Thermoelectric Conversion of Waste Heat to Electricity in an IC Engine Powered Vehicle

Presented by:

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Energy Efficiency Renewable Energy (EERE)

Waste Heat Recovery and Utilization Research and Development

for Passenger Vehicle and Light/Heavy Duty Truck Applications

IOWA STATE UNIVERSITY   NASA   JPL   MICHIGAN STATE UNIVERSITY   Cummins   TELLUREX CORPORATION

Outline

- **Phase 1 Objectives and Problem Definition**
- Design, Synthesis and Integration Issues regarding Implementation of a TEG with an IC Engine Powertrain
- Utilization and/or Storage of Generated Electrical Energy
  - Schematic of Power System
  - Mild Hybrid Technology for Cost Reduction
- Estimates of Brake Efficiency Improvement @ Cruise
  - Configurations Examined
  - Efficiency Analysis
- Summary and Next Steps – Phase 2

Phase 1 Objectives and Problem Definition

- Choose an IC engine powertrain configuration to study for TEG application
- Evaluate potential technology barriers for implementation of a TEG in the system chosen
- Estimate the benefits for the application
- Develop a plan for implementation of a realistic demonstration of TEG energy recovery in the chosen IC engine powertrain

Why an OTR (Class 8) Engine for TEGs?

- Due to the greater quantity of fuel burned by the over the road truck, there are:
  - Opportunity for fuel savings: 150k miles/yr., 5MPG, @ $3/gal
  - A 5% improvement in BSFC would reduce the average annual fuel costs of an OTR truck by $4500 saving 1500 gallons of fuel per vehicle (1.5B gal/1 M trucks)
  - A 10% improvement in BSFC would reduce the fuel cost by $26,100 over the useful emission life of the engine
- Due to the high-load duty cycle of the over the road truck the exhaust energy will be significant
- NOx emission reduction will be facilitated
- TEGs have potential for long life and thus recycled

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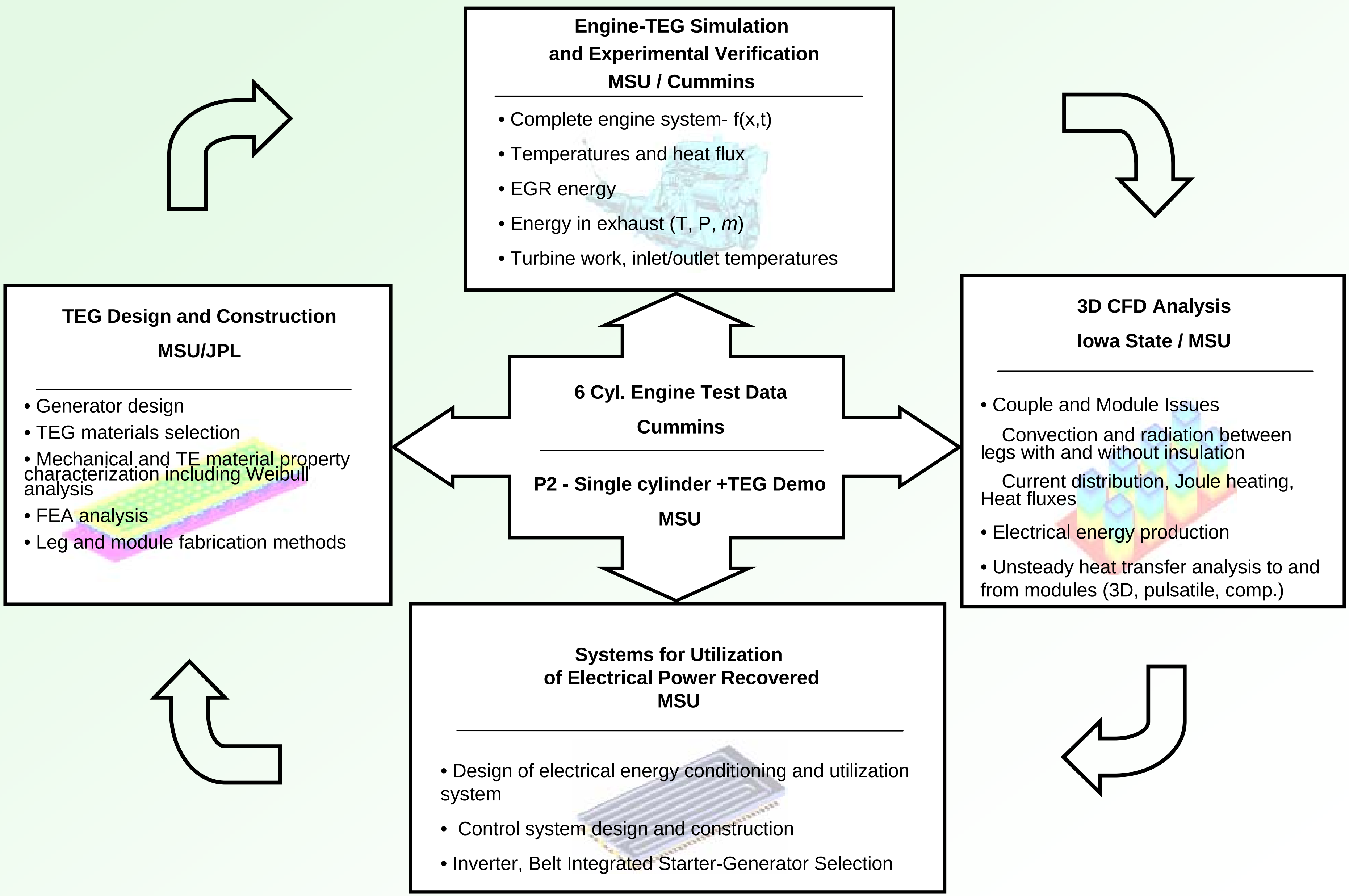
Implementation of a Thermoelectric Generator with a Cummins ISX Over-the-Road Powerplant



Material Characterization and Development

- **Synergy of characterization/processing/properties/performance, including**
  - Time-temperature profiles, materials chemistry, powder particle size processing
- **Impacts microstructure**
  - Phases present, grain size, porosity
- **Which in turn, impacts properties and performance**
  - Fracture strength, elasticity, fracture toughness, fatigue properties
- **Project integrates characterization/processing/performance**
  - **Fracture strength** characterized using **Weibull analysis** -- used to determine strength distribution, not just average strength
  - **Elastic modulus and hardness** determined by indentation methods – further evaluate mechanical integrity, evaluate microcrack damage
  - **Future work** will include **fracture toughness** (links microstructure and strength) and perform **thermal/mechanical fatigue** studies

TEG – Powertrain Team

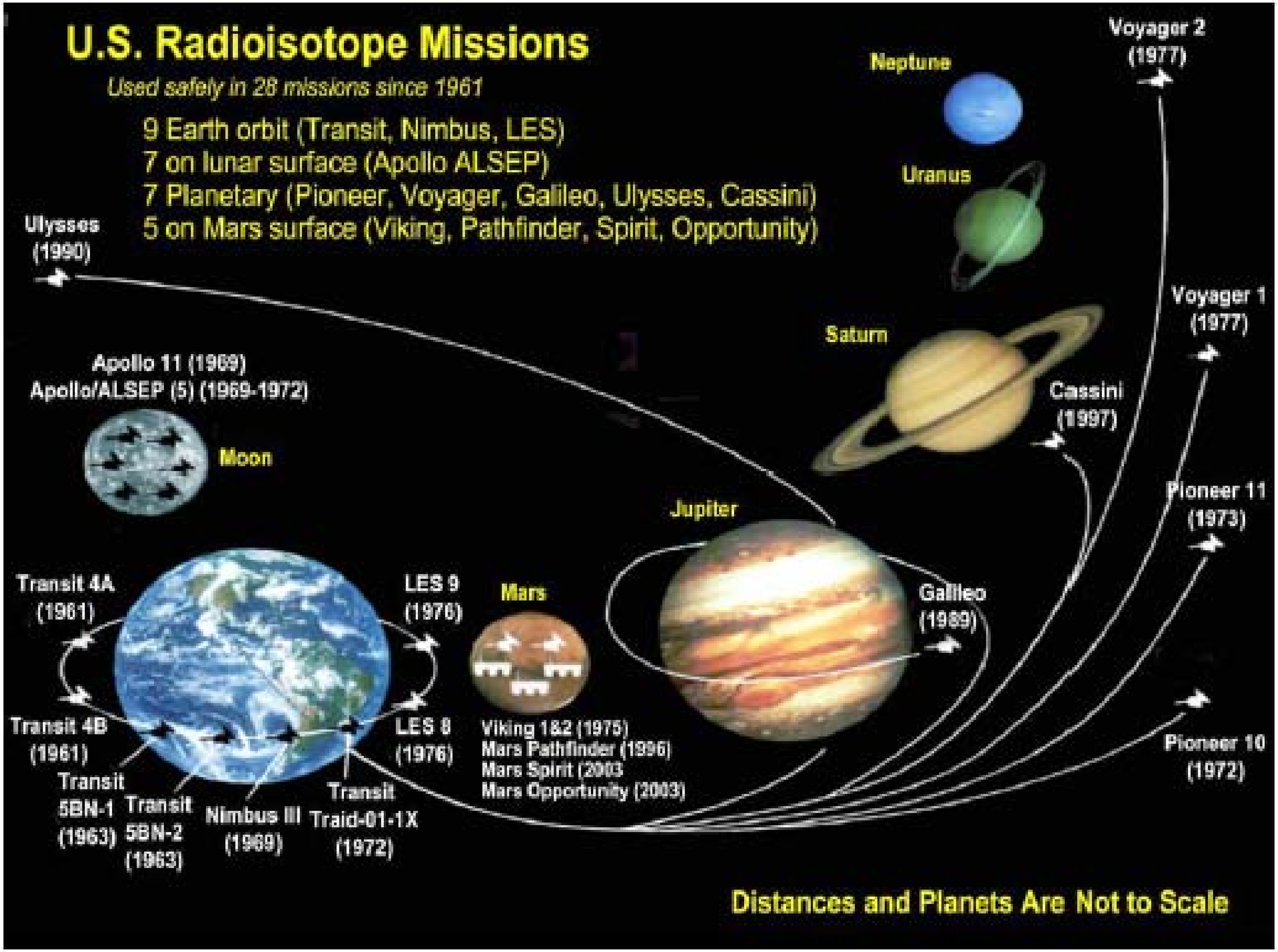
- **Michigan State University**
  - Harold Schock, Professor, Mechanical Engineering, Principal Investigator.
  - Eldon Case, Professor, Chemical Engineering and Materials Science
  - Tim Hogan, Associate Professor, Electrical and Computer Engineering
  - Mercouri Kanatzidis, Professor, Chemistry
  - John Miller, Adjunct Professor
  - Jim Novak, Visiting Professor
  - Fang Peng, Associate Professor, Electrical and Computer Engineering
  - Edward Timm, Research Associate, Mechanical Engineering
- **Iowa State University**
  - Tom Shih, Professor and Chair, Department of Aerospace Engineering
  - Bin Zhu, Research Associate, Aerospace Engineering
- **NASA Jet Propulsion Laboratory**
  - Thierry Caillat, Senior Member of Technical Staff
  - Jeff Sakamoto, Technical Staff
- **Cummins Engine Company**
  - Wayne Eckerle, Executive Engineer, Research and Technology
  - Todd Sheridan, Technical Advisor, Advanced Engineering
- **Tellurex Corporation**
  - Charles Cauchy, President

Cummins ISX 6 cylinder diesel engine

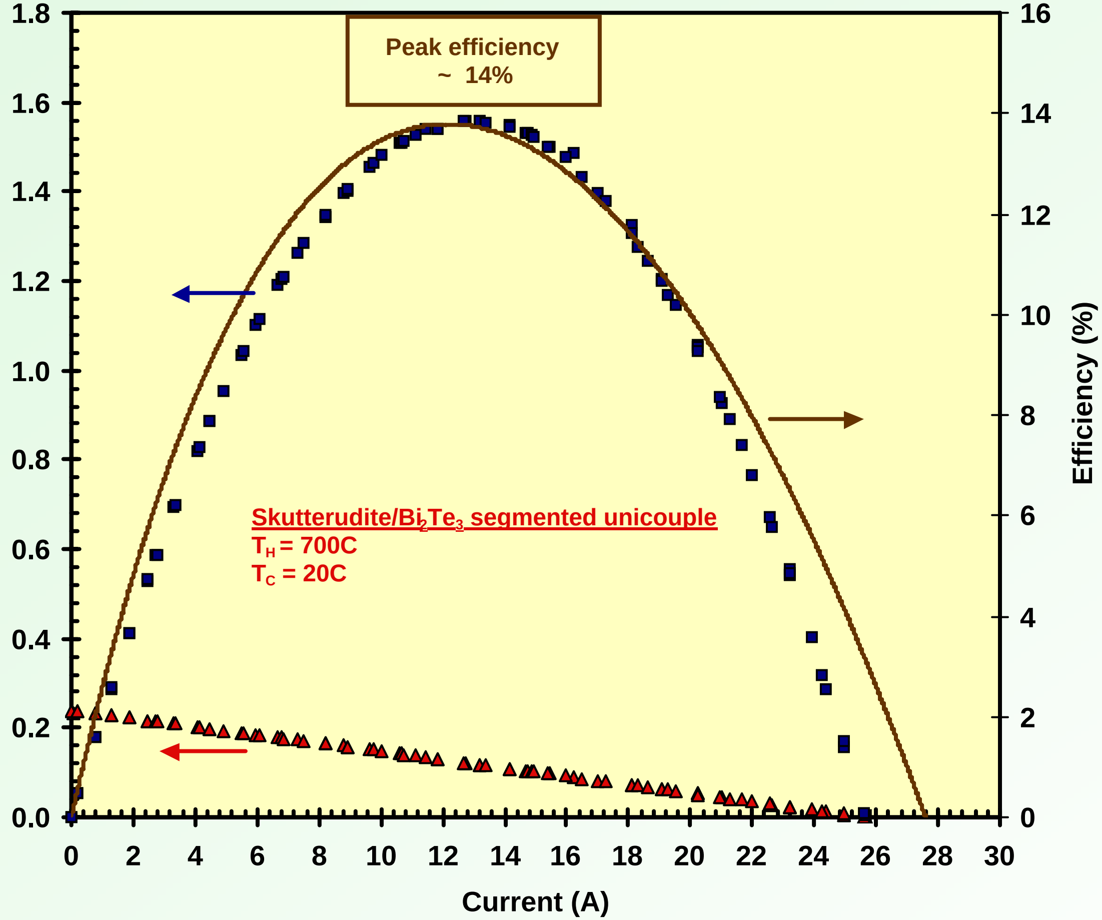
ISX Engine Operating Conditions for ESC Duty Cycle Modes

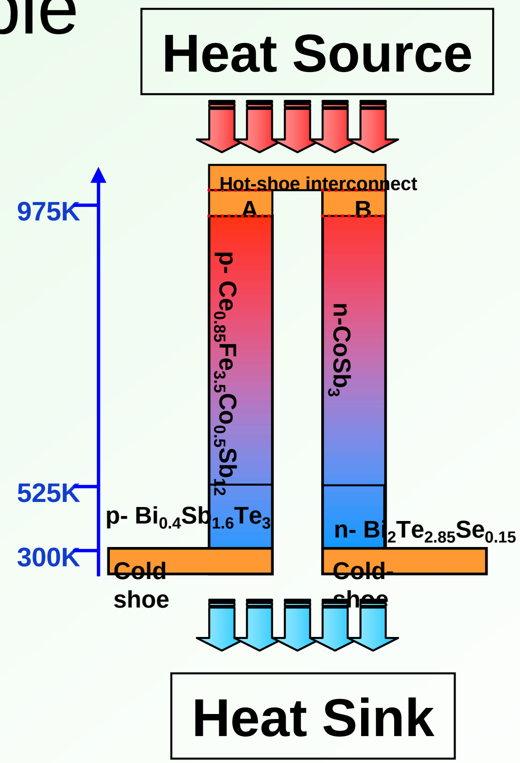
Modes		**A-25**	**A-100**	**B-62**	**B-100**	**C-100**
	Units					
Engine Crankshaft Speed	rpm	1230.00	1230.00	1500.00	1500.00	1800.00
Torque	ft-lb	472.15	1886.80	1170.20	1887.30	1577.70
BMEP	psi	78.05	311.92	193.45	312.00	260.82
Power	HP	110.58	441.88	334.22	539.02	540.72
	kW	82.46	329.52	249.23	401.96	403.22

U.S. missions using radioisotopes power and/or heating sources



Thermal and electrical testing – Segmented unicouple





- Experimental I-V curves fully validate projected performance
  - Translate into ~ 14% efficiency for 975K-300K ΔT
- Results independently confirmed at the University of New Mexico

Skutterudite unicouples fabricated by diffusion bonding

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  - **Mild Hybrid Technology for Cost Reduction**
- Calculation of Mechanical Work
  - Configurations Examined
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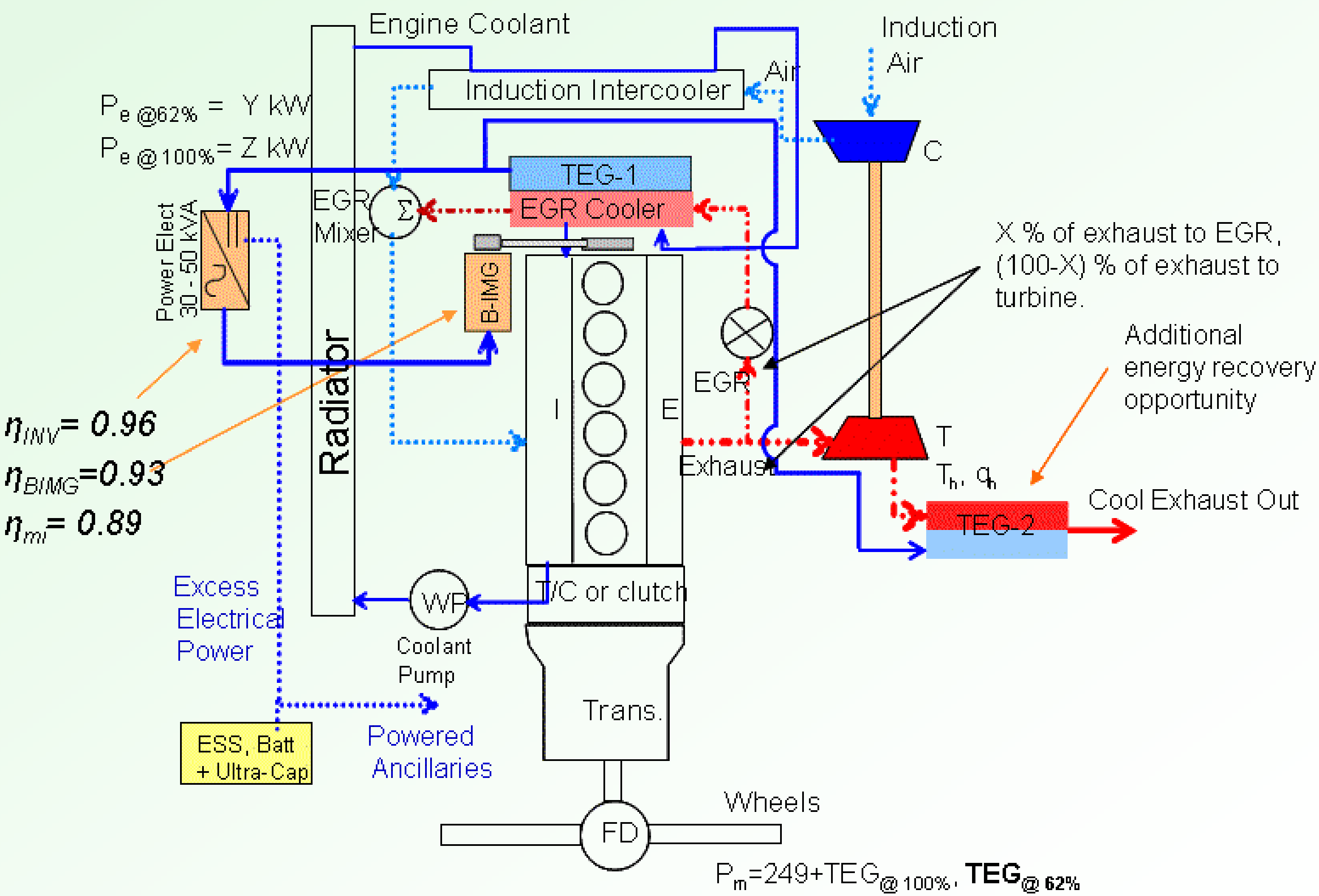
Thermal Power Split Hybrid – Options

Using the electric power recovered from waste heat



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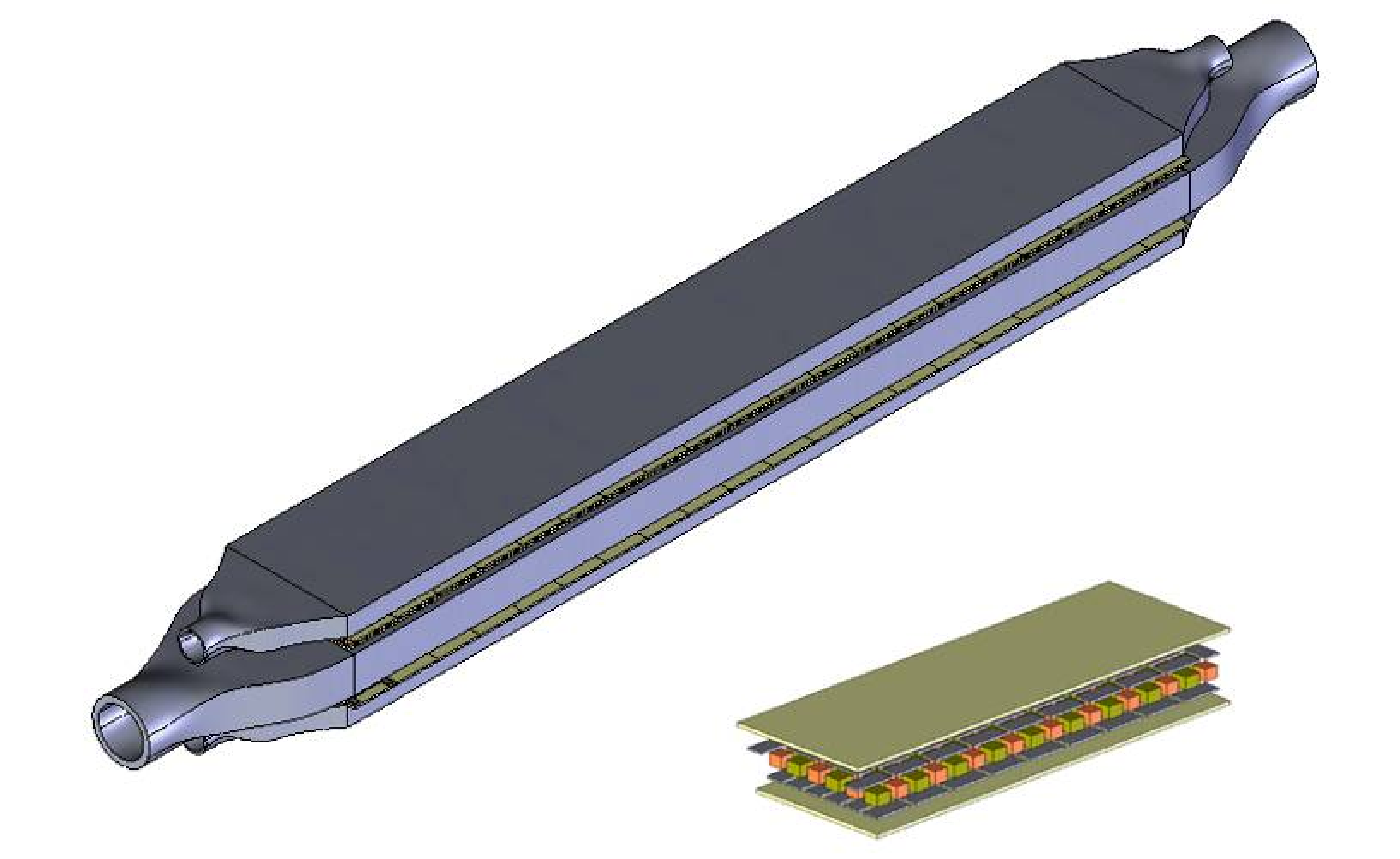
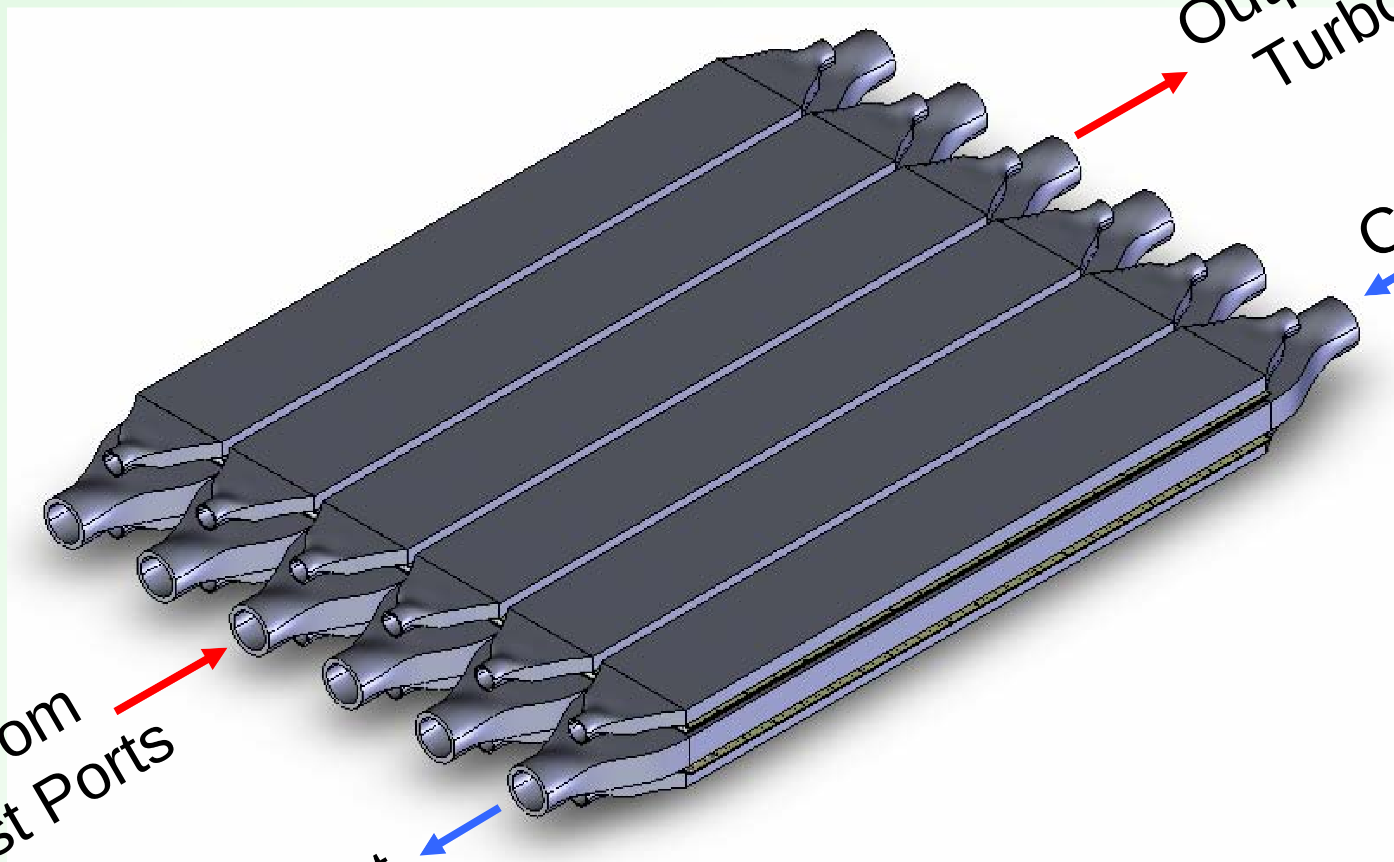
Single TEG with exploded view of a module



TEG Design Option



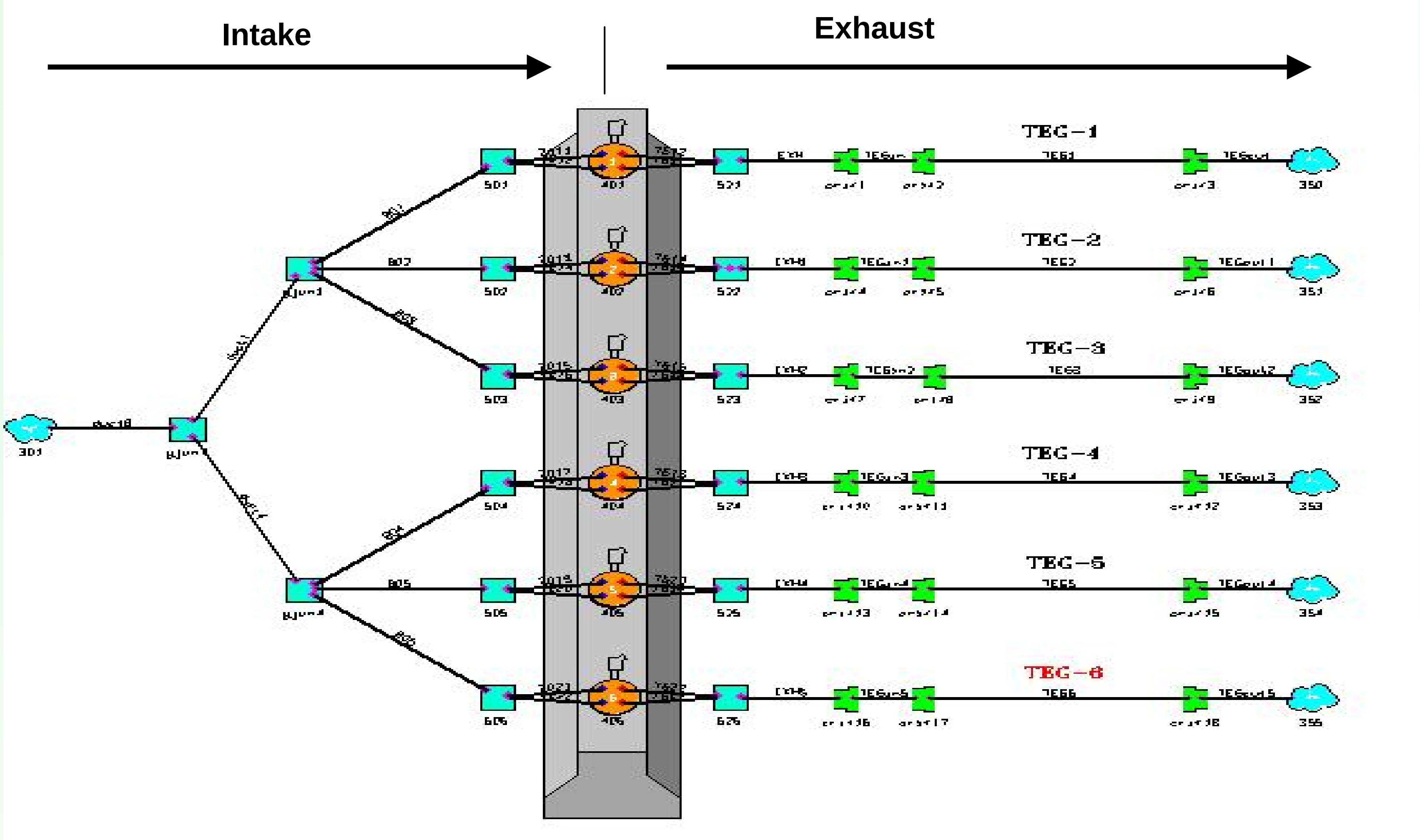
Assumptions and Comments

- Detailed model of engine and TEG configurations used
- Actual 3D flow modeled as one-dimensional transient, compressible flow
- Two layer conduction model is used for TEG and support structure
- Liquid coolant maintained at 325K
- Flow cross sectional area optimized to provide optimum heat transfer while maintaining engine BMEP
- Cylinder assumed to be adiabatic
- TE materials and performance based on models for expected operational temperature differential
- Sufficient energy will be maintained in exhaust to meet turbocharging requirements
- All exhaust passes through TEG
- Axial heat transfer in TEG is neglected
- Conservative estimate on duty cycle (38% more power at WOT)

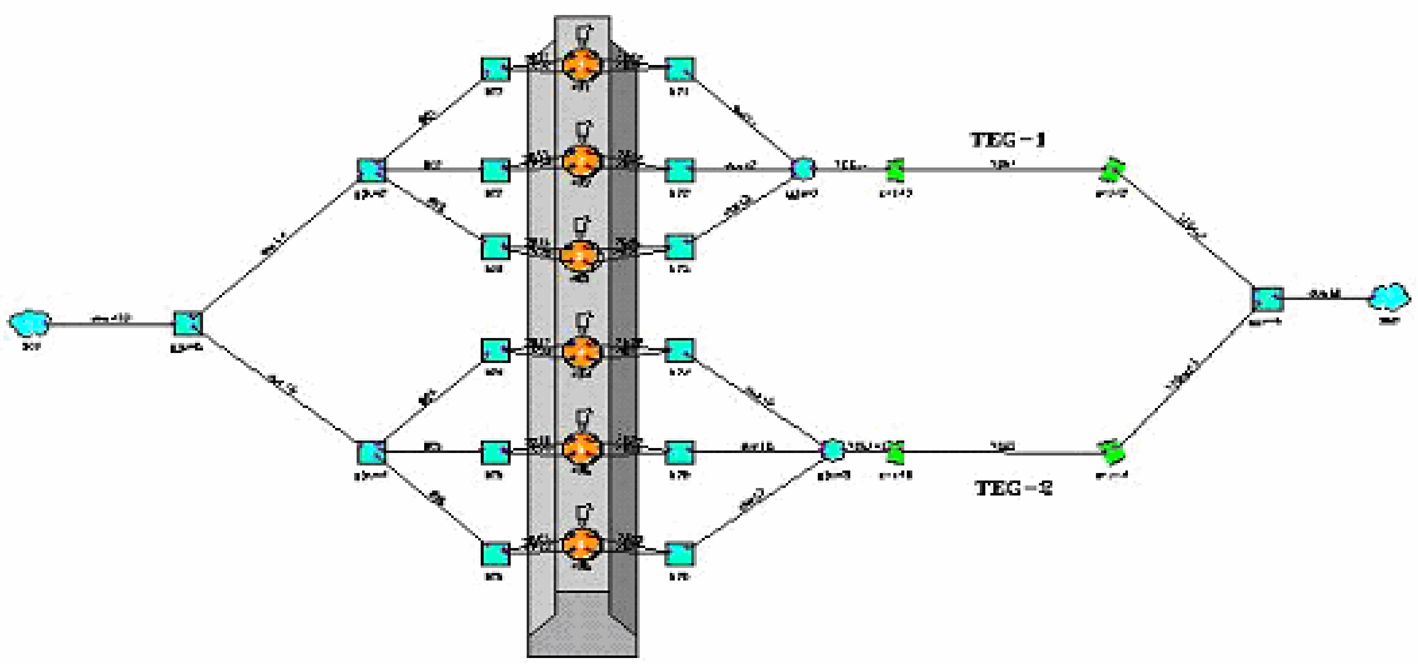
Configurations Examined

- Cummins ISX Engine with 6 Cylinders
  - 1 Cylinder into 1 TEG (6 TEGs)
  - 3 Cylinders into 2 TEGs
  - 6 Cylinders into 1 TEG
- Operating Condition B62 (Cruise)
- Ricardo WAVE Model Used for Engine-TEG System Simulations

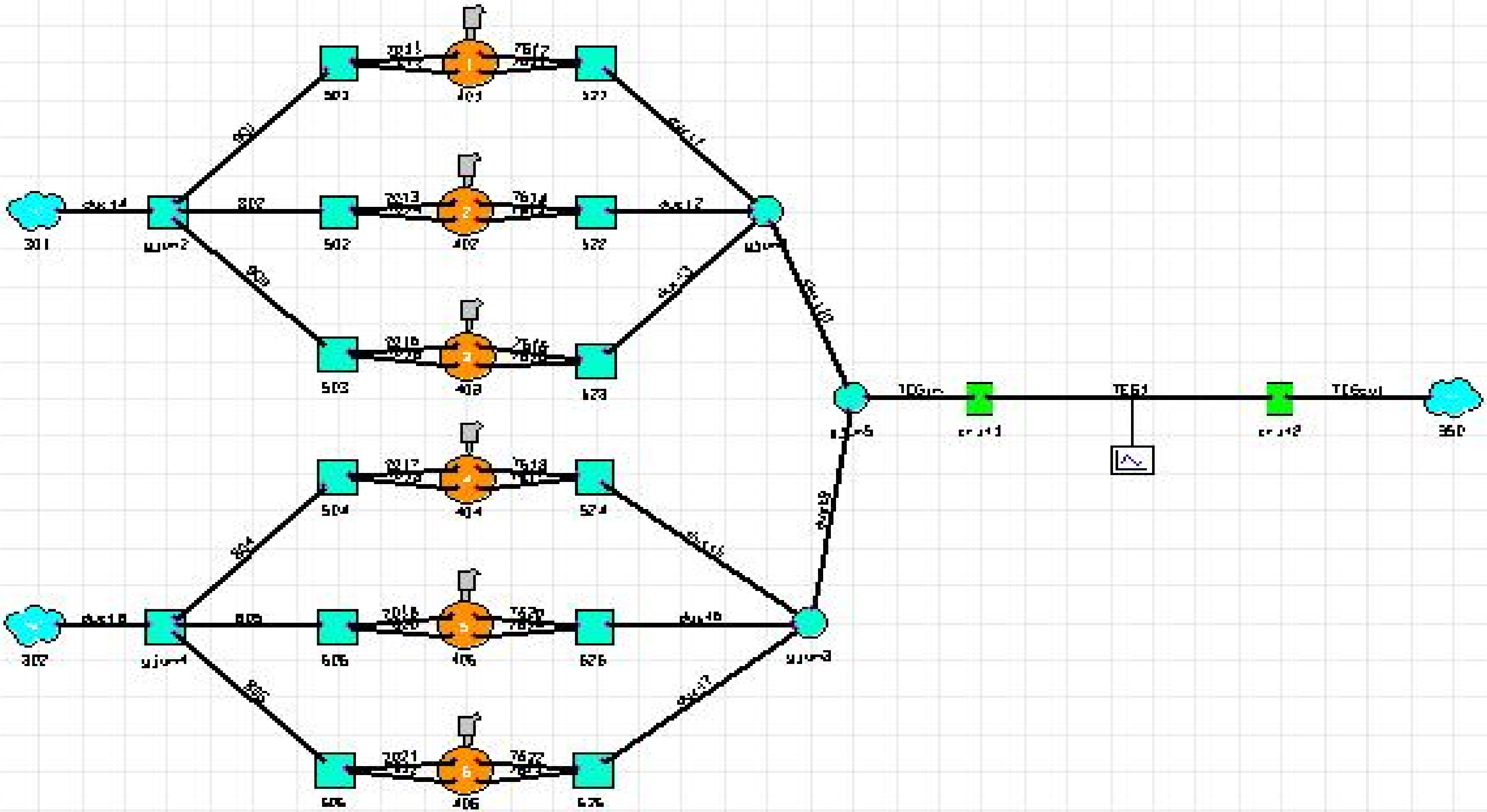
WAVE Stick Model Representation of 6-Unit TEG Connected to Engine



WAVE Representation of One TEG per 3 Cylinders

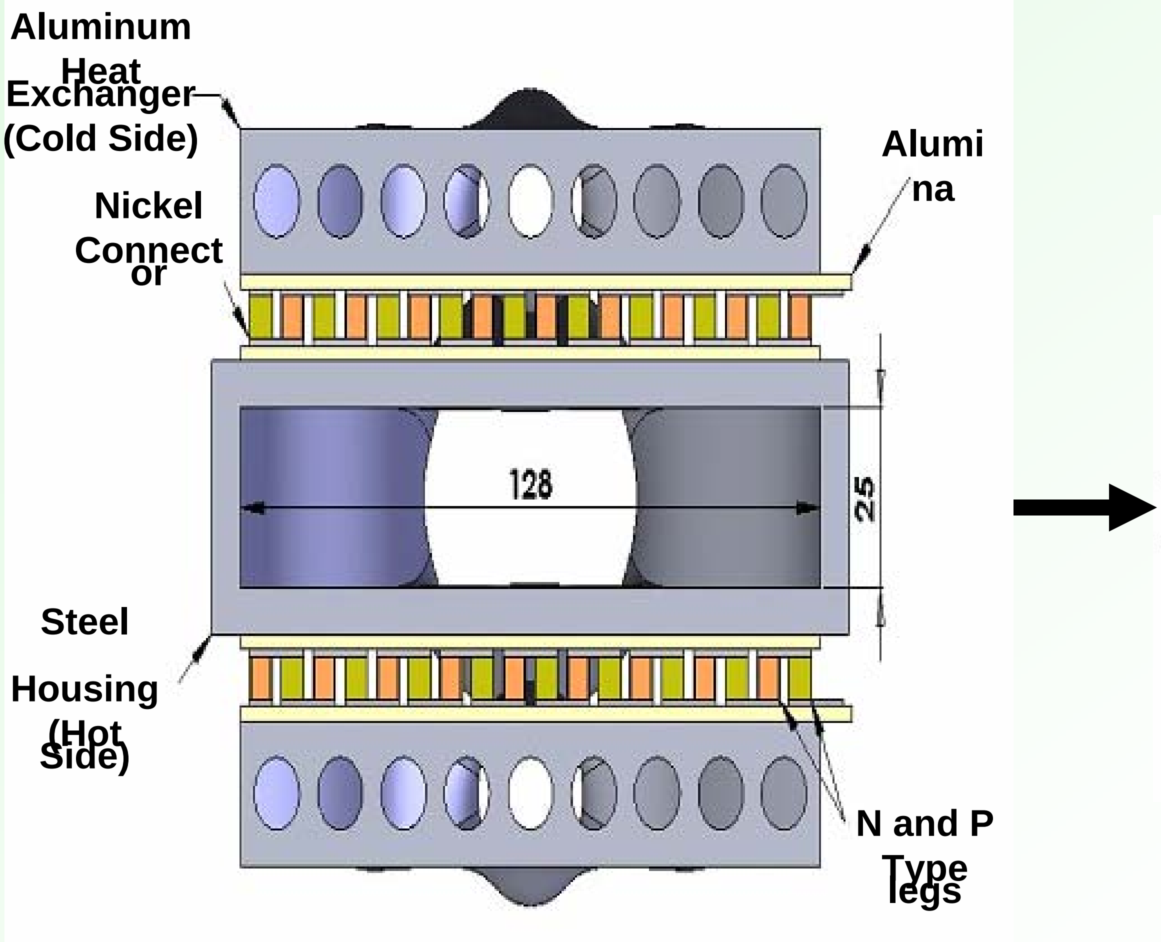


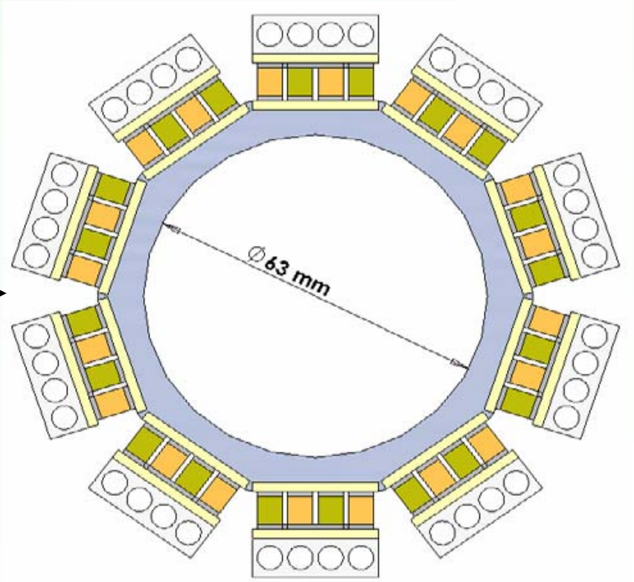
WAVE Representation of One TEG per 6 Cylinders



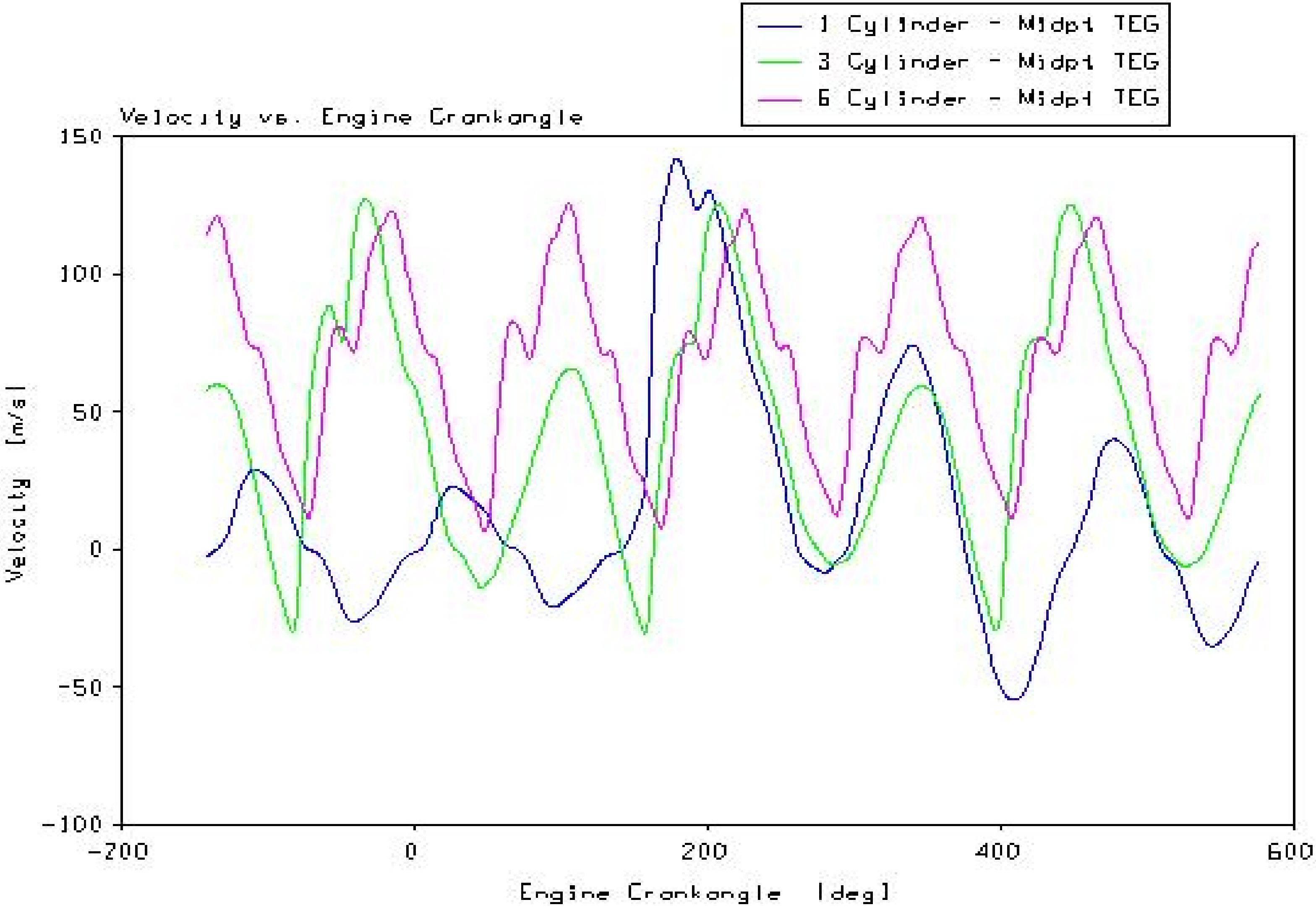
Heat Transfer Model

- Exhaust goes directly from manifold to TEG
- HX modeled as a circular duct; Flow 1D, transient, compressible, 2 layer conduction model and instantaneous heat transfer coefficients



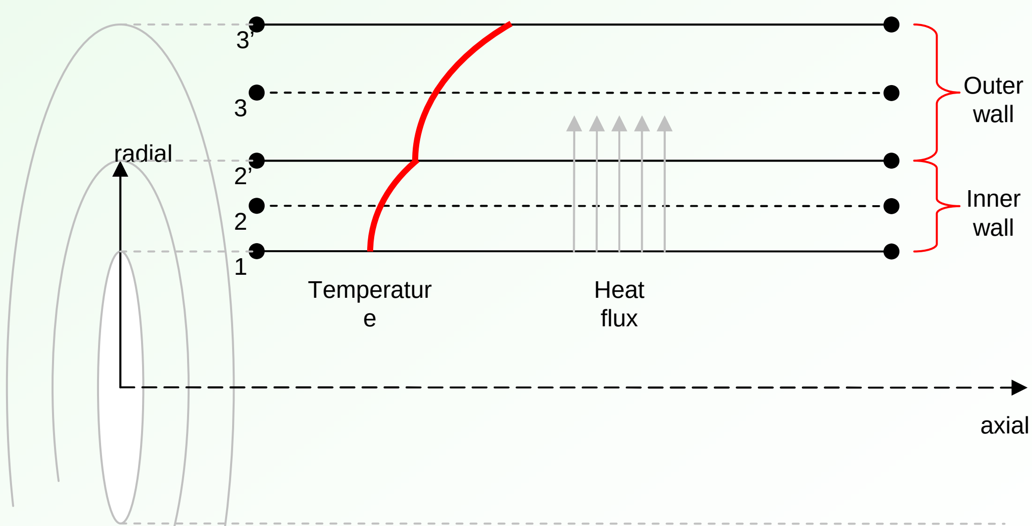


Midpoint Velocities in the TEG



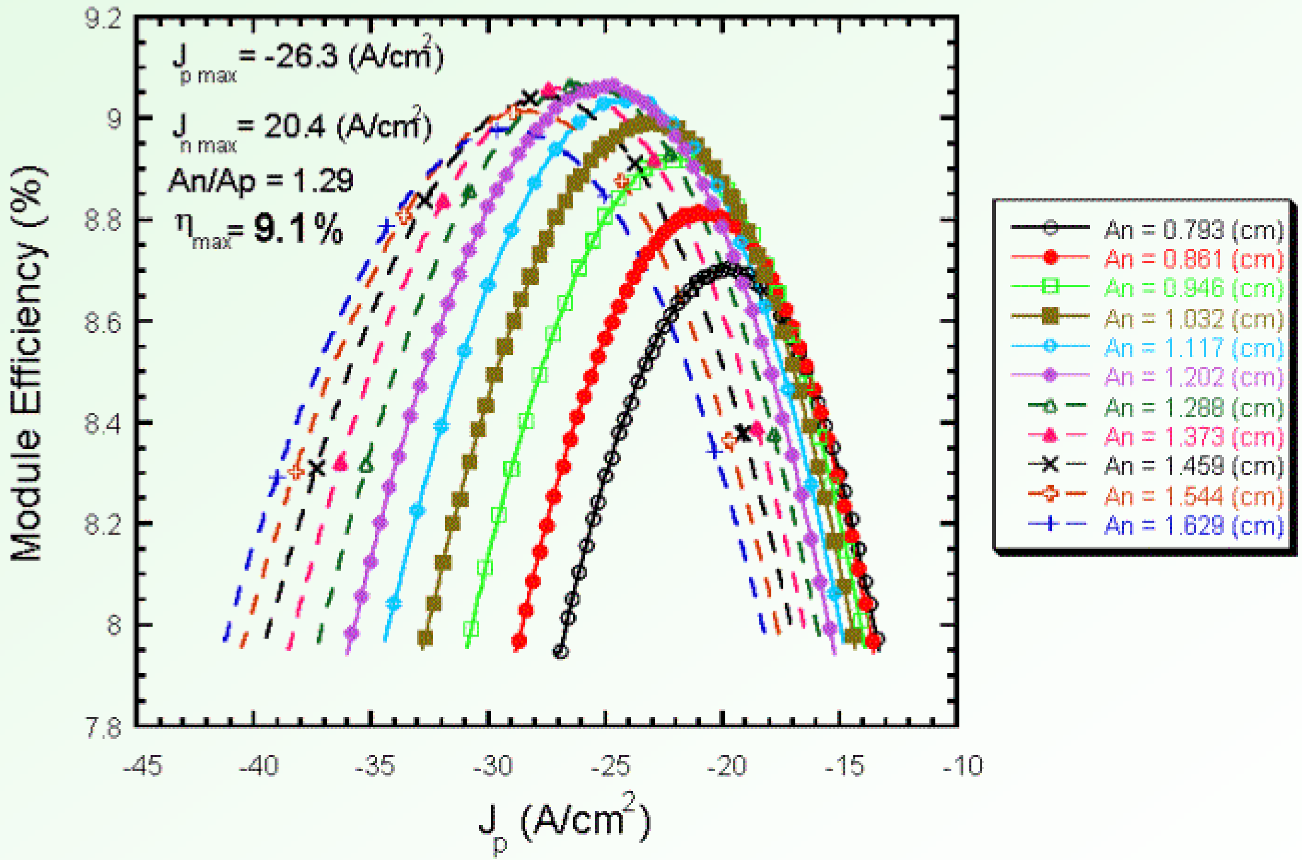
Heat Transfer Results for the Three TEG-Engine Configurations (T-K, q-watts)

Cylinders per TEG		T2	T2'	T3	T3'	R2	R2'	R3	R3'	q (calc)	q (given)	% diff
Exhaust	1	587	**584**	456	**344**	0.034	0.036	0.041	0.047	25330	31900	-21
Midpoint	1	648	**644**	481	**338**	0.034	0.036	0.041	0.047	32195	**31900**	1
Inlet	1	708	**704**	506	**333**	0.034	0.036	0.041	0.047	39059	31900	22
Exhaust	1	662	**659**	489	**338**	0.039	0.041	0.046	0.052	37826	50200	-25
Midpoint	1	730	**726**	522	**341**	0.039	0.041	0.046	0.052	45479	**50200**	-9
Inlet	1	798	**793**	555	**344**	0.039	0.041	0.046	0.052	53132	50200	6
Exhaust	1	731	**727**	524	**342**	0.044	0.046	0.051	0.057	50494	64500	-22
Midpoint	1	781	**777**	546	**338**	0.044	0.046	0.051	0.057	57446	**64500**	-11
Inlet	1	831	**826**	567	**334**	0.044	0.046	0.051	0.057	64398	64500	0



1 Cylinder per TEG MP Module Efficiency

(LAST, BiTe (470K)), T2` = 644K, T3` = 338K



Fuel economy of ISX Engine Operating at Cruise based on Calculated HT etc.

$$\% \text{ Imp. In BSFC } * = (Q_{TEG}\ \eta_{TEG}\ \ \eta_{BISG}\ \ \eta_{INV}\ )/\text{BHP}$$

1 Cylinder into 1 TEG (6TEGs) = 31.9(6)(0.091)(.96)(.93)/249.5 = **6.2%**

3 Cylinders into 1 TEG (2 TEGs) = 50.2(2)(0.11)(.96)(.93)/249.5 = 4.0%

6 Cylinders into 1 TEG (1TEG) = 64.5 (1)(0.123)(.96)(.93)/249.5 = 2.8%

Note: This does not include improvement in BSFC by utilizing an ISG which has an efficiency 2x that of current alternators or the higher TEG efficiencies at higher load operation

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Summary

- Calculated efficiency improvements:
  - 1 TEG/Cylinder: 6.2%
  - 2 TEGs/6 Cylinders: 4.0%
  - 1 TEG/6 Cylinders: 2.8%
- Addition benefits expected with integrated starter generator (2x efficiency of current alternators) and operation at greater than cruise power
- Costs of TEG can be low due to synergy with current hybrid vehicles for power electronics and the use of inexpensive TE materials
- Immediate use of electrical energy eliminates storage issues
- TE materials operating from 800-400K are expected to dominate this application …material property and fatigue characterization are of critical importance for transient operation of this device
- Single-cylinder option is the best for a Phase 2 demonstration
  - Efficiency superior to all other configurations
  - Opportunity to develop and verify detailed transient heat transfer models for modeling pusatile, 3D, compressible flow of exhaust through TEG
  - Tested tools exist for scale up to multi-cylinder application
  - Costs associated with this option provide option of evaluation of alternatives that could not be studied using the same resources in a multi-cylinder configuration

Next Steps – Phase 2

- Detailed Design: Couple engine, **turbocharger**, detailed heat transfer (3D, unsteady, compressible) and TEG performance models
- Construct and bring to operational status single-cylinder test system for heat transfer and TEG performance confirmation
- Conduct iterative studies to decide on optimum material combinations
- Develop powder processing and hot pressing techniques for TE leg fabrication
- Determine thermal and mechanical properties of TE materials…fracture strength and toughness, thermal-mechanical fatigue (long term stability) with diffusion barriers and coatings
- Develop detailed power electronic system design and evaluate dynamic response of electrical system as ΔT changes
- A scale model demonstration unit with an efficiency gain of 5% is a reasonable 5 year goal
- If materials can be developed that have an energy conversion efficiency of 18% for this temperature range, a 12.4% BSFC improvement would be predicted