Romny Scientific

Performance, Market and Manufacturing Constraints relevant to the Industrialization of Thermoelectric Devices

2011 Thermoelectrics Applications Workshop

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Romny Scientific, Inc.

Romny Scientific

Founded 2006

Mission: Driving down thermoelectric module costs to reach broad deployment in new markets.

Integrated Module and Materials Technology Company

Based in Richmond, California

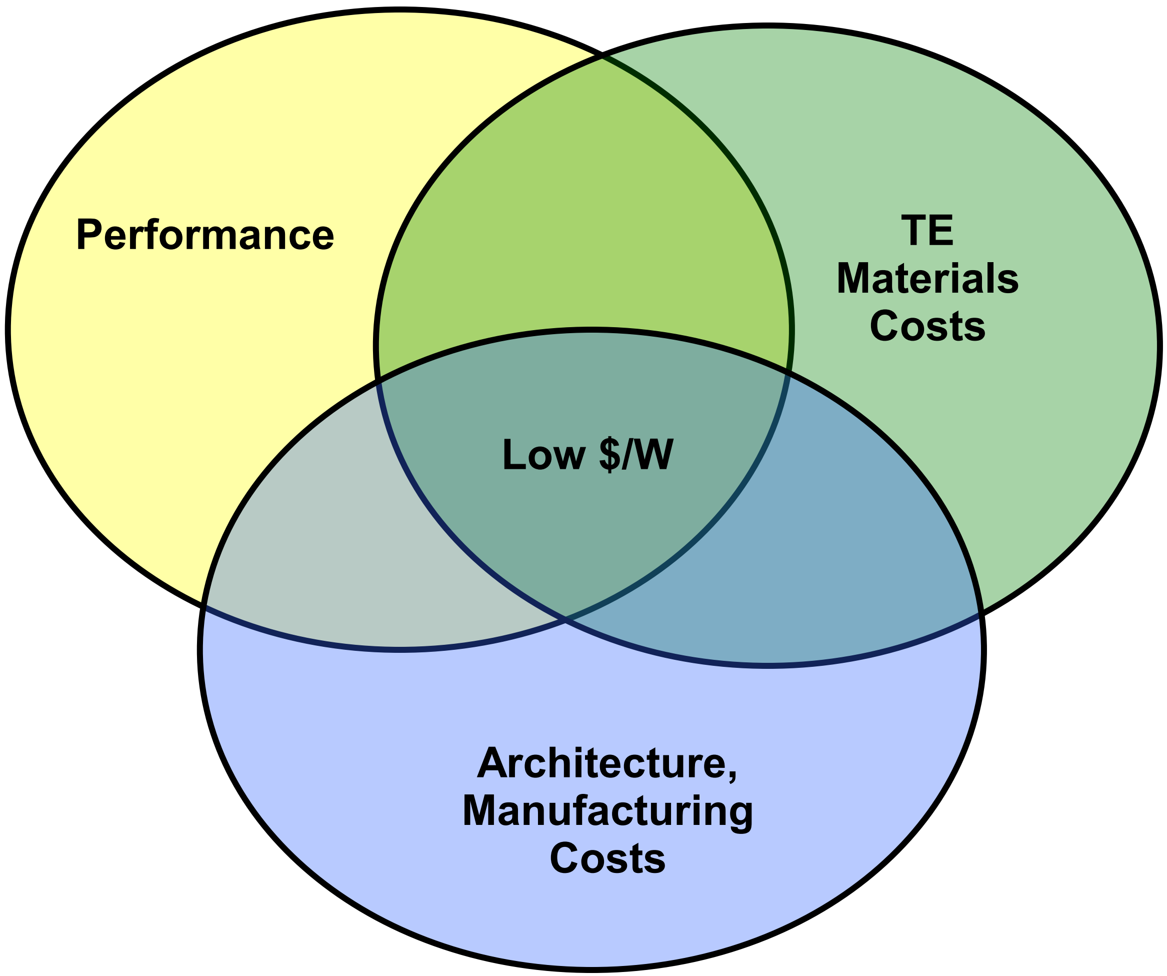
Industrialization of Thermoelectrics

What are the metrics used by the decision makers in volume power generation markets?

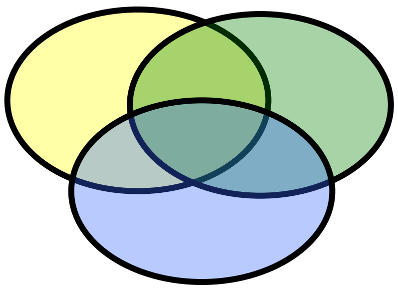
Market	Primary Metric	Secondary Metrics
Transportation	**$/Watt**	Mass/Watt, Vol./Watt
Portable Power (Military)	Mass/Watt, Vol./Watt, Mass/Watt-Hr	**$/Watt**
Portable Power (Commercial)	**$/Watt**	Mass/Watt, Vol./Watt
Aerospace	Mass/Watt, Vol./Watt	**$/Watt**

Industrialization of Thermoelectrics

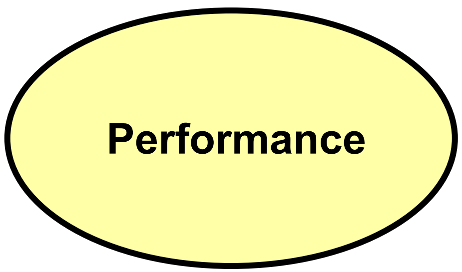
Is there overlap that enables high volume industrialization?



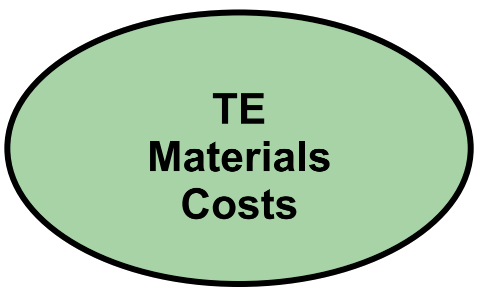
Important Factors for Industrialization



General design approach when considering end user metrics



Get the material form and scale right



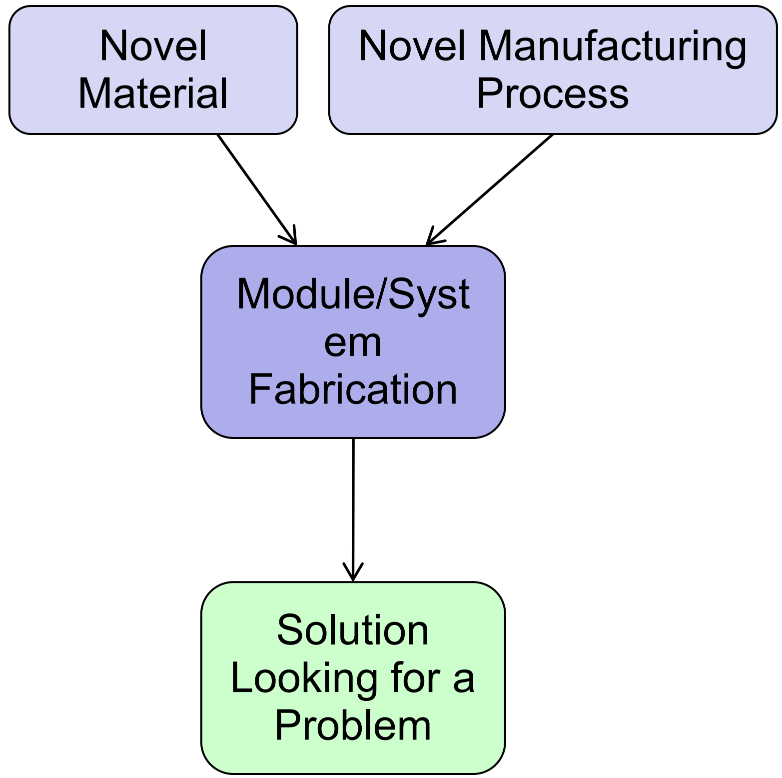
Choose your material systems carefully

General design approach (Undesirable Approach)

Innovation

Make a device with it

Find out who may want to buy it



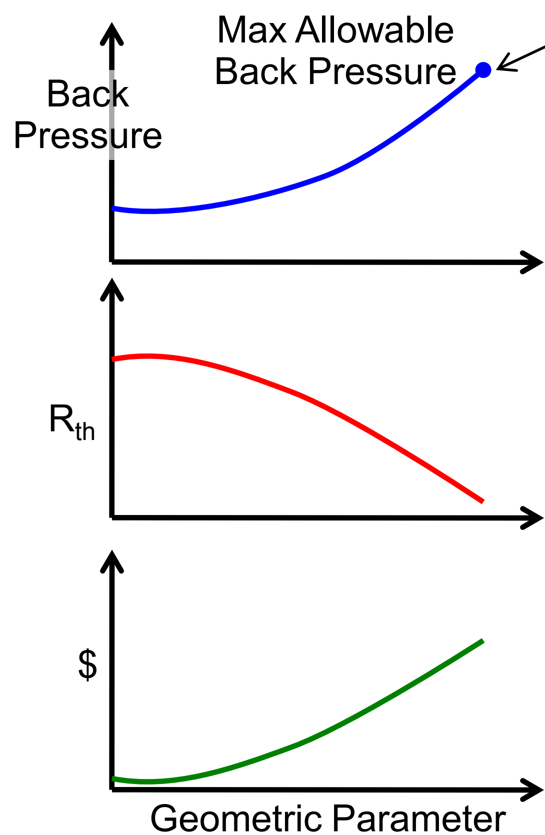
General design approach (TEG for Auto Application)

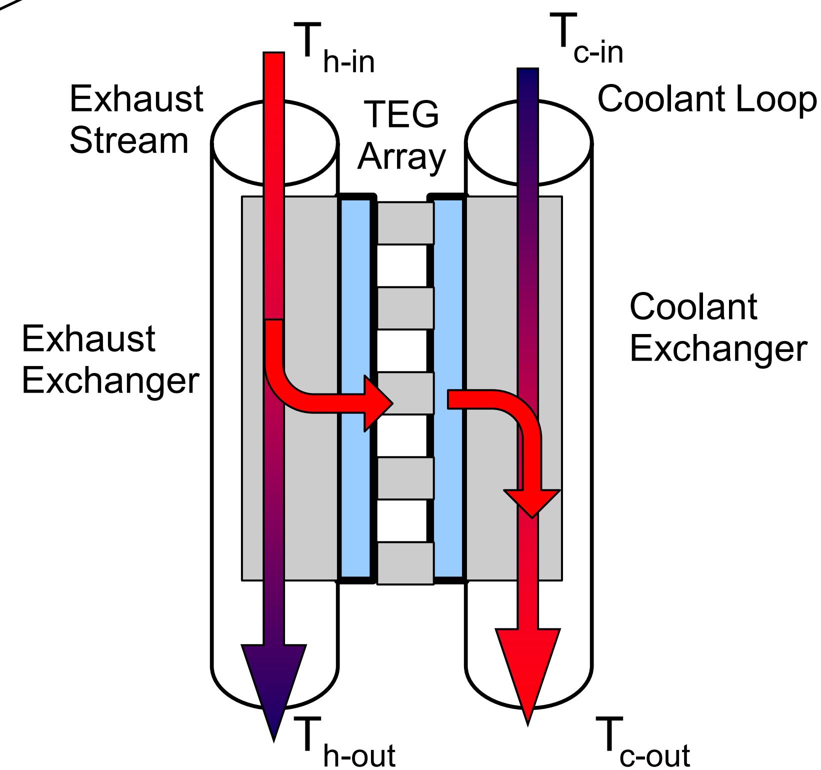
High Level Customer Requirements: $/Watt, Vol./Watt

Platform Definition allows Specific Targets to be Defined: $, Watt, Vol., Back Pressure, Reliability, etc.

Exhaust Side and Coolant Side Exchanger Modeling

- Performance characterized by many possible geometric parameters, materials, and constructions
- Back Pressure, Rth, and $ are key to the model
- Without $ as a consideration, optimum design typically seeks min Rth and at Max Back Pressure



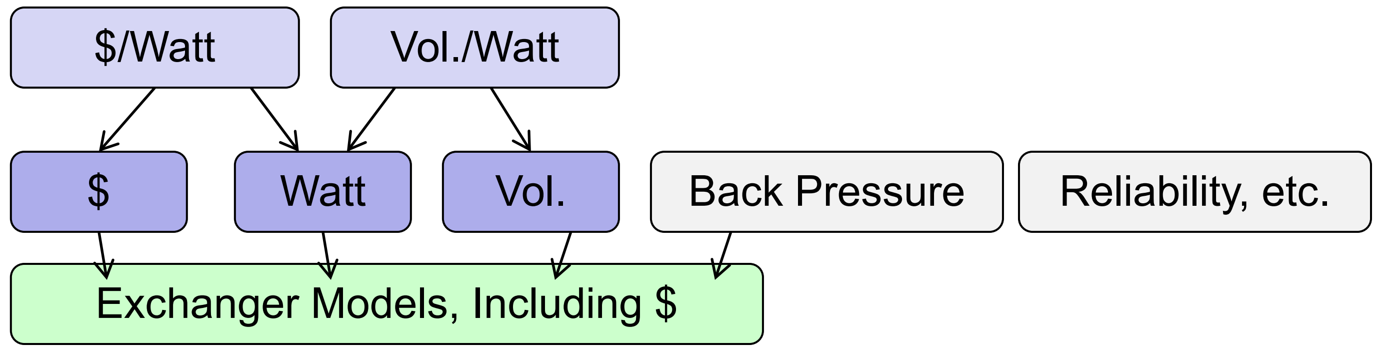


General design approach (TEG for Auto Application)

High Level Customer Requirements

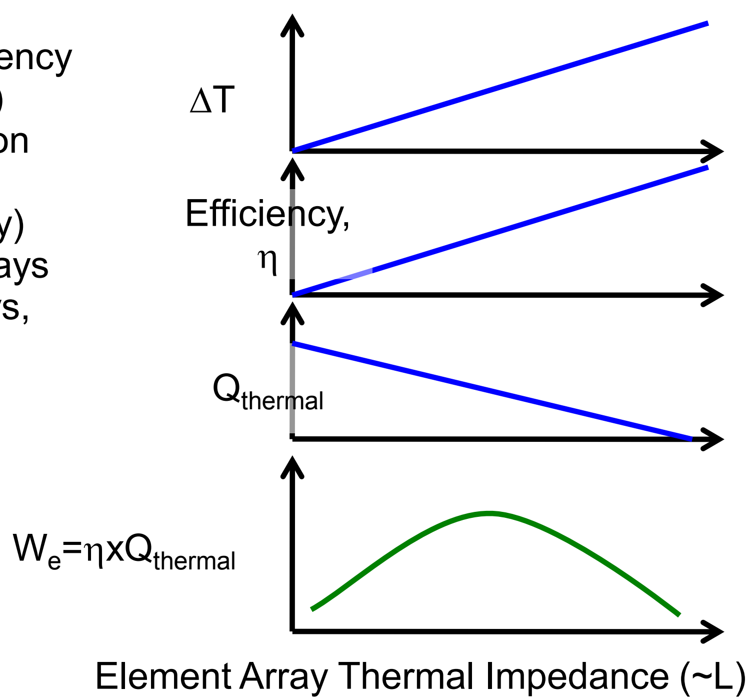
Platform Definition allows Specific Targets to be Defined

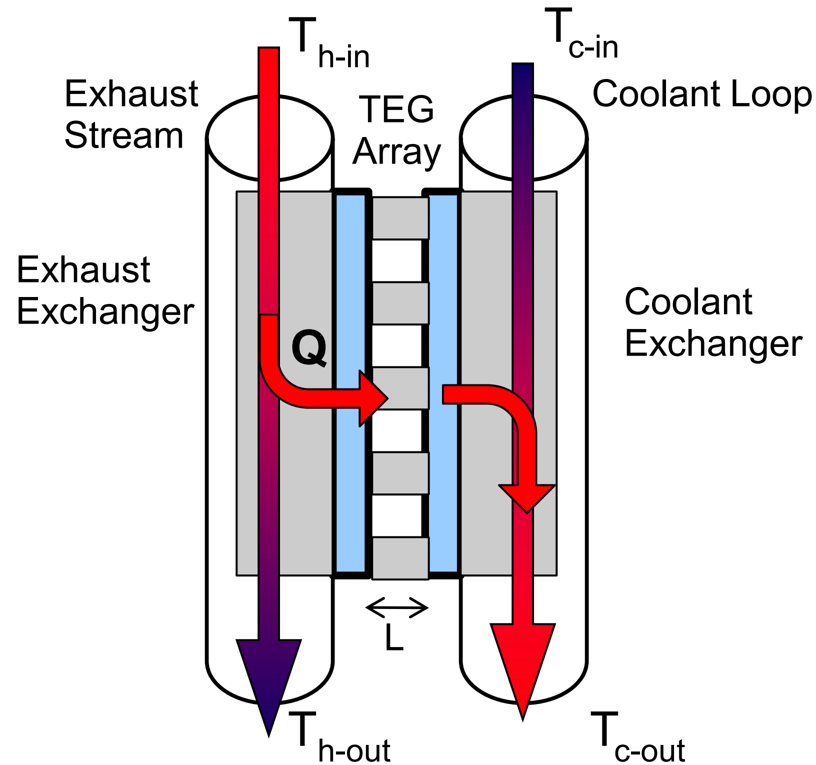
Exchanger Modeling



TEG Array Design Optimization

- Maximizing DT and efficiency is undesirable (no $Q_{thermal}$)
- Maximizing heat extraction from exhaust stream is undesirable (low efficiency)
- Low impedance TEG arrays (thin films, nanowire arrays, etc.) generally poor W



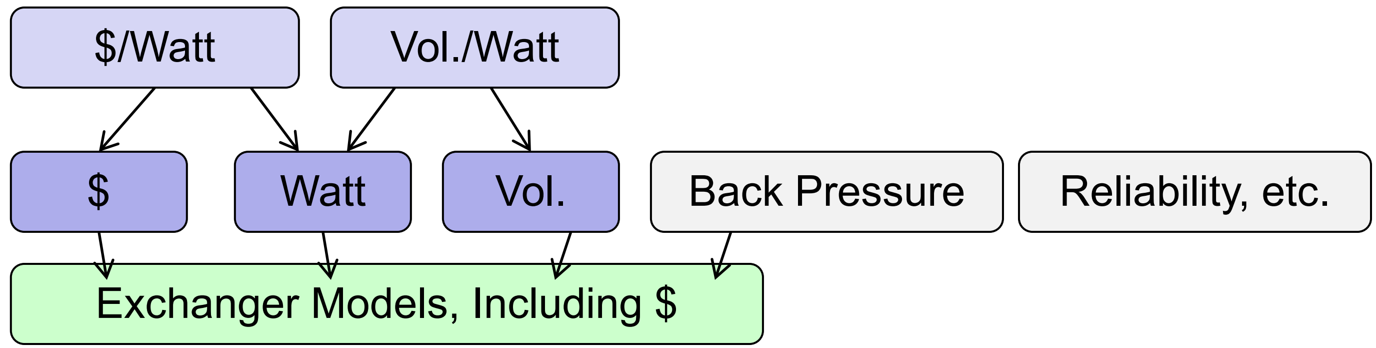


General design approach (TEG for Auto Application)

High Level Customer Requirements

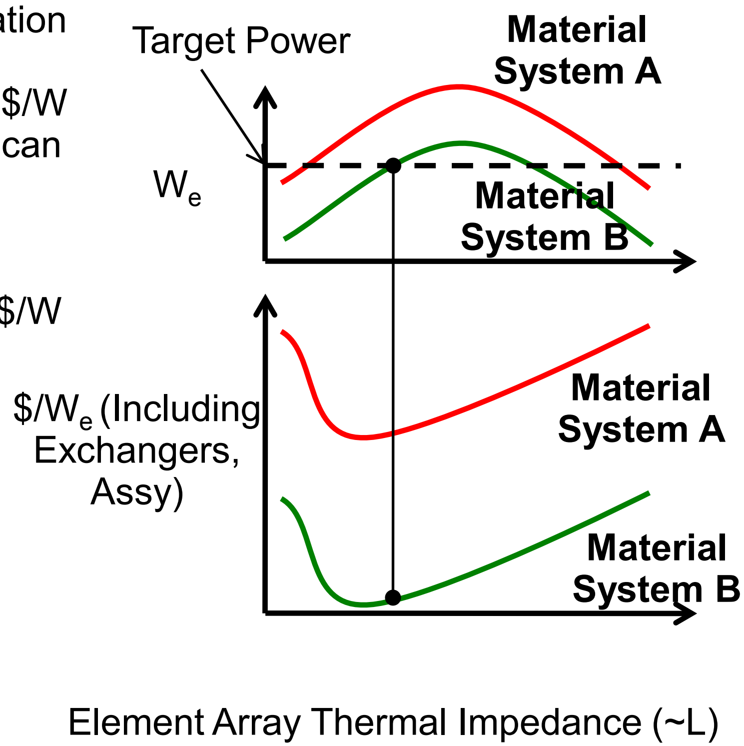
Platform Definition allows Specific Targets to be Defined

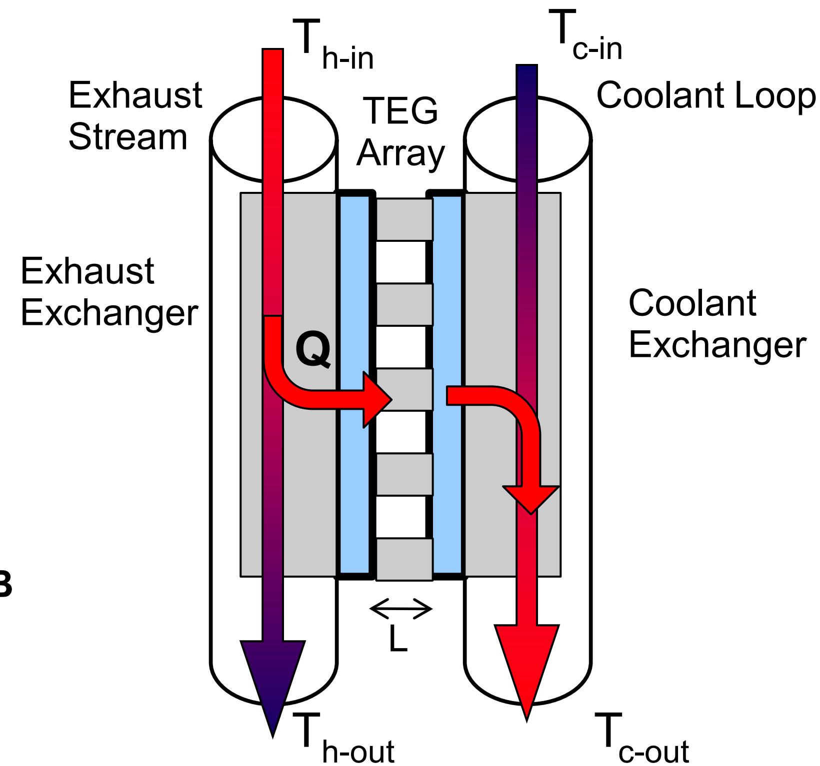
Exchanger Modeling



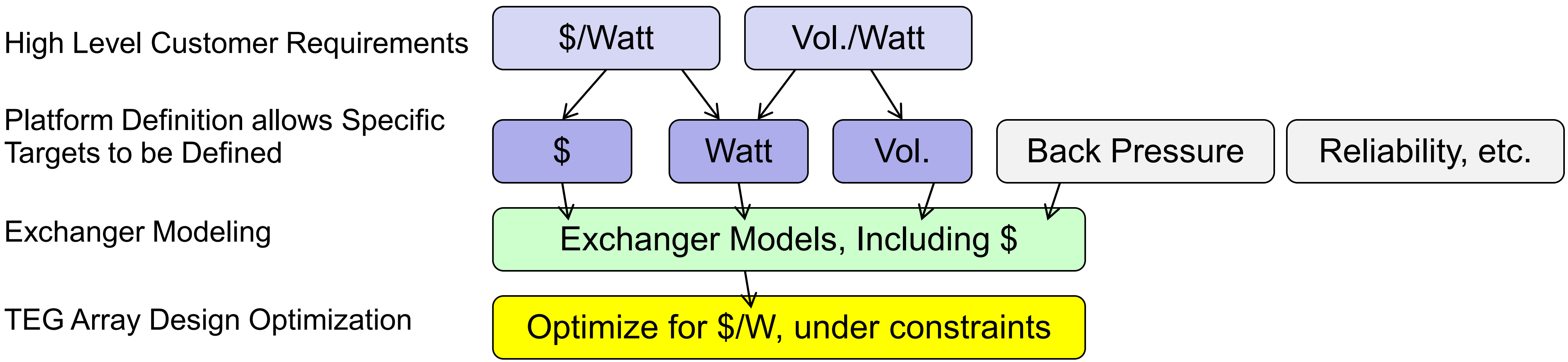
TEG Array Design Optimization
- Thinner Array = lower $/W
- Low Cost Material = lower $/W
- A minimum acceptable ZT can be determined

- Meets the Design Target Power, and potentially at a $/W that **enables wide market adoption**





General design approach (TEG for Auto Application)



When using end-user metrics for Design Optimization:

- Allows one to specify a minimum acceptable ZT for material system
- Best design may not be the highest ZT material system
- Best design may not be the most efficient heat exchange design
- Best material quite likely not a thin film

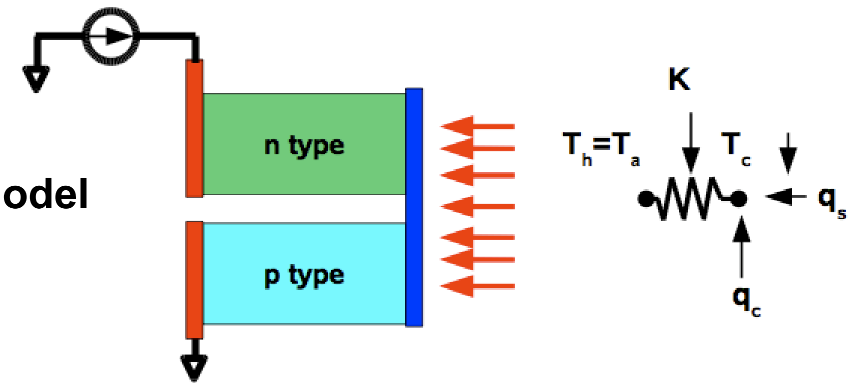
Get the material form and scale right (Cooling)

A TE Cooler is only as good as its heat sink

Thermoelectric System Performance Depends Principally on:
1. The Ratio of the element array conductance to the entry and exit thermal conductance
2. ZT

Secondarily, it depends on thermal bypass, interface resistances, compatibility factor, etc.

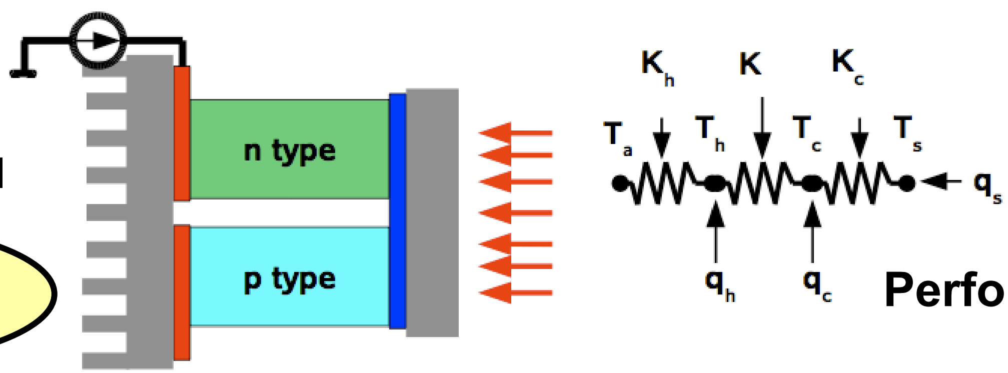
Element Model



Performance= f(ZT)

System Model

Performance

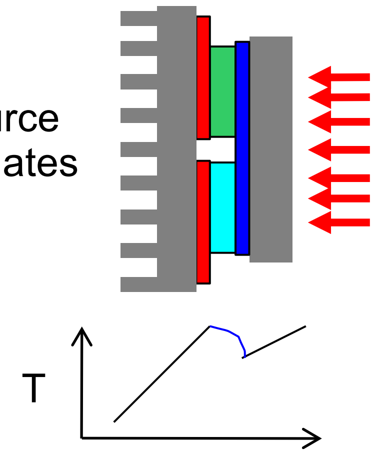


Performance= f(K/K$_c$, K/K$_h$, ZT)

Get the material form and scale right

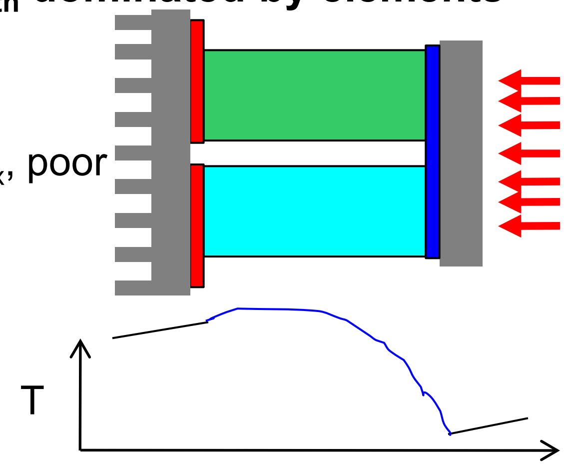
Cooling, R_{th} dominated by source and sink

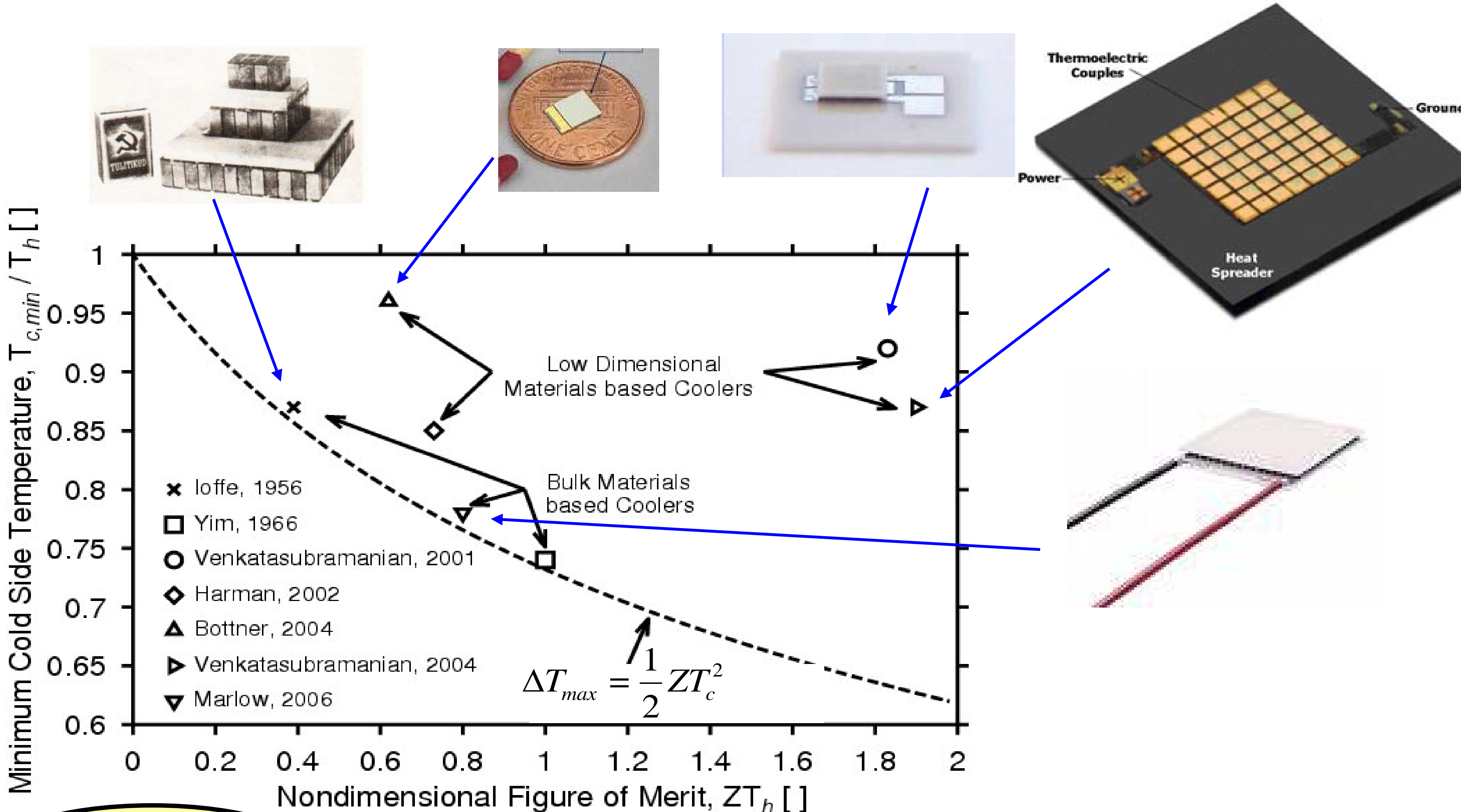
ΔT across source and sink dominates



Cooling, R_{th} dominated by elements

Good ΔT_{max}, poor Q_{max}



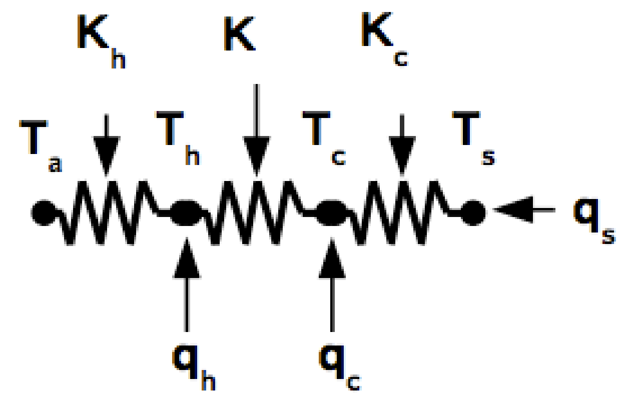


Performance

Doing the Math

System Model: Find Governing Equations

Energy balance at T_h and T_c



Nondimensionalize

Temperature

$$\theta_s = T_s / T_a$$
$$\theta_c = T_c / T_a$$
$$\theta_h = T_h / T_a$$

Thermal Conductance

$$\kappa_c = K_c / K$$
$$\kappa_h = K_h / K$$

Electrical Current

$$\gamma = |J| A_e S / T_a$$

Performance

Non-dimensionalized Cooling Performance

- Performance ≠ f(ZT)
- Performance = f(ZT, κ_c, κ_h)

Junction Temperatures

$$\theta_c(\gamma)=\frac{(\kappa_h+1-\gamma)(\gamma^2/2ZT_a+\kappa_c\theta_s)+\gamma^2/2ZT_a+\kappa_h}{(\kappa_h+1-\gamma)(\kappa_c+1+\gamma)-1}$$

$$\theta_h(\gamma)=\frac{(\kappa_c+1+\gamma)(\gamma^2/2ZT_a+\kappa_h)+\gamma^2/2ZT_a+\kappa_c\theta_s}{(\kappa_h+1-\gamma)(\kappa_c+1+\gamma)-1}$$

Minimum Cold Side Temperature

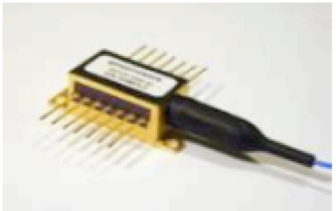
$$q=0 \qquad \theta_s=\theta_c$$

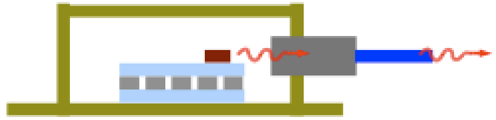
$$\theta_{(c,min)}=\frac{(\kappa_h+2-\gamma_0)\gamma_0^2/2ZT_a+\kappa_h}{(\kappa_h+1-\gamma_0)(\gamma_0+1)-1}$$

Maximum Cooling Power

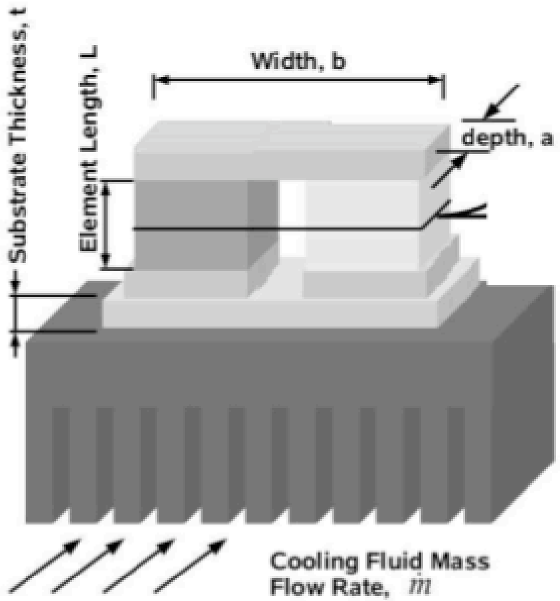
$$q_{max}/KT_a=(\theta_s-\theta_{c,q_{max}})\kappa_c$$

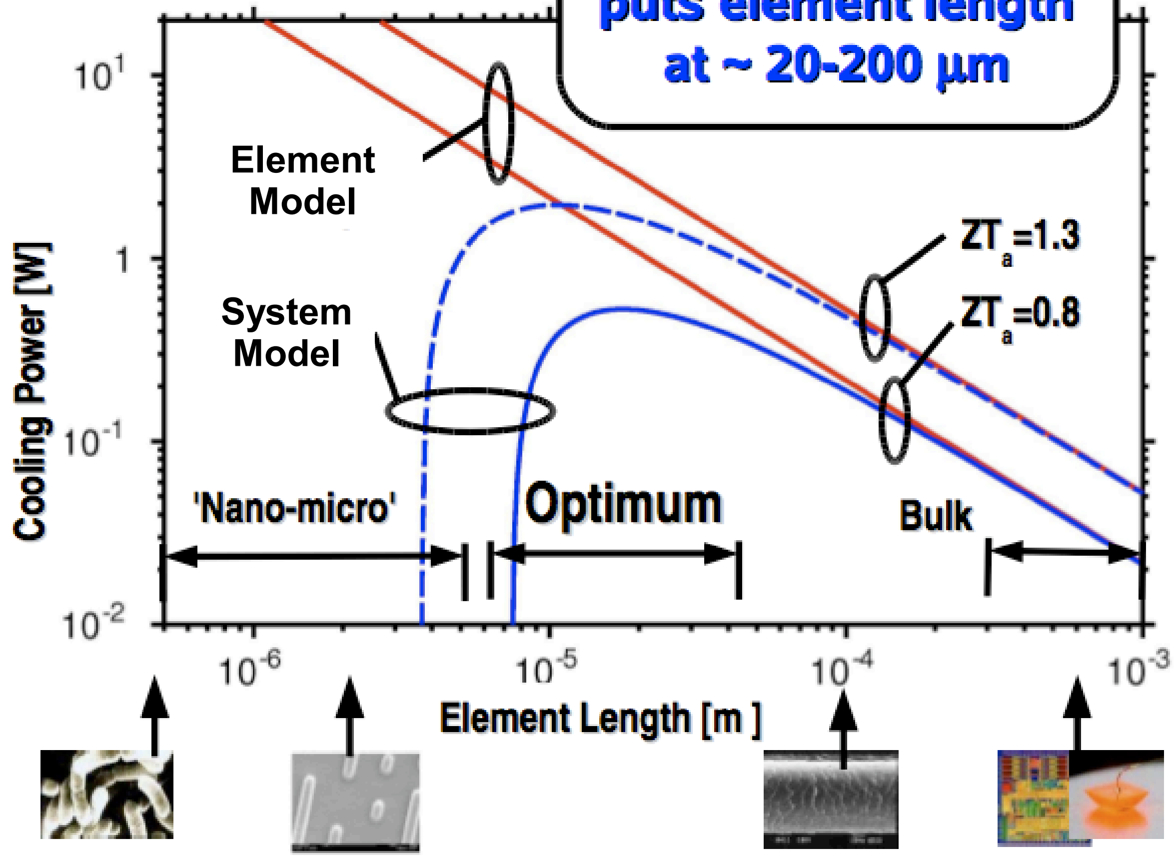
Performance





Performance for many applications puts element length at ~ 20-200 µm





4 mm² Cooler, Telecom Laser, Typical Cooling Solution

Performance

Material Choice for Performance

All ZTs are not created equal

Must choose material system capable of being formed at appropriate length scales (thin films face challenges)

Performance

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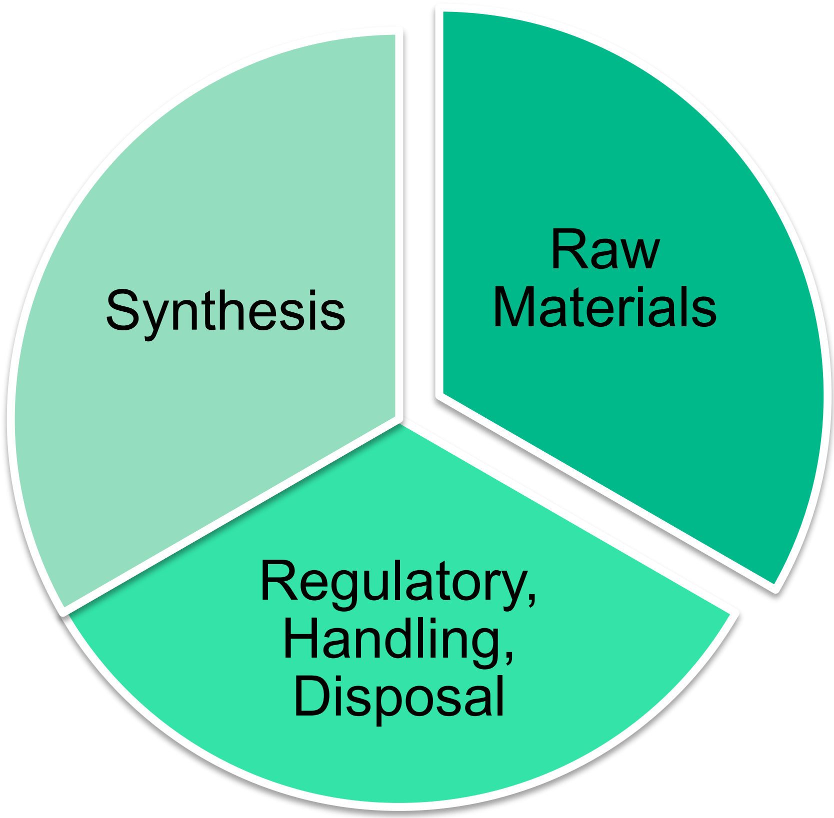
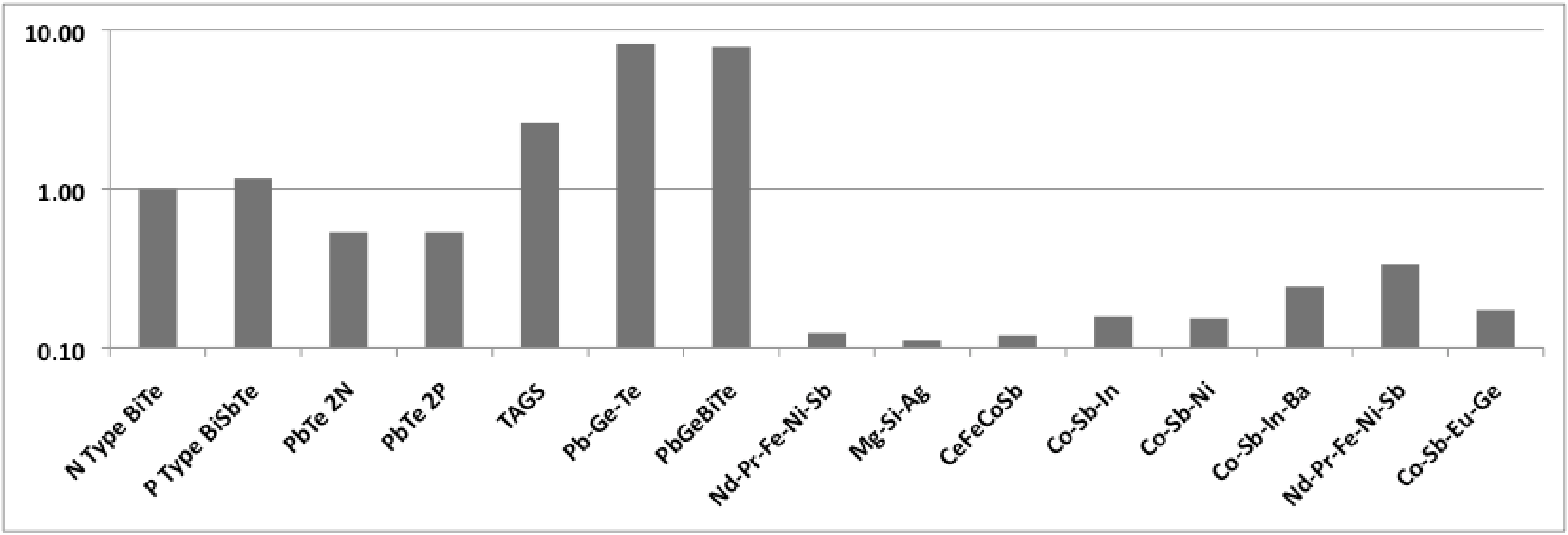
Materials Costs



Materials Synthesis Costs

Materials Costs

Relative Raw Material Costs (n-BiTe = 1.0)

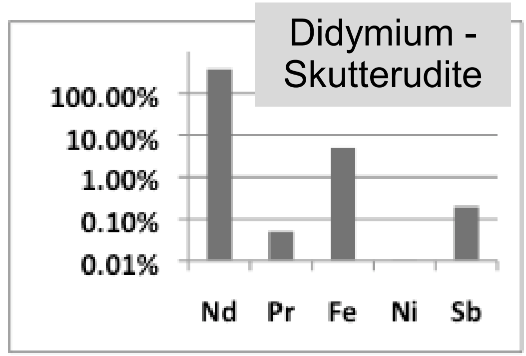


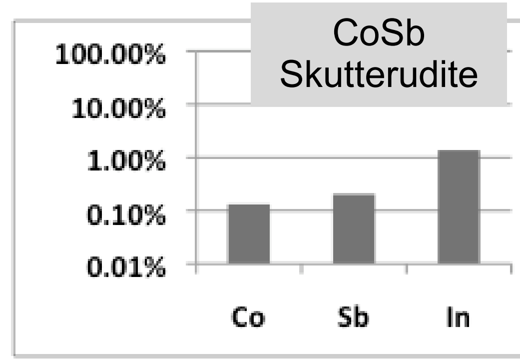
Materials Synthesis Costs

Materials Costs

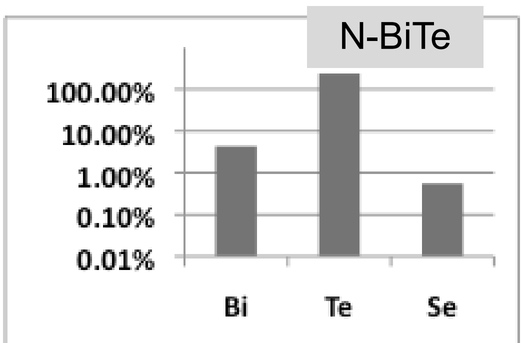
Impact of Thermoelectric Device Ramp on Today's Production Levels

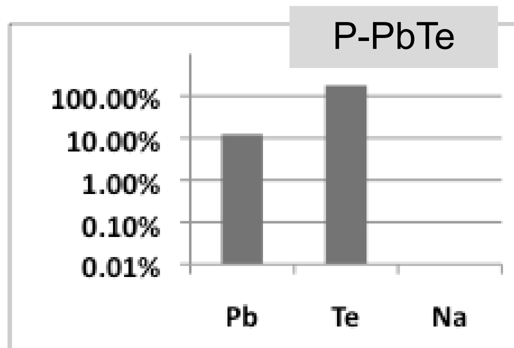
- Assume 500K Unit Production of Automotive TEG Systems
- ~130cc of TE Material per Vehicle

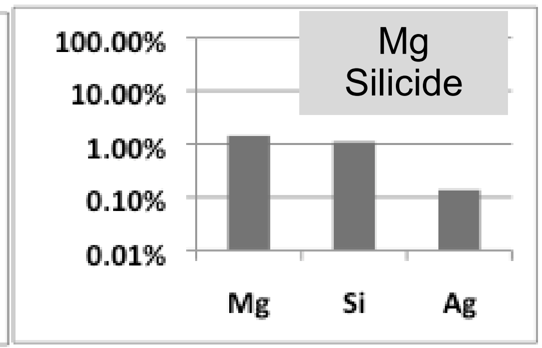


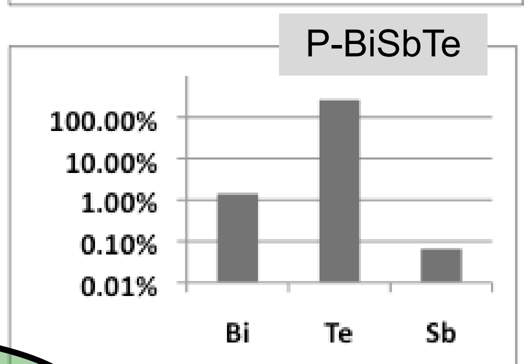


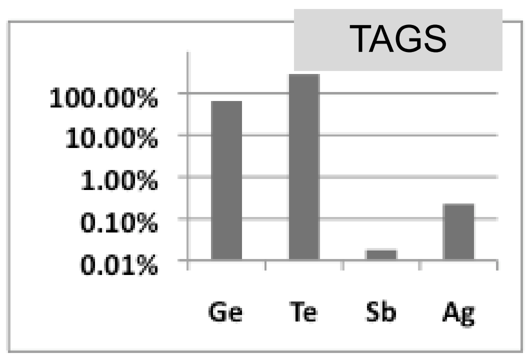
Increase in Production Required to Meet New Demand

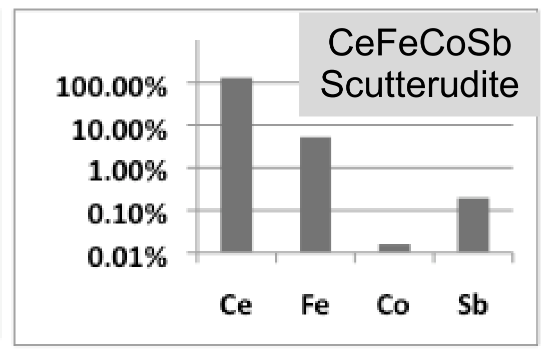










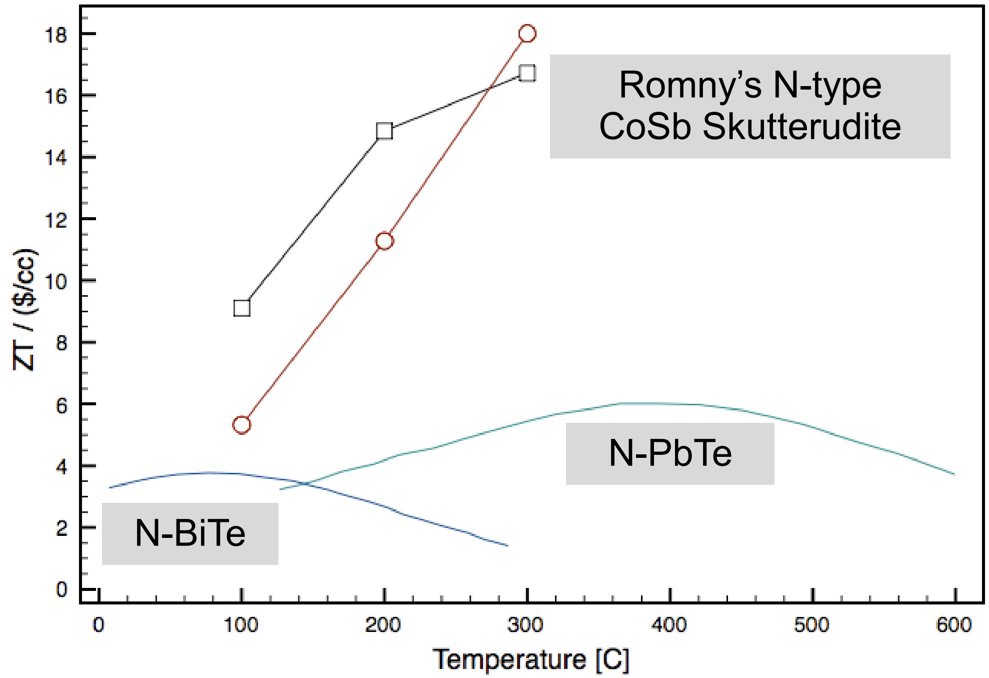


Materials Synthesis Costs

Performance per Cost

Romny's current NSF Funded work on Skutterudites

- High Performance per Price
- Integrated into Novel Module MFG process



Focus of Current DOE/NSF Funded effort with VT (Huxtable, et. al.)

- Mg-Si based alloys

Materials
Synthesis
Costs

Industrialization of Thermoelectrics

Is there overlap that enables high volume industrialization?