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A High Efficiency Thermoelectric Workshop (HETE), jointly sponsored by the Department of Energy (DOE) and the Electric Power Research Institute (EPRI), was held February 17 – 20, 2004, at the Loews Coronado Bay Resort in San Diego, California. The purpose of this workshop was to develop a strategy to accelerate the development of science of high efficiency thermoelectrics and integrate it with appropriate commercialization considerations. It considered approaches for the parallel development of advanced fabrication systems and some pilot applications to provide feedback to investigators of the fundamental technology. Accordingly, the sessions for this workshop were organized to cover the following items:

- Potential applications and status of high efficiency thermoelectrics
- Directions to enhance the understanding of the science of high efficiency thermoelectrics
- Considerations of large scale fabrication and heat transfer
- A panel discussion on possible opportunities
- A panel discussion on potential commercialization interests
- A discussion of US and European Union (EU) Government interest/role in high efficiency thermoelectrics
- An overview of the Congressional budget cycle.

Since DOE perceives a major opportunity for thermoelectrics in the transportation sector (both for direct conversion of heat to electricity and vehicular air conditioning/heating), it would like to establish a Steering Committee from the vehicle industry to provide program guidance and to track this technology, which would eventually lead to a broad range of commercial applications.

The workshop took place over six sessions. The opening session (held Tuesday, February 17, 2004) included two keynote addresses. It was followed by two sessions on Quantum Well Thermoelectrics/Nanotechnology (moderated by Terry J. Hendricks, National Renewable Energy Laboratory and John Stringer, EPRI, respectively), one session on the Manufacturing Aspects of Thermoelectrics (moderated by John Prater, Army Research Office), and two sessions on Commercial Products and Applications (moderated by Suresh Baskaran, Pacific Northwest National Laboratory and John Stringer, EPRI, respectively). The workshop also included two panel discussions: the first entitled "Are nanotechnology measurement capabilities and fabrication techniques useful to further develop QWT?" held on February 18, 2004, and the second entitled "What parameters would be necessary for acceptable risk for commercialization?" was held at the end of the final session.

Opening Session (Tuesday, February 17, 2004)

After an introduction by John Fairbanks (DOE), Edward J. Wall (Program Manger for the Office of FreedomCAR and Vehicle Technologies, DOE) welcomed the distinguished individuals attending the workshop and thanked the Electric Power Research Institute for being a co-sponsor. He lauded the role of the Department of Defense in promoting HETE research during the past decade, primarily under a multi-university research initiative funding. DOE is very much interested in this technol-

ogy due to its enormous potential for saving energy, by recuperating waste heat from automotive applications, and by utilizing various forms of universally available "low-grade" heat. If successful, it can have a truly mind-boggling impact on our day-to-day lives. For transportation, successful harnessing of waste heat from vehicle exhaust would be equivalent to developing a vehicle with 50% or higher overall efficiency. Examples of the many non-transportation uses include replacing current refrigerators/freezers, needing fewer power stations/industrial plants, and leading to new heating, ventilation, and air-conditioning systems. TE would also improve the environment. To stimulate its development, DOE would issue a request for proposals on waste heat utilization/thermoelectrics during spring 2004.

Following the welcoming remarks, in the first keynote address entitled "New Directions for Low Dimensional Thermoelectricity," M. S. Dresselhaus (Massachusetts Institute of Technology) presented an overview of low dimensional thermoelectricity, discussing the physics to yield enhanced performance in one-dimensional nanowire systems, quantum dot superlattice nanowires model calculations, and newly emerging research directions. Her model systems show that ZT values improve as dimensionality is reduced (from bulk to two-dimensional quantum wells to one-dimensional quantum wires to zero-dimensional nanowire superlattices) because of greater opportunity for the control of individual parameters in a manner not possible for bulk materials. The next phase of development for thermoelectrics is to develop composite nanostructures for thermoelectric applications that can be synthesized in large quantities by a "bottom-up" self-assembled approach in a manufacturing environment. The new methods include self assembled bulk composites of nanostructures, new three-dimensional crystalline materials with quantum dots, and new thermoelectric tools at the nanoscale.

In the second keynote address, entitled "Technology Level Requirements for Solid State Cooling, Heating and Power Generation Commercialization," Dr. Lon E. Bell (BSST, Irwindale, California), stated that the recent, extraordinary technological progress in solid-state cooling, heating and power generation may redefine the level of technology required to enable large-scale usage. He provided an assessment of current performance and the levels that would enable broad commercialization. Discussing several market sectors, including military and commercial vehicles (HVAC, waste power generation and ancillary cooling and heating), home and industry (HVAC, refrigeration and waste power recovery), electronics (cooling and thermal management), military and commercial personal comfort (portable power supplies, environmental control) and auxiliary power generation, he showed that a threshold of ZT approaching the value of 2.0 can enable usage in important vehicle systems as well as in other major applications. The market size of the initial applications would be sufficient to provide incentives that could lead to sustainable development for other significant commercial and military uses.

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The First and Second Sessions on Quantum Well Thermoelectrics/Nanotechnology (Wednesday, February 18, 2004)

In the opening presentation entitled "Chair's Overview of High Efficiency Thermoelectrics and Potential Applications," John Fairbanks (DOE) stated that although the direct conversion of heat to electricity was discovered almost 200 years ago, its only application until the 1940's was in thermocouples to measure temperature. Niche applications utilized semiconductor thermoelectrics in the latter half of the 20th century had a ZT value of 1.0 or less. But recently fabricated thermoelectric devices based on the Quantum Well Confinement concept have demonstrated measured ZT values of up to 4 (equivalent to a heat-to-electricity conversion efficiency of over 20 percent at low-temperatures). Further improvements in ZT values (to approximately 10) could make TE competitive with the internal combustion engine or the fuel cell. Numerous applications would be possible for these devices to convert low-grade heat to electricity. The potential energy savings from QWT devices used for refrigeration is enormous. A global climate change advantage is an inherent bonus. Almost two centuries after Seebeck, if these TE concepts become commercially viable, their magnitude of energy savings could make them one of the greatest contributors towards fuel conservation and greenhouse gas reduction.

Rama Venkatasubramanian (Research Triangle Institute, Research Triangle Park, North Carolina), in his presentation entitled "Superlattice Thermoelectric Technology," described how thin film nanoscale superlattice materials, based on the concept of phonon-blocking-electron transmission, have demonstrated higher figure-of-merit (a ZT value of 2.4 at 300K), very high cooling power density, very rapid cooling or heating and also same-or-better functionality, as quantified by heat pumping, with 1/40000th of the active-material-usage compared to bulk thermoelectric technology. These represent major advantages, especially for applications like small-footprint laser coolers or microprocessor hot-spot coolers or portable thermoelectric power sources. RTI, over the last two years, is attempting to transition the enhanced ZT in superlattices, to performance at the couple and module levels. He described the progress with these transitions using specific examples and engineering prototypes, for both cooling and power conversion, as well as the approach to leveraging superlattice technology with other thermoelectric device components for efficient waste-heat-recovery in automobile systems.

In a presentation entitled "Nanoscale Heat Transfer for Thermoelectric Energy Conversion," Gang Chen (Massachusetts Institute of Technology, Cambridge, Massachusetts), discussed that heat transfer in nanostructures differs significantly from macrostructures because of classical and quantum size effects on phonons, electrons, and photons. Size effects on phonon transport in nanostructures can be utilized to engineer new devices with improved energy conversion efficiency. He reviewed various nanoscale heat transfer phenomena, and followed it with a discussion of phonon heat conduction in superlattice systems. Experimental and modeling results on the thermal conductivity of superlattices were discussed. Some pos-

sible approaches to engineer phonon transport in nanostructures were illustrated, to improve the solid-state thermoelectric energy conversion efficiency.

Terry Aselage (Sandia National Laboratories, Albuquerque, New Mexico) made a presentation entitled "Thoughts on Inhomogeneous Thermoelectrics." He stated that dramatic enhancements of the thermoelectric power factor have been reported in several different materials, including sputtered and annealed films of boron and carbon, as-sputtered films of silicon and germanium, and films of conducting polymers with dispersed nanoscale metal particles. In each instance, a large increase in electrical conductivity was measured, without the expected concomitant drop in the Seebeck coefficient. A common feature of these systems is the presence of material interfaces and multiple conducting pathways. He discussed possible approaches to enhance understanding of the underlying phenomena.

David C. Johnson (University of Oregon, Eugene, Oregon), in his presentation entitled "Crystal Engineering of Novel Thermoelectric Materials: Films and Bulk," stated that recently made "designer" superlattice compounds such as (Bi2Te3)x(TiTe2)y promised high Seebeck coefficients and conductivities, making them attractive n-type materials for thin film devices. The same synthesis approach was used to prepare several other superlattices. Efforts are currently ongoing to determine the "design rules" on how the charge transfer between dissimilar layers and the relative and absolute layer thicknesses affect properties.

In the presentation entitled "Measurement of Thermoelectric Properties of Thin Films," L.C. Olsen (Pacific Northwest National Laboratory, Richland, Washington) focused on approaches to measure electrical conductivity and Seebeck coefficient of thin films grown on conducting substrates. Determination of electrical conductivity and Seebeck coefficient of a thin film grown on silicon requires one to know properties of the silicon substrate and an appropriate model for the film/substrate system. Ideally, one measures the effective Seebeck coefficient and resistance for the film/substrate system and then utilizes the assumed model and known properties of the substrate to calculate the film properties. Potential problems with such an approach were discussed.

J.C. Bass (Hi-Z Technology, San Diego, California), made a presentation entitled "The Design and Application of Quantum Well Film Based Modules," in which he discussed the design and application of thermoelectric modules using multi-layer quantum well films. He described several different module configurations that can be made from these films for different applications. Both the physical arrangement of the modules for a wide range of power and the expected performance were discussed. Several applications for quantum well film based modules were described, including examples of both the production of power and for cooling/heating applications, covering power levels ranging from milliwatts to kilowatts.

The presentation entitled "Department of Defense (DoD) Interests in High Efficiency Thermoelectrics," given jointly by Mihal Gross (Office of Naval Research, Washington, D.C.), and

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John Prater (Army Research Office, Research Triangle Park, North Carolina), provided a survey of the existing DoD research program, DoD needs for advanced thermoelectric materials, and future research directions. The significant breakthroughs have resulted in exciting changes in a field amazingly stagnant for nearly three decades. It was noted that the figure of merit values for thermoelectric materials have more than doubled over the past decade.

Arvid Pasto (Oak Ridge National Laboratory, Oak Ridge, Tennessee)(, in a presentation entitled "Thermoelectric Materials Characterization at High Temperature Materials Laboratory (HTML)" described the capabilities of the HTML. The HTML measurement capabilities relevant to TE include thermal diffusivity and conductivity of bulk and thin film specimens, as well as specific heat and thermal expansion, electrical resistivity and Seebeck coefficient. The center's considerable resources include new aberration-corrected transmission electron microscopes offering sub-Angstrom resolution, the synchrotron and neutron beamlines, rapid, high-temperature resolution IR imaging, and the recently developed high thermal conductivity graphite foam. This material has been utilized to cool high power electronics, and could offer advantages to lightweight, high-power thermoelectric systems.

Angelica Stacy (University of California, Berkeley, California), in her invited presentation entitled "Bi2Te3 and Bi1-xSbx Nanowire Arrays: A New Generation of Thermoelectric Materials," described a project to synthesize dense nanowire arrays of thermoelectric materials by electrodeposition, and to measure the thermoelectric efficiencies of these nanowire arrays. The first part of the project involves determining optimal conditions for electrodeposition of Se-doped and Sb-doped Bi2Te3 nanowires and Bi1-xSbx nanowires into a porous alumina template. The second part of the project involves studies of the thermoelectric figure of merit, ZT, as a function of nanowire diameter, nanowire composition, and concentration gradients produced by heat treatments. The conditions required for optimized nanowire growth and the strategies for evaluating the thermoelectric efficiencies of the arrays were reported.

James J. Krajewski (DuPont Research and Development, Wilmington, Delaware), provided a bird's eye view of Dupont's recent approaches to the discovery of high performance environment-friendly TE materials in his presentation entitled "Emerging Material Needs in Thermoelectrics."

D.S. Marshall (Ceramic Energy Technologies, Chandler, Arizona), made a presentation entitled "Efficient Micro-Combustor for Thermoelectric Modules," in which he described an efficient micro-combustor developed in an established ceramic technology allowing quick design changes and integration of numerous features including a counter-flow heat exchanger capable of recuperating over 90% of the exhaust gas heat. The final exhaust stream of this device is liquid water and gaseous combustion by-products emerging at 65°C, while heat is delivered to thermoelectric modules at throttlable temperatures

ranging from 200ºC to over 600ºC, all the while maintaining high thermal efficiency.

A panel discussion entitled "Are nanotechnology measurement capabilities and fabrication techniques useful to further develop QWT?" followed the above presentations.

Session on Manufacturing Aspects of Thermoelectrics and the First Session on Commercial Products and Applications (Thursday, February 19, 2004)

In the opening presentation of the day, entitled "Thermoelectric Technology Readiness for Large Scale Commercialization," Lon Bell (BSST, LLC, Irwindale, California) analyzed two advancements addressing cost and power density, and their quantitative contribution to performance increase. He discussed recent major advancements that have partially or completely resolved each of the three barriers of low efficiency, low power density and high cost per kilowatt output. Full resolution of these efficiency limitations would come with the availability of promising new superlattice materials and integration with advanced thermodynamic cycles.

Jim Magdych (Power Chips, Queensway, Gibraltar) made a presentation entitled "High Efficiency Cooling and Power Generation using Electron Tunneling through a Vacuum Gap," and described the company's research that resulted in a new diode design relying on electron tunneling through a nanometer-scale vacuum gap. Experiments to date have resulted in consistent production of devices with conformal electrode surfaces, with measured electron tunneling currents in excess of 10Å through the vacuum gap. These devices could offer high-performance, low-cost replacements for just about any existing cooling or power generation solution, at efficiencies far greater than thermoelectric alternatives.

In the presentation entitled "Recent Progress in Scale of Thermoelectric Quantum Well Films," P.M. Martin (Pacific Northwest National Laboratory, Richland, Washington) described progress in scale up of Si/ Si0.8Ge0.2 and B4C/B9C quantum well films for thermoelectric applications. PNNL has scaled up the magnetron sputtering process to produce large quantities of Si/ Si0.8Ge0.2 and B4C/B9C quantum well films at low process cost. Initial studies show that their power factor is high enough to produce a ZT significantly greater than 1. These results are encouraging for the use of quantum well materials in large scale thermoelectric power generation.

S. Ghamaty (Hi-Z Technology, Inc., San Diego, California) made a presentation entitled "Thermoelectric QW Device," in which he described two-dimensional quantum well nanostructures (synthesized by alternating layers of B4C and B9C in one system and alternating layers of Si and Si0.8Ge0.2 in another system), candidate thermoelectric materials for high figures of merit. The predicted enhancement is attributed to the confined motion of charge carriers and phonons in the two dimensions and their separation from the ion scattering centers. Hi-Z has measured power and efficiency demonstrating a QW couple conversion efficiency of 14, by dividing the power output of the couple by the power input, and without correction for extraneous heat losses, such as through the Si substrate and the heater wires.

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The presentation "Thermoelectrics R&D at Delphi Corporation," by Joseph P. Heremans (Delphi Corporation, Shelby Township, Michigan) focused on the use of thermoelectricity for climate control. The advantages to this approach include the absence of greenhouse effect producing gases, reversible heating and cooling, a favorable transient response, easy proportional control by means of the Peltier current, and compactness. He outlined the different requirements for the thermoelectric materials and systems and also reviewed previous work on bismuth nanowires.

In the presentation entitled "A Roadmap for Waste Heat Recovery: From Here to Successful Usage," Hylan Lyon (Marlow Industries, Dallas, TX) proposed a roadmap detailing the desired TE path from the present to its widespread commercial usage for waste heat recovery. The roadmap includes an assessment of competing technologies with and without thermoelectric options, an endpoint representing volume production of devices meeting customer needs in: capacity, efficiency, weight, cost, reliability and durability. He described an approach, based on experience, to get from the start point to the end point, detailing out the implications of the most relevant past and ongoing research, and how the best mix of physics and technologies can provide a stepwise pathway over the next few years.

Gustavo Ray (Southwest Research Institute, San Antonio, Texas) made a presentation entitled "Survey of Thermoelectric Generator Performance in a Harsh Automotive Environment," in which he described a project whose goal was to provide practical information concerning the capabilities and limitations of thermoelectric generators for automotive use. Thermoelectric modules of various sizes and power ranges, acquired from four different suppliers, were evaluated in stationary and harsh vibration situations. The performance validation was integrated with analytical models to estimate potential engine exhaust energy recovery.

Ctirad Uher (University of Michigan), in the presentation entitled "Filled Skutterudites for Efficient Power Conversion Applications," stated that the true economic impact of TE technology depends on the availability of more efficient materials, such as filled skutterudites, compounds realized by filling the structural voids in the skutterudite lattice with, for instance, rare-earths or alkaline-earths ions. He reviewed the fundamental material attributes that could make filled skutterudites excellent thermoelectric materials, discussing the approaches for further significant improvement in the figure of merit, and their prospect for power conversion applications in the intermediate to high temperature range of operation.

In her presentation entitled "High Efficiency Thermoelectrics for the Aircraft, Aerospace, and Refrigeration Industries: Potential Applications within United Technologies Corporation (UTC)," Rhonda Willigan (United Technology Research Center, East Hartford, Connecticut) covered potential applications of thermoelectrics and discussed the current programs at UTC to study thermoelectrics. These included discussions of potential applications and TE activities for Pratt & Whitney, Hamilton Sundstrand, and Carrier, all operating units of UTC.

Terry J. Hendricks (National Renewable Energy Laboratory, Golden, Colorado) made a presentation entitled "Advanced Thermoelectric Energy Recovery Systems in Future Vehicle

Systems," in which he stated that current estimates of available waste thermal energy from current light-duty vehicle systems range from 20kW to 400 kW depending on engine size and engine torque-speed conditions. An energy equivalent of 46 billion gallons of gasoline is annually wasted down the exhaust pipe of the 200 million light-duty vehicles nationwide. Thermoelectric conversion systems, using advanced next-generation thermoelectric (TE) materials, currently hold the most promise for satisfying the three requirements of energy conversion technologies would be completely solid state, no noise, no vibration, no moving fluids, high reliability, and low cost. NREL is investigating system power benefits and system thermal integration challenges of using TE conversion systems with various advanced, next-generation TE materials, such as skutterudites, quantum-well materials, and superlattice materials. He discussed the system design challenges, system temperatures, magnitude of power output available at various vehicle locations, and the effect on R&D planning and future TE system marketing opportunities.

U. Ghoshal (NanoCoolers, Inc., Austin, Texas) made a presentation entitled "Loop Refrigeration with Advanced Fluidics and Thermoelectric Coolers," in which he described loop refrigeration concepts combining magnetofluiddynamic (MFD)-based liquid metal heat transport loops and high efficiency thermoelectric coolers. The MFD liquid metal loops developed at NanoCoolers are powered by ultra-low power, silent, non-moving pumps that are reliable, robust, and not dependent on the orientation of the loops. The ideal thermophysical fluidic properties of liquid metals can handle high heat fluxes typical of thin film thermoelectric coolers, and combined with the spatial and temporal refrigeration techniques, can result in compact, high efficiency air-conditioners operating at temperature differentials larger than 30K.

In the presentation entitled "Automotive Applications for Thermoelectric Technology," Francis Stabler (General Motors, Pontiac, Michigan) emphasized that the automotive industry offers a huge potential market for thermoelectric technology, even with a moderate market penetration which can represent the sale of many millions of thermoelectric modules. The level of market penetration and the number of thermoelectric modules used annually depends on several factors. Currently there are only low volume automotive cooling applications available with off-the-shelf thermoelectric modules. He discussed how high efficiency thermoelectric technology can help grow the automotive market to large-scale cooling and electric power generation applications.

Jeffrey Snyder (Jet Propulsion Laboratory–California Institute of Technology, Pasadena, California) in the presentation entitled "Advances in Thermoelectric Materials and Energy Conversion Technologies at NASA/JPL," described an approach for engineering improved materials for thermoelectric applications based on a phenomenological and microscopic understanding of the thermoelectric effects. The improved thermoelectric properties of many new thermoelectric materials, such as skutterudites and zinc antimonide, can be understood using this principle. Up to 20% thermal to electric conversion efficiency can be achieved by segmenting different materials over a wide temperature range. For segmented devices the compatibility

factor, recently derived from the intensive formulation of efficiency, must also be considered for material selection.

Ali Shakouri (University of California, Santa Cruz, California) in his presentation entitled "Thermionic Energy Conversion Center," described research activities at that newly formed ONR MURI center. It is investigating an integrated approach to engineer electrical, thermal and optical properties of nanostructured materials and devices. Materials design is focused on increasing the efficiency of heterostructure thermionic power generators using embedded quantum dot structures and metallic superlattices. The Center also works on the development of vacuum thermionic emission from nanostructured carbon surfaces and low work function wide band gap nitrides and diamond emitters and collectors. Measurements of electrical, optical and thermal transport at both device and nanostructure level are used to verify model predictions and thereby lay the foundation for improved device and material design.

James Bolen (Global Thermoelectric, FuelCell Energy, Inc., Danbury, Connecticut) made a presentation entitled "Perspectives from 29 Years of Thermoelectric Power Generation," provided a history of Global Thermoelectric's participation in thermoelectrics, including its TE products and their applications. In addition, he summarized the insights drawn from engineering, manufacturing, marketing and servicing these generators in some challenging markets, which focused on the past 10 years.

In the presentation entitled "Designing Advanced Thermoelectric Materials for Automotive Applications," Jihui Yang (General Motors R&D Center, Warren, Michigan) explained GM interest in advanced thermoelectric technology. Over the past few years, GM has been studying several potential thermoelectric material systems to understand, control, predict, and optimize their thermoelectric properties. The talk focused on effect of Fullerene (C60) additions on the thermoelectric properties of binary (unfilled) skutterudite CoSb3. A significant increase in thermoelectric figure of merit is achieved for 6.54 mass% C60 as compared to the undoped CoSb3. He expects that this method of improving the ZT can be applied successfully to high efficiency materials such as the filled skutterudite, clathrate, and half-Heusler compounds.

The Second Session on Commercial Products and Applications (Friday, February 20, 2004)

In the first presentation of the day, entitled "Status of Current Thermoelectrics Projects and R&D at Teledyne," Mal McAlonan (Teledyne Energy Systems Incorporated (TESI), Hunt Valley, Maryland) provided an account of the activities of TESI. TESI has developed generators using thermoelectric conversion since the late 1960's. It has exploited various technologies originally developed for space to meet similar power requirements for remote terrestrial locations. Over time, it developed skills and long term test data to design custom generators and predict performance of various classes of TE materials (including original TESI compositions, lead telluride, and bismuth antimony telluride). Recently it teamed with Boeing to win a contract to develop a Multi-Mission RTG for NASA. It also won two NASA Research Awards. It is working with Boeing on a JPL sponsored program to investigate higher temperature materials and tech-

niques to exploit in real hardware and on a project to investigate SiGe.

Mahmoud Taher (Caterpillar Corporation, Peoria, Illinois) described in the presentation "Opportunities and Applications for High Efficiency Thermoelectrics," some of the applications envisioned at Caterpillar that can potentially benefit from HETE as well as specific challenges to resolve before its adoption in such applications. The challenges exist at thermocouple (pellet), device (module) level and system levels.

In a presentation entitled "High Efficiency Thermoelectric Devices Integrated with Nuclear Heat Source for Dense Long Life Portable Power," Lewis Larsen (Lattice Energy LLC, Chicago, Illinois) described a concept which he called Low Energy Nuclear Reactions (LENRs) representing a next generation "green" energy source that can be integrated with high-efficiency thermoelectrics to enter large, rapidly growing markets for portable battery-like devices.

Andreas Eder(BMW, Palo Alto, California) in the presentation entitled "BMW's Perspective of Potential Thermoelectrics for Vehicle Applications," stated that the application of thermoelectrics for onboard electric power generation requires questions to be answered by an engine manufacturer. These include an adequate location for the thermoelectric generator (TEG). The layout of a TEG device, considering fluid dynamics and heat transfer of the exhaust-gas flow as well as the fluid-flow at the cold side is one of the key issues. Automotive application is possible if the module cost is brought down to ~0.10 $/W and a ZT-value above 3 can be achieved over a broad temperature range. TE success depends on future development of materials and production engineering techniques as well as the performance of TE compared to other technologies.

Marco Scandurra (Massachusetts Institute of Technology, Cambridge, Massachusetts), presented "A Novel, Thermoelectrically Driven Engine for Air and Ground Vehicles," which he claimed to be a new propulsion concept based on thermal forces arising in air when a temperature gradient is applied. It would not require large temperatures, but large temperature gradients. An advantage of this concept is that it can operate at nearly room temperatures. A TE engine would be contained on a plate on which nano-scale temperature gradients would be applied by means of thin film superlattice micro-coolers, and generate the force to power vehicles. Using Bi2Te3/Sb2Te3 superlattice micro-coolers, the estimated power consumption of the device would be 1.5 Watt per Newton of thrust. The propulsion concept is currently being experimentally validated at MIT.

Next, Hylan Lyon (Marlow Industries, Dallas, Texas) presented a "Status Report on the Application and Support of Thermoelectric Devices in Asia and Europe," containing results of assessments of thermoelectrics activities in those countries.

In the last presentation, entitled "Electric Energy Generation from the Exhaust of a Light Truck," Eric Thacher (Clarkson University, Potsdam, New York) described a Clarkson University project to design, build, test, and develop a plan to commercialize a thermoelectric generator (TEG) for recovering some of the energy in the exhaust from light trucks and passenger cars. The team members include Clarkson University, Hi-Z Technology, Delphi Automotive Systems, and General Motors.

The TEG consists of sixteen Hi-Z's thermoelectric modules connected in series, clamped between exhaust and coolant heat exchangers, and electrically connected to the DC bus through a power conditioning unit. It is sized to generate 330 Watts of electric power at its design temperature differential.

This presentation was followed by a panel discussion entitled "What parameters would be necessary for acceptable risk for commercialization?" After the panel discussion, the workshop Chairman made the closing remarks thanking the sponsors, presenters and attendees for their participation. After that, the workshop was concluded.