Design and Manufacture of Thermoelectrics for Automotive Applications

2009 Thermoelectric Applications Workshop

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Automotive Thermoelectric Applications

- Current Automotive Applications
  - Car Seats
  - Cup Holders
- Future Automotive Applications
  - Waste heat recovery
  - Zonal Air Conditioning/Heating

- What are the implications of these new applications on TE Manufacturers?
- What factors drive the material selection and design?
- How do we assess reliability?
- Readiness Assessment

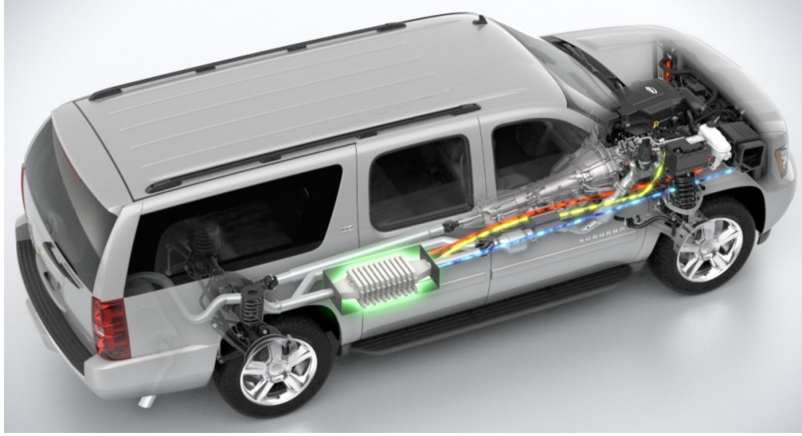
Traditional TE Cooling vs. Zonal AC/Heating

Heat Pumped: mW's to 10's W
Mostly Single TEC Systems

Heat Pumped: low KW's
Many, Many TECs per system

Traditional TE Power Gen vs. Auto Waste Heat Recovery

Power Produced: (<10W)
Single TEG per System
Co-Generation ➔ Not driven by TEG Efficiency



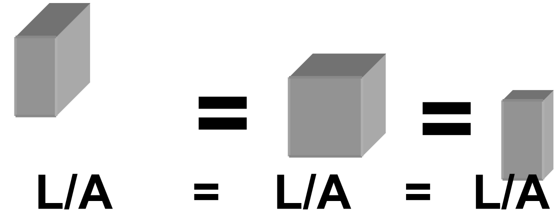
Power Produced: 100's W to KW
Many, Many TEGs per system
Waste Heat Recovery ➔ Efficiency matters

High Volume Automotive TE Applications

- Both Zonal AC and Waste heat recovery TE auto applications will require a significant number of TE modules in each vehicle
- Using traditional size and capacity TE devices, it would take:
  - ~100 TECs to produce 2kW cooling system
  - ~50 TEGs to generate 500W for a waste heat recovery system
- Estimated world wide production of TE Devices in 2008: ~25M
- Each year about 50M vehicles are produced
- Entire current production would address only 0.3% of those vehicles
- Given the price volatility, scarcity of Tellurium, clearly for thermoelectrics to have any impact in the automotive industry,

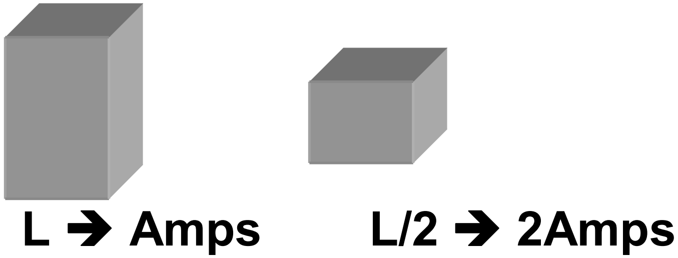
we can't just build more TE modules.

Scalability of TE Devices



L/A = L/A = L/A

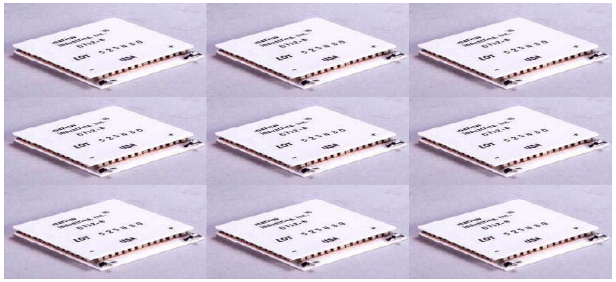
Elements with the same L/A ratio are thermoelectrically identical



L ➔ Amps

L/2 ➔ 2Amps

For the same element area (A), cutting element L in half, doubles Imax (and Qmax)



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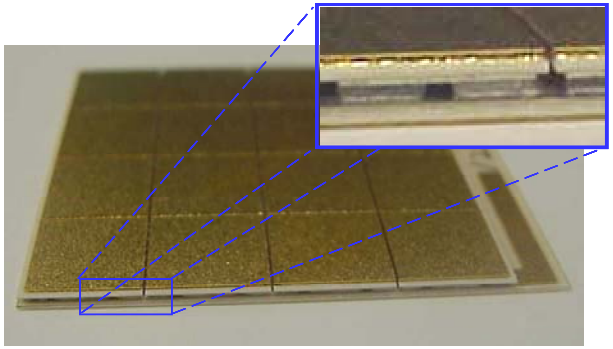


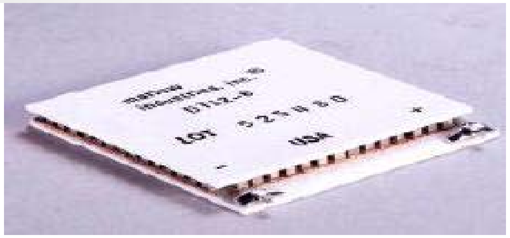
Nine commercially available 40 mm square TECs
Total Q_{max} ~ 650 W

Single 40 mm TEC
Qmax > 650 W

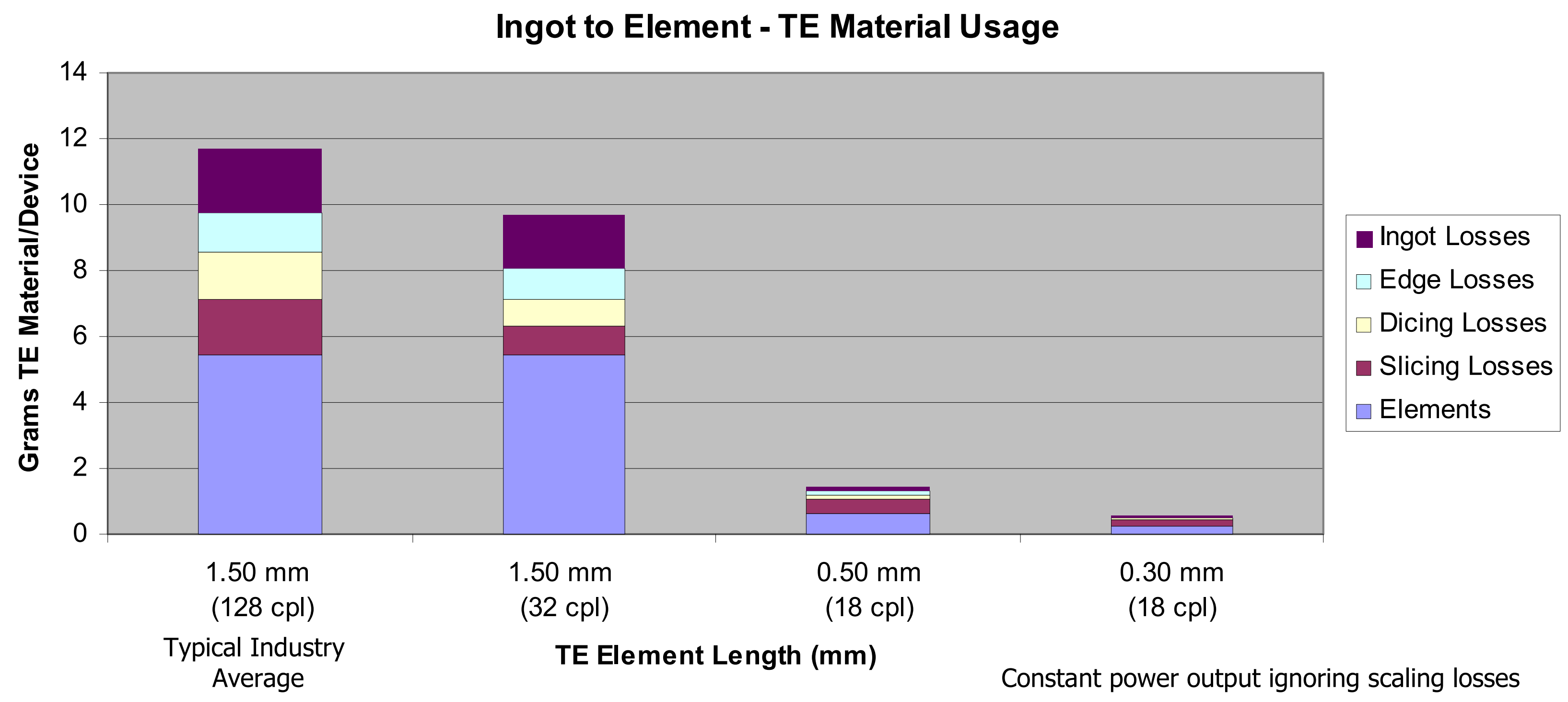
Why don't we do more scaling today?

- Many applications today are single TEC applications make it harder to implement smaller devices
  - Voltage constraints
  - Mechanical and thermal constraints
- Crystalline Bi_2Te_3 material formats support only limited scaling
- Fine grain Bi_2Te_3 material formats can be scaled but are not as rugged as crystalline and more costly
- Reducing the size of the TEC lowers efficiency
  - Smaller size → Higher heat flux → higher thermal interface losses, ceramic conduction losses, larger spreading losses

Impact of Scaling and Fewer couples/Device



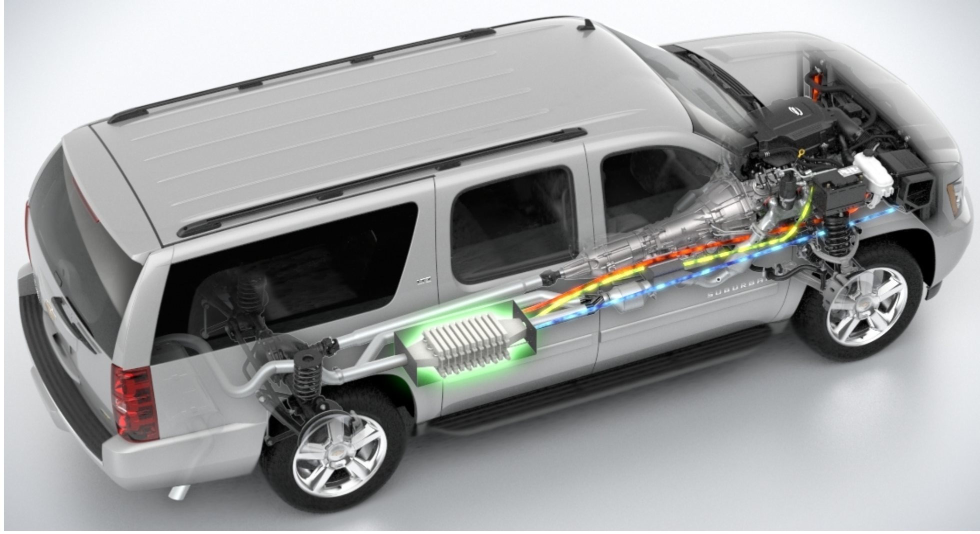
- For waste heat recovery, target: \$0.10/W for raw TE material (1)
- Device costs are driven by the cost of the TE materials
- Will have to do everything we can to minimize TE material



(1)Buschmann, G, IAV GmbH, ICT 2009, Freiburg, Germany

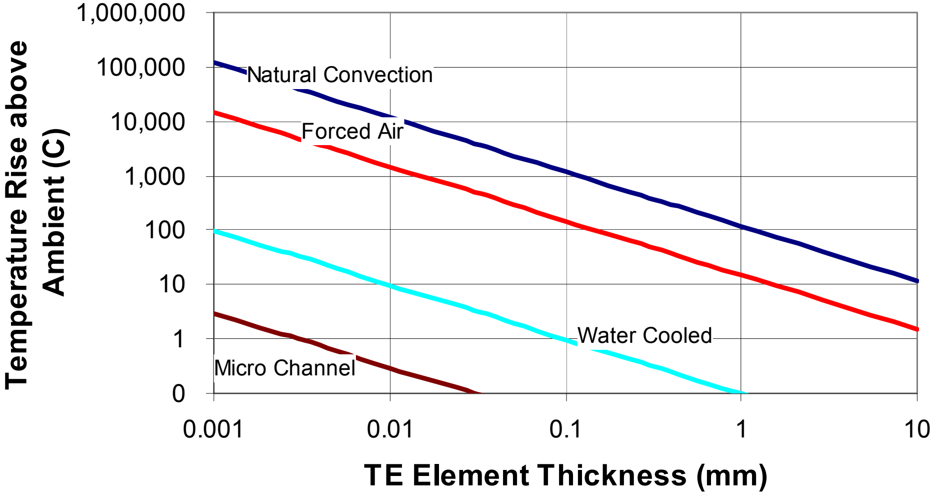
How Far Can We Scale Down The TE Devices?

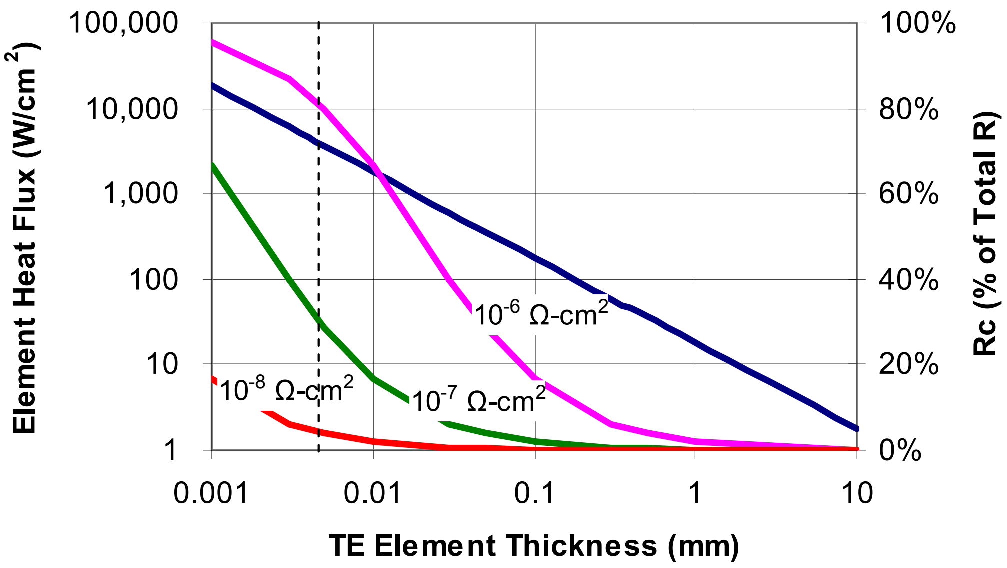
- Auto Applications are driven by low watt density air
  - Zonal AC
    - Cooling volumes of air in the cabin
    - Heat has to be dissipated eventually to air
  - Waste heat recovery
    - extracting heat from high temperature air stream
    - dumping that heat to ambient



TE Device Design – Dictated by Heat Sinking

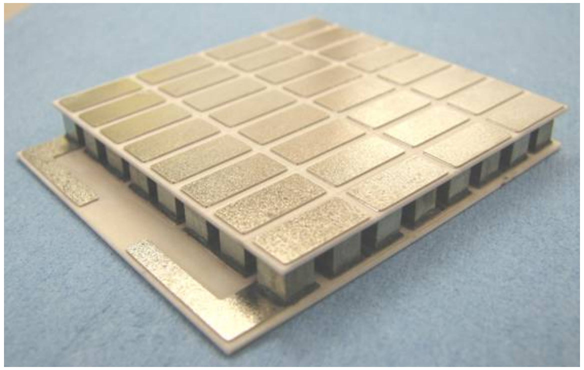
- Heat sink technology dictates TE device heat flux
- Must have flexibility on TE element thickness to match TE heat flux with heat sink capability
- Must be able to minimize all losses including electrical contact resistance, interconnect losses, etc.



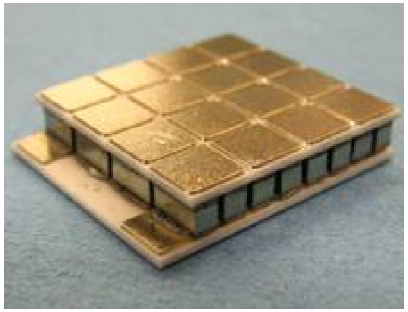


Automotive TE Module Designs

- TE module cost will dominate
  - Designs will be driven to highest heat flux (shortest elements) that the chosen heat sink technology can support w/o significant spreading and thermal losses
  - Need capability to vary material thickness from 0.30 – 1.2 mm to be able to optimize system (performance vs. cost) – raw material formats that can support these thicknesses
- TE devices will have few couples
  - Low voltage output + Many devices = Few couples needed per device and still be able to provide some redundancy w/ series parallel wiring configurations
  - Minimizing TE material losses
- Cooling devices: single stage
- Power generation: both single stage and either segmented or cascade needed.

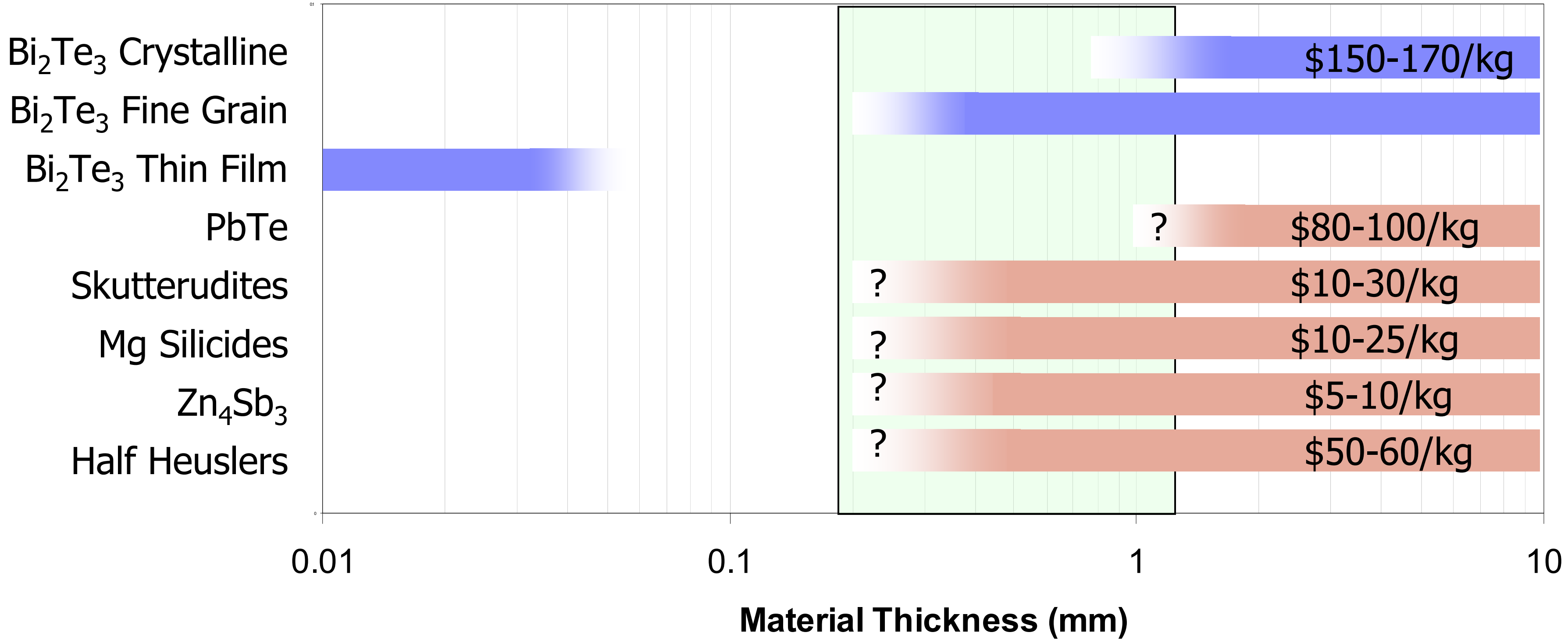


Marlow 1st Generation PbTe Prototype Devices



Power Generation TE Material Selection

- Selection will not be based solely on ZT
  - Raw material cost and cost to process it into elements
  - Can it be scaled to thicknesses that can optimally match the available heat exchange technology?



TE Assembly

- Existing TE manufactures typically have 50-100 devices on web sites
- TE factories set up around high product mix
- Why so many products?
  - Scalability – Range of products needed for varying design inputs
  - Severe performance penalty for operating TE devices “off optimum” conditions
- New Auto applications
  - One size will not fit all - customization will be required
  - Will be able to vary the number of devices to help optimize
  - Shouldn’t simply try duplicating existing manufacturing processes
  - Will offer more opportunities for limited levels of automation trading off capital cost vs. low cost Asian labor

Long Term Reliability Assessment

- For Bi_2Te_3 cooling devices, methodologies pretty well defined for predicting TEC life
  - Activation energies determined from storage and aging (powered) at various hot side temps
  - Basic endurance testing to assure TE devices are sufficiently rugged
- All testing is Pre-Design Verification or application specific qualification testing

Long Term Degradation	Typical Test Conditions	Notes
High Temp Storage (unpowered)	85°, 125°C, 150°C	Inexpensive test: ovens set at various temperatures. Determine activation energy. Degradation rates generally 2X those of Aging.
Aging (Powered)	Imax @ 65, 85, 125°C Thot	Thot increased to accelerate degradation. Activation energy determined.
Endurance Tests		
Thermal Shock	-55 to +125 C, 500 cycles	Test is only useful if qualifying TE device mounted to CTE mismatched component. Upper temp generally 30-50 C above operating temp
Power Cycling	@ Imax 85°C, 5000 cycles	Peltier cooling creates ~90°C temperature difference and thermal stresses TEC
	0 - 100°C Cycling, 50 C Thot	reverse polarity heating to cooling cycle

Long Term Reliability Assessment – Power Gen

- For Power generation, evaluations & predictions become much more complicated
  - Operating temperature range can be an order of magnitude greater than cooling
  - Multiple materials within a device complicates testing
- All testing is Pre-Design Verification or application specific qualification testing

Long Term Degradation	Test Conditions	Issues w/ Power Generation
High Temp Storage (unpowered)	150°C, 300°C, 450°C	Still a good, inexpensive screening test for single stages of TEG. Can not use for segmented or cascade devices (will exceed operating range for lower temp materials).
Aging (Powered)	Imax @ 65, 85, 125°C Thot	Impose ΔT or possibly use controlled Peltier heating (assuming electromigraion or electron enhanced diffusion is not an issue)
Endurance Tests		
Thermal Shock	-55 to +500C?, 100? cycles	Now becomes a useful test due to large TE elements and CTE mismatches between elements and interconnects but standard shock chambers generally limited to 200-225 C. Manual tests.
Power Cycling	0-450°C?, 5000 cycles	TEG ΔT ~ 250-300°C. Controlled Peltier heating of each individual TEG needed to create ΔT or large sink and source.

TE Industry Manufacturing Readiness Assessment

Technology Readiness	-- --	--	0	+	+ +	
TE Material Selection	●		🔴			**No consensus winning high temp material for PG. At least 4 material needed for PG**
TE materials ZT			● 🔴			**ZT may be sufficient for product demos and introduction – long term improvements necessary**
Diffusion Barriers		●	🔴			**Improvements over bulk Rc values needed for both cooling and PG applications**
Material Capacity	●			🔴		**Cooling: can build off existing infrastructure. PG starts from scratch; different process.**
Assembly Processes		●		🔴		**Solders well suited for cooling; PG likely to use brazing or TLPS processes.**
Long Term Reliability	●			🔴		**Unproven for PG materials. Well established for traditional Bi_2Te_3. May change depending on higher ZT formulations**
Production Capacity	●	🔴				**Can leverage some off existing production process**
Mechanical Properties	●		🔴			**Significant need for mechanical properties and reliable high temp thermoelectric properties**

🔴 Zonal AC/Heating
● Waste Heat Recovery

Conclusions

- Zonal AC/Heating and Waste Heat Recovery: lots of work needed to make these applications a reality

- Zonal AC will be able to leverage off existing TE cooling infrastructure.
  - Scalable Bi_2Te_3 alloys are available today
  - Higher ZT cooling materials are still likely to be Bi_2Te_3 based

- Waste heat recovery faces many additional challenges
  - Still in material research phase – no consensus winning material
  - Higher risk for manufacturers

- Many opportunities for Government funding to accelerate the manufacturing