SCHOOL OF ENERGY

Thermoelectric power generation from waste heat

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Technical Seminar- Sep. 23, 2011

Context and motivation

- The idea was developed during a “casual chat” between the authors!
- This project is in-line with our School’s Energy initiatives and focus theme
- Also will help the sustainability and energy conservation objective as listed in BCIT Strategic & implementation plans
- Supports CEER objectives and the building, itself
- It can become a model for application to other buildings at our campus
- We present here phase 1 results, obtained so far.

Background

- **Existing power plant (boilers, condenser, turbine, exhaust stack) as well as future Co- Gen plant in SE8 are sources of waste heat**

Background continued

- **The waste heat can be used to generate electrical power using thermoelectric power generation (TEPG) devices**
- **The generated electrical power can supply the electronics and control systems or can be used for other purposes to increase the overall efficiency**

Theory and the Technology

- **When "electrons" are in motion, we have an electrical current (i.e., charge per unit time per unit area)**
- **Electrical voltage ("pressure") usually is the driving force**
- **But, other forces like temperature difference and hence flow of thermal energy/heat can drive the electrons!**

Theory….continued

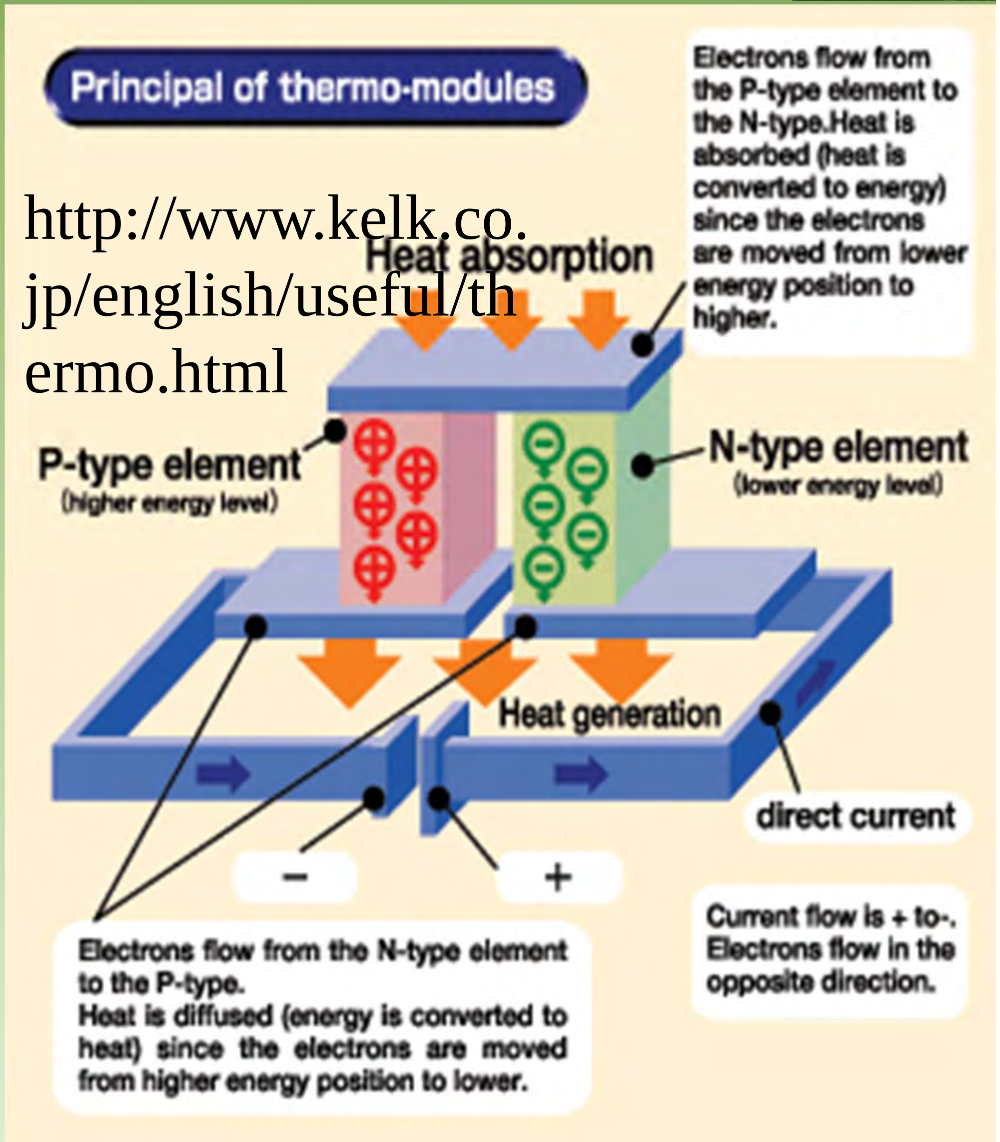
- Seebeck (1822) discovered this phenomenon
- N-type is phosphorous doped silicon

(creates extra loose electrons)

- P-type is Boron doped silicon

(creates extra loose holes)

- A quick video-demo



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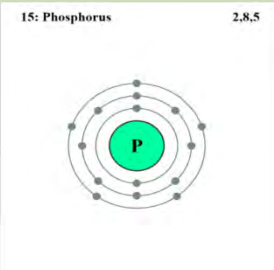
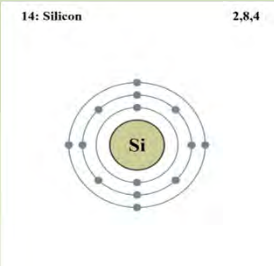
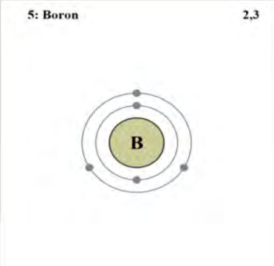
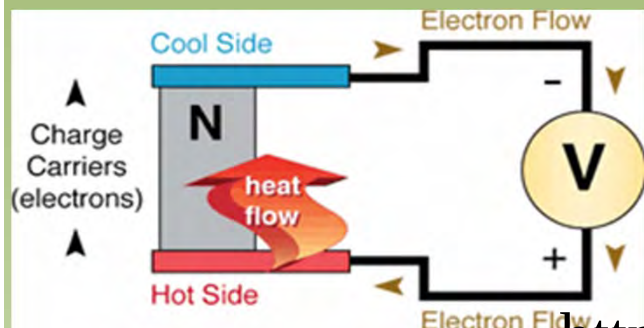


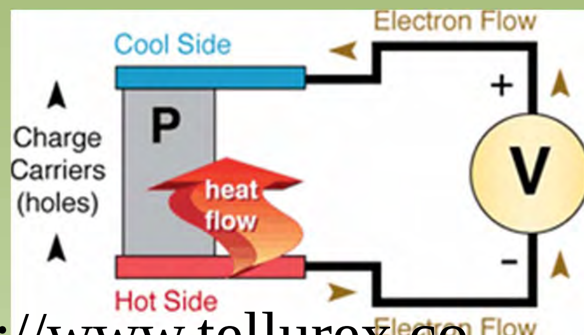


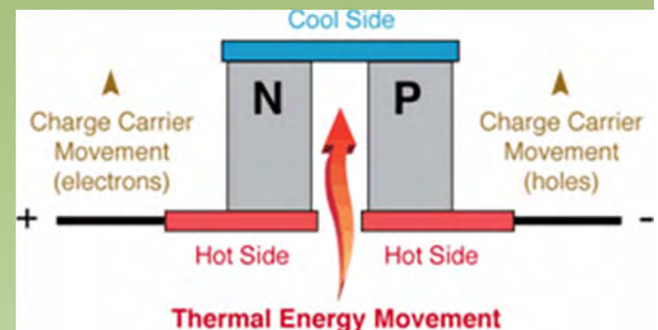


Theory….continued

Thermoelectric power generation (TEG) devices typically use special semiconductor materials which are optimized for the Seebeck effect.







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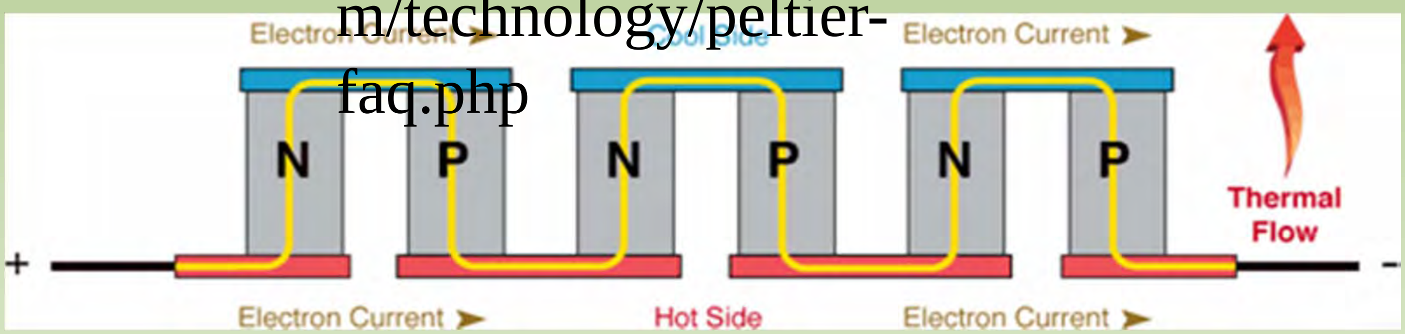


Theory….continued

- **Performance of TE materials is calculated and measured by their “figure-of-merit”, Z**

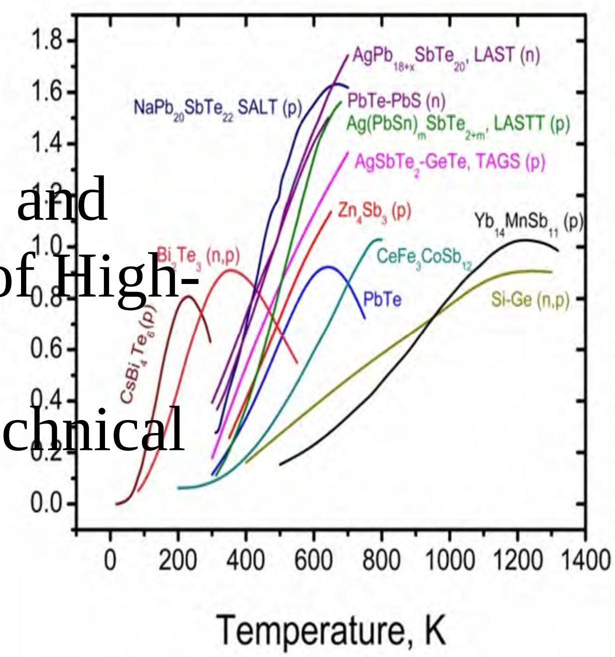
$$Z = \frac{\alpha^2 \sigma}{k}$$

Where; α is Seebeck coefficient (μV/K), σ electrical conductivity (S/m), and thermal conductivity (W/m.K)

- **The dimensionless ZT, is used for performance measures**

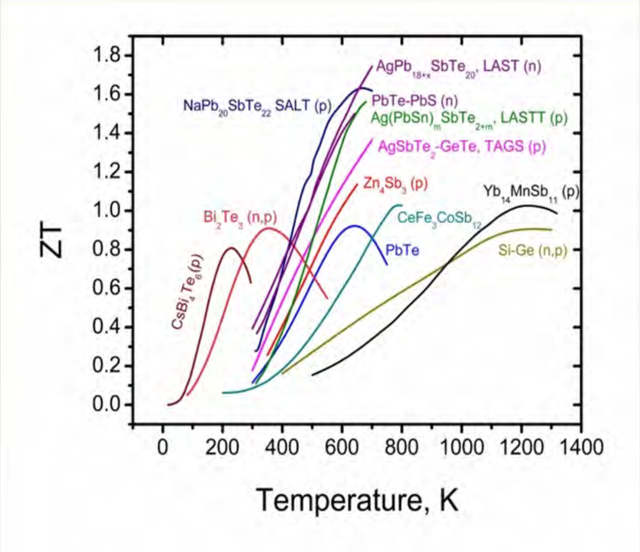
Material	Composition	Conduction type	Optimum temperature (°C)	Production process	ZT	Mechanical properties	Thermal stability	Environmental impact
Silicides	Mn-Si	p	300 – 600	Melting & refining	0.80	Young's modulus: 12,000MPa Poisson's ratio: 0.34	○	○
	Mg-Si	n	[illegible]	Melting & refining	[illegible]		Unstable without coating	○
Si-Ge-based	$Si_{0.8}Ge_{0.2}$	n	730	Hot press	1.00	Compressive strength: 653 MPa	Stable for over 10 years.	○
	$Si_{0.8}Ge_{0.2}$	p	730	Hot press	0.70	Compressive strength: 473 MPa		○
Oxide-based	$NaCo_2O_4$	p	[illegible]	Flux	1.20	–	○	○
	$(Ca,Sr,Bi)_2Co_2O_5$	p	330 – 730	Glass annealing	[illegible]	–	○	○
	$(ZnO)_5(In_{0.97}Y_{0.03})_2O_3$	n	430 – 800	RTGG	0.31	–	○	○
	$Zn_{0.98}Al_{0.02}O$	n	[illegible]	Solid phase reaction	0.42	–	○	○
PbTe-based	PbTe	n	230 – 577	Hot press	0.70	–	Subject to heat history.	–
TAGS-based	$GeTe\text{-}AgSbTe_2$	p	[illegible]	[illegible]	1.40	–	○	–
LaTe	$LaTe^{\sim}1.4$	n	[illegible]	[illegible]	[illegible]	–	–	–
filled-Skutterudites	$YbCo_{0.9}(ptPd)_{0.1}Sb_3$	n	330 – 630	Plasma sintering	1.12	–	–	–
	$Ce_{0.12}Fe_{0.7}Co_{3.29}Sb_{12}$	p	330 – 630	Plasma sintering	0.93			–
Bi-Sb-Te-Se	Bi-Sb-Te-Se	n, p	-180 – 250	Hot press	0.3 – 1.01	–	Sufficient data available.	–
Zn_4Sb_3-based	$Zn_4(Sb_{0.97}Sn_{0.03})_3$	p	230 – 480	Plasma sintering	1.00	–	Somewhat unstable.	–
	Zn_4Sb_3	p	230 – 480	Plasma sintering	1.22	–		–

Seijiro Sano, Hiroyuki Mizukami and Hiromasa Kaibe.” Development of High-Efficiency Thermoelectric Power Generation System”, Komatsu Technical Report Vol. 49 No.152, 2003



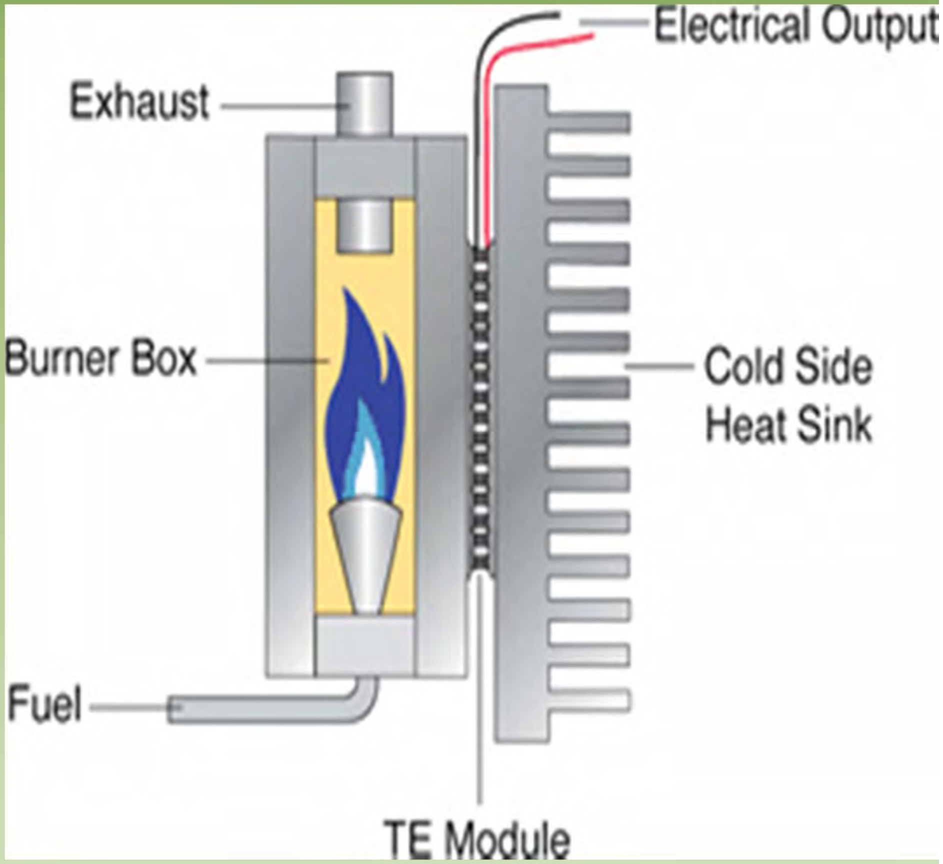
Efficiency

- Under best-case conditions, using layered thermoelectric elements, material efficiencies over 10% may be achieved (in practice 3-5%)
- High ΔT's and the formulation of materials which are optimized at high temperatures, allow for greater efficiency
- In our application, categorized as low-temp., we need to look for materials with high Seebeck coef., and low thermal conductivity



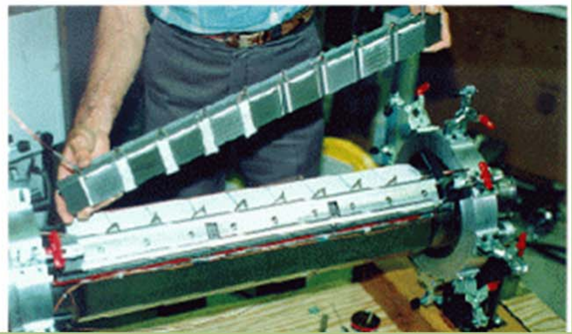
Technology- Typical TEPG system

- **There are four basic components:**
  1) **a heat source,**
  2) **a TE module (i.e., a thermoelectric generator—also known as a Seebeck device),**
  3) **a "cold-side" heat sink, and**
  4) **the electrical load.**



Technology- Continued

1 kWe Thermoelectric Generator Installed in Place of Muffler– (HiZ-Technology)

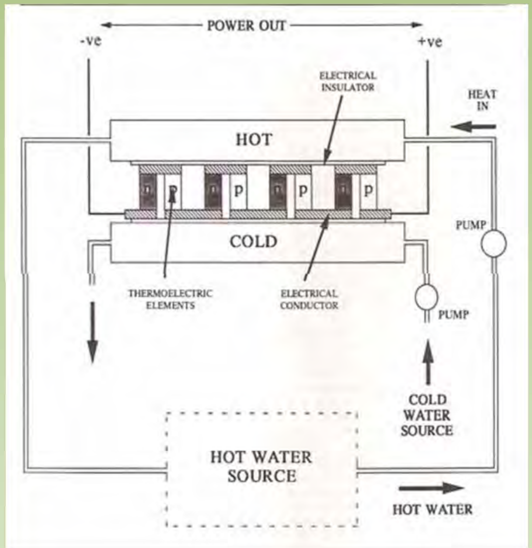


1 kWe TE Mounted under PACCAR vehicle - (HiZ-Technology)

Stove with self-powered fan using thermoelectric generator –(Philips Research)

Advantages and challenges

- They are extremely reliable
- They are simple, compact and safe
- They are environmentally friendly
- They are “flexible” power sources
- Efficiency is low!
- Selling prices are from $7 - $42
  - Bi_2Te_3 - $1.00/Watt
  - QW - $0.11/ Watt



Thermoelectric Performance

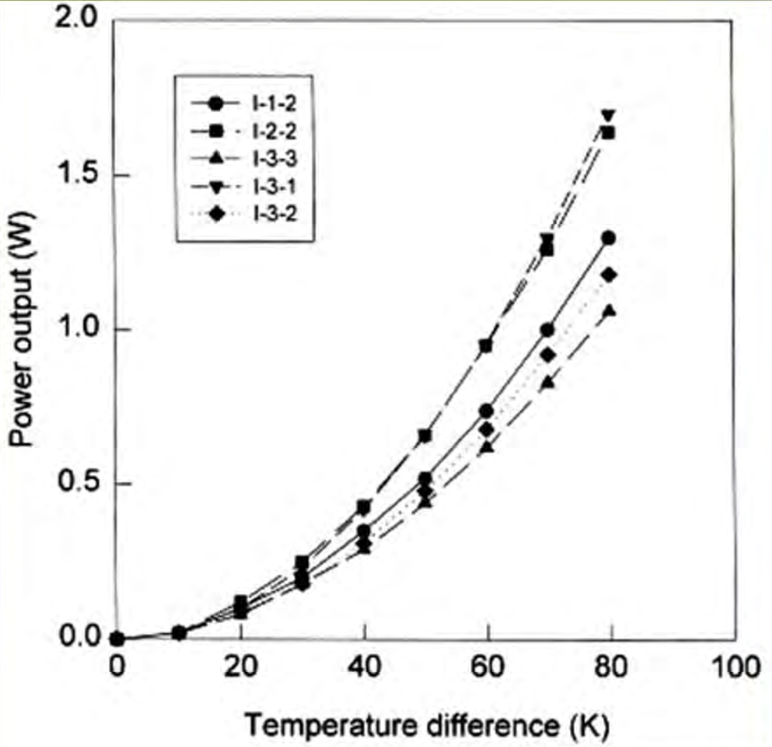
Thermoelectric Module Material	Temperature Difference °C	Voltage at Maximum Power	Maximum Efficiency %	Maximum Power W
N & P-type bulk Bi_2Te_3	200	1.6	5.8	14
	Hi-Z's Commercial Alloys			
N type Si/SiC & P-type B_4C/B_9C Quantum Well Kapton substrate 25 µm thick	200	16.0	17	60
	250	12.4	20.9	72
	Under Development			
N type Si/SiC and P-type B_4C/B_9C Quantum Well SiGe Substrate ~5µm thick (too hot for Kapton)	450	23.6	32.5	338
	Under Development			

High Efficiency Quantum Well Thermoelectrics for Waste Heat Power Generation

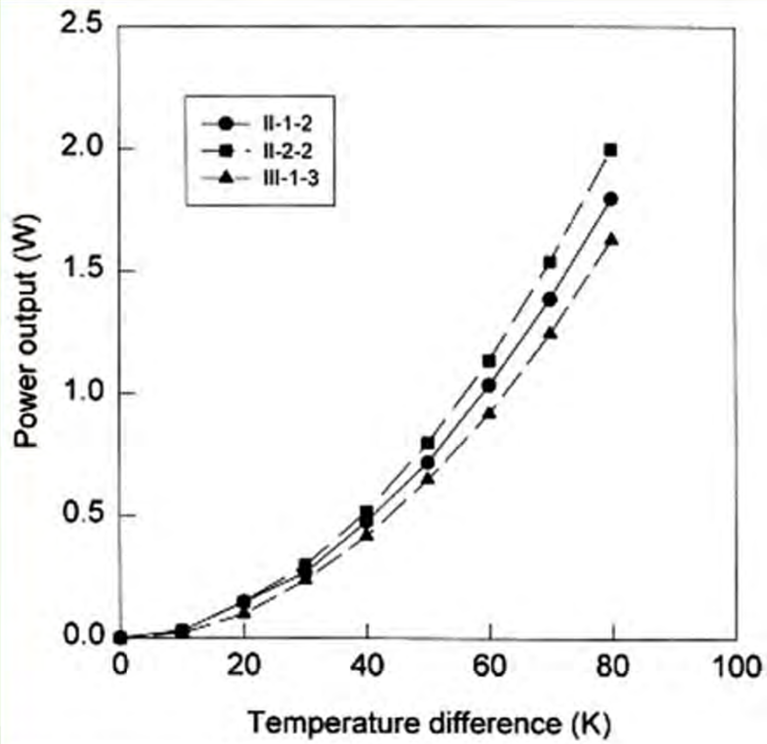
Milliwatts to Kilowatts of Power

John C. Bass
Norbert Elsner
Saeid Ghamaty
Velimir Jovanovic
Daniel Krommenhoek
Hi-Z Technology, Inc.
San Diego, CA 92126

Maximum power output as a function of temperature for a) 127 elements and b)31 elements
(Basel Ismail and Wael Ahmed)



(a)

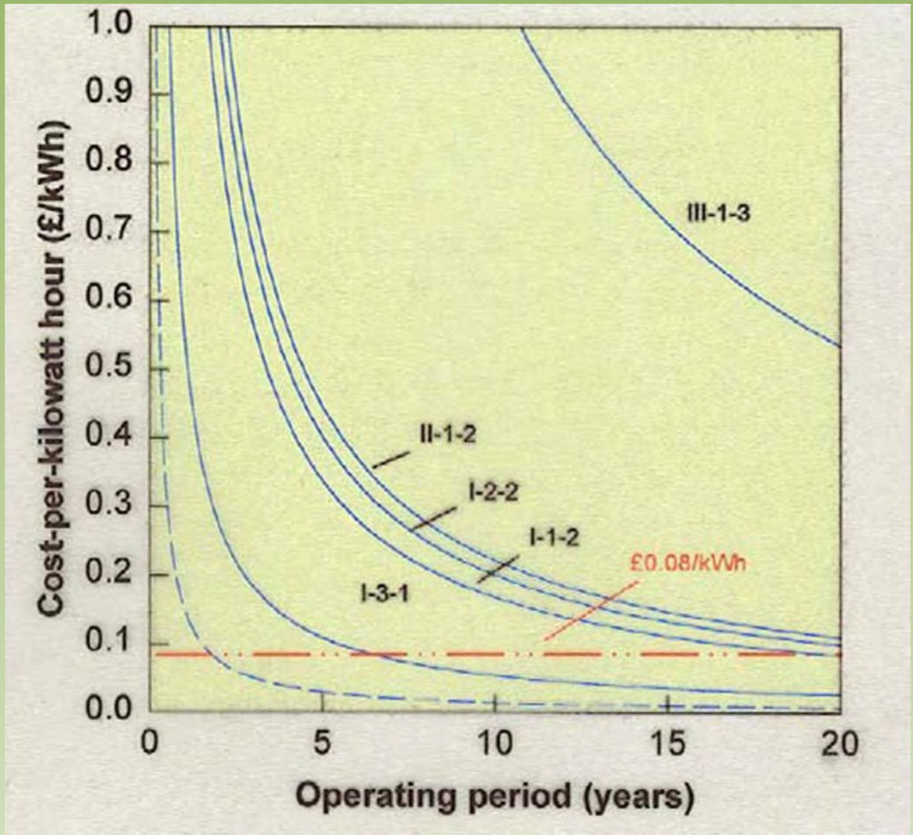


(b)

Modules	N	A (mm^2)	l (mm)	A/l (mm)
I-1-2	127	1.35×1.35	1.53	1.19
I-2-2	127	1.47×1.47	1.47	1.47
I-3-1	127	1.40×1.40	1.14	1.72
I-3-2	127	1.40×1.40	2.03	0.96
I-3-3	127	1.40×1.40	2.54	0.77
II-1-2	31	4.30×4.30	1.52	12.16
II-2-2	31	4.50×4.50	1.67	12.12
III-1-3	50	5.00×5.00	3.00	8.33

Economics of waste heat recovery

The family of curves refer to modules from suppliers each having different cost- per-watt. The horizontal dashed line is the consumers purchase price of electricity in the UK, around £0.068 per kWh. (David M. Rowe)



Objectives & Project management

- Feasibility-Phase1:
  - To study the feasibility, cost and applicability of this technology at CEER
  - The operation and fuel consumption cost reduction
  - Identify the system components and vendors
- Design and installtion-Phase2
  - Confirm quotes and procurement
  - Applications of the installed system for student education (Capstone projects) and research projects
  - Help establishing our School energy initiatives/focus
- Data acquisition-Phase3
  - Data acquisition and modelling
  - Students education and projects
  - Publication

Results of Phase 1 and systems specs.

- **In the present set up in BCIT Power House, the low temperature waste heat sources from View Boiler, Cleaver-Brooks and Nebraska boilers(120^{o}C - 200^{o}C) are available. After reviewing 32 articles including reports from the leaders in TEG industry (Kamatsu and Hi-Z Technology) we concluded that low temperature TEG model will apply for available waste heat sources.**

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1. Takeshi Matsui, Yoshiak Aoki, Naoyuki Kayukawa and Noriyuki Okinaka ,"The MHD Energy Conversation System with Thermo Electric Generator ",
2. Jovanovic, V. Ghamaty, S. Elsner, N.B., "Design, Fabrication and testing of quantum well thermoelectric generator " , Hi-Z Technol., Inc., San Diego, CA
3. Bass J., Elsner N., Ghamaty S.,V. Jovanovic V, Krommenhoek D., "High Efficiency Quantum Well Thermoelectric for Waste Heat Power Generation - Milliwatts to Kilowatts of Power", Hi-Z Technol., Inc., San Diego, CA
4. Richard J. Buist and Paul G. Lau, "Thermoelectric Power Generator Design and Selection from TE Cooling Module Specifications" , TE Technology, Inc., 1590 Keane Drive, Traverse City, MI 49686 USA
5. P.G. Lau, R.J. Buist. "Calculation of Thermoelectric Power Generation Performance Using Finite Element Analysis", Proceedings of the XVI International Conference on Thermoelectrics, August 26-29, 1997 Dresden, Germany.
6. Seijiro Sano, Hiroyuki Mizukami and Hiromasa Kaibe, "Development of High-Efficiency Thermoelectric Power Generation System"
7. Luan Weiling and Tu Shantung, "Recent developments of thermoelectric power generation", Chinese Science Bulletin 2004 Vol. 49 No. 12 1212_1219
8. S. Yamaguchi, N. Kondoh, I. Yonenaga, Y. Hasegawa and T. Eura, " New Proposal of High Temperature Thermoelectric Conversion in Power Plant", 18th International Conference on Thermoelectrics, 1999
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16. David Michael Rowe, "Thermoelectric Heat Recovery as a Renewable Source of Energy", International Journal of Innovations in Energy Systems and Power, Vol. 1, no. 1 (November 2006)

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21. Riffat SB, Ma X. Thermoelectrics: A review of present and potential applications. Appl Therm Eng 2003; 23: 913-935.

22. Kawamoto H., "R&D Trends in High Efficiency Thermoelectric Conversion Materials for Waste Heat Recovery", S C I E N C E & T E C H N O L O G Y T R E N D S

23. Vasilevskiy D., Kukhar N., Turenne S., Masut R., "Hot Extruded $(Bi,Sb)_2(Te,Se)_3$ Alloys for Advanced Thermoelectric Modules",

24. Giauque P. and Nicolet M.," Miniaturized Thermoelectric Power Sources", Copyright 8 1999 Society of Automotive Engineers, Inc.

Papers reviewed- continued

25. Virojoghe O., Enescu D., Ionel M., Stan F., “Numerical simulation of Thermoelectric System”, ISSN: 1792-4235 - ISBN: 978-960-474-214-1
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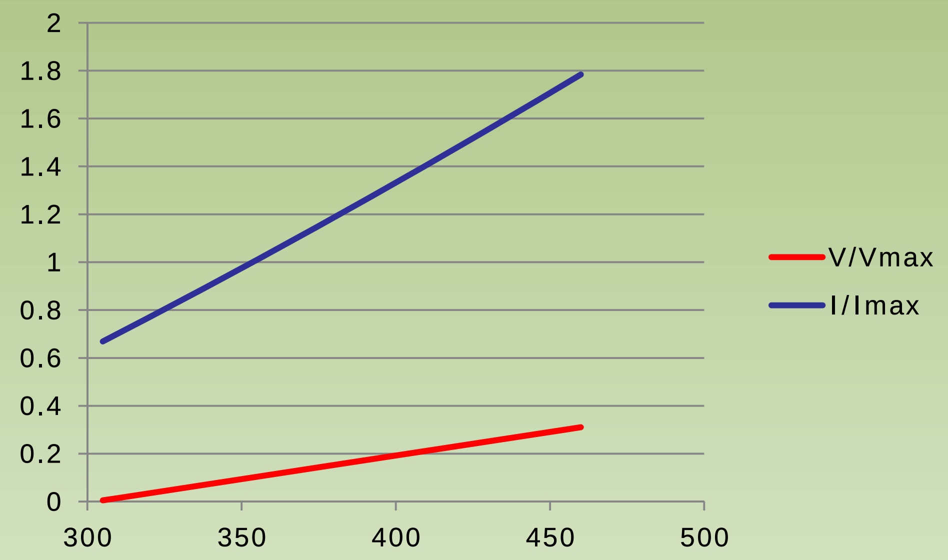
31. Hachiuma H., Fukuda K.Hsu T., Huang G., “Activities and Future Vision of Komatsu Thermo modules”, Komatsu Electronics Inc.
32. Hsu C., Huang G., Chu H., Yu B., Yao D., “ Experiments and Simulations on Low-Temperature Waste Heat Harvesting System by Thermoelectric Power Generators”, Applied Energy 88 - 2011

Results of Phase 1 and systems specs. - continued

- **Materials based on bismuth telluride are the best "low temperature" TE**
  - **Maximum efficiency 20%**
  - **With temperature of hot and cold junctions 100 ^oC and ambient temperature respectively, efficiency is 5%**
- **High efficiency quantum well thermoelectric materials developed by Hi-Z Technology Incorporation**
  - **Maximum efficiency 24%**
  - **With temperature of hot and cold junctions 250 ^oC and 50 ^oC respectively efficiency is 7%**

Results of Phase 1 and systems specs. - continued

- **A thermoelectric power generator is to be used to supply power to a small sensing electronic system in our plant using waste heat. The following conditions are planed to be used:**
- **Thot = 305 -450 K**
- **Tcold = 300 K**
- **Ta = 280K**



V/V_{max} and I/I_{max} as a function of hot temperatures (Richard Buist and Paul Lau)

Results of Phase 1 and systems specs. - continued

- **In order to produce 100 W of the power it is estimated that 14 TEG elements are needed with following specifications:**
- **Size : 40mm x 40mm**
  Output : Max. 14W
  (when 230°C in the high-temperature side and 30°C in the low-temperature side)
  Temperature range for use : 280°C (max.) and 250°C or lower in the high-temperature side and 150°C (max.) in the low-temperature side
  Conversion efficiency : Max. 7.2%
  Raw material : BiTe family

Results of Phase 1 and systems specs. - continued

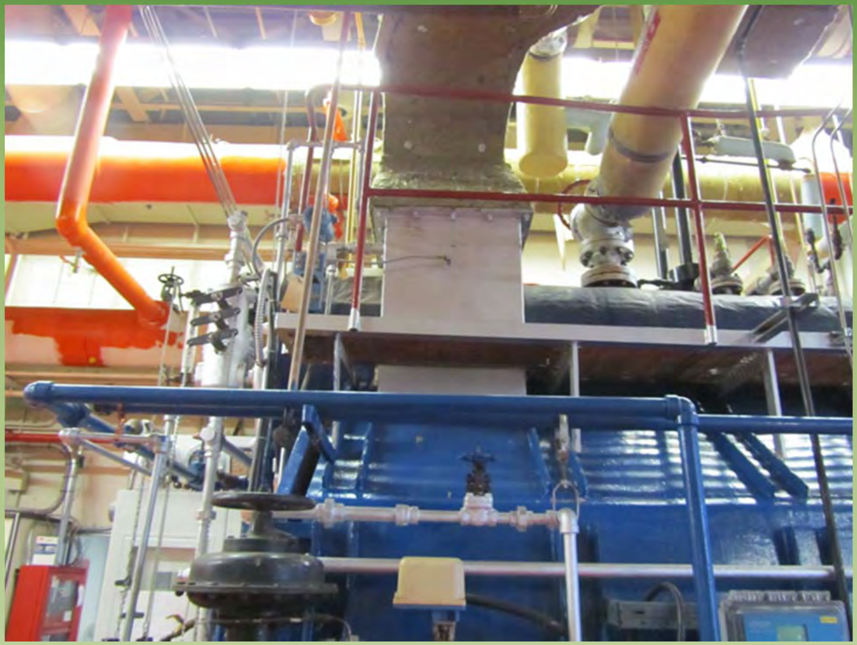
System components	Cost ($/W)	Energy savings/produced (kWh/year)	Recovery years	Cost of Energy generation ($/kWh)
TEG models 12640 – Merit Tech Group + Inverter + Heat Exchanger	**12.5**	**34**	**13**	**0.1**

Results of Phase 1 and systems specs. - continued

- "Your application of QW's to the exhaust of flue gasses sounds very interesting. We believe the efficiency of such a system would be in the range of 10.6% for QW of Si/SiGe. This takes into account 10 C temperature loss on both the hot and cold end of the thermoelectric for heat transfer. - John C. Bass", Vice President of Hi-Z

The Existing facilities

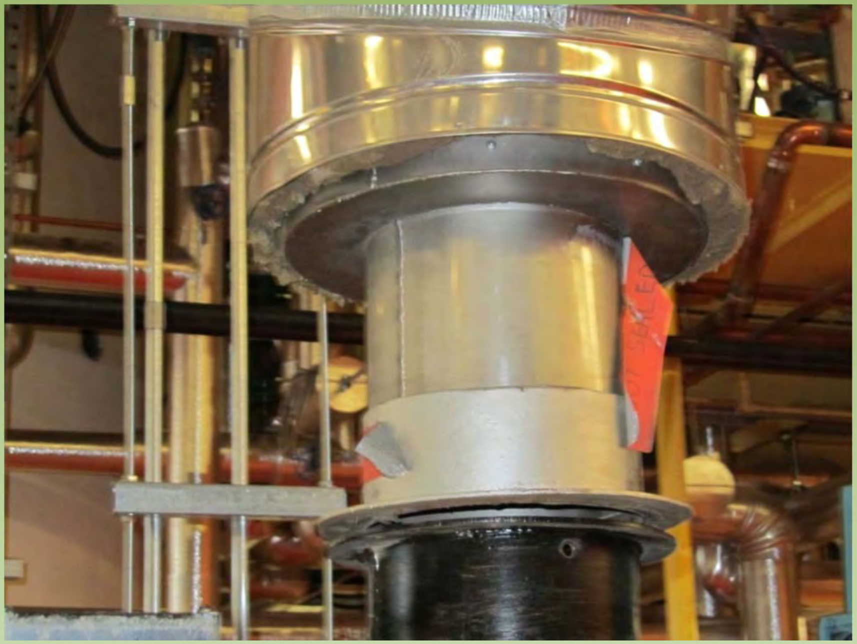
- **The VIEW boiler is a high pressure water tube boiler. It is an A-type packaged water tube boiler. Boiler operates at 1034 kPa and can produce about 2170 kg of steam per hour.**



VIEW boiler flue gases exhaust

The Existing facilities - cotinued

- **The Cleaver Brooks is a small low pressure heating boilers that produces steam at about 90 kPa. It is a firetube boiler meaning that the fire and hot gases pass through tubes which are surrounded by water.**



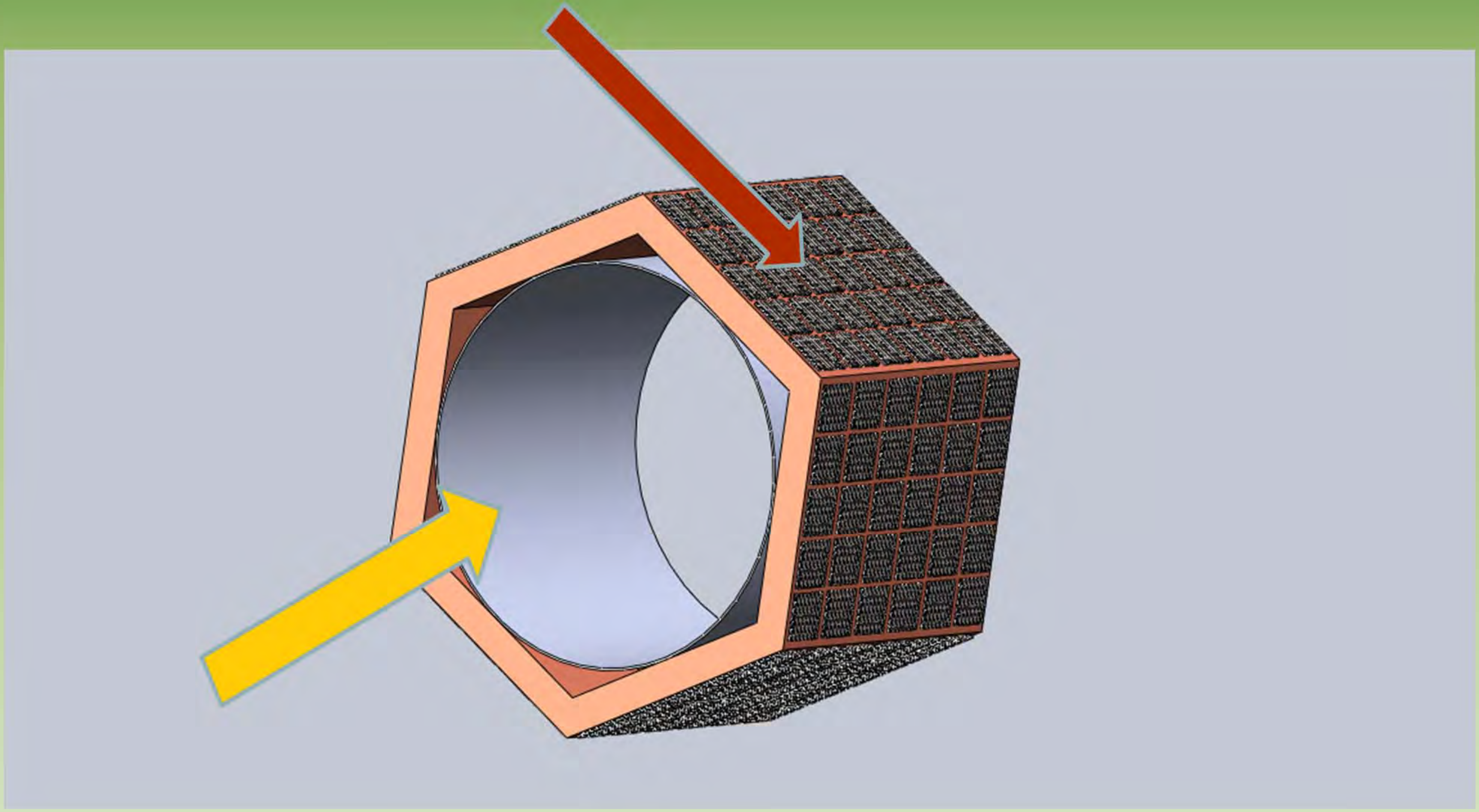
Cleaver Brooks boiler flue gases exhaust

The Existing facilities - cotinued

- **The Nebraska boiler is a high pressure water tube boiler similar to VIEW boiler. The Nebraska boiler can produce 9090 kg of steam per hour and operates at 1723 kPa. The Nebraska boiler is D type high pressure boiler.**

Nebraska boiler flue gases exhaust

SolidWorks model for TEPG



Future work / plan

- Order the system components/Fund
- Involve students/Capstone
- Install the system
- Collect data (for about a year)
- Data and energy analyses (life-cycle)
- Publish report/conferences
- Investigate installation of the TEPG systems for more locations at our campuses, based the outcomes?

Discussion (Q/A)?

CCS+

+Hybridization

+Conservation