High Efficiency Quantum Well Thermoelectrics for Waste Heat Power Generation

Milliwatts to Kilowatts of Power

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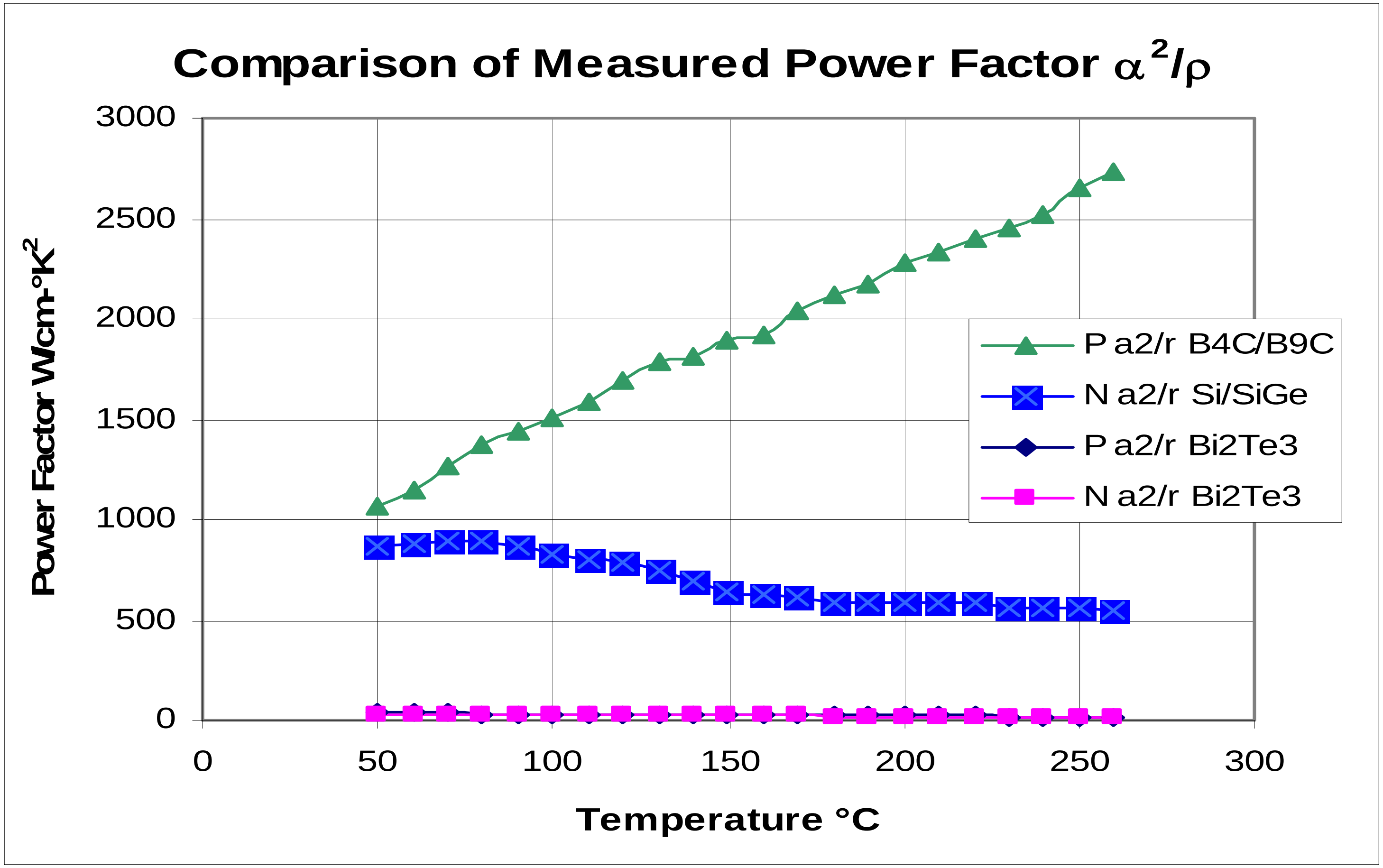
Measured Power Factor

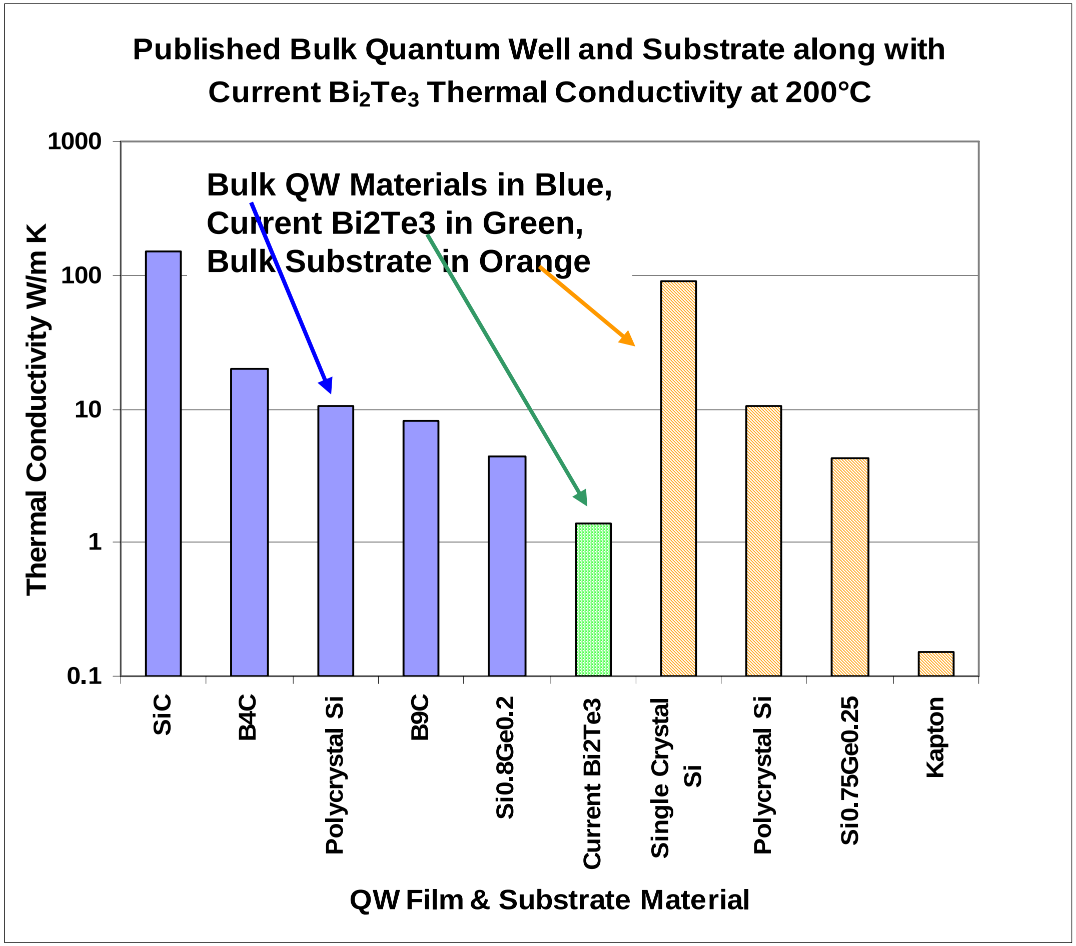
Quantum well is Significantly Better than Bi_2Te_3



Quantum Well & Substrate Thermal k

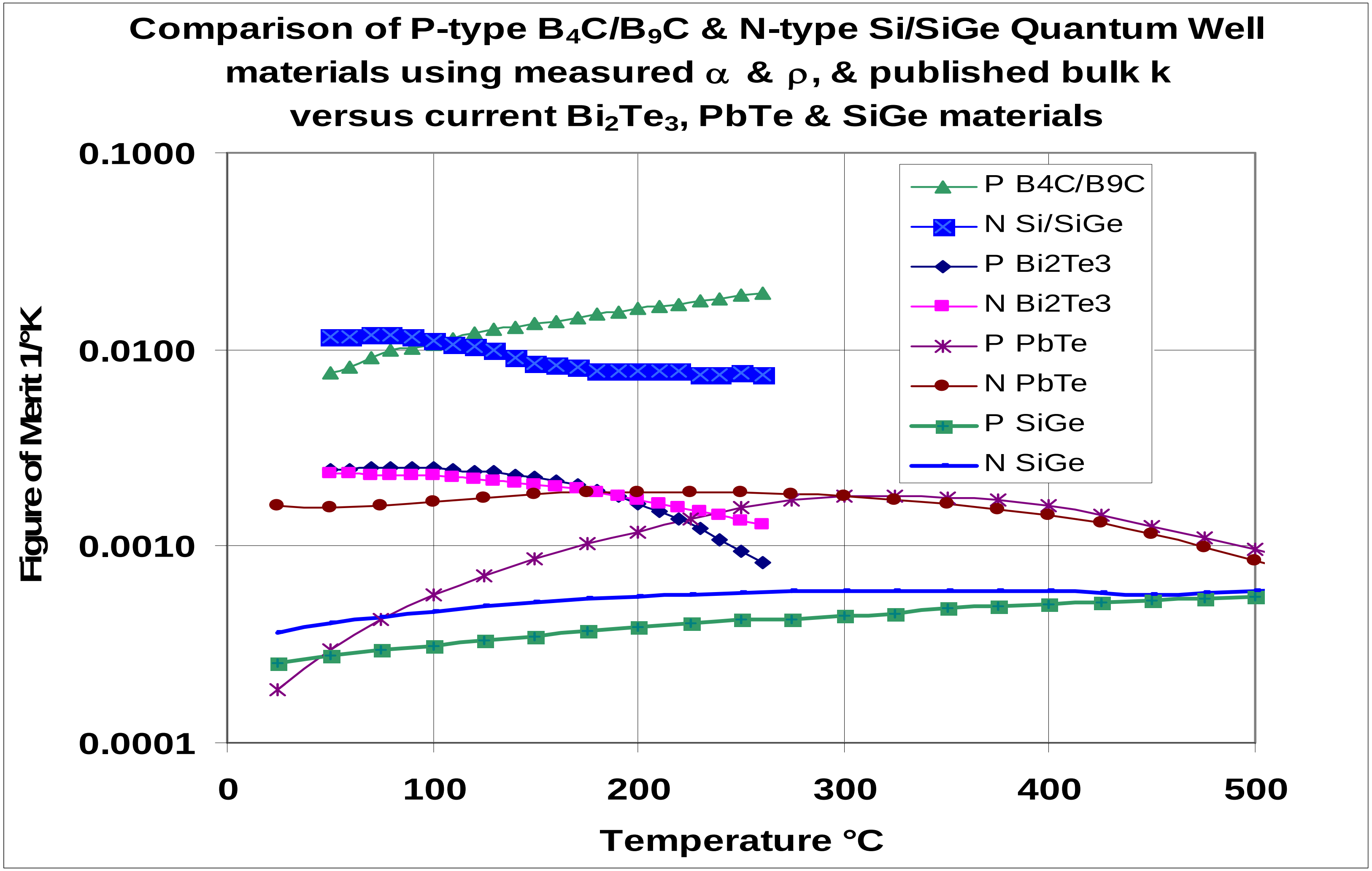
Kapton substrate reduces thermal loss to a small fraction

- Published data used to generate chart
  - Bulk properties
- QW film is expected at 1/3 bulk thermal k from literature
- Substrate could represent large thermal loss
  - 5 micron poly Si is ~50% loss with 11 micron QW film
- Kapton at 25 microns is 3% loss in efficiency with 11 micron QW film



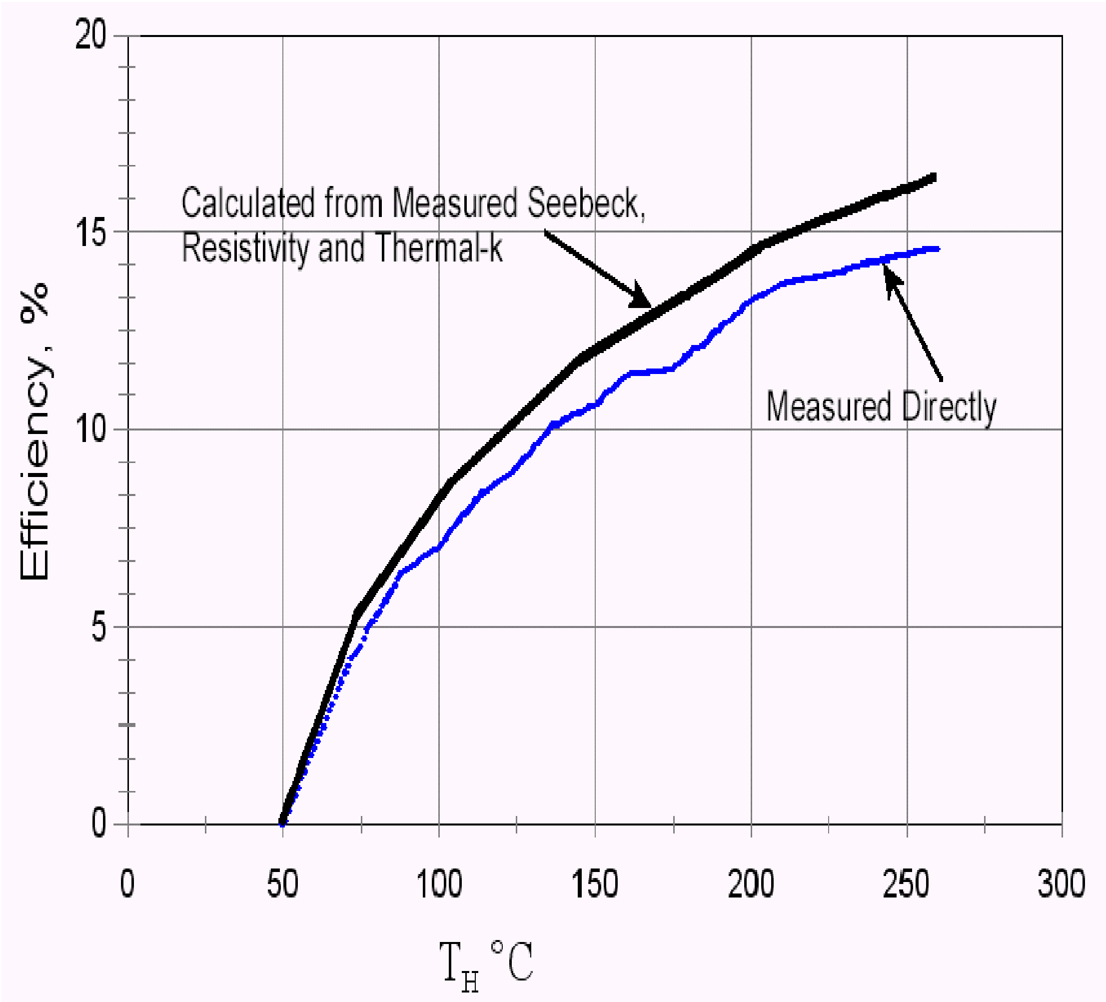
Quantum Effect in B_4C/B_9C & Si/SiGe

Quantum well ZT >3x higher than other current materials



Quantum Well Couple Efficiency

Highest Measured Thermoelectric Efficiency



- Measured Quantum Well Couple Efficiency Versus temperature at a T_C = 70°C
- Over 100 Data Points Were Obtained – N-leg Si/SiGe, P-leg B_4C/B_9C
- Both Films 11 µm Thick and Deposited on a 5 µm Thick Si Substrate

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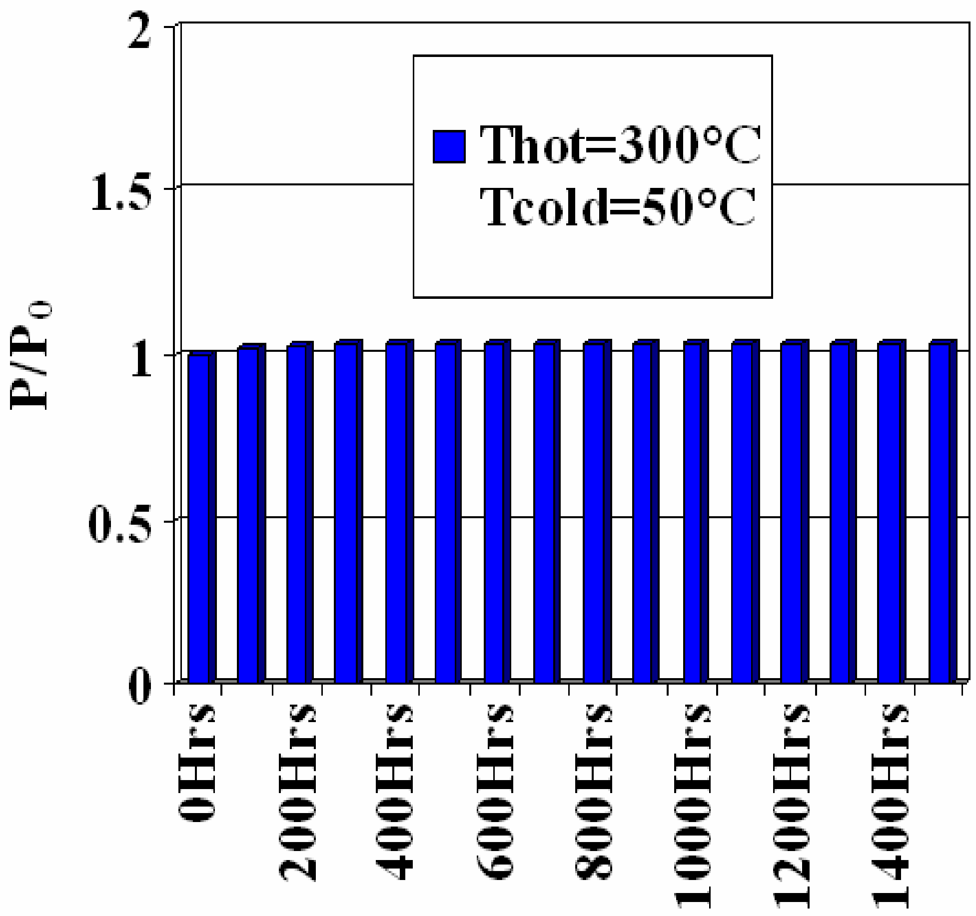
Thermal Stability of Quantum Well Couple

N-type Si/SiGe and P-type B_4C/B_9C

- There are no changes in Seebeck (α) and Electrical Resistivity (ρ) after 1400 hours (July 2005)
- Power Factor (α^2/ρ) shown as P/P_0



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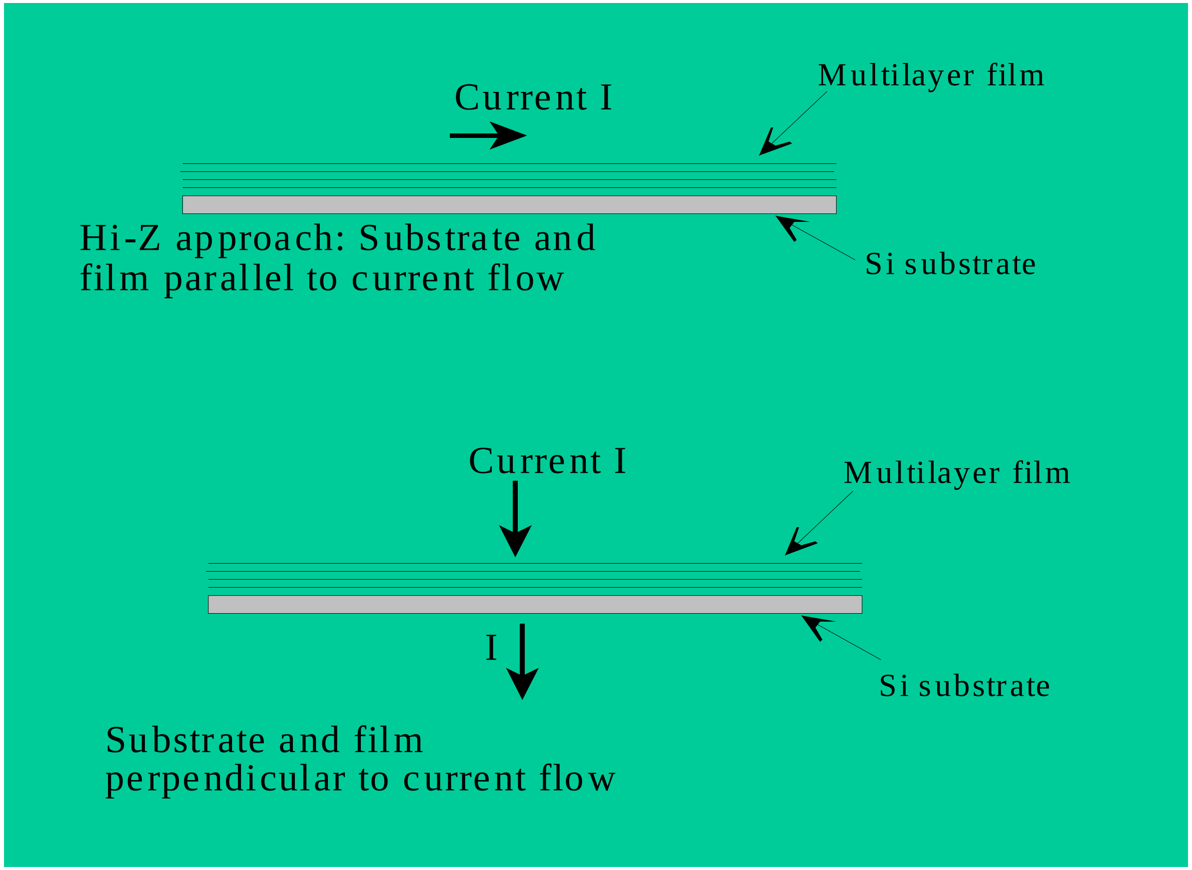
QW Films Parallel or Perpendicular to Current Flow

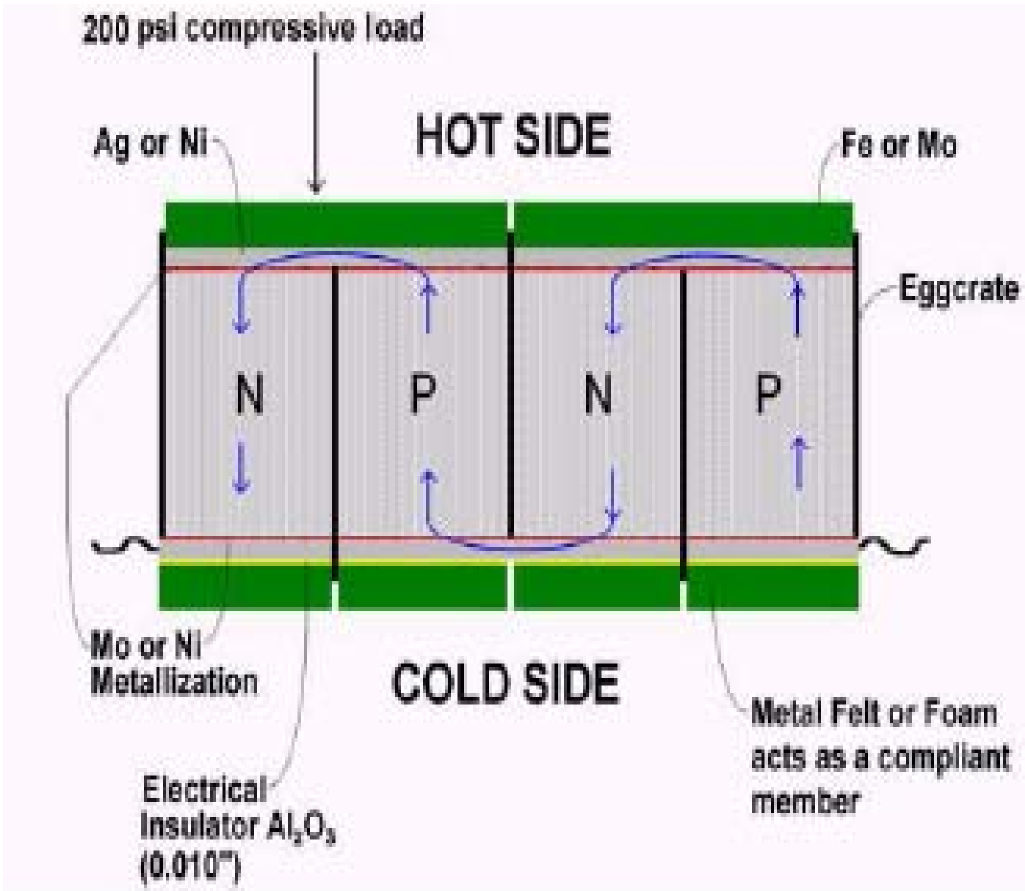
Hi-Z uses parallel approach to give higher Zs



Two Couples with Pressure Contacts

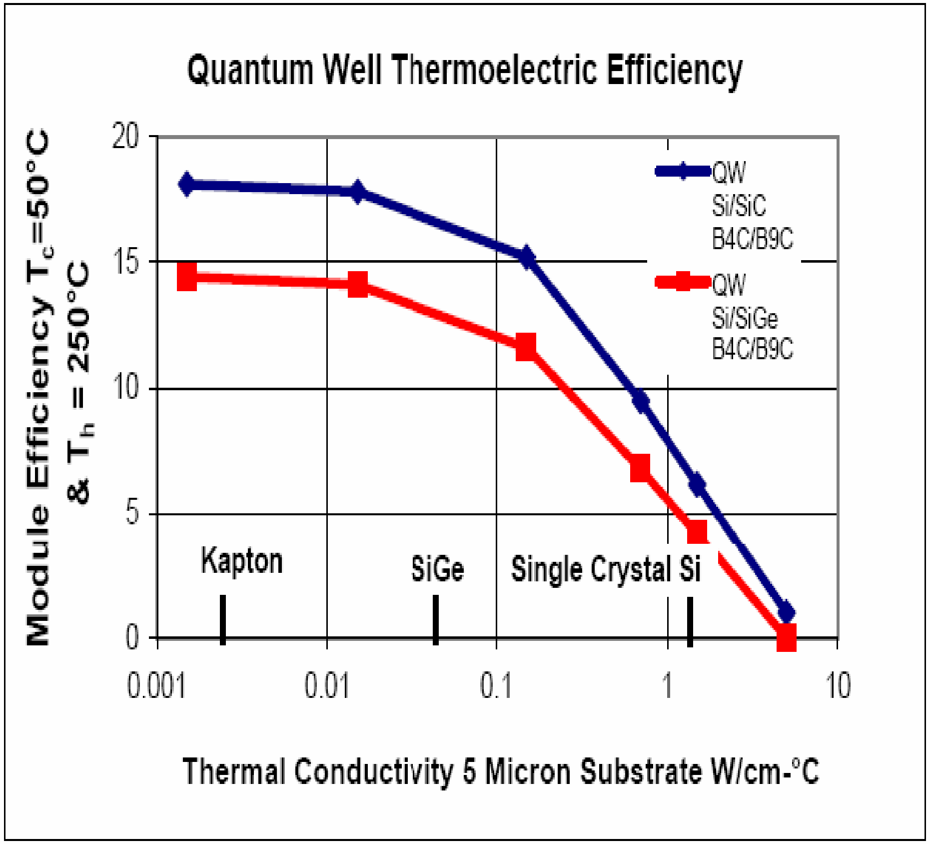
Approach successfully used in PbTe TE Generator

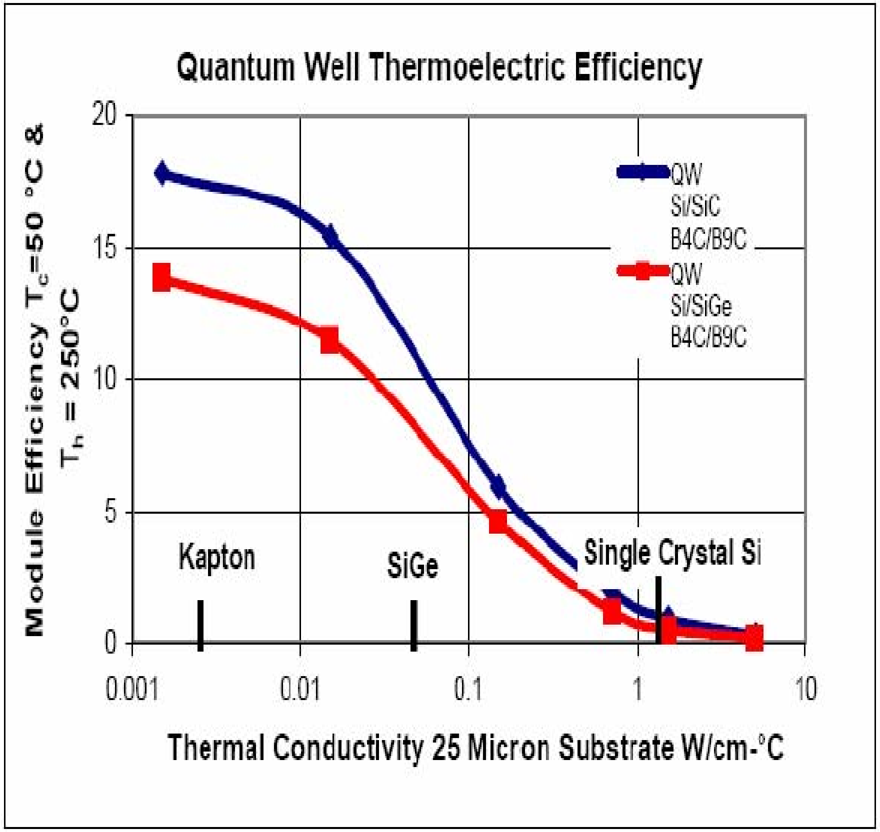
- Surfaces must be free of oxides
- Connect quantum well film to metal
- Thermal expansion must be accommodated
  - Thermal spray technique
- Recent data fabrication of $Si/Si_{0.8}Ge_{0.2}$ surfaces metallized with molybdenum
  - Life tested to 1400 hours



Efficiency Depends Strongly on Substrate

Efficiency improves and cost is greatly reduced with Kapton substrate





Si substrate is 80% of materials cost and large heat leak
Kapton substrate is 12% of materials cost and very small (<5%) heat leak

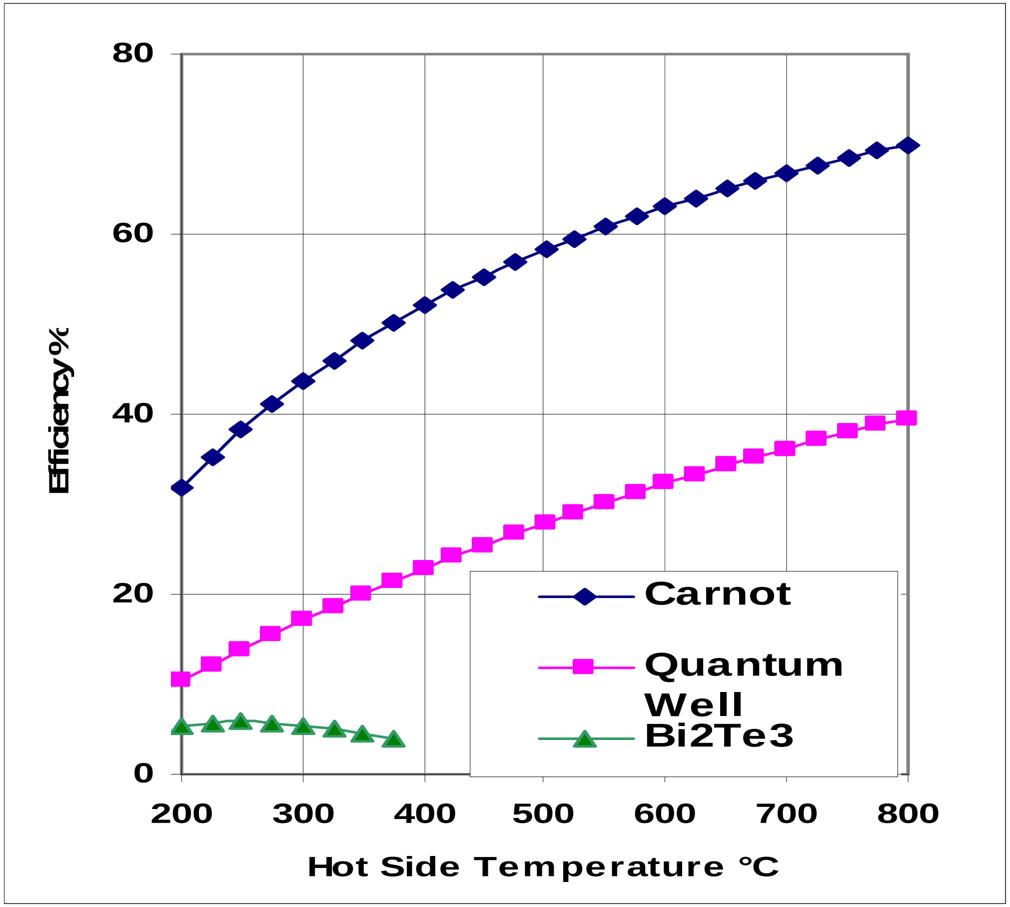
Comparison of Quantum Well and Current Thermoelectric Performance

Thermoelectric Module Material	Temperature Difference °C	Voltage at Maximum Power	Maximum Efficiency %	Maximum Power W
N & P-type bulk Bi_2Te_3	200	1.6	5.8	14
	Hi-Z's Commercial Alloys			
N type Si/SiC & P-type B_4C/B_9C Quantum Well Kapton substrate 25 µm thick	200 250	10.0 12.4	17 20.9	60 72
	Under Development			
N type Si/SiC and P-type B_4C/B_9C Quantum Well SiGe Substrate ~5µm thick (too hot for Kapton)	450	22.6	32.5	338
	Under Development			

Predicted Efficiency of Quantum Well Thermoelectric Module

Efficiency >50% Carnot at higher temperatures

- **N-Type Si/SiC & P-type B_4C/B_9C**
- **Cold side at 50°C**
- **Based on measured α & ρ, and literature κ (bulk thermal conductivity)**
- **Efficiencies compete with gasoline & diesel engines, & fuel cells.**



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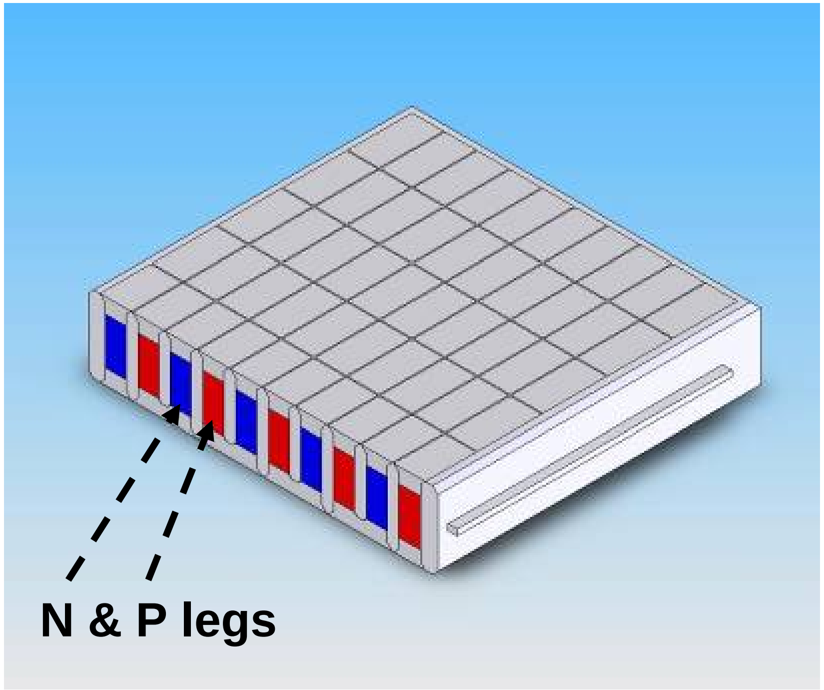
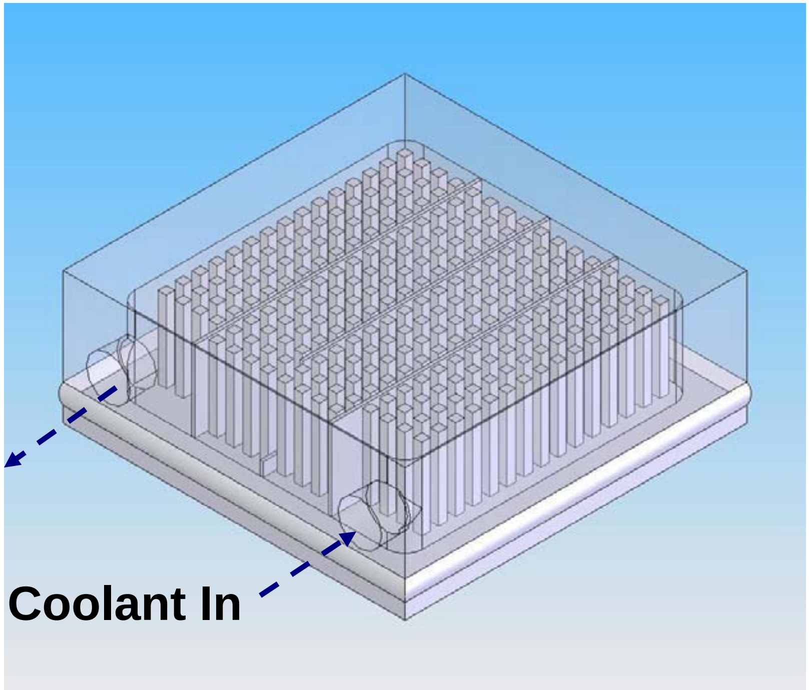
Hi-Z Quantum Well Thermoelectric Module and Heat Exchanger



50 Watt Quantum Well
Thermoelectric Module
T_H 300°C T_C 100°C



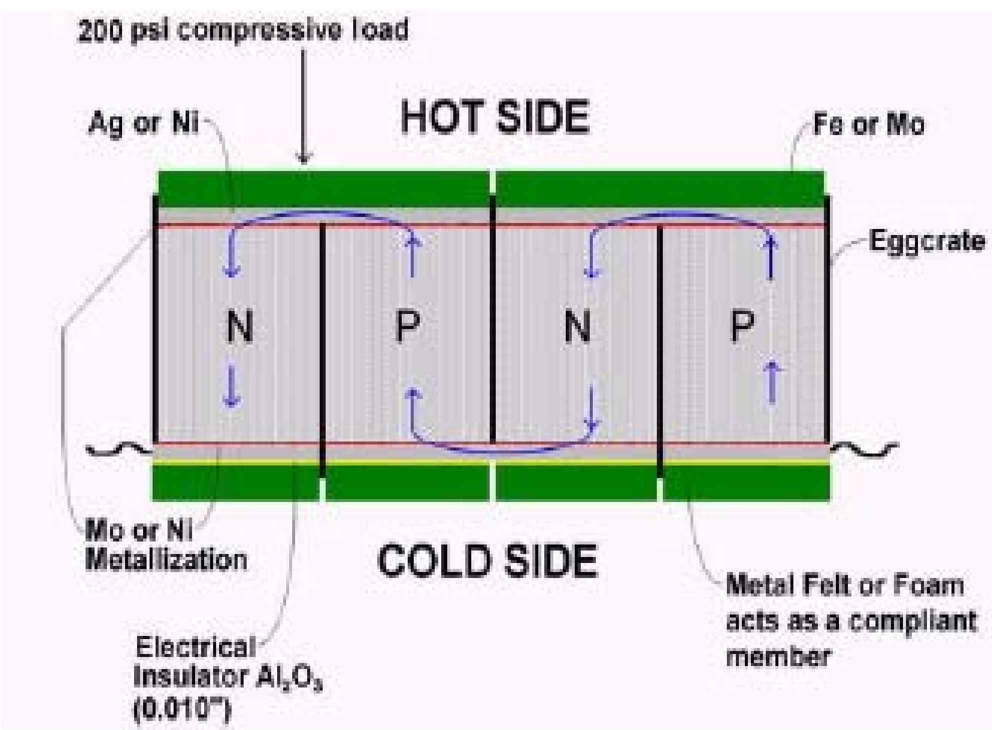
Heat Exchanger

Kapton substrate for quantum well films forms module in place of eggcrate design

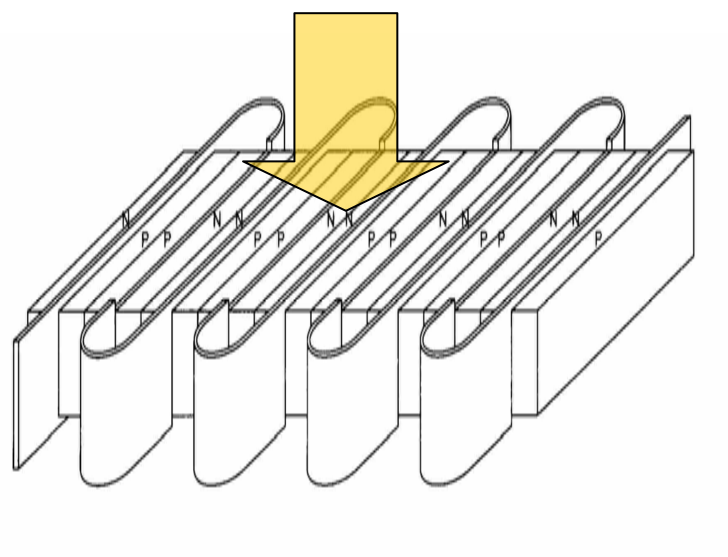
Quantum well efficiency 15% versus 5% Bi_2Te_3

Module size 6.3 x 6.3 x 1.0 cm

Pressure contact showing 2 of 49 couples



Heat Flow



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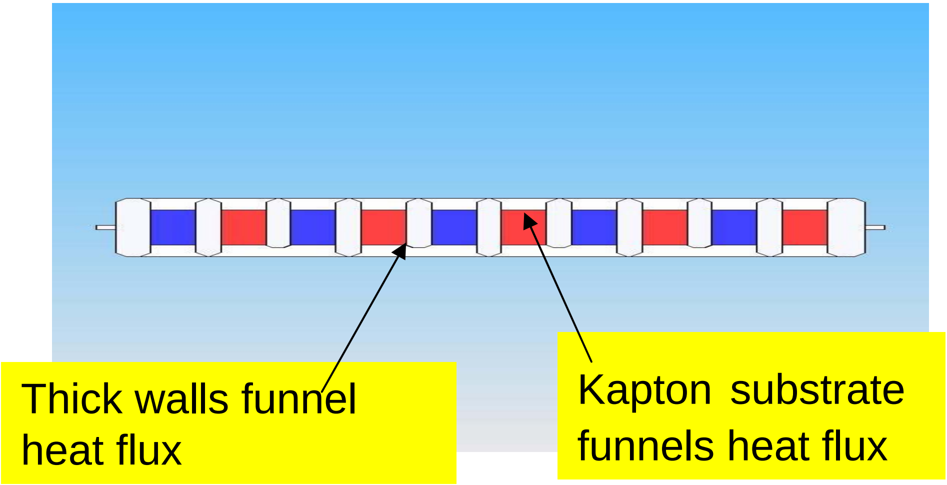
Funneled Heat Flux Module

Increases power & reduces amount of QW material

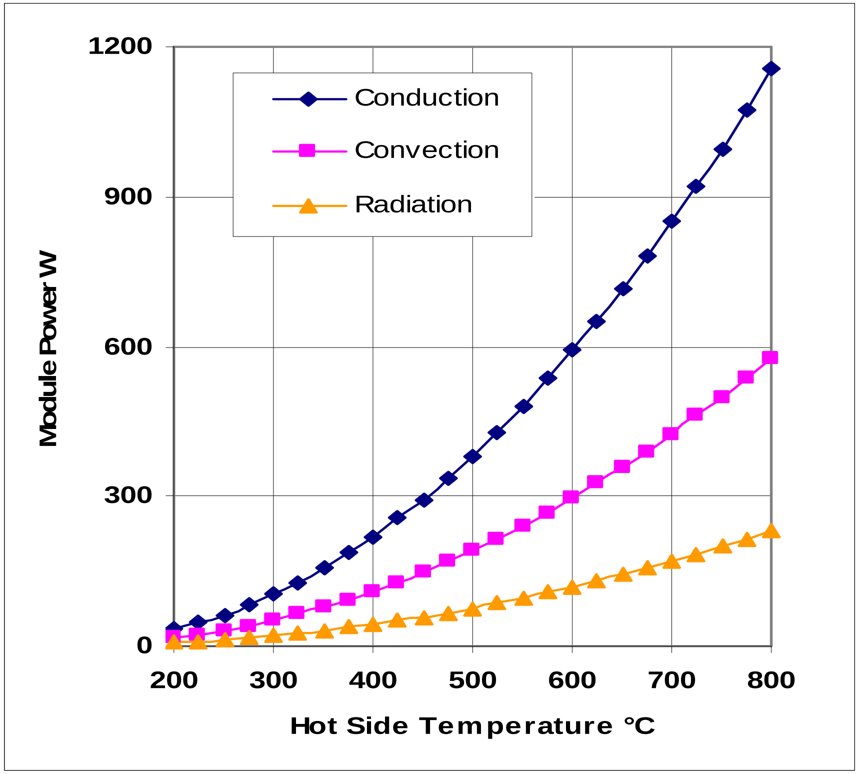


Method to match module resistance with heat flux of hot and cold sides while increasing power putput

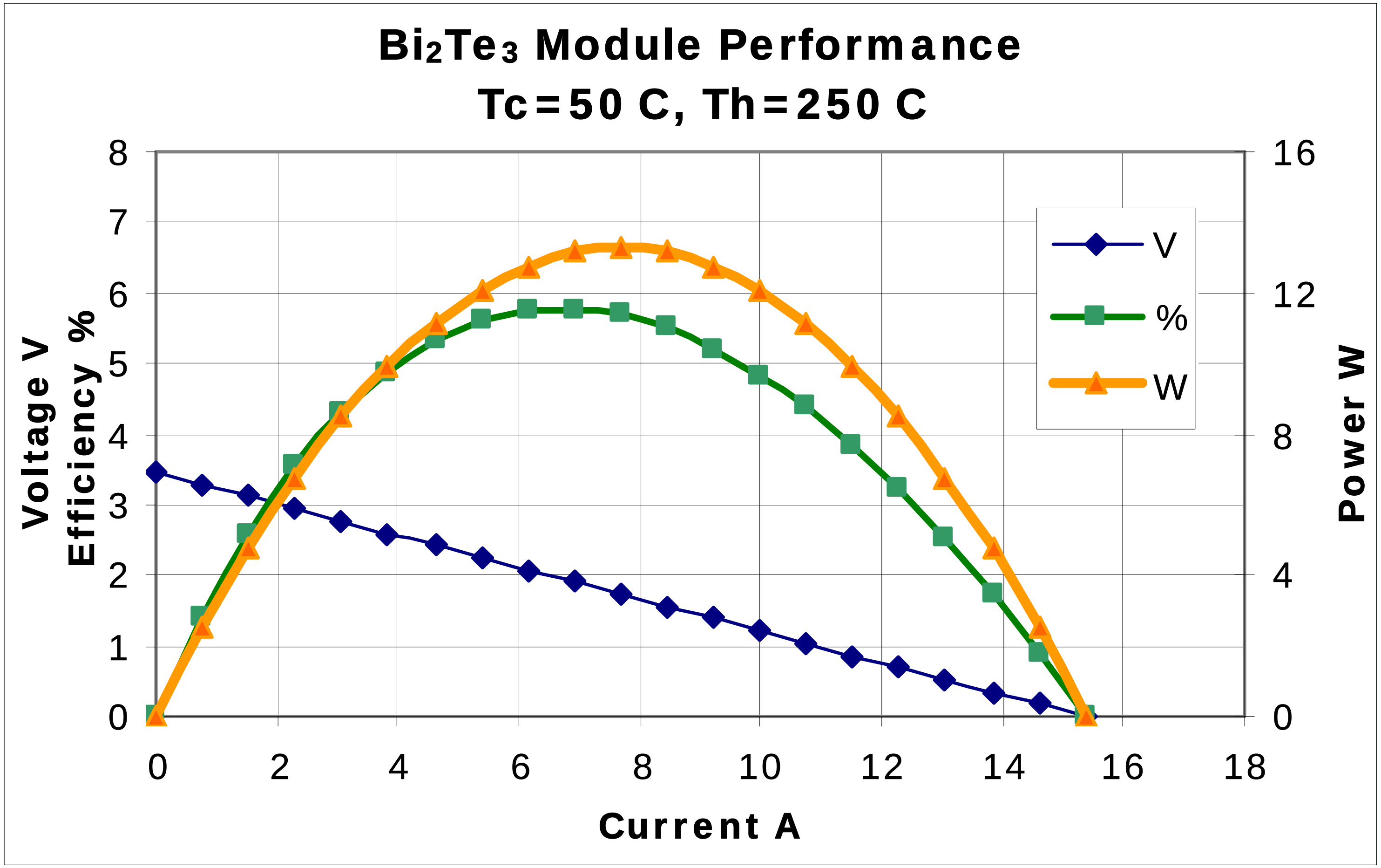
Predicted Power of Quantum Well Thermoelectric Module

Radiation coupling is practical design for high temperature; conduction or convection higher power

- **N-Type Si/SiC & P-type B_4C/B_9C**
- **Cold side at 50°C**
- **Module is 2.5 x 2.5 in.**
  - **Thickness changed to match heat flux from source**
    - **Conduction**
    - **Convection**
    - **Radiation**
- **Based on measured α & ρ, and literature κ (bulk thermal conductivity)**
- **Requires high temperature eggcrate**



Hi-Z Bi_2Te_3 Thermoelectric Power Generator at 200°C Temperature Difference



Present Technology

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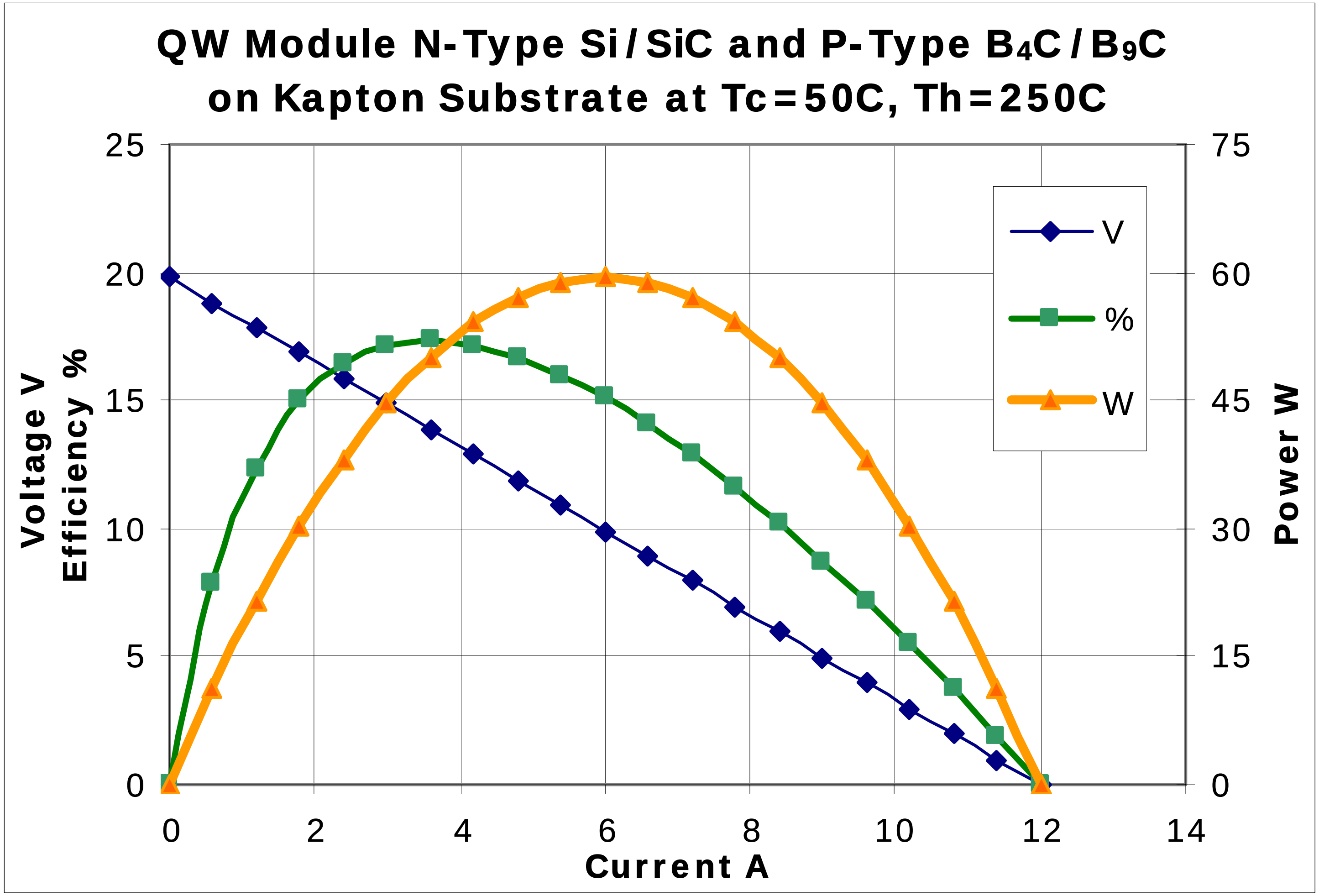
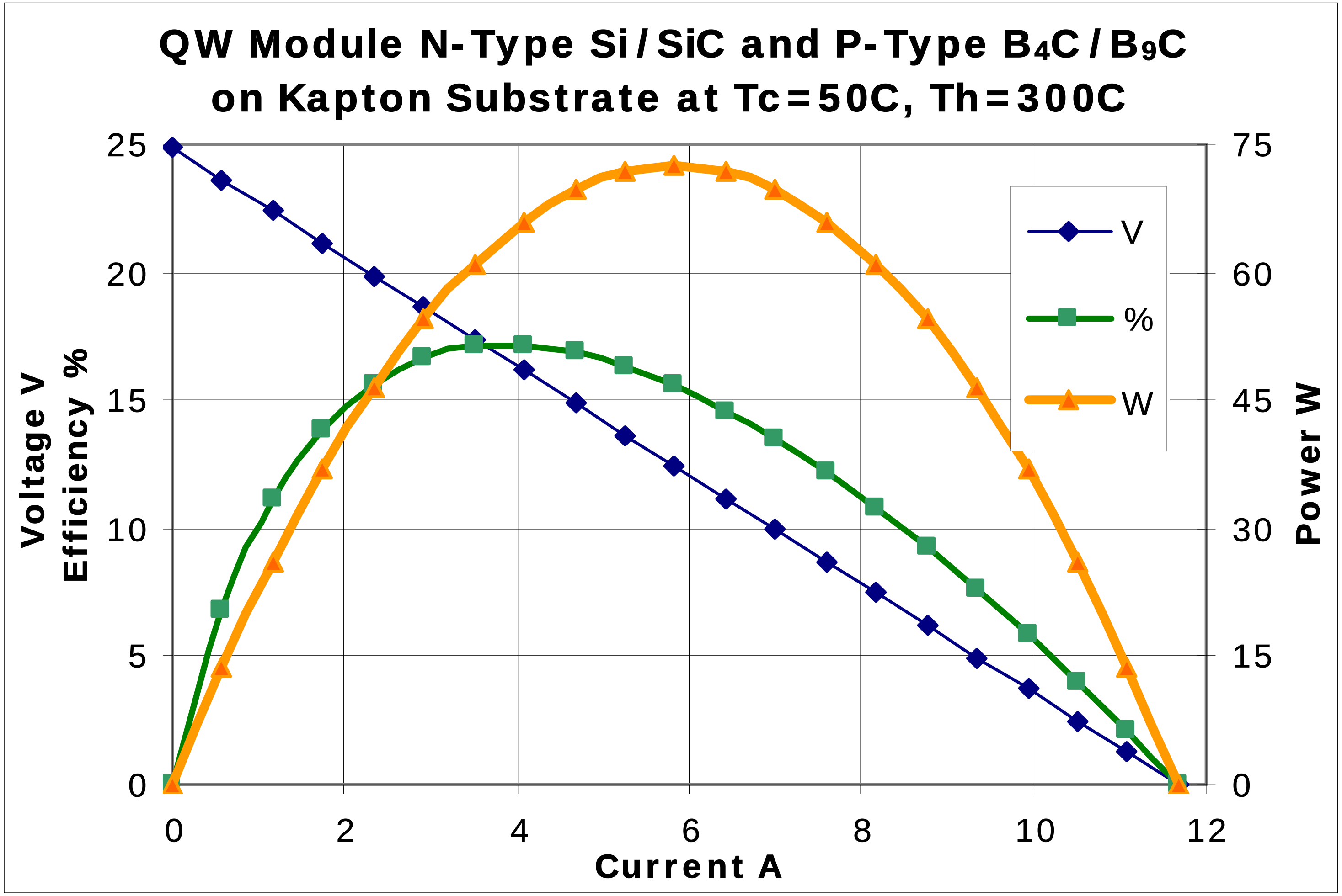
Predicted Hi-Z Quantum Well Thermoelectric Power Generator at 200°C Temperature Difference



Under Development

Predicted Hi-Z Quantum Well Thermoelectric Power Generator at 250°C Temperature Difference



Under Development

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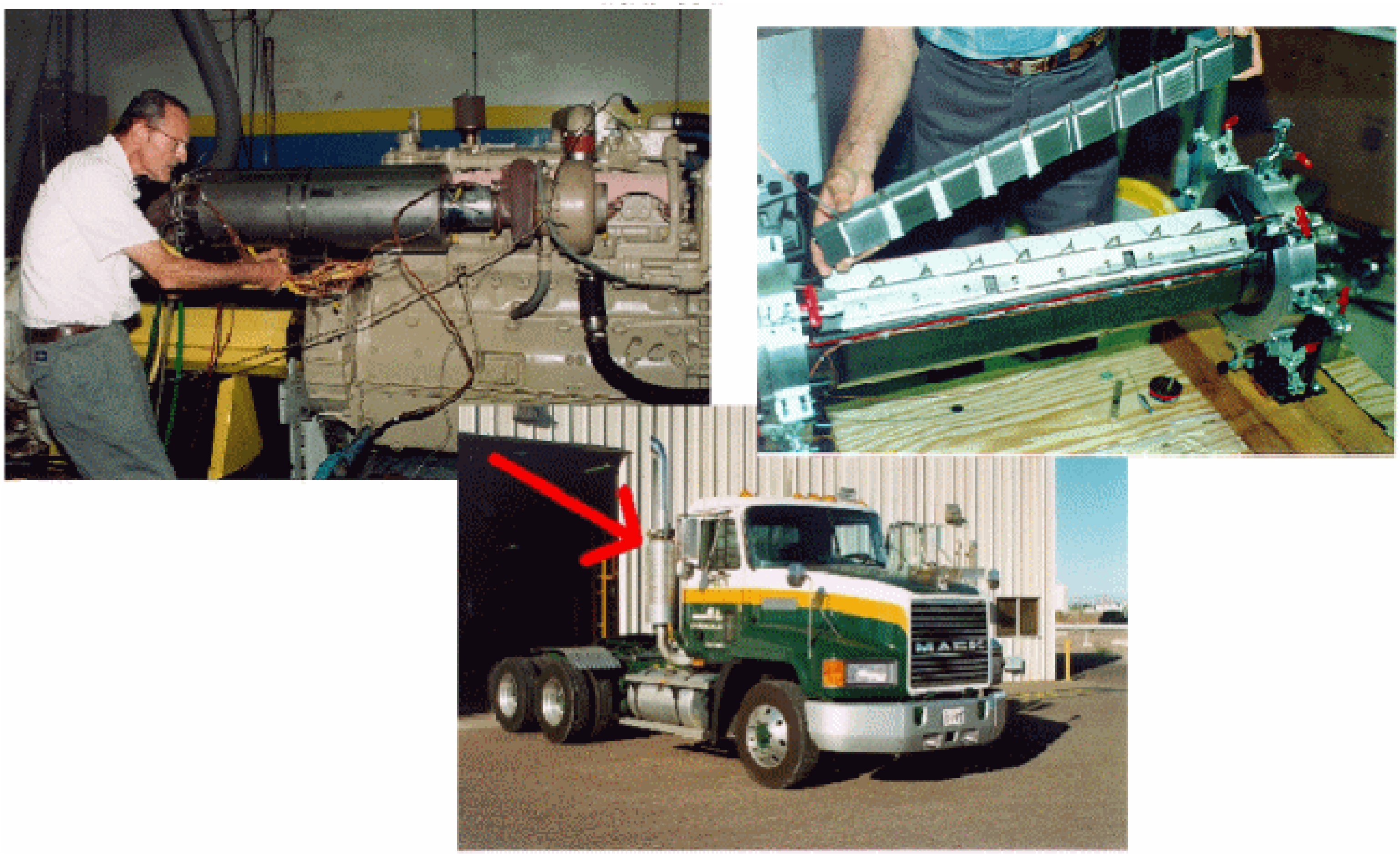
1 kW_e Thermoelectric Generator Installed in Place of Muffler



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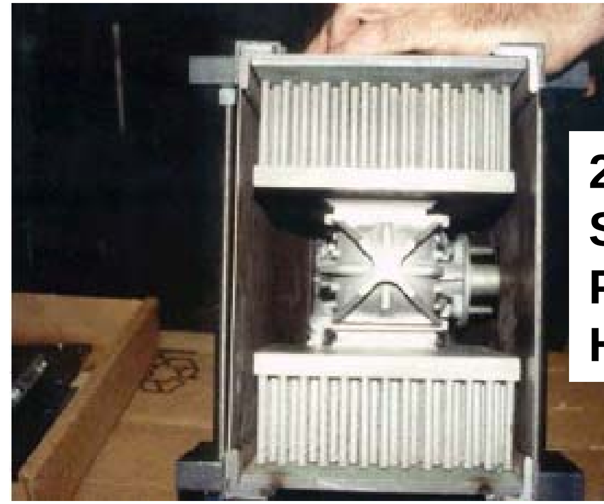
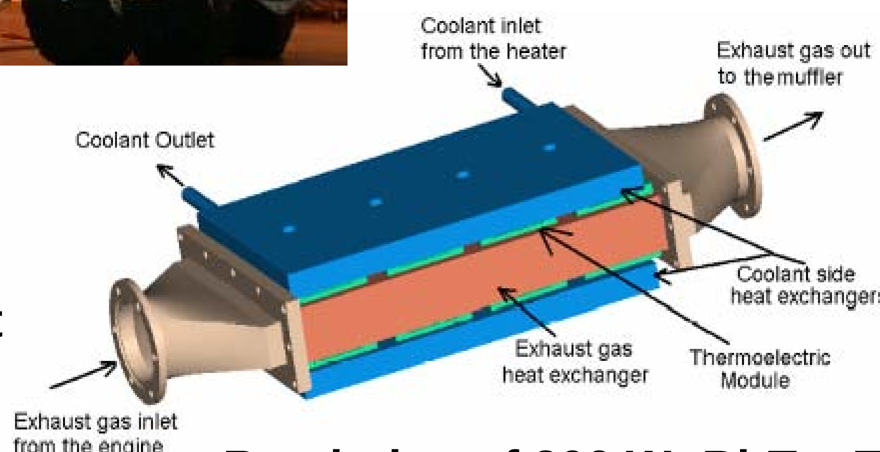
Applications of Hi-Z Thermoelctrics



20 W_e Self-Powered Heater

1 kW_e TE Mounted under PACCAR vehicle Tested for ~500,000 equivalent miles

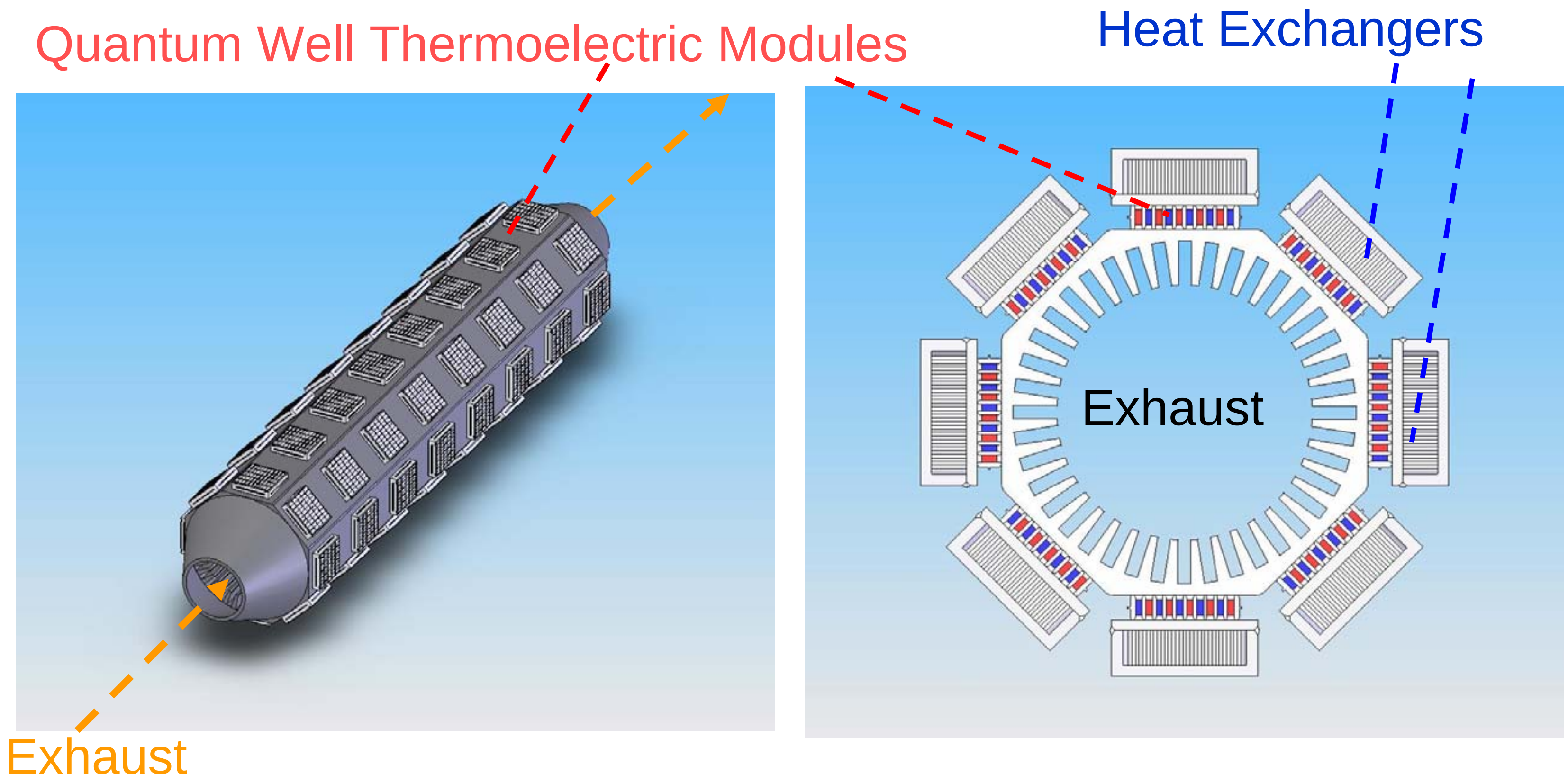


Rendering of 300 W_e Bi_2Te_3 TE Generator Under test in Sierra pick-up truck

Army Stryker Vehicle

Five kW$_e$ Quantum Well Thermoelectric Generator

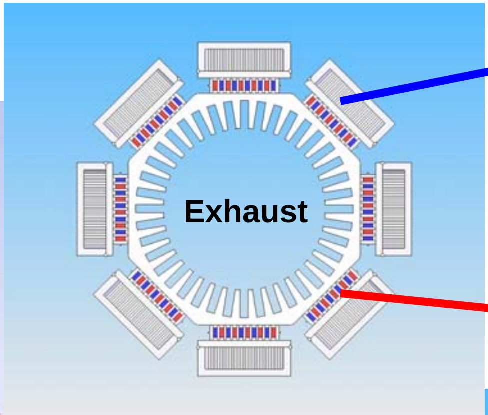
Thermoelectric Modules and Assembly with Coolant Heat Exchangers



Under Development

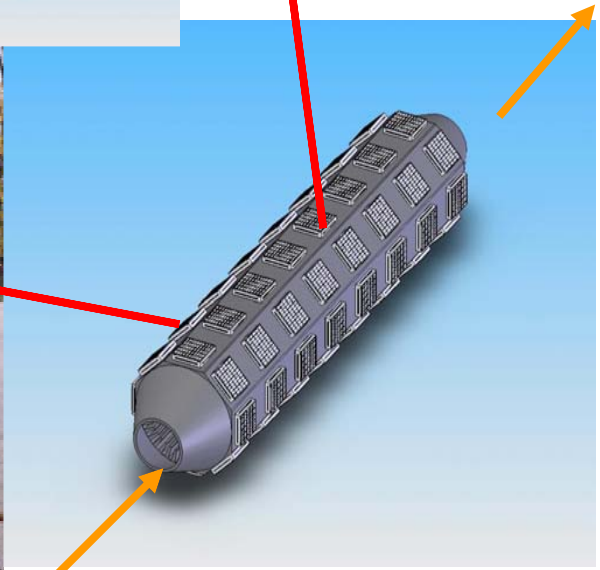
Stryker Vehicle and Underarmor Quantum Well Thermoelectric Generators

Two 5 kWe QW Generators Can Be Placed Underarmor



Heat Exchangers

Quantum Well Thermoelectric Modules



Exhaust

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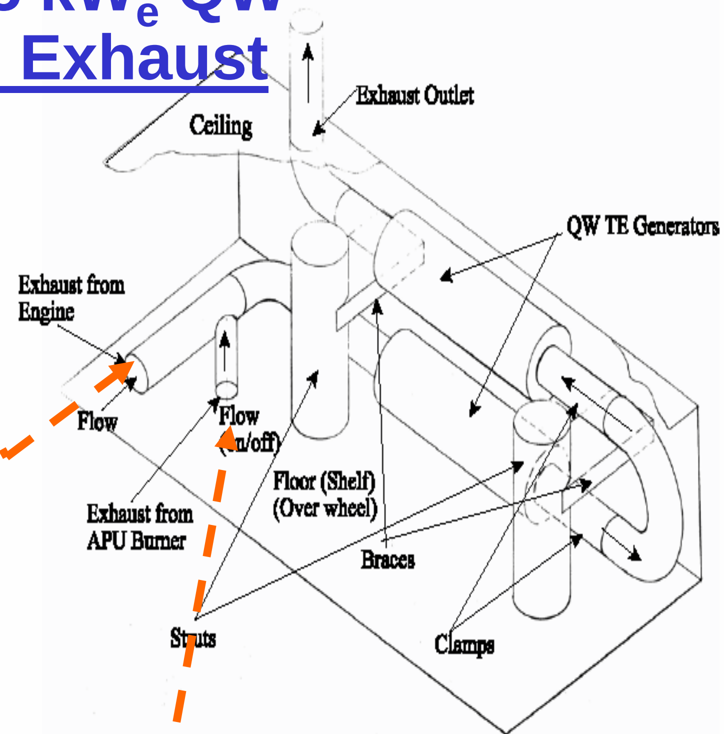
Stryker Vehicle Has Space for Underarmor Quantum Well Thermoelectric Generators

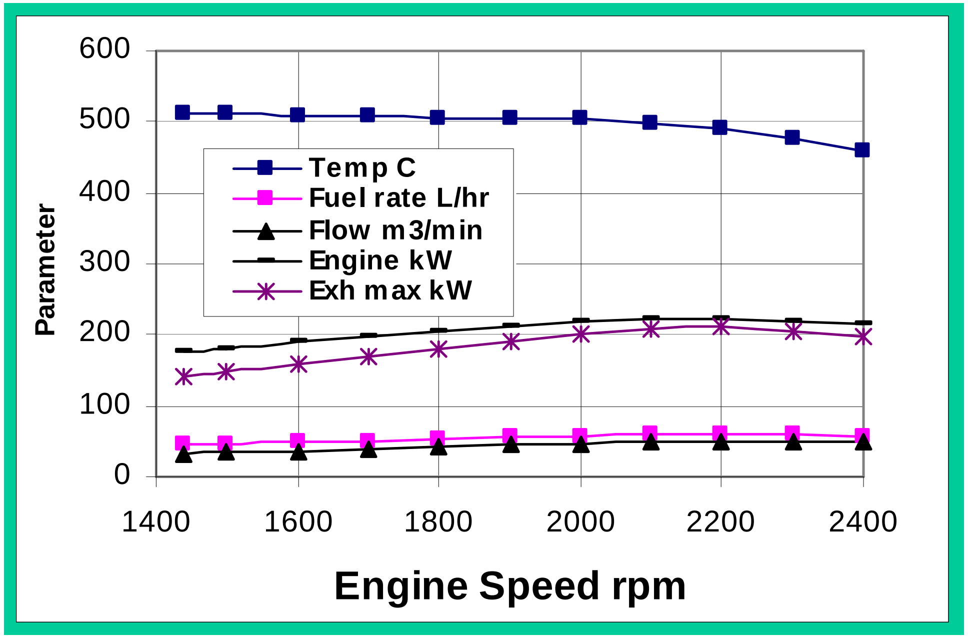
15% Efficiency Predicted with two 5 kW_e QW TE Generators Driven by <u>Vehicle Exhaust</u>

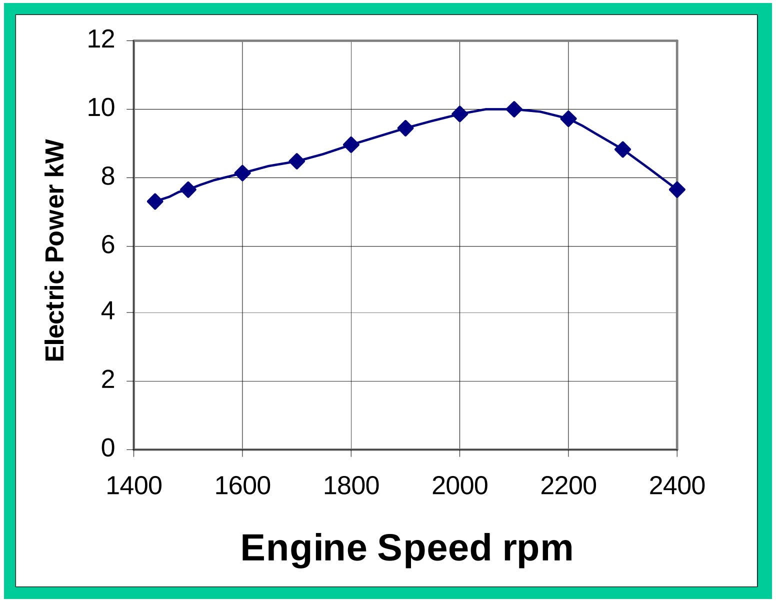


Under Armor Space for <u>APU Burner</u> to Provide Quiet QW TE Operation

Stryker CAT 3126 300 hp Diesel Performance Data

Predicted QW TE Generator Power





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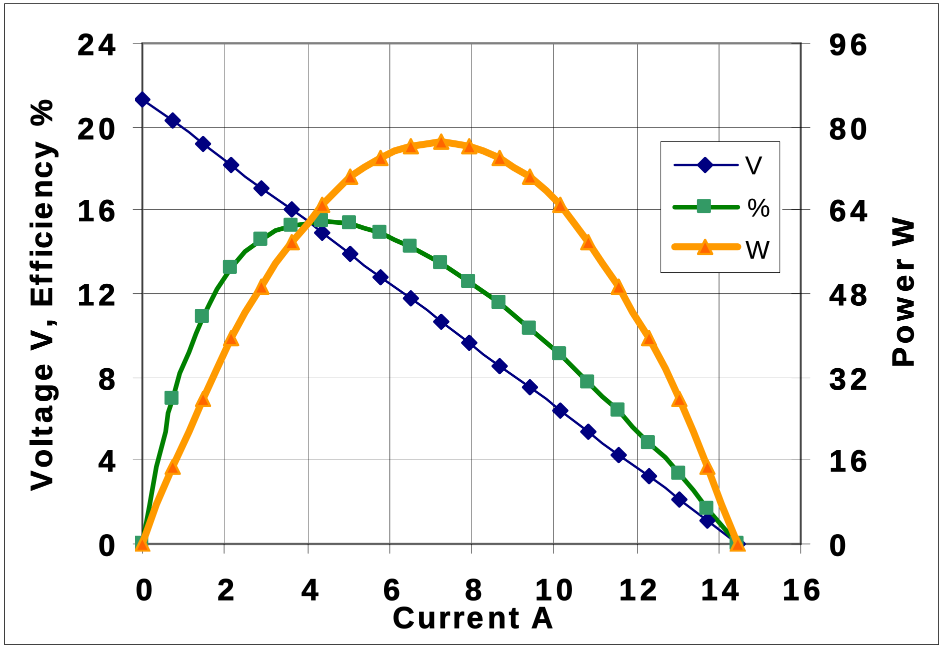
Predicted Hi-Z Quantum Well Thermoelectric Performance

Greater than 42% Carnot Efficiency

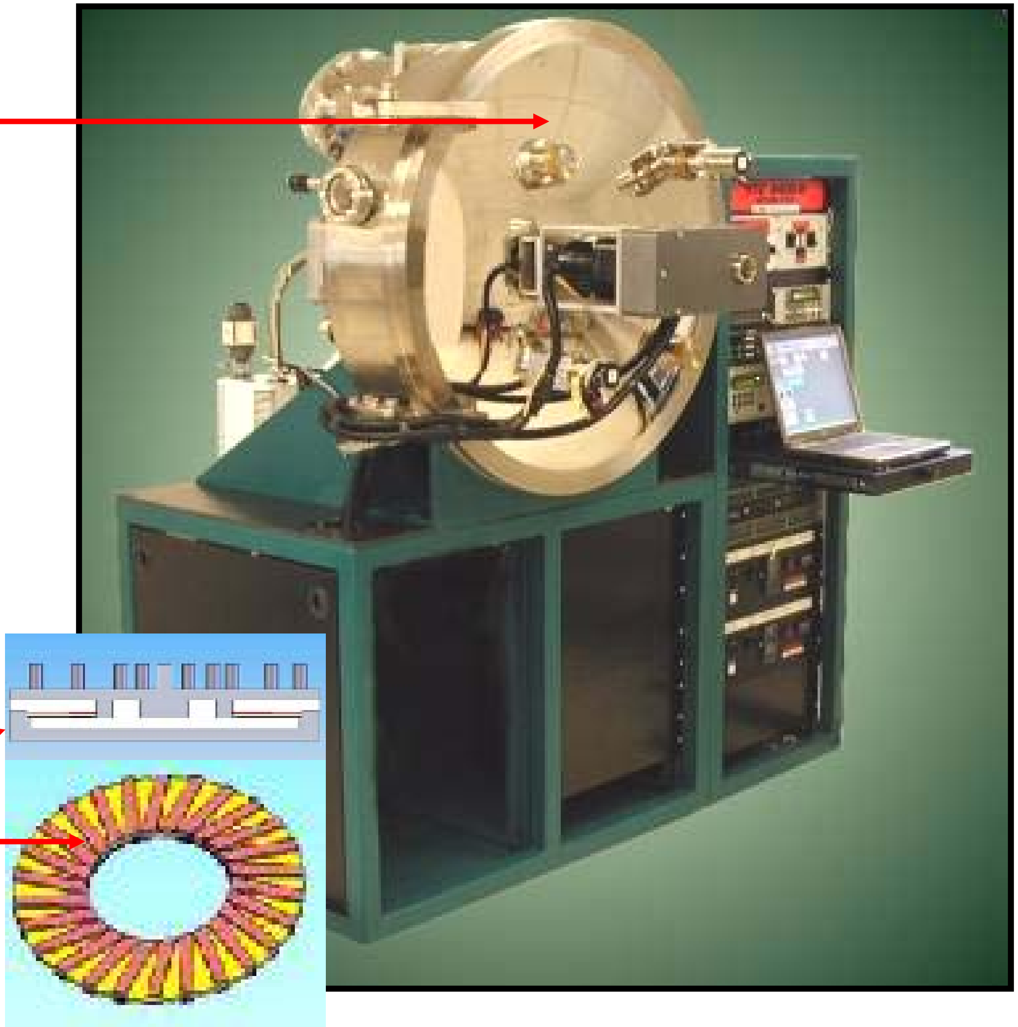
- **Operating Conditions**
  - T_h = 300 °C, T_c = 100 °C
  - Heat Flux = 10 W/cm^2
- **Quantum well films**
  - N-type Si/SiGe
  - P-type B_4C/B_9C
- **Kapton substrate**
  - Reduces parasitic thermal losses & lowers costs
- **Module footprint – square with 2.35 in./side**
- **64 modules will produce 5 kW$_e$ TE Generator**
  - Gas exhaust - 5 in. ID
  - QW arranged in 8 in. OD, & 28 in. long generator



New Quantum Well Sputtering Machine at Hi-Z

Operational check-out in February 2005

- **The new Zero Footprint batch coater has a 34 inch diameter chamber that processes up to six(6) 8 inch wafers or nine(9) 6 inch wafers to increase output by 100x**
- **Currently depositing QW films on milliwatt radial heat flow sensor power supply**
  - **2 inch diameter**
  - **Radial N QW on one side and P QW on other side of substrate**



Application of Quantum Well Thermoelectrics

Price per Watt competitive in several years

- Quantum well raw materials cost less than current materials
  - QW $0.11/Watt
  - Bi_2Te_3 ~$1.00/Watt
- Process improvements reduce costs
  - New substrate
  - Increased sputtering area and rate > 40 Å/minute
  - New design with module surrounding substrate
- DOE five year effort on “Cost Effective Fabrication Routes for the Production of Quantum Well Materials for Waste Heat Recovery from Heavy Duty Trucks”
  - UTRC prime with Hi-Z, CAT, & PNNL

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