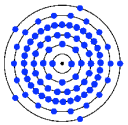



# Romny Scientific, Inc.

**1192 Cherry Avenue**
**San Bruno, CA 94066**


# The Industrialization of Thermoelectric Power Generation Technology


**Andrew Miner, Ph.D.**



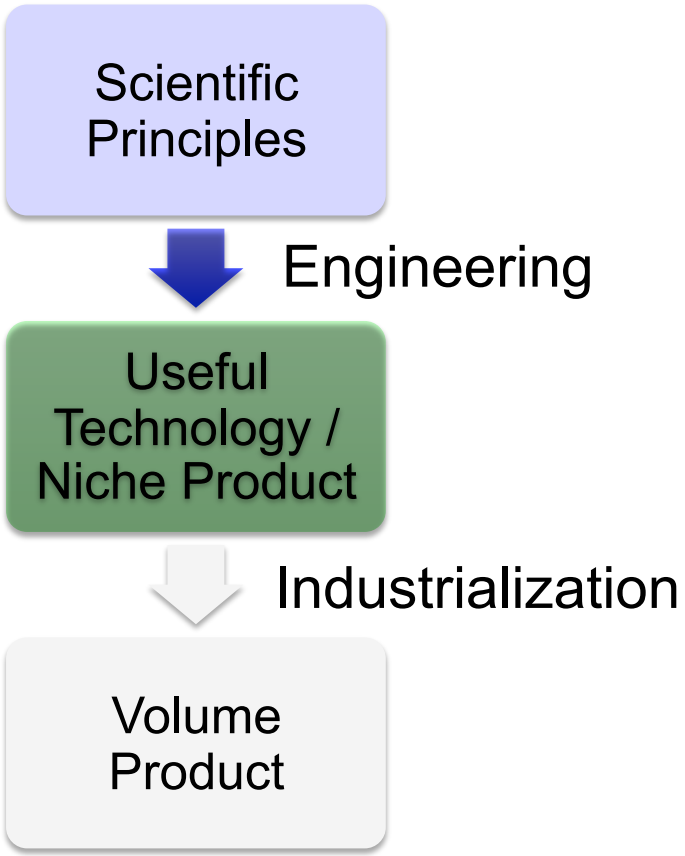
2012 DOE Thermoelectric Applications Workshop, Baltimore Maryland

# Company Overview

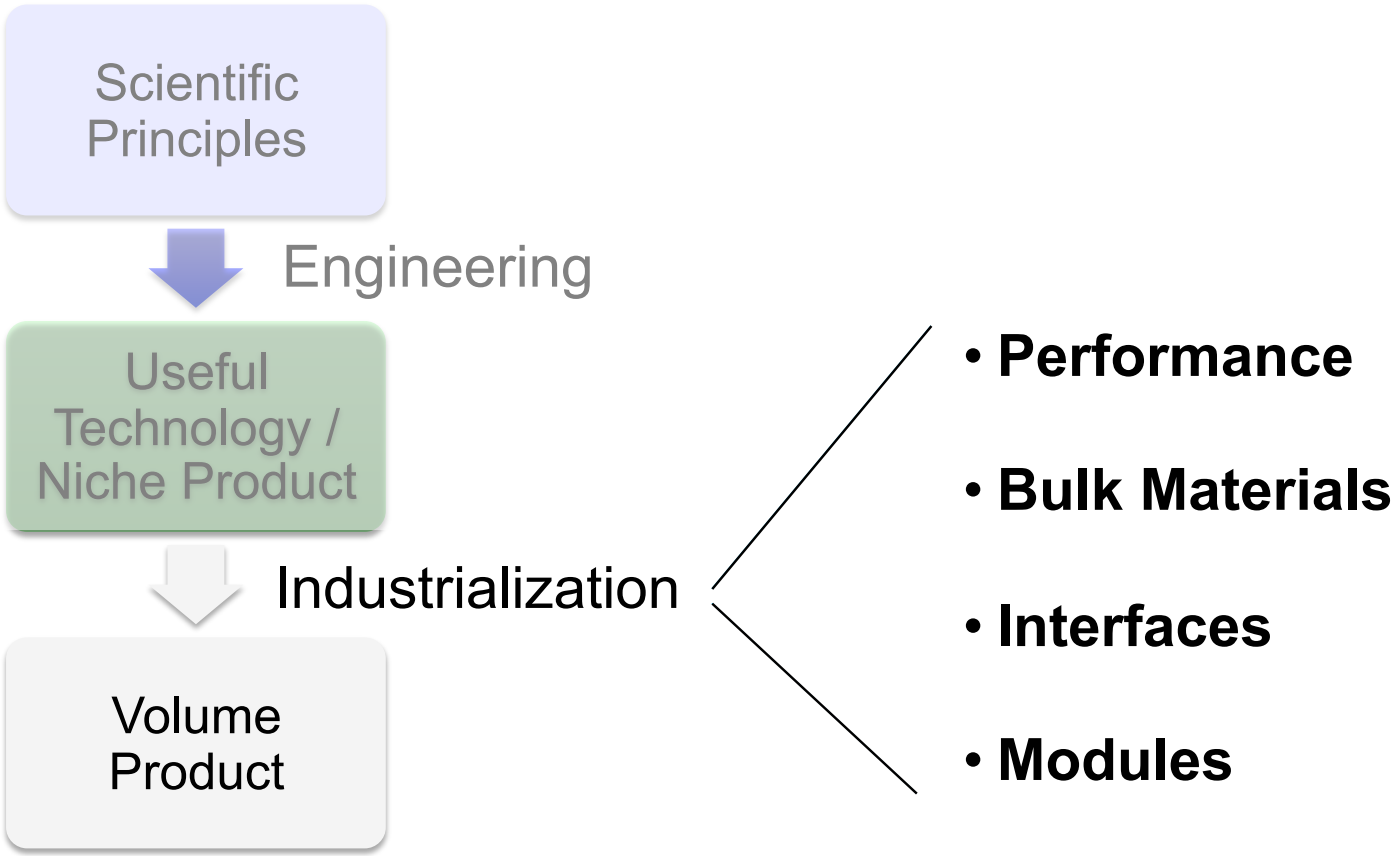
- Founded January 2007
- Developers and Manufacturers of:
  - Thermoelectric Materials
  - Modules
  - Systems

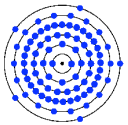
Headquarters in San Bruno, California
- Office
- Development laboratory
- Production facilities

# Outline


Scientific Principles
Engineering
Useful Technology / Niche Product
Industrialization
Volume Product

# Outline


Scientific Principles
Engineering
Useful Technology / Niche Product
Industrialization
Volume Product
• Performance
• Bulk Materials
• Interfaces
• Modules

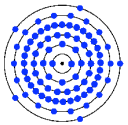


# Performance in thermoelectric power generation

**Performance is ….**

ZT?

*"A ZT of (insert number greater than 1) will enable (insert high volume application that thermoelectrics will dominate)"*



# Performance in thermoelectric power generation

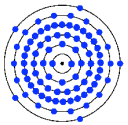
**Performance is ….**

ZT?

*"A ZT of (insert number greater than 1) will enable (insert high volume application that thermoelectrics will dominate)"*

**For the Industrialization of a High Volume Product, Performance Metrics may be:**

- Power output / Cost (aka $/Watt)
- Power output / Weight
- Power output / Volume
- Power output / Pressure Drop
- Module Efficiency
- System Efficiency
- MTBF
- Effective Module ZT
- Effective System ZT
- Etc.



# Performance in thermoelectric power generation

**Performance is ….**
ZT?

*"A ZT of (insert number greater than 1) will enable (insert high volume application that thermoelectrics will dominate)"*

- Bulk Material ZT
- Electrical interface resistance
- Chemical compatibility of barriers, interfaces
- Element thermal impedance
- Coefficient of thermal expansion
- Raw material cost
- Material production cost
- Module design / geometry
- Module manufacturing technology
- Solder / Braze technology
- Heat exchanger design
- Hot and Cold flow stream characteristics
- Application temperature ranges
- Application temperature / mechanical cycling conditions among other factors…

"performance" metrics are derived from

**For the Industrialization of a High Volume Product, Performance Metrics may be:**

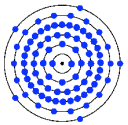
- Power output / Cost (aka $/Watt)
- Power output / Weight
- Power output / Volume
- Power output / Pressure Drop
- Module Efficiency
- System Efficiency
- MTBF
- Effective Module ZT
- Effective System ZT
- Etc.

# Performance Metrics Derived from Bulk Materials

- Bulk Material ZT
- Electrical interface resistance
- Chemical compatibility of barriers, interfaces
- Element thermal impedance
- Coefficient of thermal expansion
- Raw material cost
- Material production cost
- Module design / geometry
- Module manufacturing technology
- Solder / Braze technology
- Heat exchanger design
- Hot and Cold flow stream characteristics
- Application temperature ranges
- Application temperature / mechanical cycling conditions among other factors…

**For the Industrialization of a High Volume Product, Performance Metrics may be:**

- Power output / Cost (aka $/Watt)
- Power output / Weight
- Power output / Volume
- Power output / Pressure Drop
- Module Efficiency
- System Efficiency
- MTBF
- Effective Module ZT
- Effective System ZT
- Etc.



# Performance Metrics Derived from Bulk Materials

- Bulk ZT is not power output, but can be an indicator of potential power output
- Nonlinear relationship: doubling your ZT results in less than twice the performance
- Material Production Cost is one way to look at costs.

$$\frac{\text{Power output}}{\text{Cost}} \sim \frac{\text{Bulk ZT}}{\text{Material Production Cost}}$$

# Performance Metrics Derived from Bulk Materials

$$\text{Bulk ZT} = \frac{\text{Material Production Cost}}{}$$

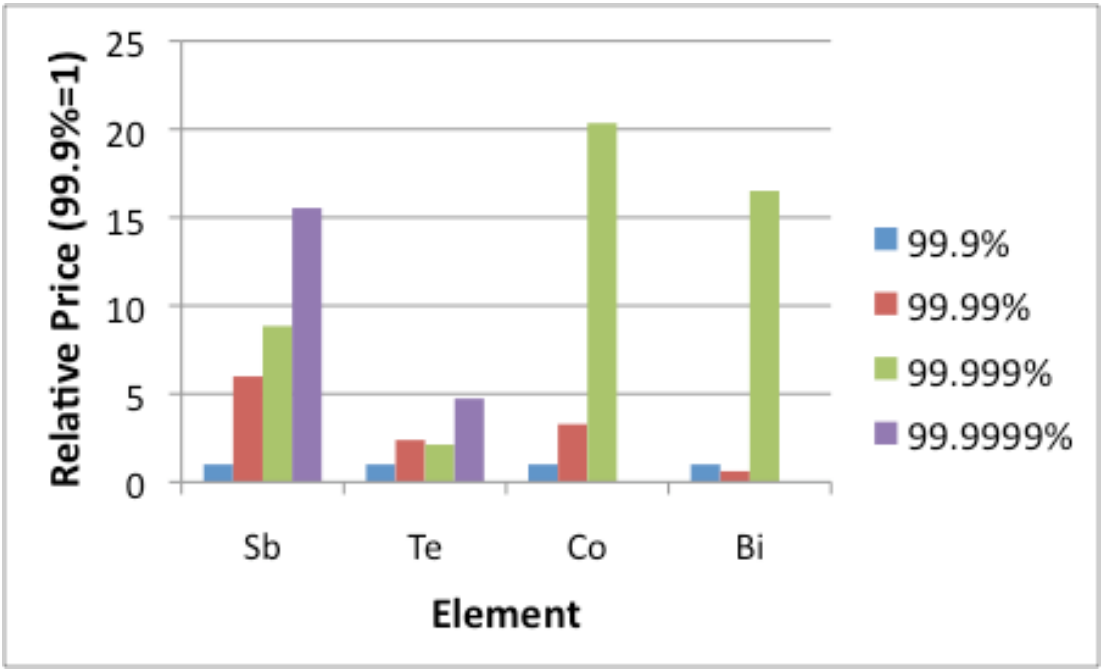
**Raw Materials at What Purity?**

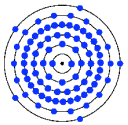
- The lower the purity that the material system's ZT can tolerate, the lower the cost

**All Impurities are not Created Equal:**

- Are your impurities dopants, or inert components?

**The Cost of Purity**





# Performance Metrics Derived from Bulk Materials

**Fidelity of Romny's ZT Measurements**

| Property | Measurement Method | Measurement Orientation | Measurement Range | Calibration Standard |
|---|---|---|---|---|
| Electrical Resistivity | Van der Pauw | In plane | 30C – 350C | NIST traceable graphite, ORNL provided BiTe |
| Seebeck Coefficient | Steady State $\Delta T$ | out of plane | 30C – 350C | ORNL provided BiTe |
| Thermal Diffusivity | Flash diffusivity | In plane | 30C – 300C | Netzsch Pyroceram 9606 , ORNL provided BiTe |
| Density | Archimedes Method | NA | Room temp | Pure metal standards |
| Heat Capacity | DSC | NA | 30C-600C | Sapphire |
| Heat Capacity | Dulong – Petit | NA | NA | NA |

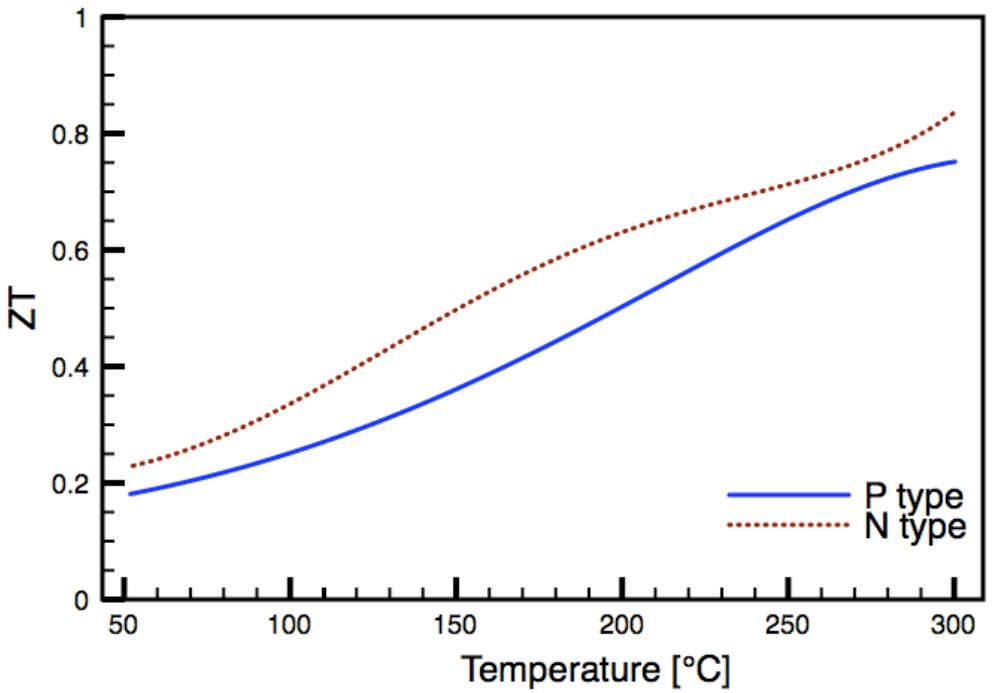
Bismuth telluride standards
Color: Romny
Gray: Other Round-Robin Participants

# Performance Metrics Derived from Bulk Materials

$$\frac{\text{Bulk ZT}}{\text{Material Production Cost}}$$

**Lead Free, Tellurium Free materials for High Power / $**

- N type: $Mg_2Si$ Based
- P type: $Zn_4Sb_3$ Based
- All raw materials <=99.95% pure



# Performance Metrics Derived from Bulk Materials

$$\frac{\text{Bulk ZT}}{\text{Material Production Cost}}$$

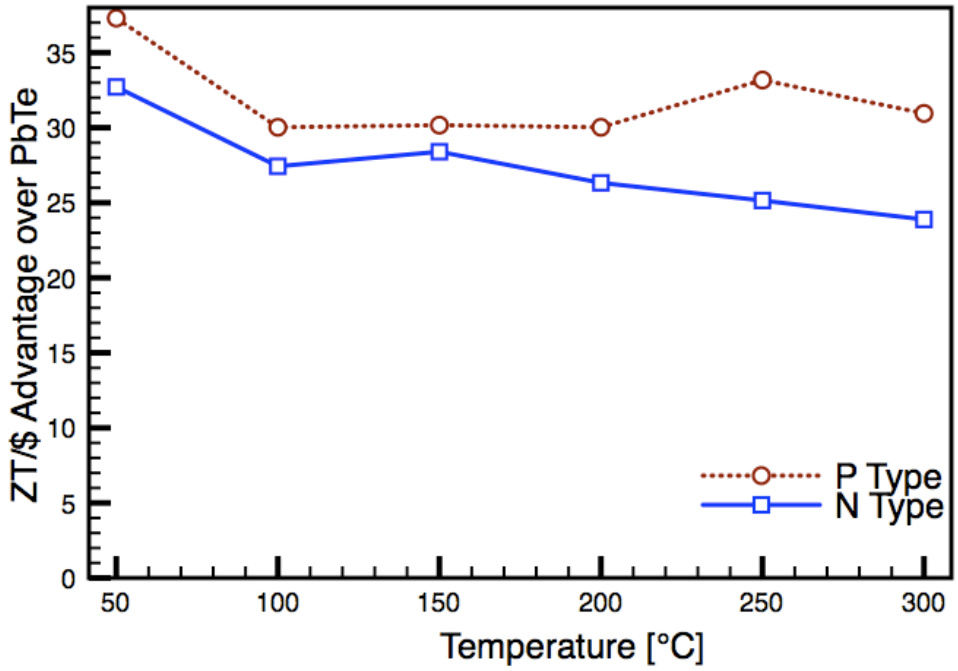
**Material Production Cost Modeling Based on:**

- Broad adoption in an automotive application: 4M/Yr
- Synthesis methods scaled to volume
- Raw material pricing from global sources
- Labor
- Amortized capital equipment

**Price impact due to Global Production:**

- Broad adoption (4M/Yr) of a TEG based c PbTe would consume >15% of the world tellurium production.
- Broad Adoption of these materials would consume <1% of rarest element.

**Performance/Cost Advantage over PbTe for Broad Adoption (4M/yr)**



# Performance Metrics Derived from Interfaces

- Bulk Material ZT
- Electrical interface resistance
- Chemical compatibility of barriers, interfaces
- Element thermal impedance
- Coefficient of thermal expansion
- Raw material cost
- Material production cost
- Module design / geometry
- Module manufacturing technology
- Solder / Braze technology
- Heat exchanger design
- Hot and Cold flow stream characteristics
- Application temperature ranges
- Application temperature / mechanical cycling conditions among other factors…

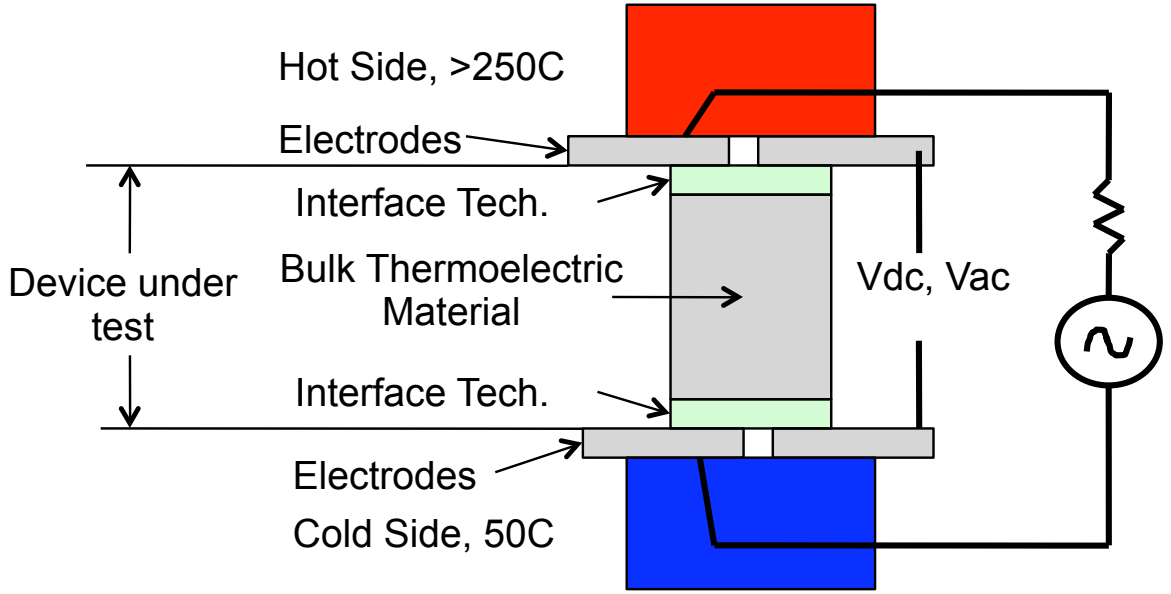
**For the Industrialization of a High Volume Product, Performance Metrics may be:**

- Power output / Cost (aka $/Watt)
- Power output / Weight
- Power output / Volume
- Power output / Pressure Drop
- Module Efficiency
- System Efficiency
- MTBF
- Effective Module ZT
- Effective System ZT
- Etc.

# Performance Metrics Derived from Interfaces

**Stability Testing of Interface Technology**

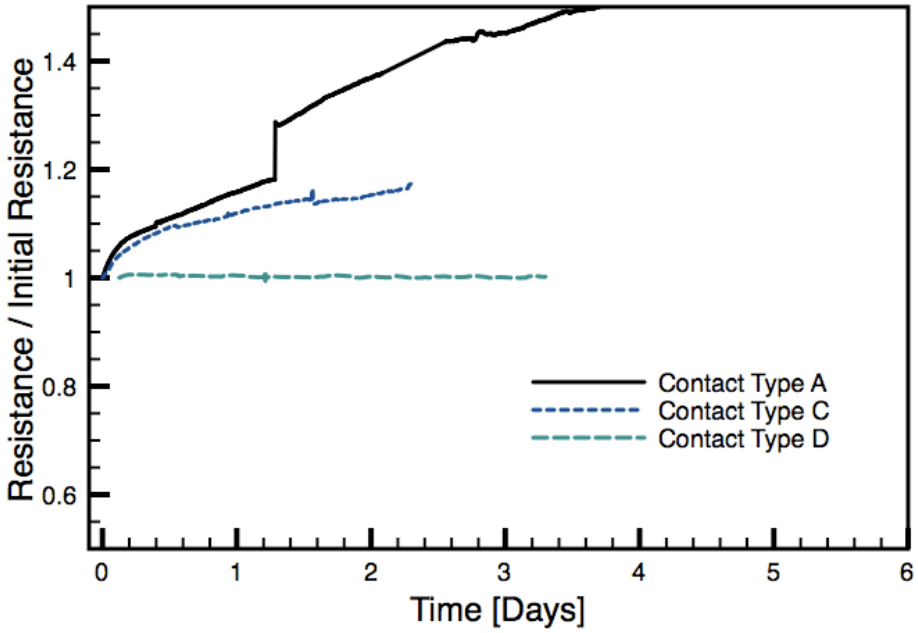
- Monitor the stability of the bulk resistance, interface resistance, and Seebeck voltage over time

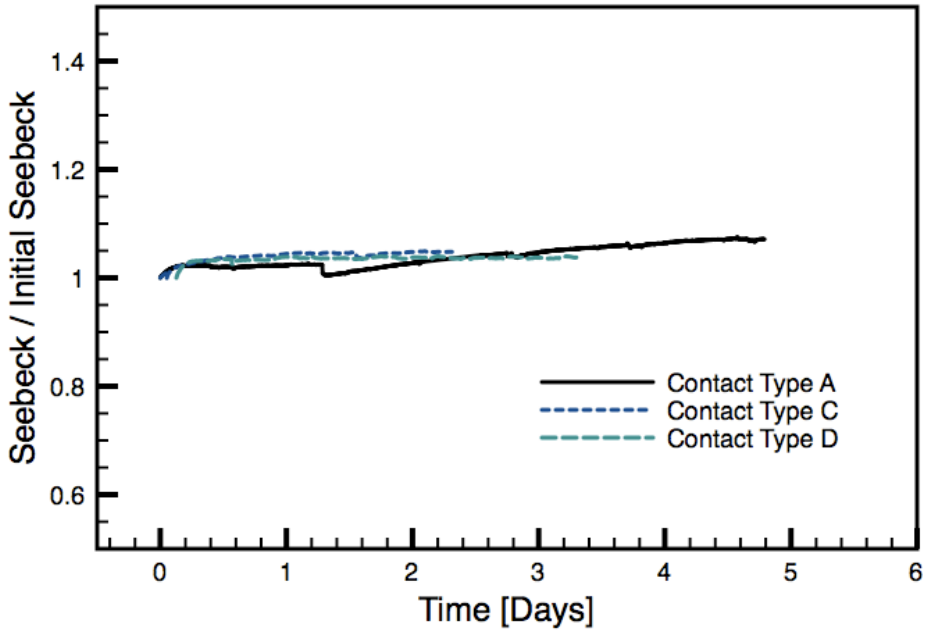


# Performance Metrics Derived from Interfaces

**Stability Testing of Interface Technology: P-type**

- Monitor the stability of the bulk resistance, interface resistance, and Seebeck voltage over time

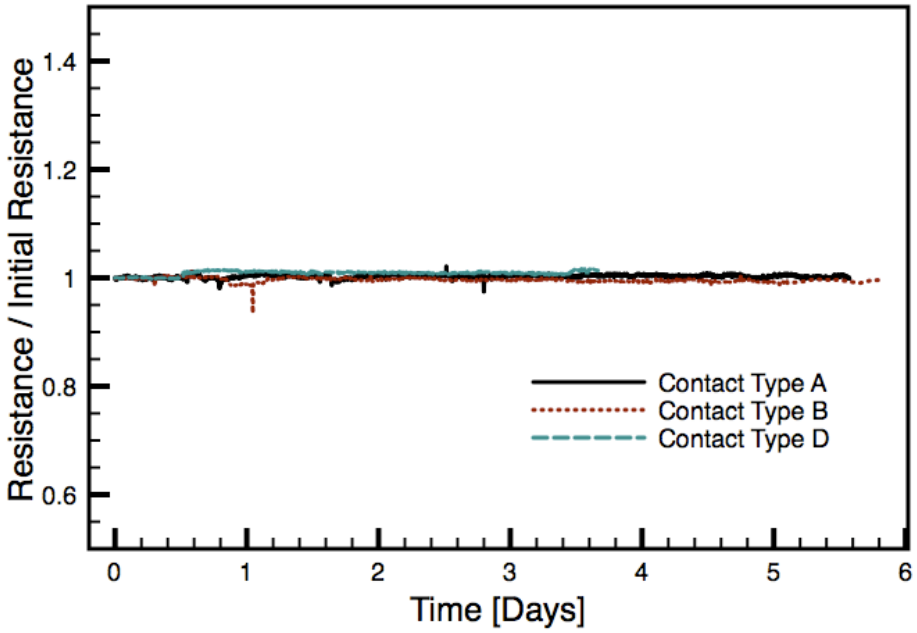


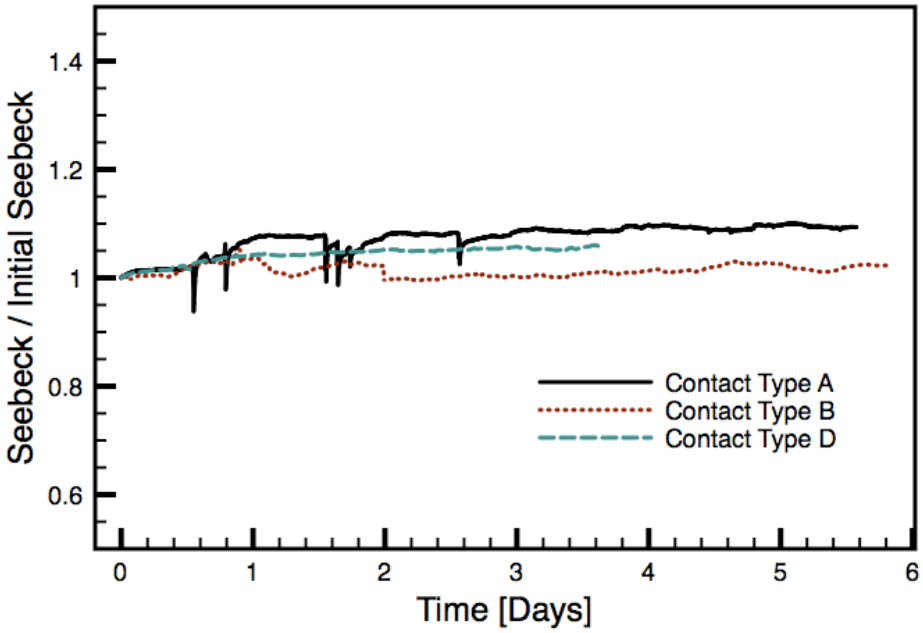



# Performance Metrics Derived from Interfaces

**Stability Testing of Interface Technology: N-type**

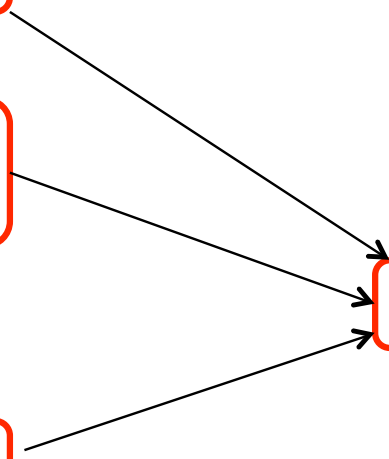
- Monitor the stability of the bulk resistance, interface resistance, and Seebeck voltage over time



# Performance Metrics Derived from Module Technology

- Bulk Material ZT
- Electrical interface resistance
- Chemical compatibility of barriers, interfaces
- Element thermal impedance
- Coefficient of thermal expansion
- Raw material cost
- Material production cost
- Module design / geometry
- Module manufacturing technology
- Solder / Braze technology
- Heat exchanger design
- Hot and Cold flow stream characteristics
- Application temperature ranges
- Application temperature / mechanical cycling conditions among other factors…



**For the Industrialization of a High Volume Product, Performance Metrics may be:**

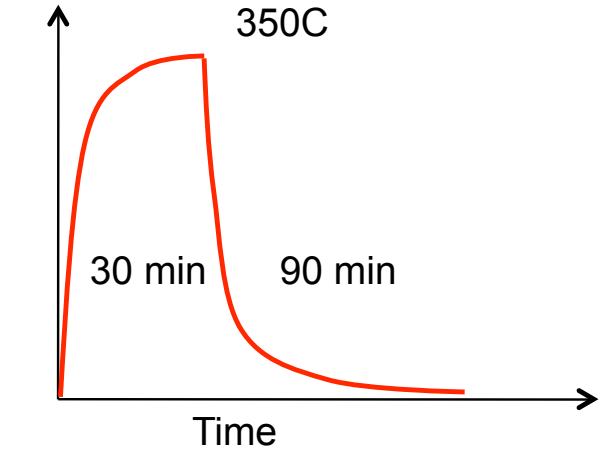
- Power output / Cost (aka $/Watt)
- Power output / Weight
- Power output / Volume
- Power output / Pressure Drop
- Module Efficiency
- System Efficiency
- MTBF
- Effective Module ZT
- Effective System ZT
- Etc.

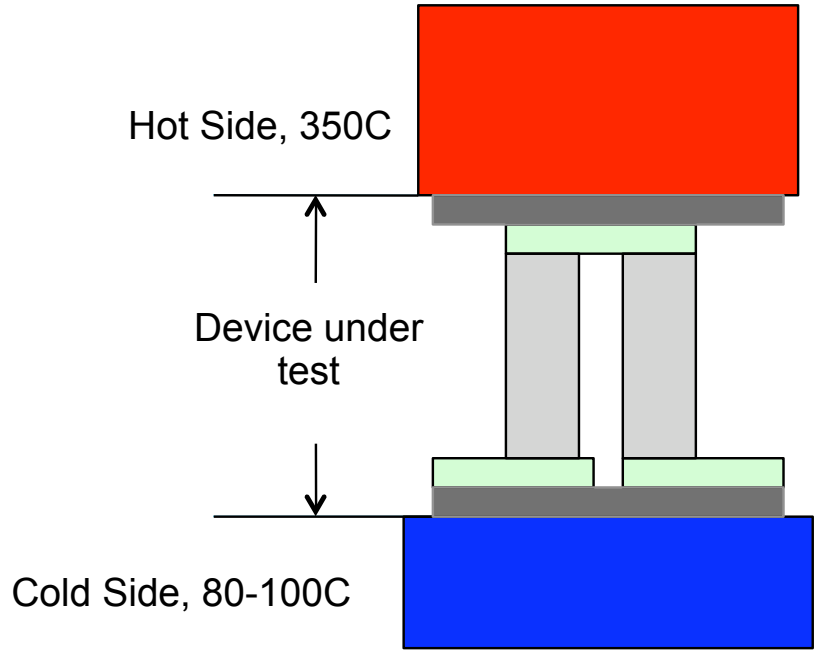
# Performance Metrics Derived from Module Technology

**Stability Testing of Modules Technology**

• Temperature cycle modules, monitor circuit electrical resistance

**Typical Cycle**

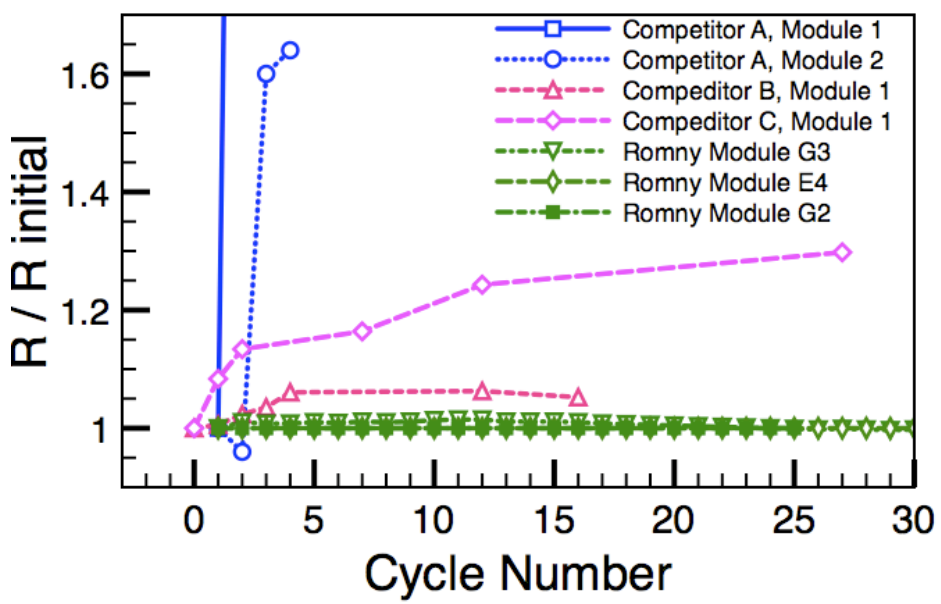


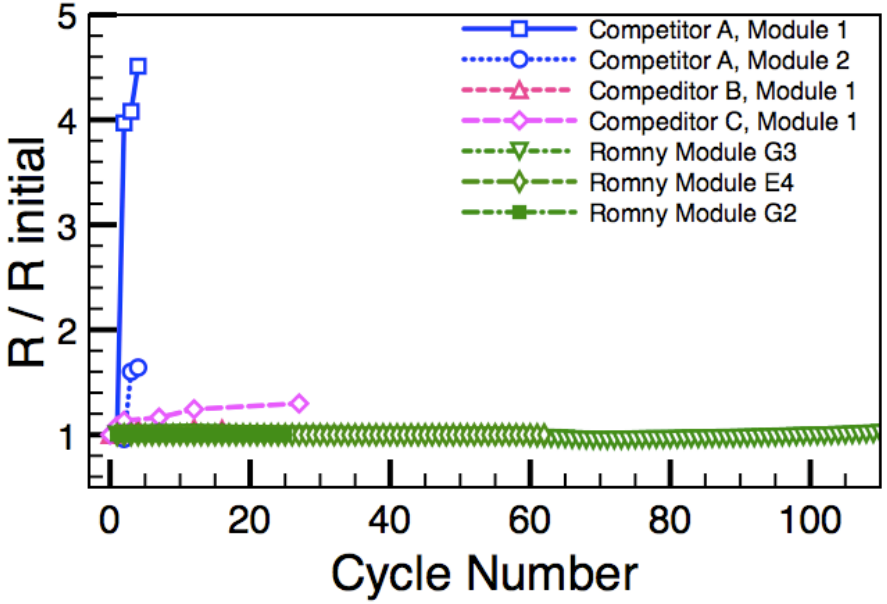



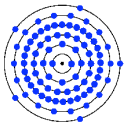
# Performance Metrics Derived from Module Technology

**Stability Testing of Modules Technology**

• Temperature cycle modules, monitor circuit electrical resistance





# Conclusion

- To develop TEG systems for broad market adoption, it is important to develop TEGs considering the sellable metrics of TEG systems.
- Romny has developed the foundations for volume scalable TEGs by demonstrating:
    - Lead free materials
    - Tellurium free materials
    - Materials that do not require high purity feed stock
    - High performance/$ materials
    - Contact technology for these materials
    - Robust device technology for TEGs

# Acknowledgements


## Romny Contributors

- Michael Wright
- Catherine Uvarov, Ph.D.
- Michele Stawowy

## Collaborators

- Professors Scott Huxtable, Shashank Priya, and Srinath Ekkad's research groups, Mechanical Engineering, Virginia Tech

## This work is supported in part by:

- **DOE / NSF / Virginia Tech** Thermoelectrics Partnership: An Integrated Approach Towards Efficient, Scalable, and Low Cost Thermoelectric Waste Heat Recovery Devices for Vehicles Award #CBET 1048708
- **NSF:** Manufacturing Innovation SBIR Program Award # IIP-0848530
- **NSF / ASEE:** Postdoctorate Fellowship Program Award # IIP-1059286

Any opinions, finding, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of Virginia Tech, the US Department of Energy, the National Science Foundation, or the American Society for Engineering Education.