Engineering and Materials for Automotive Thermoelectric Applications

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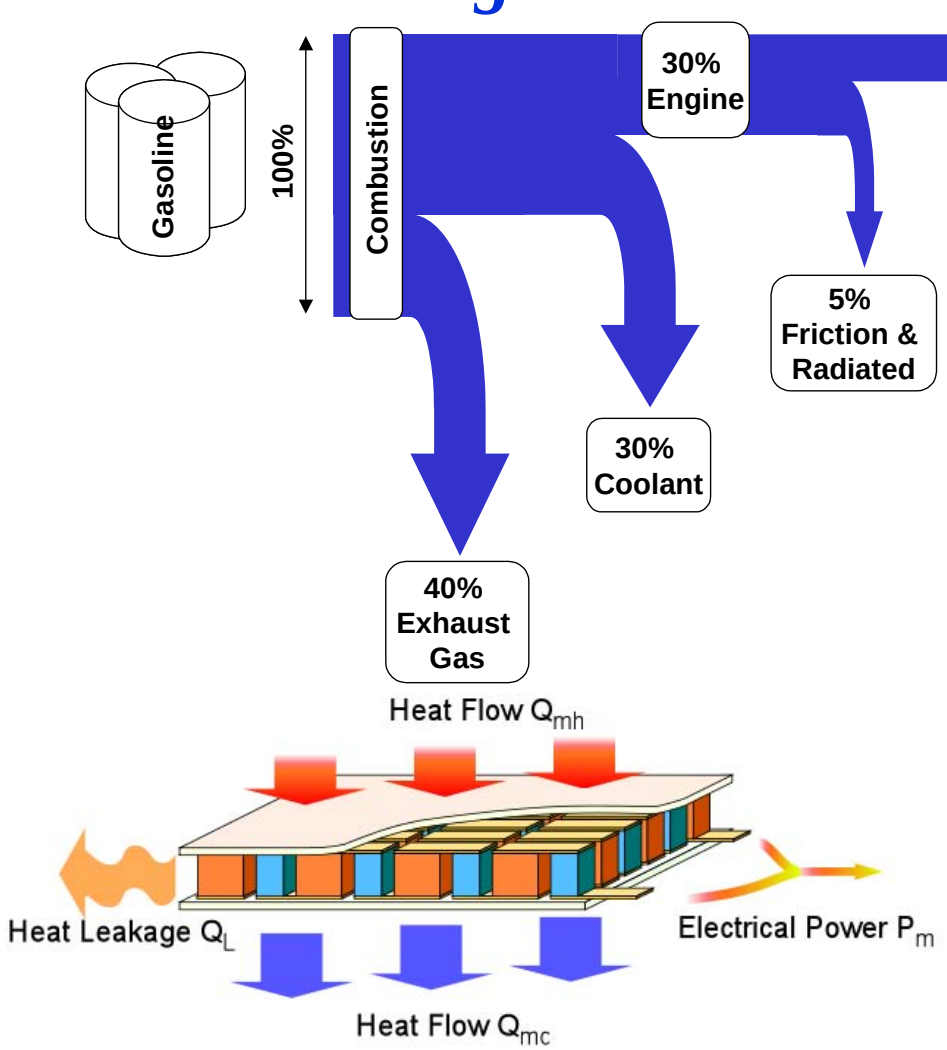
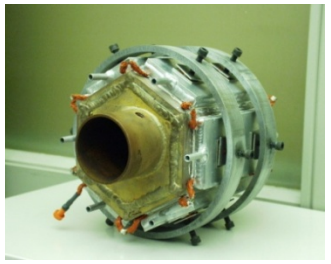
Outline

- Potential automotive applications
  - DOE waste heat recovery program
  - System design and performance
- Thermoelectric materials by design
  - skutterudites
  - high efficiency clathrates
- Conclusions

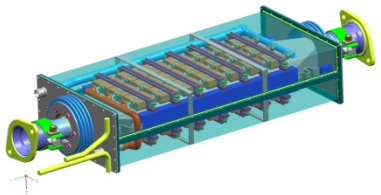
Typical Energy Path in Gasoline Fueled Internal Combustion Engine Vehicles





GEN I

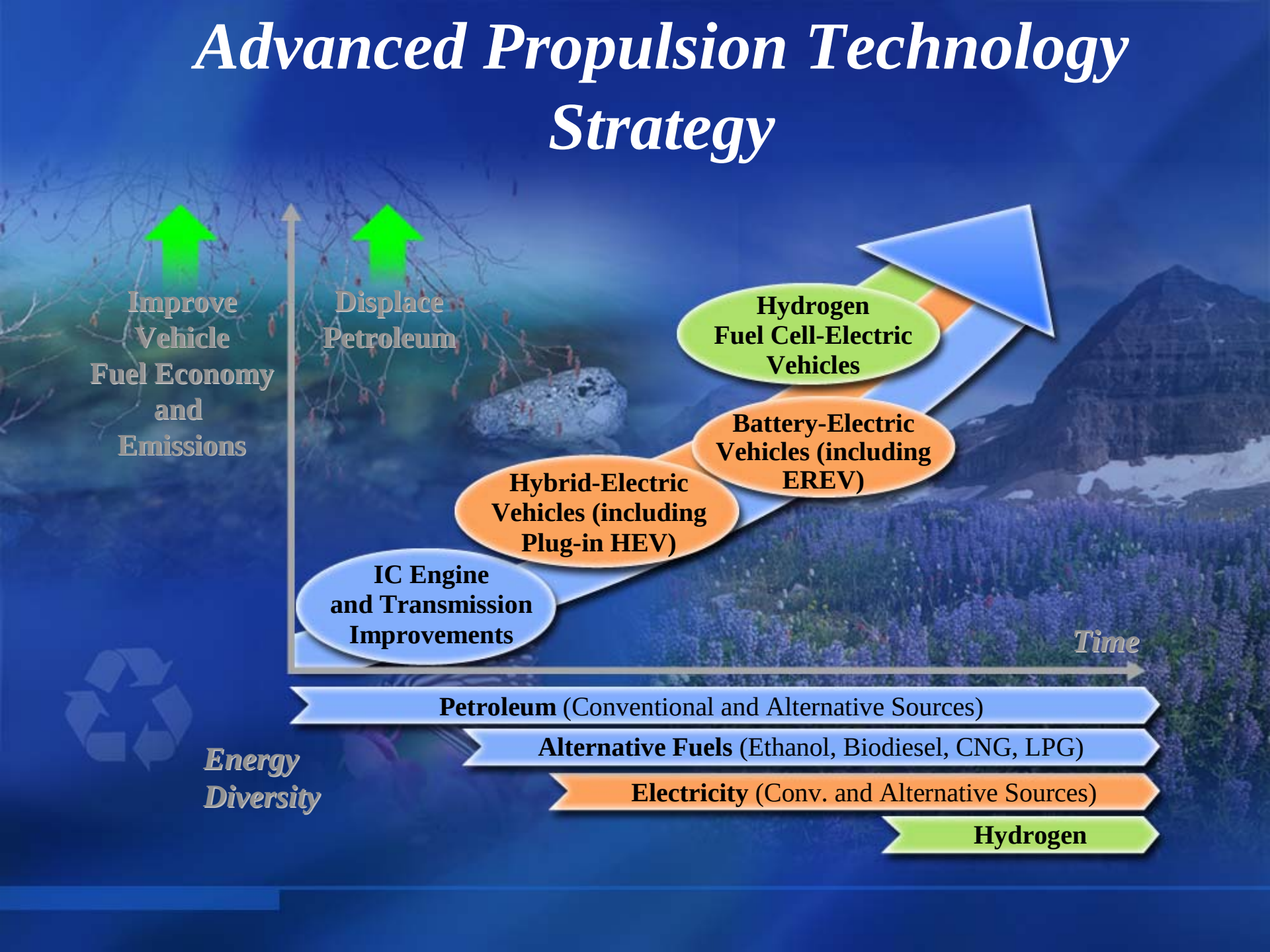
GEN II



GEN III

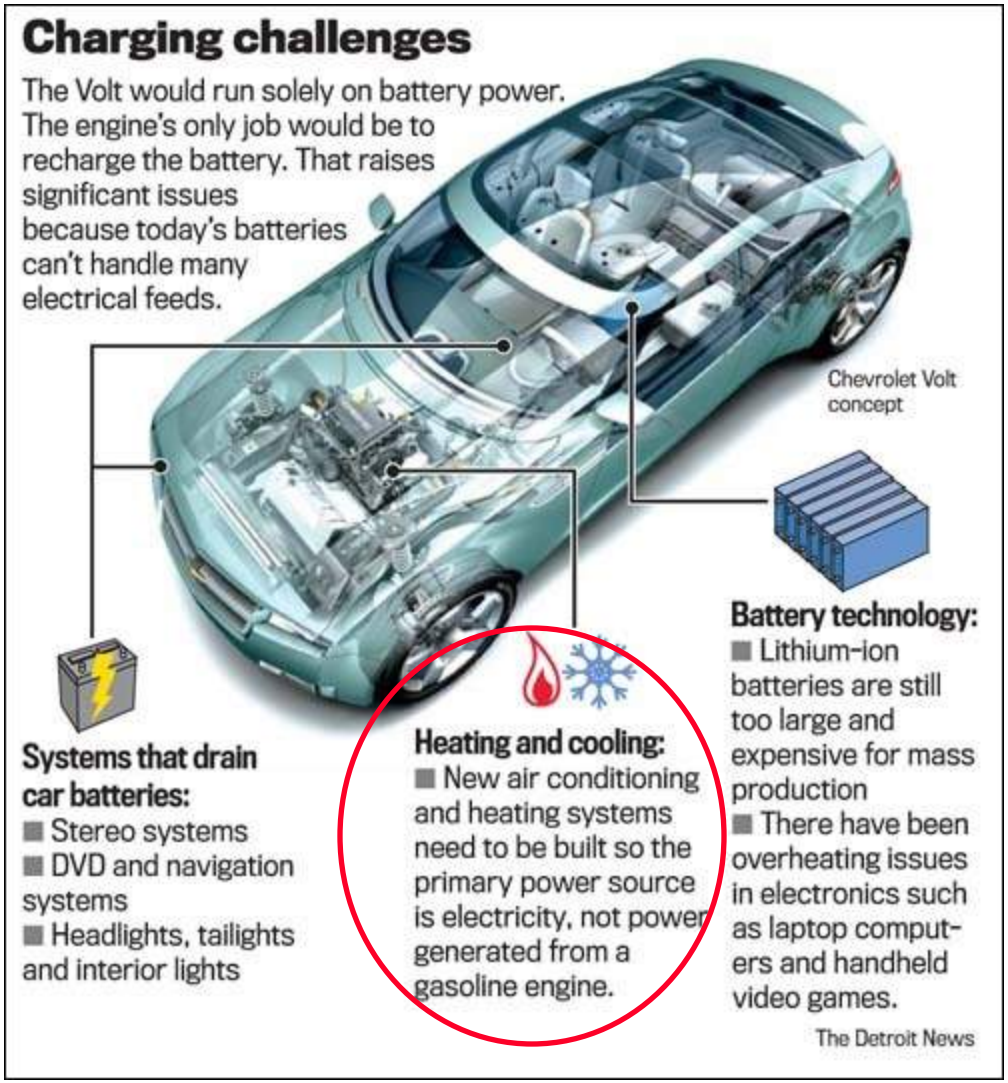
- Today's ICE-based vehicles: < 20% of fuel energy is used for propulsion
- > 60% of gasoline energy (waste heat) is not utilized

Advanced Propulsion Technology Strategy



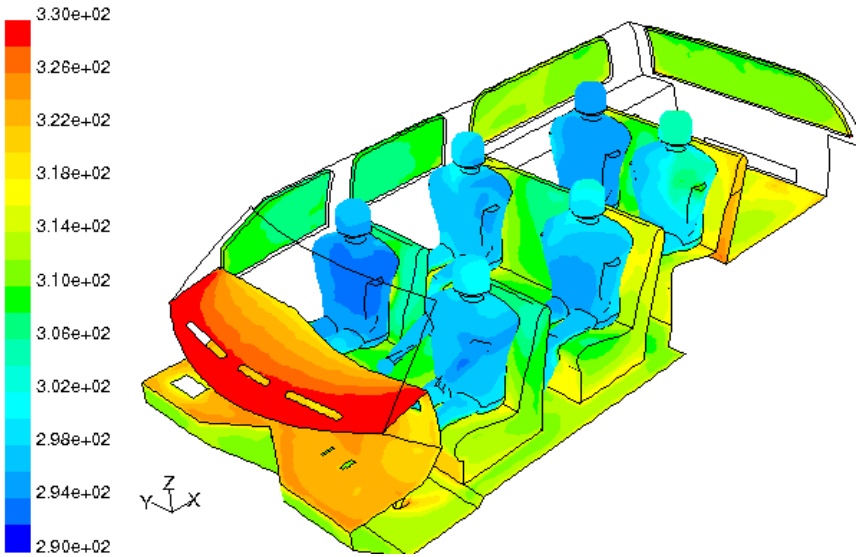
GM's Path to Electrification

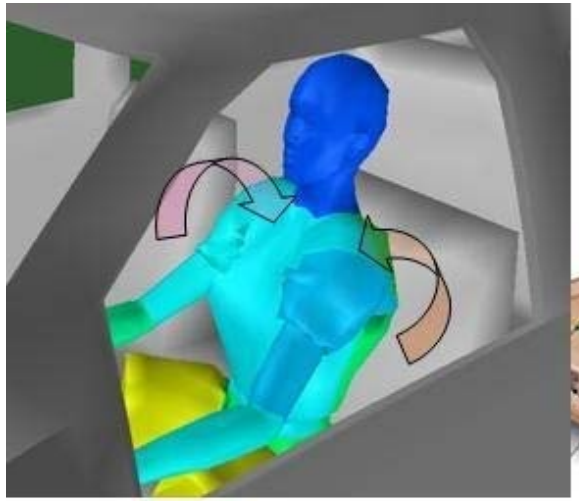
Opportunity for TE Cooling

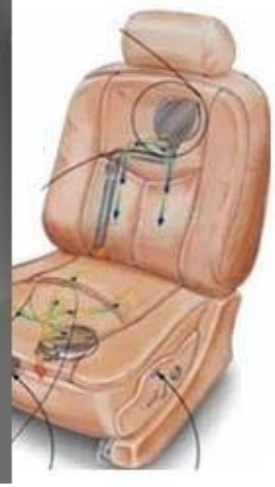


Distributed Cooling for High Efficiency HVAC System

- Reduce onboard AC without sacrifice passenger comfort level
- Improve fuel economy and CO_2 emission
- DOE award in place to start in 2009





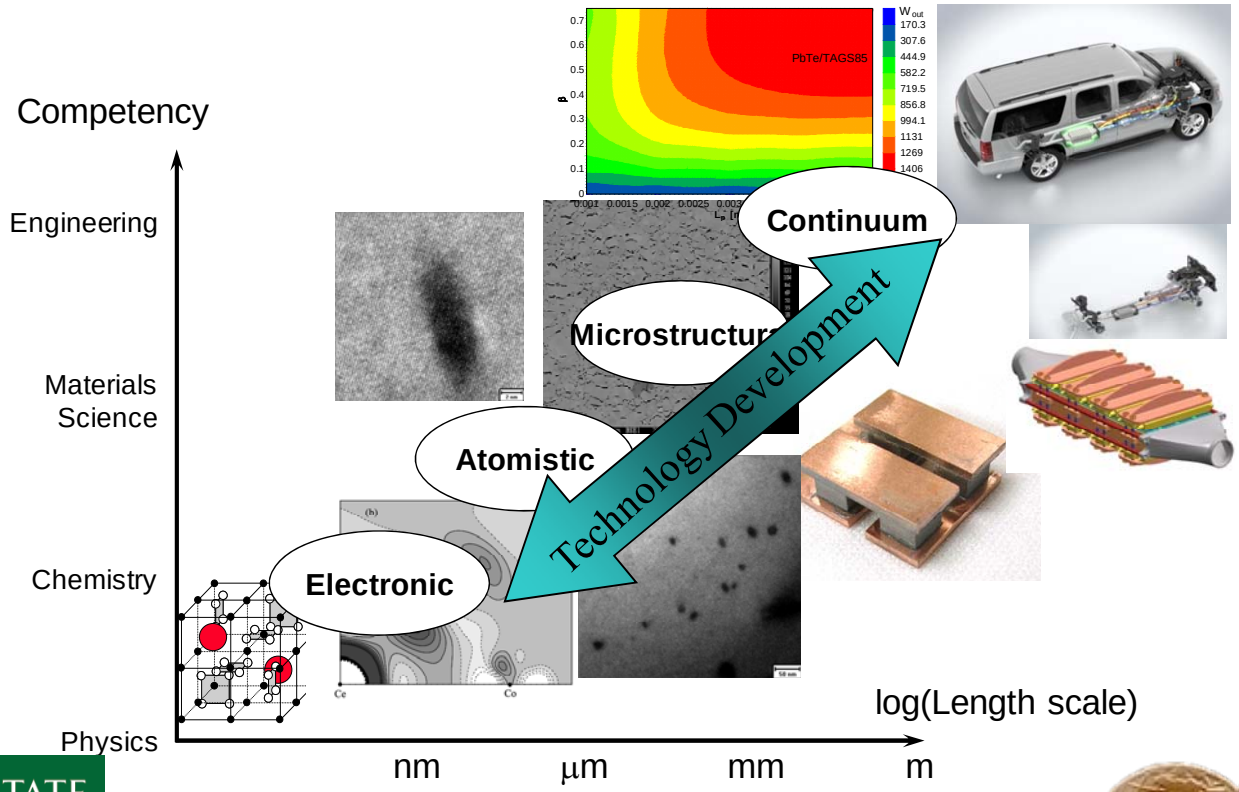


"If all passenger vehicles had ventilated seats, we estimate that there could be a 7.5 % reduction in national air-conditioning fuel use. That translates to a savings of 522 million gallons of fuel a year,"

John Rugh, project leader for NREL's Vehicle Ancillary Loads Reduction Project.

TE Power Generation from Automotive Waste Heat Recovery (Sponsored by EERE-DOE)

- Target : 10% fuel economy improvement without increasing emissions



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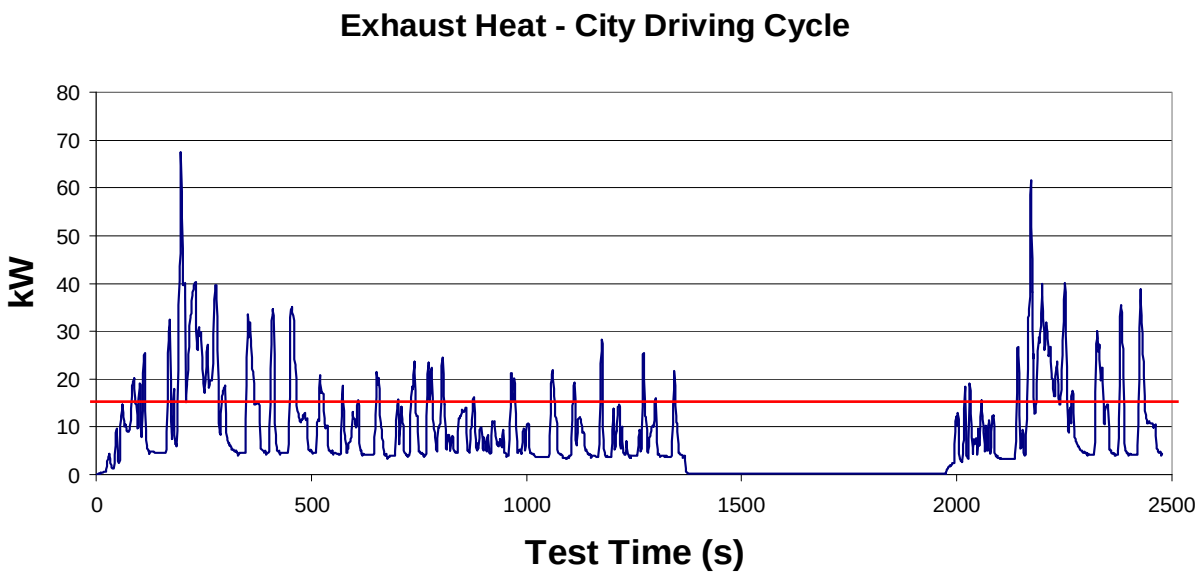
TE Automotive Waste Heat Recovery Vehicle Selection – Chevy Suburban

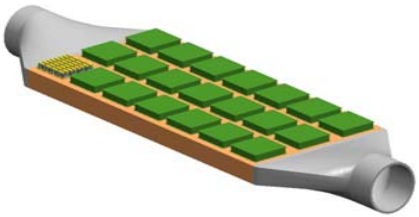


- The Suburban was selected as a test vehicle because it simplified the modifications and installation of the prototype.

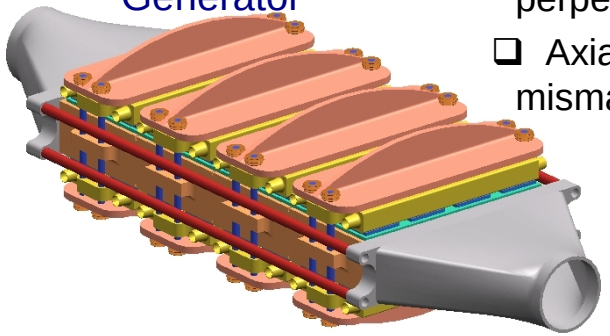
- Fuel efficiency improvement will be better in small, fuel efficient vehicles than in large vehicles because the electrical load in small vehicles is a larger portion of the engine output.

Exhaust Generator GEN III Design

Interior View
(module mounting)

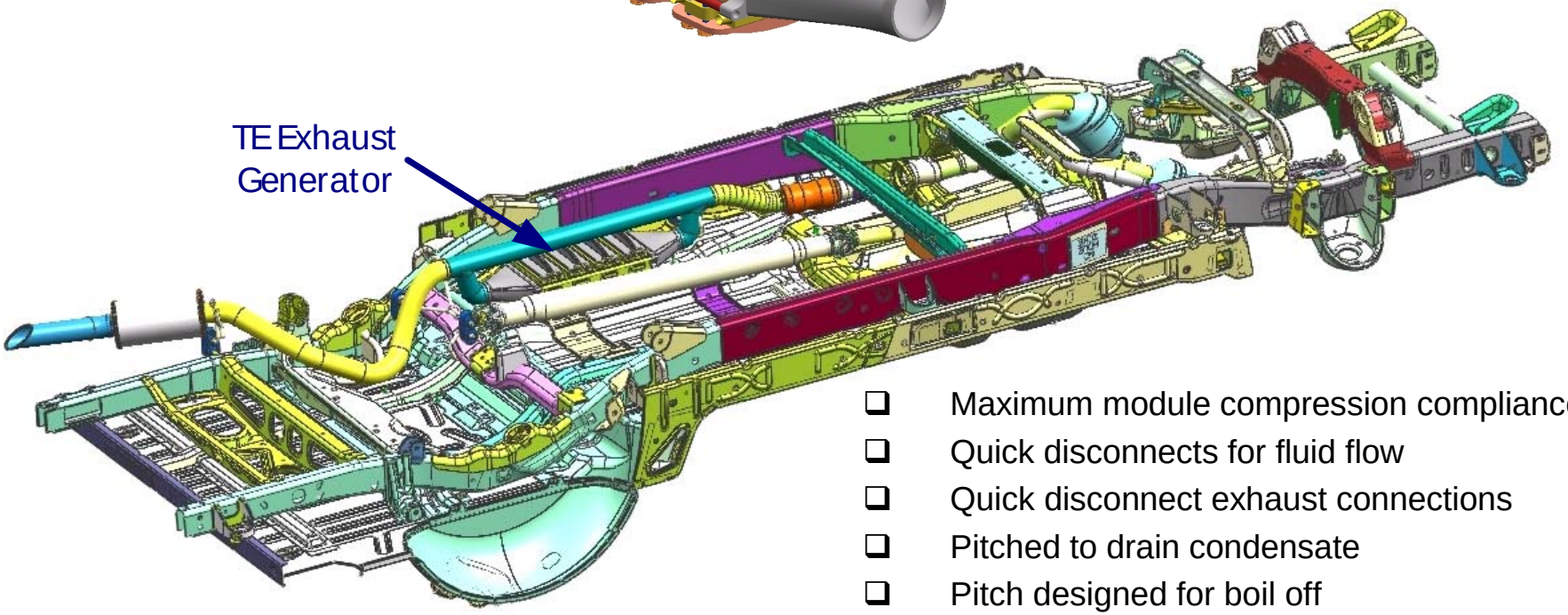


TE Exhaust
Generator



- Located where current muffler is placed; new muffler will be located behind the axle perpendicular to vehicle axis
- Axially compliant for thermal expansion mismatch

TE Exhaust
Generator

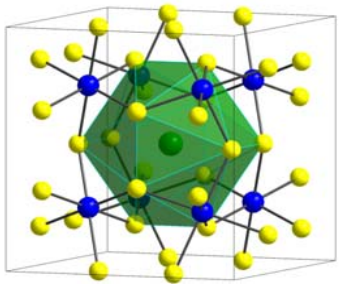


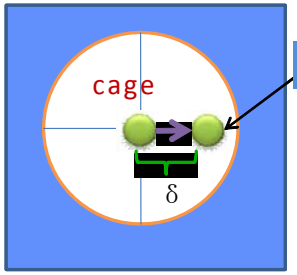
- Maximum module compression compliance
- Quick disconnects for fluid flow
- Quick disconnect exhaust connections
- Pitched to drain condensate
- Pitch designed for boil off
- Sealed electronics

Generator Animation

- We expect ~ 1 mpg (~ 5 %) fuel economy improvement for Suburban (average 350 W and 600 W for the FTP city and highway driving cycles, respectively.)
- This technology is well-suited to other vehicle platforms such as passenger cars and hybrids.

Filler Atoms in Skutterudites Rattle with Different Frequencies - Theory





		[111]		[100]	
R	Mass (10^{-26} Kg)	k (N/m)	ω_0 (cm^{-1})	k (N/m)	ω_0 (cm^{-1})
La	23.07	36.10	66	37.42	68
Ce	23.27	23.72	54	25.18	55
Eu	25.34	30.16	58	31.37	59
Yb	28.74	18.04	42	18.88	43
Ba	22.81	69.60	93	70.85	94
Sr	14.55	41.62	90	42.56	91
Na	3.819	16.87	112	17.18	113
K	6.495	46.04	141	46.70	142

Small displacement δ of the filler from it equilibrium x will lead to an increase of the total energy of the system.

$$E(x+\delta) = E(x) + \frac{1}{2}\ddot{E}(x)\delta^2 + \frac{1}{6}\dddot{E}(x)\delta^3 + \cdots$$

harmonic term — anharmonic term

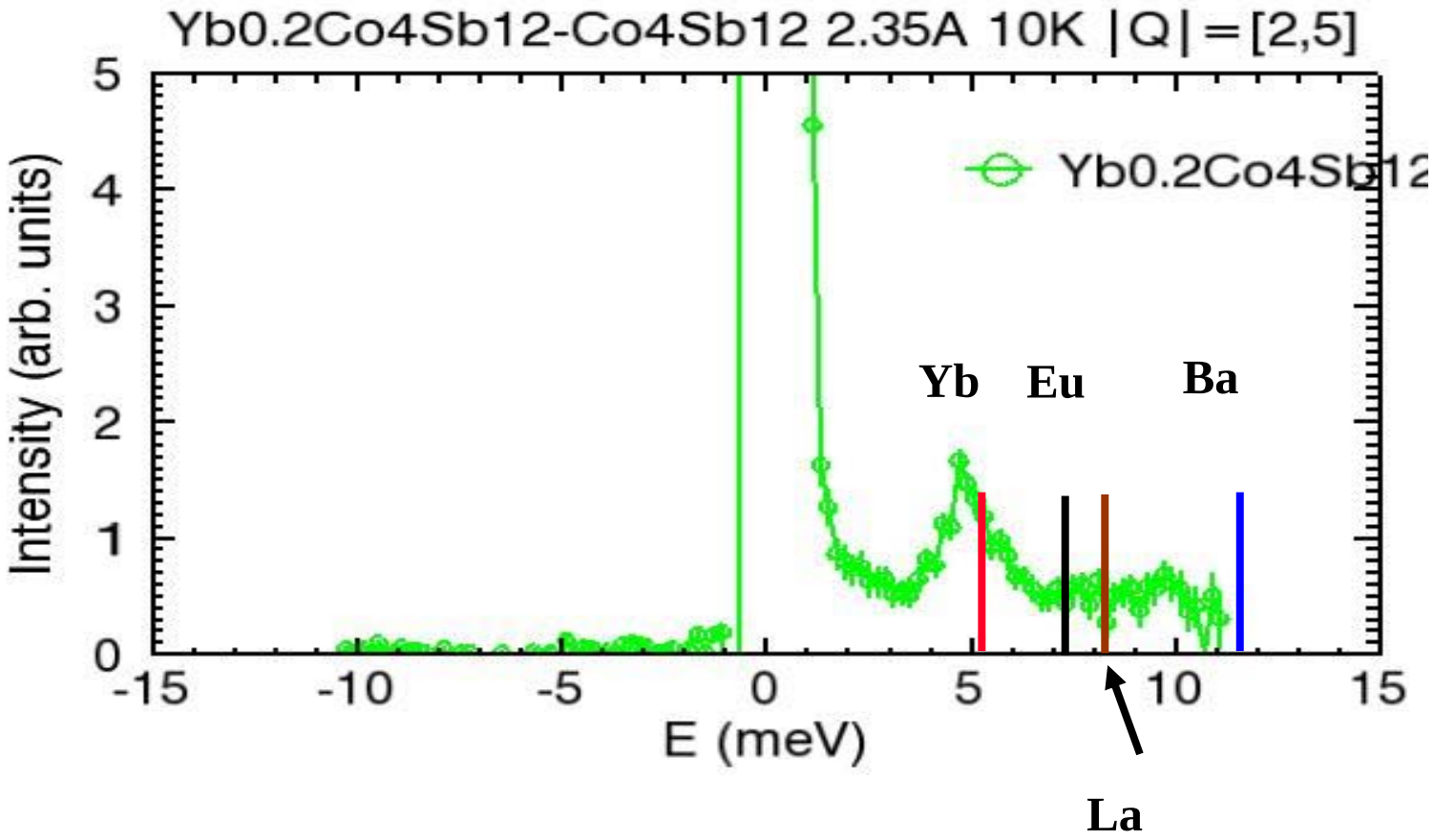
In a harmonic approximation, $\ddot{E}(x)$ is the spring constant.

$$\omega_0 = \sqrt{\frac{\ddot{E}(x)}{m}}$$

- Multiple-element filling will scatter a broad range of lattice phonons, lower thermal conductivity, and improve ZT[1-3]

1. Shi, X., Zhang, X., Chen, L. D., and **Yang, J.**, *Phys. Rev. Lett.* **95**, 185503, 2005.
2. **Yang, J.**, Zhang, W., Bai, S. Q., Mei, Z., and Chen, L. D., *Appl. Phys. Lett.* **90**, 192111, 2007.
3. Shi, X., Kong, H., Li, C.-P., Uher, C, **Yang, J.**, Salvador, J. R., Wang, H., Chen, L., and Zhang, W., *Appl. Phys. Lett.* **92**, 182101, (2008)

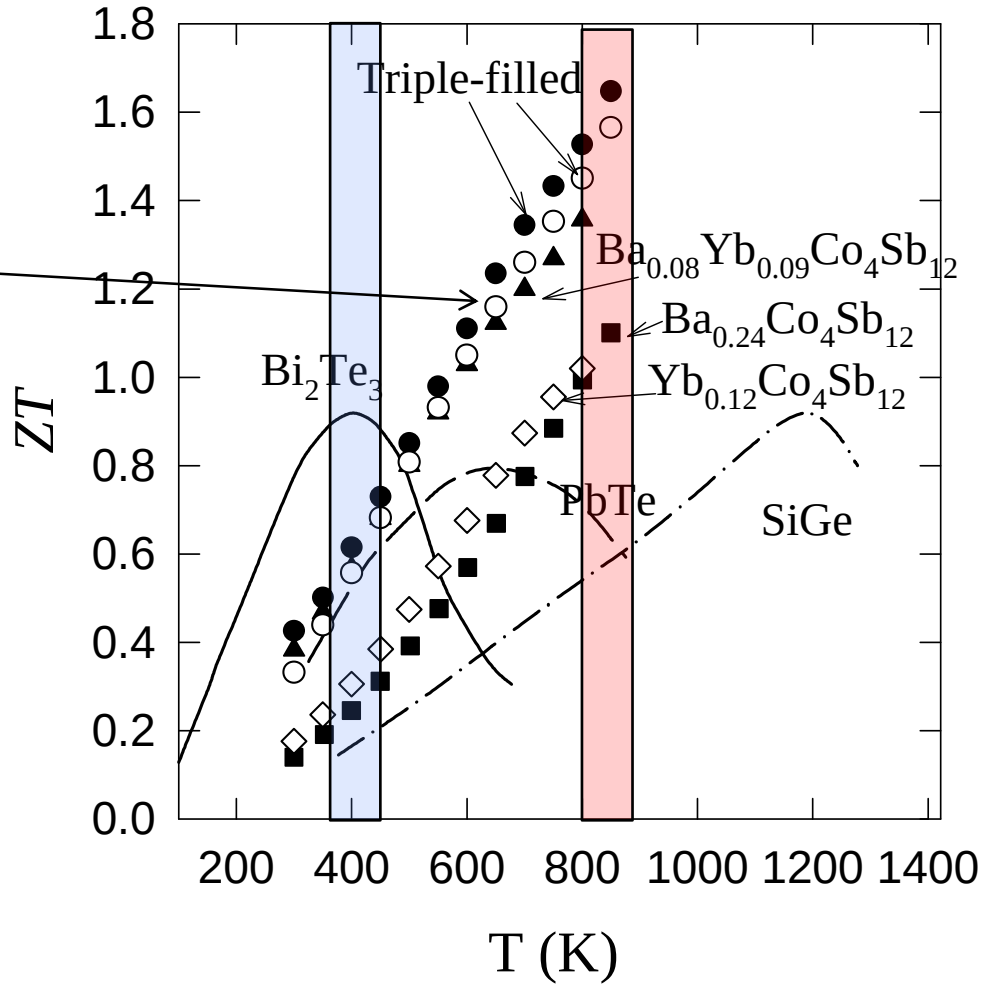
Phonon DOS Measured by Inelastic Neutron Scattering – Experiment



- Calculated resonant phonon frequencies are experimentally validated

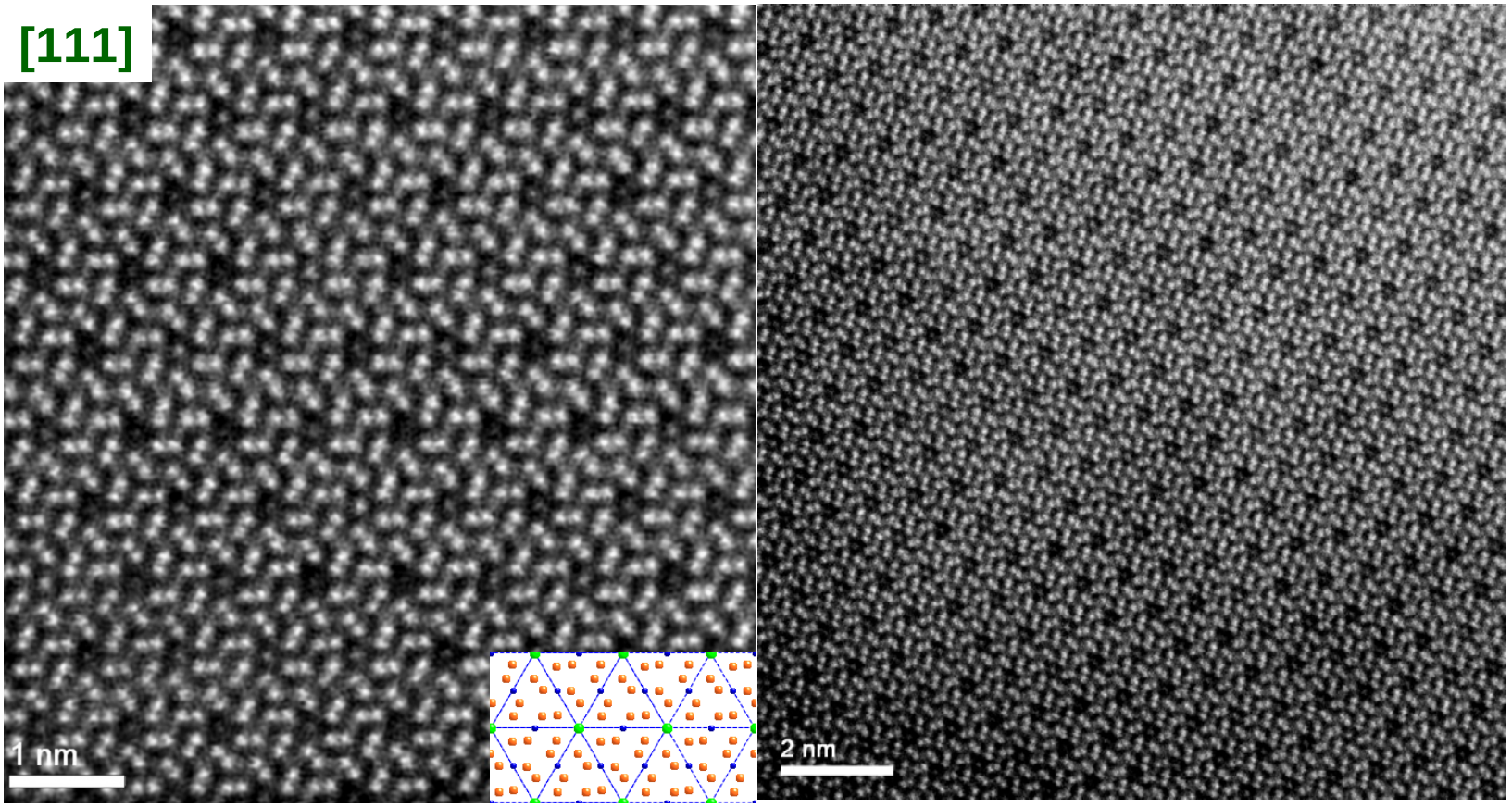
Multiple-filled Skutterudites – Much Improved ZT values

$ZT_{ave} = 1.2$



1. X. Shi, et al. Appl. Phys. Lett. **92**, 182101 (2008)
2. X. Shi, et al., submitted (2009)

STEM Images of the Triple-Filled Skutterudites



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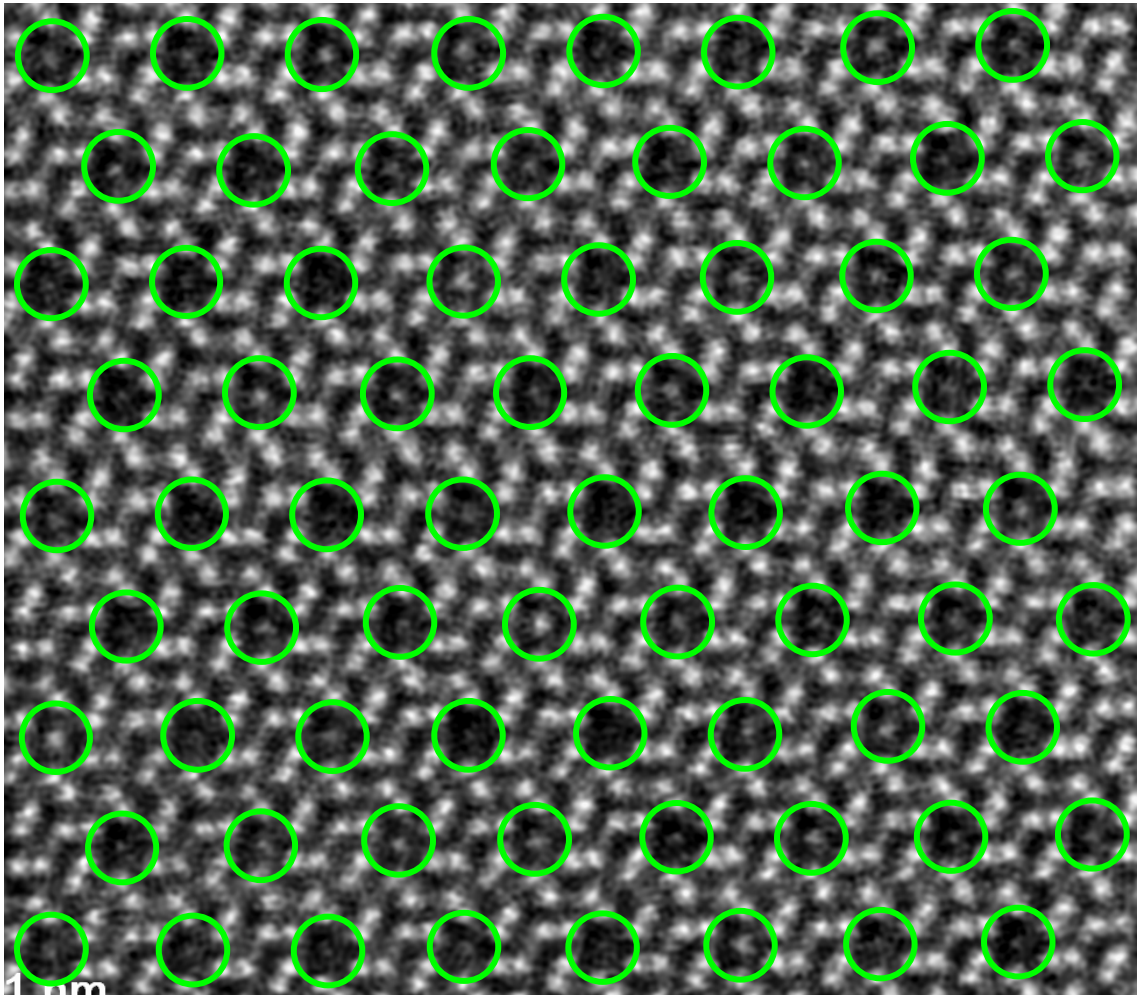
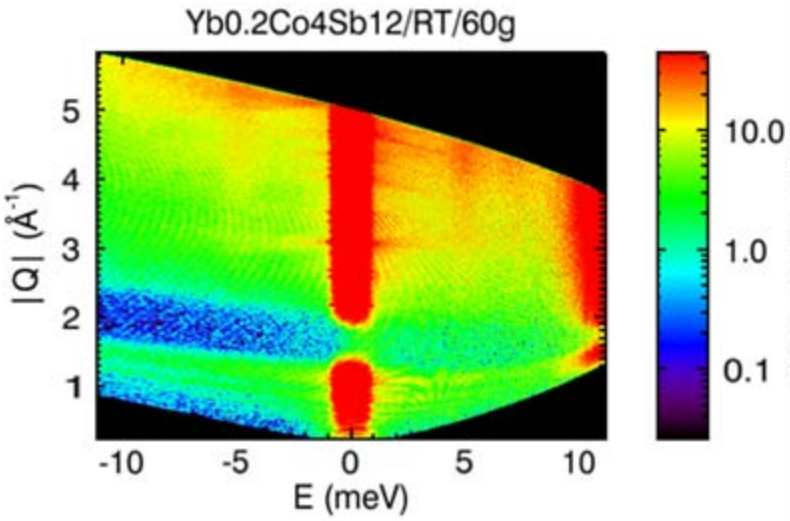
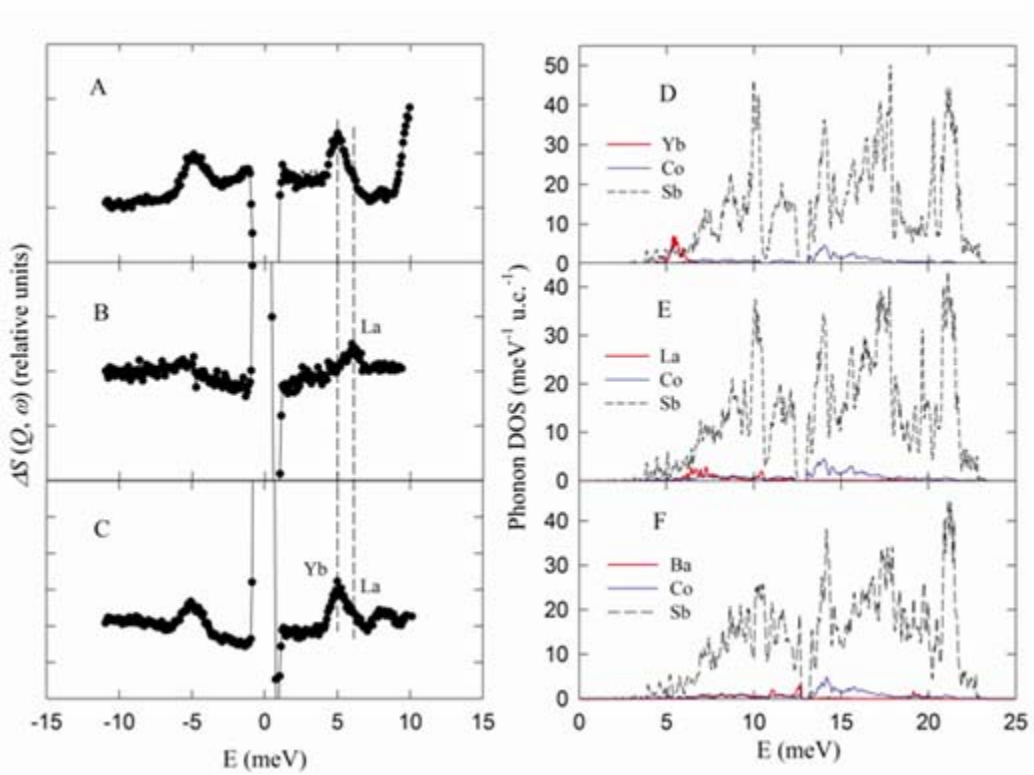
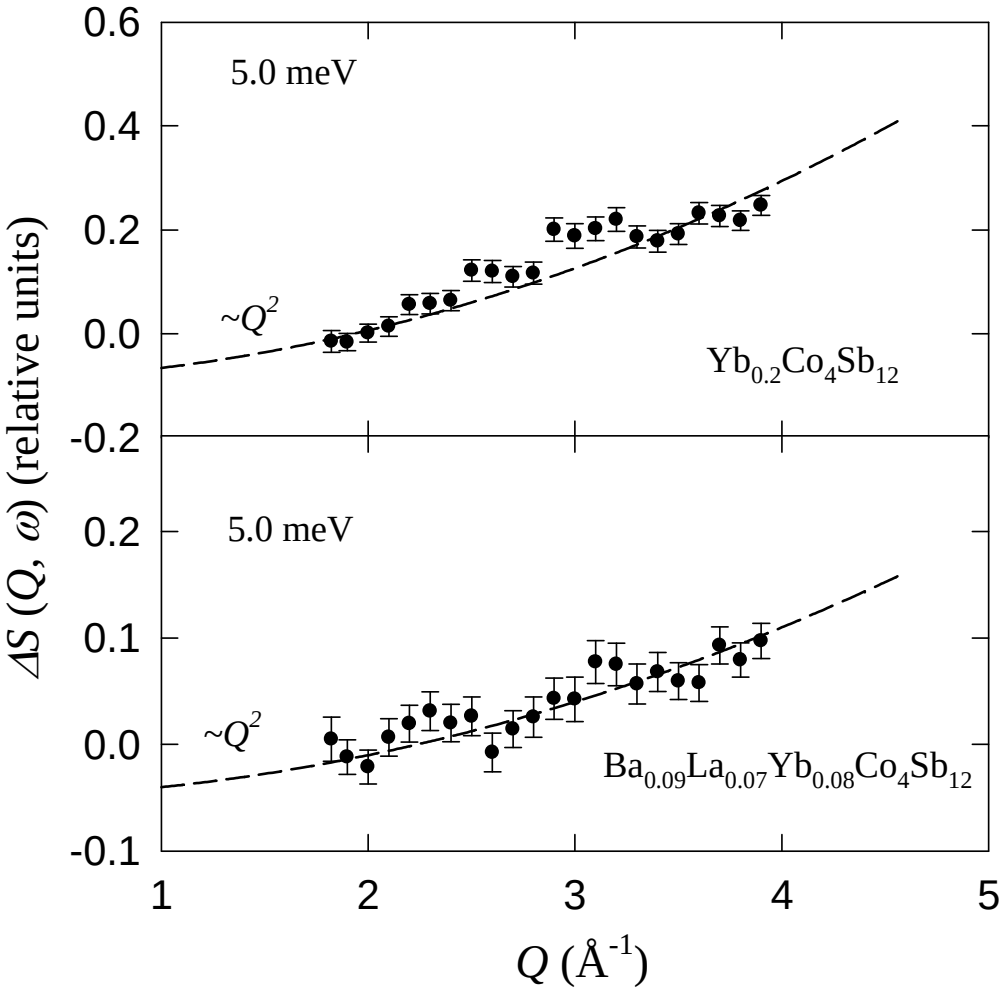


Phonon DOS Measurement – Inelastic Neutron Scattering

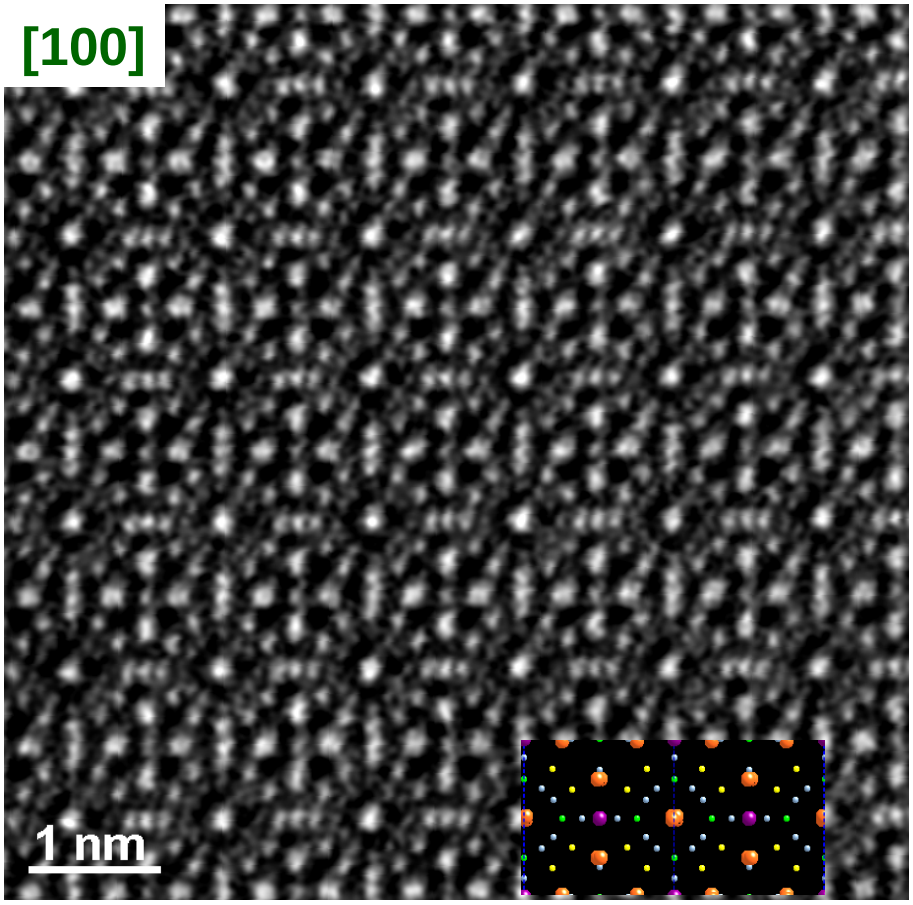


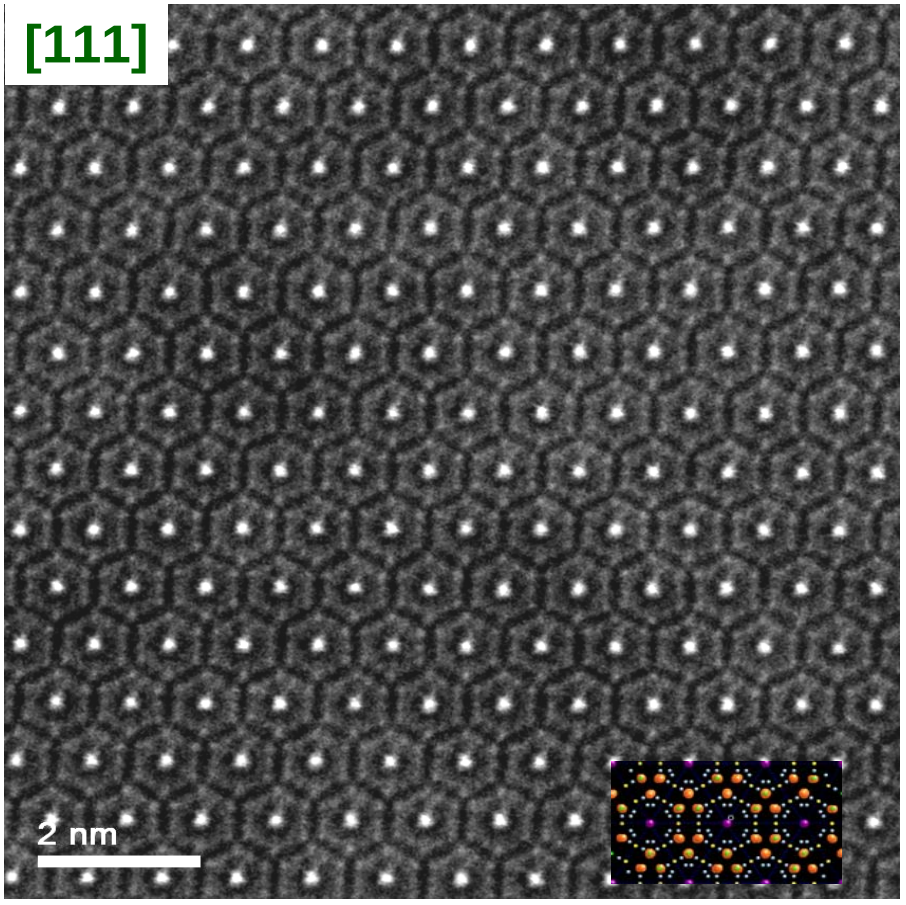


Evidence for Incoherent Rattler Mode – Phonon Glass

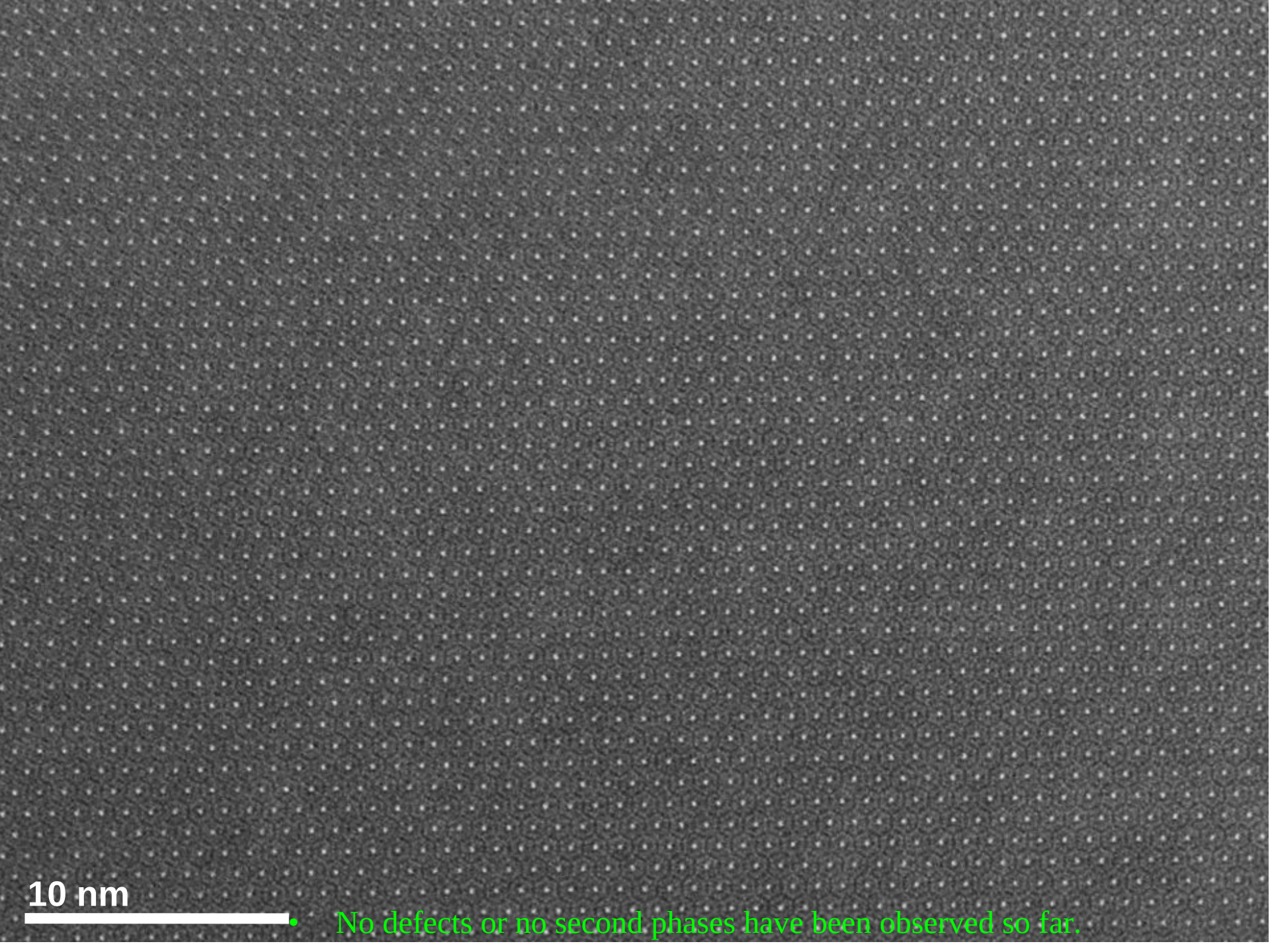


High Efficiency Clathrates $Ba_8Ni_{0.5}Ga_{14}Ge_{31.5}$



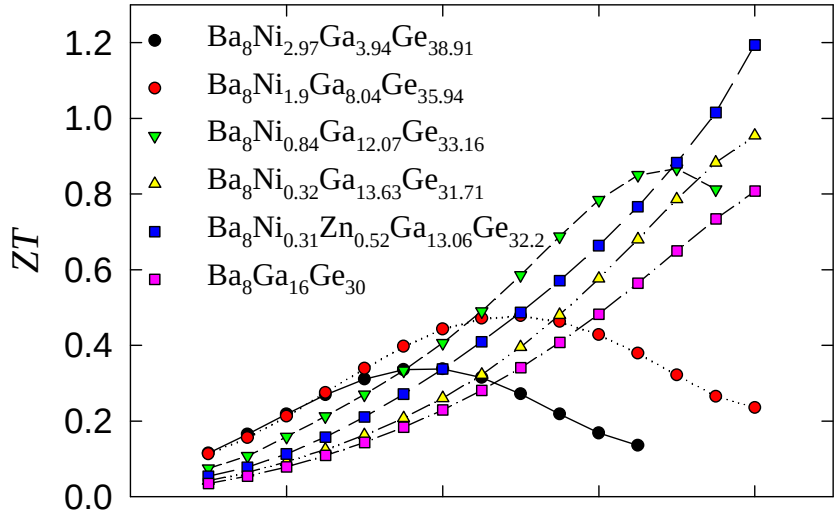


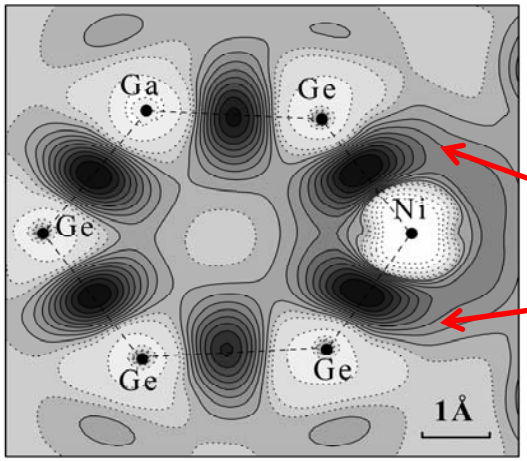
Ba1
Ba2
Ga1
Ga2
Ga3



- No defects or no second phases have been observed so far.

Tunable ZT





Strong charge distortion

Conclusions

- Thermoelectric technologies potentially offer significant energy savings through waste heat recovery and augmented cooling
- There are plenty of science and engineering to be done

Acknowledgement

- DOE for support under corporate agreement DE-FC26-04NT42278 and DOE INCITE award

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- Mike Reynolds and Francis Stabler for many useful discussions

Thank You !