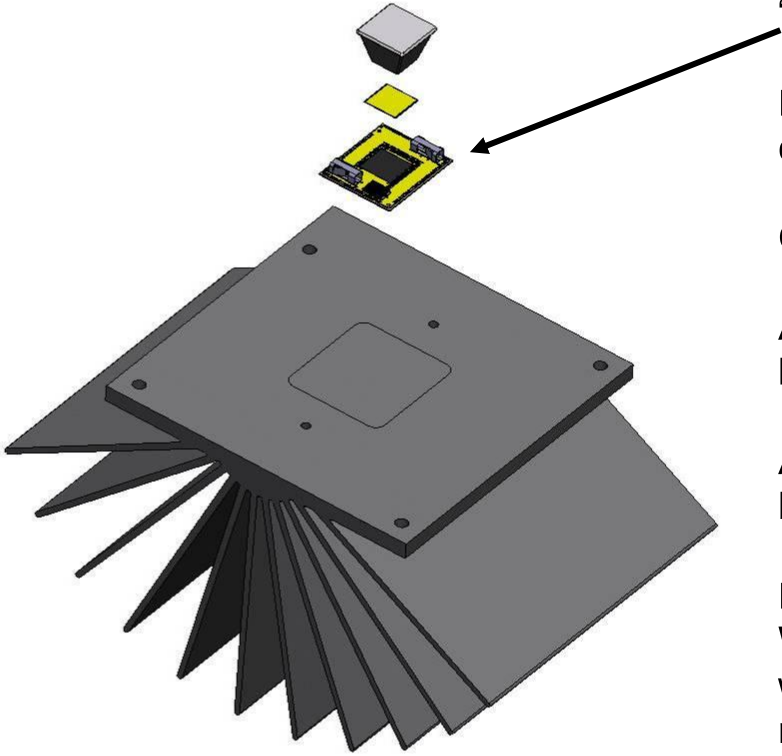
- ***Change in $/W = 1.50 $/W – 1.21 $/W = -0.29 $/W, a 19% improvement.***

Unaccounted Costs

- **Note that there are costs not accounted for:**
  - **This was a simplified example**
  - **Most notably missing: the metal required to hold the module together**
  - **The flat backplane had been a structural member**
  - **Use lighter and less expensive materials for the structure**
  - **This is part of an overall design change for the new product**
  - ***When all is accounted for, the heat sink is still wins in terms of $/W.***
  - **Important: that's because we replaced an expensive component**
    - **Simply adding a new component is still limited to 9 cents per °C per receiver.**
    - **Look closely at the economics of heat pipes or spreaders *added to* the heat sink**

Internal Receiver Components

- **Internal thermal resistances exist in the receiver package itself**
  - **A similar performance and cost optimization may be made on each of those components**



“DBC”: Direct-bond copper circuit board

Provides electrical insulation with good thermal conductance

Choice of ceramic materials:

Al_2O_3 has lower thermal conductivity, but can be made thinner. It’s less expensive.

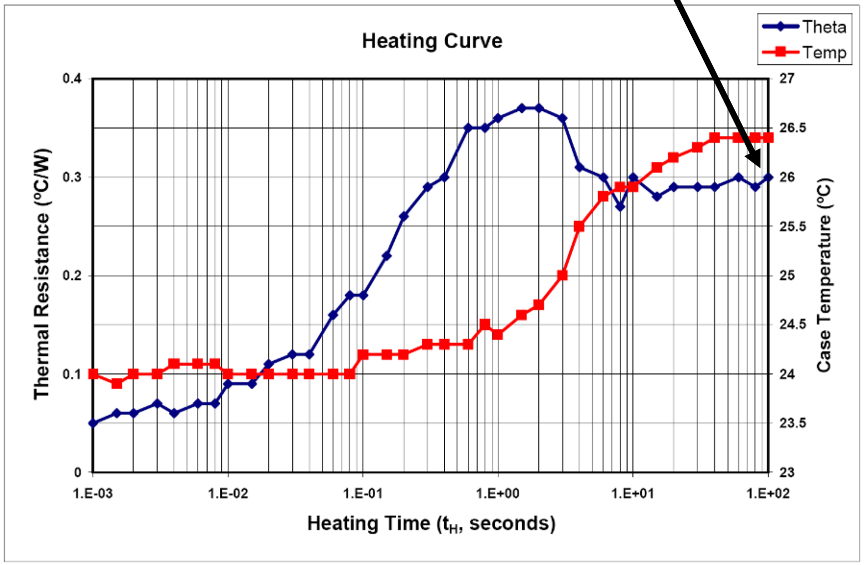
AlN has higher thermal conductivity, but has to be thicker. It costs more.

How to decide? Use the same $/W analysis
We won’t do the whole thing again here, but we will look at measurement of DBC thermal resistance.

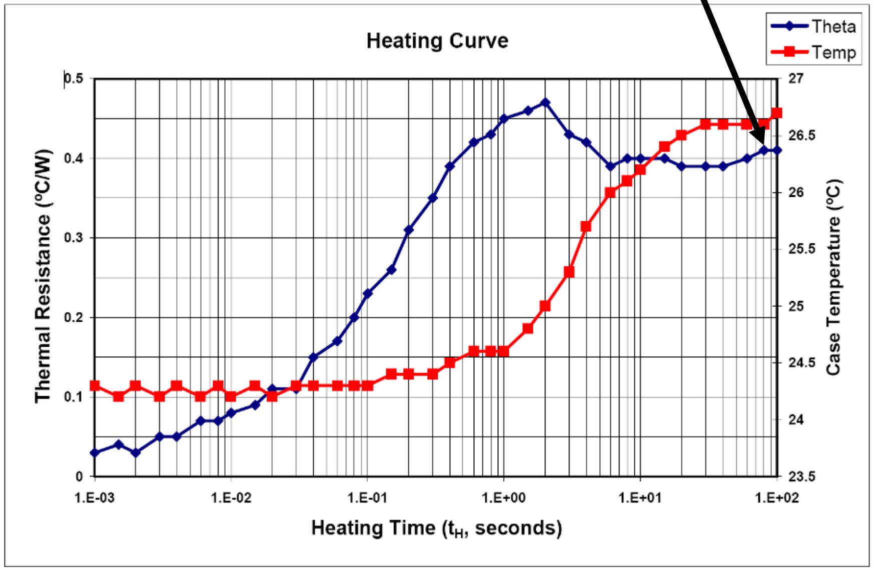
DBC Thermal Resistance

- **Measurement of thermal resistance for packaged semiconductor devices is an established practice.**
  - **Basics:**
    - **excite junction(s) with robust current in forward bias to generate heat in a transient pulse**
    - **Rapidly switch to a small, calibrated, excitation current to sense cell temperature**
    - **Repeat for increasing pulse lengths**
  - **Test results from Thermal Engineering Associates:**

AlN (nitride) ~ 0.3 °C/W



Al2O3 (oxide) ~ 0.4°C/W

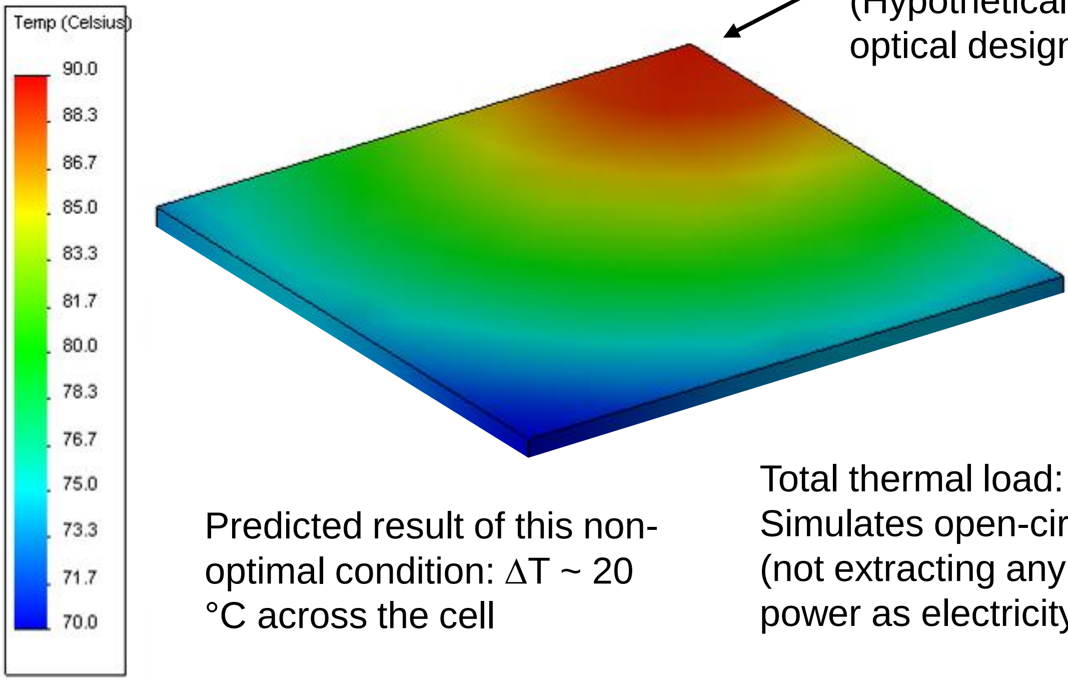


Complications

- **Things that detract from this simple view of cell temperature:**
  - **Optical flux non-uniformity causes temperature gradients across the cell. There is no longer a single cell temperature, but a distribution of temperatures that constantly moves around as the system tracks the sun.**

Non-uniform incident flux: 6 times more intense here than opposite corner. (Hypothetical, could result from poor optical design.)

Concentration in a corner of the cell simulates off-axis tracking.

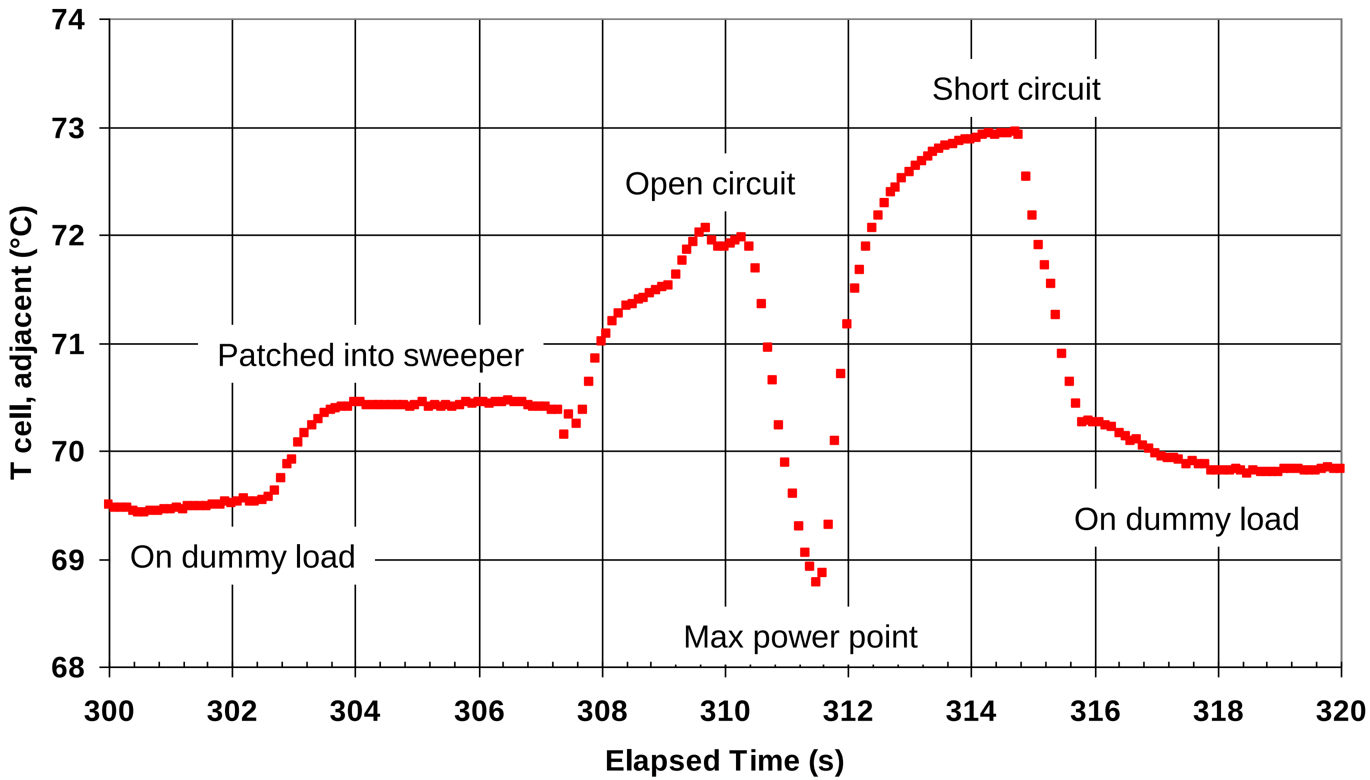


Predicted result of this non-optimal condition: $\Delta T \sim 20$ °C across the cell

Total thermal load: 80 W
Simulates open-circuit operation (not extracting any incident power as electricity).

Complications

- **Things that distract from this simple view of cell temperature**
  - **Cell temperature is constantly changing in time**
  - **Chart: temperature *on DBC adjacent to cell* on-sun**
    - **sweeping through max power point to generate I-V curve during test**
    - **i.e. not normal use conditions**
    - **temperature excursions in the cell itself would be larger**

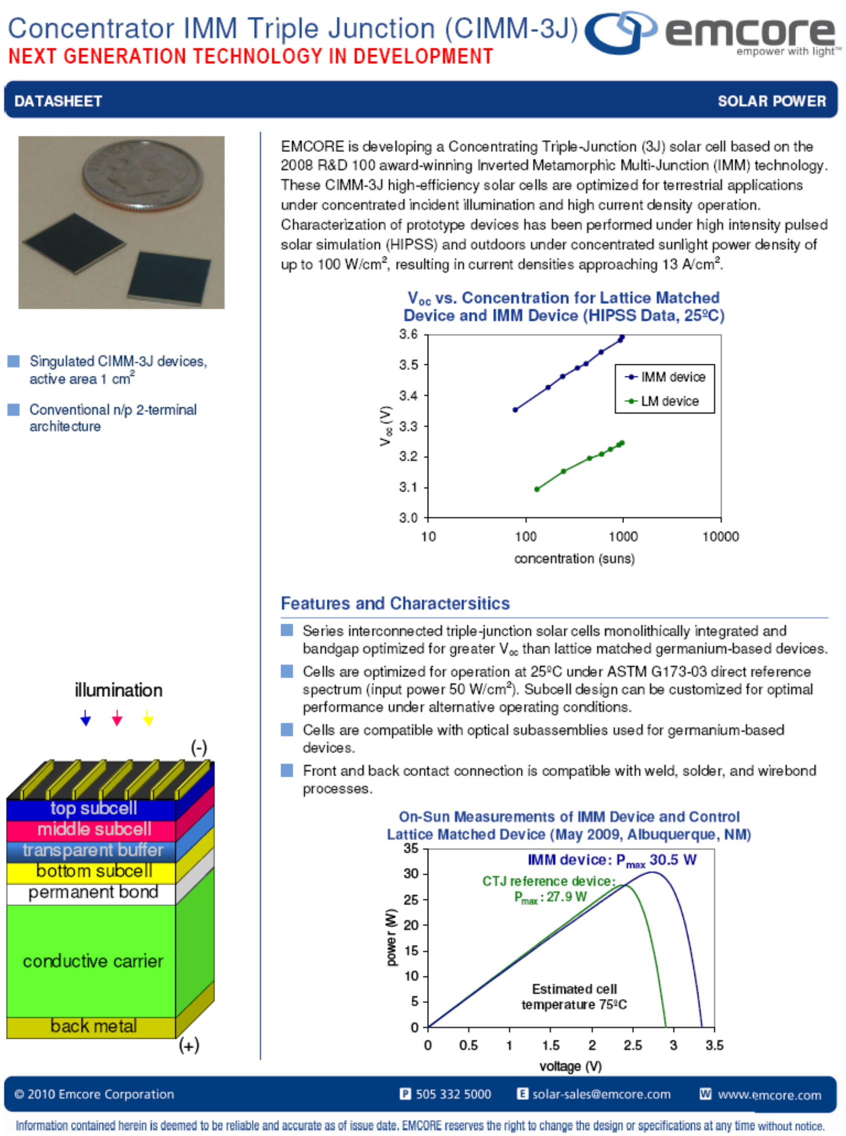


Reliability

- **Temperature-related reliability concerns**
  - **This is a complicated topic in its own right.**
  - **Limiting case: *if you do a bad job things catch on fire*.**
  - **Elevated temperature accelerates many failure modes**
  - **Certain materials such as adhesives or encapsulants have a fairly low temperature tolerance, but are otherwise desirable**
    - **Look carefully at aging phenomena**
  - **There can be dangerous positive feedbacks**
    - **Such as degradation of the DBC attachment causing increased package thermal resistance**
  - **Because of such things the design team may decide to set stricter limits on cell temperature.**

Future Improvements

- **Coming soon…**
  - **Emcore's Inverted Metamorphic Multijunction (IMM) cell**
  - **Higher efficiency**
  - **Lower heat rejection**
  - **Lower internal thermal resistance**
  - **Lower junction temperature**



Concentrator IMM Triple Junction (CIMM-3J) emcore empower with light™

NEXT GENERATION TECHNOLOGY IN DEVELOPMENT

DATASHEET SOLAR POWER

- Singulated CIMM-3J devices, active area 1 cm^2
- Conventional n/p 2-terminal architecture

EMCORE is developing a Concentrating Triple-Junction (3J) solar cell based on the 2008 R&D 100 award-winning Inverted Metamorphic Multi-Junction (IMM) technology. These CIMM-3J high-efficiency solar cells are optimized for terrestrial applications under concentrated incident illumination and high current density operation. Characterization of prototype devices has been performed under high intensity pulsed solar simulation (HIPSS) and outdoors under concentrated sunlight power density of up to 100 W/cm^2, resulting in current densities approaching 13 A/cm^2.

Features and Charactersitics

- Series interconnected triple-junction solar cells monolithically integrated and bandgap optimized for greater V_{oc} than lattice matched germanium-based devices.
- Cells are optimized for operation at 25ºC under ASTM G173-03 direct reference spectrum (input power 50 W/cm^2). Subcell design can be customized for optimal performance under alternative operating conditions.
- Cells are compatible with optical subassemblies used for germanium-based devices.
- Front and back contact connection is compatible with weld, solder, and wirebond processes.

 P 505 332 5000 E solar-sales@emcore.com W www.emcore.com

Questions

- ***Thanks for your kind attention…***