Executive Summary

A joint Defense Advanced Research Projects Agency/Office of Naval Research (DARPA/ONR) Program Review and Department of Energy (DOE) High Efficiency Thermoelectric Workshop was held March 24 – 27, 2002, at the Loews Coronado Bay Resort in San Diego, California. This joint DARPA/ONR Program Review and DOE High Efficiency Thermoelectric Workshop focused on identifying and prioritizing the outstanding technical challenges that need to be addressed in order to facilitate the transition of new developments in advanced thermoelectric materials to commercially viable thermoelectric devices.

Some of the scientific and technical goals of this joint meeting included: 1) identify potential cooling and/or power generation applications for first generation advanced thermoelectric devices that exploit the superior properties observed in low dimensional thermoelectrics (quantum well and/or superlattice structures) and other newly discovered thermoelectric materials; 2) assess the level of understanding of the physics underlying recently reported enhanced figures-of-merit in low dimensional thermoelectric material systems; 3) explore the feasibility of scale-up processing of quantum well and/or superlattice thermoelectric structures; 4) identify potential engineering challenges associated with overall system integration of thermoelectric devices, i.e. thermal transfer issues, electrical interconnects, etc.; and 5) identify potential areas for future investment that would accelerate the commercialization of newly developed and demonstrated thermoelectric materials and devices.

The front part of the program review/workshop event (from Sunday, March 24 to approximately mid-day on Tuesday, March 26) primarily consisted of presentations that were part of the DARPA/ONR Program Review under the Multi-University Research Initiative (MURI). For this part, only those presentations whose authors have expressly agreed to their inclusion in these proceedings are included here. The latter part of the event (from approximately mid-day on Tuesday, March 26 to the end of the day on March 27) consisted of presentations that were primarily funded by the DOE or commerical concerns and formed the core of the high efficiency thermoelectric workshop component of this event.

Sunday, March 24, 2002

In her keynote speech entitled "The Promise of Low Dimensional Systems for Thermoelectric Applications", Prof. Mildred Dresselhaus (Massachusetts Institute of Technology, Cambridge, MA) discussed the practical limits to increasing the Thermoelectric Figure of Merit (FOM) "ZT" in bulk materials, and the advantages of using a low-dimensional approach for that purpose. A limit to Z is rapidly obtained in conventional materials. So far, the best bulk material ($Bi_{0.5}Sb_{1.5}Te_3$) has reached a ZT value of approximately 1 at 300 K temperature. The use of low dimensions gives additional control via enhanced density of states due to quantum confinement effects, increased Seebeck coefficient without reducing electrical conductivity, boundary scattering at interfaces reducing the thermal conductivity, and the possibility of carrier pocket engineering to further improve the ZT. The promising low dimensional systems include $PbTe/PbEu_{1-x}Te_x$, Si/Ge and GaAs/AlAs for 2-dimensional systems (quantum wells), Bi and $Bi_{1-x}Sb_x$ for 1-dimensional systems (quantum wires), and $PbSe_xTe_{1-x}$ segmented nanowires for 0-dimensional systems (quantum dots). Currently, for 2-dimensional systems, the proof of principle of enhanced ZT has been applied (using $PbTe/Pb_{0.927}Eu_{0.073}Te$ superlattice samples), the carrier pocket engineering concept applied (in GaAs/AlAs quantum well superlattice systems) and experimental results show a high ZT for cross-plane geometry. For 1-dimensional systems, theoretically predicted enhancements of ZT have been made and validated by experiments (for Bi nanowires). For 0-dimensional systems, experimental results of quantum dot superlattices show a high ZT, and preliminary modeling results show enhanced Seebeck coefficients for segmented nanowires.

Monday, March 25, 2002

In his presentation entitled "Characterization, Devices, and Modeling", Prof. Gang Chen (Massachusetts Institute of Technology, Cambridge, MA) summarized the major results related to Seebeck coefficient measurements, quantum dots and nanowires thermal properties, device fabrication, and modeling on thermoelectric transport. He also discussed highlights of the fifth-year MURI research in the area of thermal conductivity reduction mechanisms, anisotropic thermal conductivity measurements, Seebeck/electrical conductivity measurements, and broader Nanoscale transport modeling.

In a subsequent presentation entitled "Nanowires for Thermoelectric Applications", Prof. Mildred Dresselhaus (Massachusetts Institute of Technology, Cambridge, MA) summarized the progress made on this topic over the past four years. This includes an improved theoretical model of nanowire systems, validation with experimental results, fabricating undoped Bi, Te-doped Bi, and $Bi_{1-x}Sb_x$ nanowire arrays of high crystalline quality, single wire measurements by various techniques, fabrication of ordered porous alumina templates on a large (10 cm size) Si substrate, measurement of optical properties of nanowire arrays, and relating results to model calculations. During the fifth year, the major progress has included improved synthesis of Bi-related nanowires to increase ZT and to solve practical issues for device performance, applying carrier pocket engineering to $Bi_{1-x}Sb_x$ nanowire systems to further enhance the ZT performance, investigating the electronic transport properties of $Bi_{1-x}Sb_x$ nanowires for various Sb concentrations and wire diameters, thermoelectric properties of segmented nanowires (e.g., $Bi/Bi_{1-x}Sb_x$ nanowires), and improving single nanowire measurement techniques of resistivity and Seebeck coefficient as a function of temperature, diameter, and composition.

In his presentation entitled "Phonons and Thermal Conductivities of Ge Quantum Dot Superlattices", Prof. Kang Wang (University of California, Los Angeles, CA) reviewed the research work done at UCLA in this area during the last five years. The research encompassed areas of SiGe growth, grading of SiGe buffer layer growth technique by Sb mediation, relaxing SiGe layers by low-temperature Si, Si/Ge quantum well superlattices, Ge quantum dot superlattices, phonon measurement and modeling, lattice thermal conductivity reduction due to phonon confinement effect, multiple scattering effect/strain relaxation effect in Ge quantum dot superlattices, and thermal conductivity modeling of Ge quantum dot superlattices. The fifth-year research has been focused at optical phonons in Ge QD SLs (strain relaxation effects), acoustic phonons in Ge QD SLs: multiple scattering effects, and the thermal conductivity of Ge QD SLs measurements/modeling.

The above presentation was followed by several other presentations by various MURI participants. The concluding presentation of the day by Dr. Hylan Lyon (Marlow Industries, Dallas, TX) was entitled "Thin Film Thermoelectrics from an Applications Perspective". He presented results of a comparison of different thin film formats for electronic cooling. The formats include Perpendicular Peltier, Parallel Peltier, and Ettingshausen. An analysis of the heat flux indicated that severe challenge for thermal pathway exists, which is a direct result of film thickness (10 microns assumed) and current requirement. With 1 W/cm-K materials (alumina), a thickness of 100 microns between load and cold or hot junction causes a 10 ºC loss of ΔT. Further analysis indicates that neither Peltier nor Ettingshausen cooling makes sense for material thickness less than 100 microns in the direction of the temperature gradient. It may be possible to use thin films perpendicular to the temperature gradient but they will need to be supported in some way. A thick film technology is needed to make electronic refrigeration feasible.

Tuesday, March 26, 2002

In the first presentation of the day, entitled "New Thermoelectric Materials and Devices at Michigan State University", Prof. Mercouri G. Kanatzidis (Michigan State University, East Lansing, MI) discussed the findings of research done on promising new thermoelectric materials formed on the basis of reaction chemistries of A_2Q, PbQ, and Bi_2Q_3, where "A" represents potassium, rubidium, or cesium, and "Q" represents selenium or tellurium. Based on research among the most promising TE materials (n-BiSb, n-SiGe sintered, $CsBi_4Te_6$, $LaFe_3$, $CoSb_{12}$, Bi_2Te_3, and PbTe), bismuth chalcogenide ($CsBi_4Te_6$) was found to be a low temperature material with a ZT at 240 K of ~0.8 (p-type). $CsBi_4Te_6$ could function in a temperature range where $Bi_2Te_{3-x}Se_x$ looses effectiveness. In a segmented configuration, $CsBi_4Te_6$ and $Bi_2Te_{3-x}Se_x$ may significantly lower the minimum achievable cooling temperature of TE devices, enabling various cooling

applications. β-$K_2Bi_8Se_{13}$ is another new material with potential to outperform all others at high temperatures (300 K-700 K).

In the next presentation, entitled "Superlattice Thermoelectric Materials and Devices", Dr. Rama Venkatasubramanian (Research Triangle Institute, Research Triangle Park, NC) discussed the significant enhancement accomplished at Research Triangle Institute (RTI) in the thin-film thermoelectric material figure of merit ZT. The value of ZT had stayed at about 0.8 to 1 for the last 40 years, limiting the scope of TE applications. More importantly, cooling power density (PD) in bulk devices is too low to be of interest for many electronics cooling applications. ZT needs to improve to over 1.5 at 300 K for a major impact and around 3 for a revolutionary impact. A larger PD would also open up new applications for these materials. One approach for thin-film materials includes superlattices which utilize interfaces, to impede phonons that cause undesired reverse flow of heat but not impede forward-flowing electrons. In such systems, current and heat transport occurs perpendicular to the superlattice interfaces and there is an easy adaptability for device implementation. RTI's breakthrough has resulted in a material level ZT of over 2.5 at 300 K in p-type superlattices and device level ZT of approximately 2.4 at 300 K through the development of ultra-low resistivity contacts. RTI's superlattice material has a 10Å/50Å Bi_2Te_3/Sb_2Te_3 structure and is optimized for disrupting heat transport while enhancing electron transport perpendicular to the superlattice interfaces. The advantages include fast cooling and heating, enhanced power density, more flexible cooling/heating technology, and significantly improved compactness. Thin-film devices can lead to high power density, fast response, wafer-scale integration for both cooling and power conversion.

In a later presentation entitled "Boron Carbides: Unconventional High-Temperature Thermoelectrics", Dr. Terry Aselage (Sandia National Laboratories, Albuquerque, NM) discussed how Sandia uses thermoelectric power sources, recent novel contributions to boron carbides' thermoelectric properties, and their implications for boron carbide quantum wells. Boron carbides are formed from covalently bonded, light elements with high stiffness, high sound velocity and high carrier density. One would expect a high thermal conductivity and very low Seebeck coefficient from them. Yet paradoxically, the Seebeck coefficients are large and the thermal conductivity low, and these materials provide surprisingly good high-temperature thermoelectrics (with a ZT ~0.3 at 1000 °C, and Z continuing to increase with T). This is explained by their "hopping-type" electronic transport properties. Novel contributions enhance the thermoelectric properties by creating high densities of localized charge carriers, thermally activated mobilities which increase with temperature, a large, carrier-induced softening enhancement of Seebeck coefficients, and a slow, incoherent vibrational energy transfer – vibrational disorder.

In the next presentation, entitled "Prospects for Efficient Thermoelectric Materials in the Near Term", Dr. Roger Richman (Hi-Z Technologies, San Diego, CA) examined the issue of thermoelectric efficiency from the standpoint of the material figures of merit (FOMs) which will enable solid-state devices to compete with conventional electricity generators or vapor-compression refrigerators. He estimated that a ZT at or above 8 will be required for this purpose. He expected that some of the emerging new bulk materials may eventually reach that level of performance, but probably not in the near term. The reasons for that are twofold: the avenues suggested by theory, however meritorious, cannot be explored quickly. Systematic, experimental searches must be conducted, for example, for mixed-valence rare-earth compounds or for ternary systems with voids in the crystal structures. Secondly, it is not certain that the requisite high Seebeck coefficient, low electrical resistivity, and low thermal conductivity are even achievable simultaneously in a real bulk material. Multilayer thin films appear to have the best chance of attaining the requisite FOM within the next few years.

The next presentation was made by Dr. Saeid Ghamaty (Hi-Z Technologies, San Diego, CA) and was entitled "Quantum Well Thermoelectric Devices". The objective of the described effort was to exploit the features of quantum well structures to obtain high efficiencies via high figure of merit TE materials. The quantum-well confinement of multilayer film by the adjacent barrier layers results in an active layer sandwiched between materials with band offset to form a barrier for the charge carriers. Improvement in Z results from an increased Seebeck coefficient, an increase in the density of states, and a significant reduction in resistivity and thermal conductivity. Quantum-well effects become significant for layer thickness of <200 Å. The project

has resulted in the discovery of new TE materials with high energy conversion efficiency (>20%), verified that 2-dimensional QW improves TE properties, and established that ZT enhancement to values much higher than 1 are possible. The programs at Hi-Z include the Si/SiGe multi-layer QW film thermoelectrics, and the p-type B_4C/B_9C high temperature thermally stable multilayer QW films. The power and efficiency measurements included current and voltage power measurements, straight power-in and power-out (no correction) efficiency measurements, power-in (heater), and power-out (QW device) measurements.

In the next presentation, entitled "Sputter Deposition of Thermoelectric Films and Devices", Dr. Joseph Farmer (Lawrence Livermore National Laboratory, Livermore, CA) discussed the evolution and current status of the thermoelectric program at LLNL. In the early 1990's, LLNL started work on thermoelectric quantum well, and a wide variety of epitaxial single-layer and multilayer thermoelectric films were produced with multi-magnetron sputtering, with precise control of substrate temperature and bias, as well as sputter gas pressure. Films were characterized with X-ray diffraction and a variety of electronic measurements. The work advanced to the fabrication and evaluation of thin-film thermoelectric coolers. The systems investigated at LLNL include Bi_2Te_3/B_4C, $Si_{0.2}Ge_{0.8}/Si$, $Bi_{0.9}Sb_{0.1}/PbTe_{0.8}Se_{0.2}$, $Bi_{0.9}Sb_{0.1}/Bi_2Te_3$, $Bi/Bi_{0.86}Sb_{0.14}$, and $(Bi_{0.25}Sb_{0.75})_2Te_3/(Bi_{0.25}Sb_{0.75})_2(Te_{0.5}Se_{0.5})_3$. He discussed the importance of substrate choice and the optimization of deposition conditions in the growth of epitaxial single-layer and multilayer films, the characterization of XRD, SEM, and TEM thermoelectric properties, and results of device fabrication and testing. The important conclusions regarding materials synthesis via sputter deposition included that, for $PbTe_{0.8}Se_{0.2}/Bi_{0.9}Sb_{0.1}$ and $Bi_2Te_3/Bi_{0.9}Sb_{0.1}$ multilayers, interdiffusion causes excessive doping of individual layer causing the Seebeck coefficients to degrade, and the sputter deposition of epitaxial multilayer films is possible. The main lessons from the fabrication of miniature single-stage cooler based on thermoelectric films, the approaches for further improvement in performance, and potential applications in various areas were discussed.

Wednesday, March 27, 2002

In the first presentation on this day, entitled "Sputtering Capabilities for Quantum Well Thermoelectrics", Dr. Jud Virden (Pacific Northwest National Laboratory, Richland, WA) discussed the work being done at PNNL to develop methods to scale up deposition of quantum well thermoelectric devices, with a view to eventually transfer the technology to private industry. The scale-up projects are focused at $Si/Si_{0.2}Ge_{0.8}$ and B_4C/B_9C structures and emphasize high volume, low-cost and heavy truck applications. He described the considerable coating applications and thin film deposition facilities present at PNNL, consisting of both large optics chambers and small box chambers. The recently started TE project would replicate high-Z quantum well structures in mid-size chambers for both $Si/Si_{0.2}Ge_{0.8}$ and B_4C/B_9C quantum wells and scale up the process to accommodate multiple 15 cm or larger substrates, web substrates, plastic roll coater, and magnetron sputtering. Battelle also has in place an internal R&D program to sputter deposit thin films of BiTe for thermoelectric energy conversion which attempts to form thin film TE arrays on flexible substrates so that the TE power sources can be fabricated in relatively small volumes.

The next presentation was delivered by Dr. James Patten (Battelle Columbus Laboratory, Columbus, OH) and was entitled "Department of Energy National Laboratories as Resources for Thermoelectrics R&D". He described the resources of twelve DOE national laboratories (Ames, Argonne, Brookhaven, Idaho, Lawrence Berkeley, Lawrence Livermore, Los Alamos, National Energy Technology Laboratory, National Renewable Energy Laboratory, Oak Ridge, Pacific Northwest, and Sandia) plus other more specialized laboratories. This laboratory system is the largest of its kind in the world, evolving over more than 50 years, focused on human and physical resources, with significant computing capabilities/facilities, remote operation capabilities, virtual co-laboratories, representing 30,000-50,000 scientific and technical staff and over $6 billion in annual R&D. Dr. Patten also discussed the special thermoelectrics capabilities present at the various DOE national laboratories. These include radioisotope thermoelectric generator (RTG) and basic thermoelectric materials research at Sandia, multi-magnetron sputter deposition (in collaboration with Hi-Z) and deposition on heated surfaces at LLNL, thin film and multilayer stack coating processes at PNNL, and modeling and simulation for physical and electronic structure of quantum wells at ANL. He also provided a description of the collaborative funding mechanisms that can be used by individual institutions to take advantage of these considerable resources and technical expertise.

In the next presentation, entitled "Transportation Market Potential of ThermoElectric Devices (TED)", Dr. Sam Ciray (ArvinMeritor Inc., Columbus, IN) described his company's vision related to TEDs. ArvinMeritor is a $7-billion global supplier of a broad range of integrated systems, modules and components to the motor vehicle industry employing 33,000 people at more than 150 manufacturing facilities in 27 countries. It is interested in TEDs because, although today's average vehicle operates at power levels of 1– 2 kW, vehicle electrical system requirements have more than doubled over the last 30 years and are expected to continue to increase at a rate of 5% annually. The creation of an additional 1 kW could result in a fuel savings of 10 – 15% on a medium-sized vehicle. TED devices can also assist in meeting more stringent emissions regulations in both the US market (Tier 2, starting 2007) and the European market (Euro 5, starting in 2008). Competing technologies include fuel cells, advanced batteries and alternators, etc. Unaccounted benefits include better emissions and the use of solid-state components in place of moving parts. The technical challenges include optimizing the package size and ensuring availability of sufficient waste heat at the time of cold start. Some data was presented for preliminary TED testing on exhaust pipes. The company views TED technology as having a strong growth potential in the automotive market. Its initial focus is on recovery of exhaust waste heat. It does not find current devices cost-competitive with batteries and alternators which they must become in order to be viable. It continues with research to develop this technology.

The next presentation, entitled "The Rest of the Story: What Lies Beneath Material Performance and Market Acceptance?" by Dr. Hylan Lyon (Marlow Industries, Dallas, TX), discussed the underlying requirements for the market acceptance of new thermoelectric cooling technology. The initial demand for such technology would come from specialized applications, including those requiring cooling at the point of need, gravity independence, etc. One key parameter to document an improved ZT should be demonstration of maximum temperature differences in excess of bulk materials, since that determines the maximum coefficient of performance (COP). The device considerations include heat pumping capacity, additions to the Altenkirch equation, additional factors besides Altenkirch inclusions, testing, and the loss in ZT with increased size. Using the past as a guide, the successful technology must address present customers (by ensuring price reduction and performance increases over time), niche markets (transitioning to commodity markets), and new entrants (non-US competitors). After the proof of concept, one must focus on the non-transport property aspects of the materials science, where the competing technology price/value sets the requirements. To build upon the "good science" accomplished so far, customers (end users) will have to be engaged in the transition to device feasibility in order to provide explicit device design constraints and objectives. A whole new set of skills are necessary to conduct an honest assessment of the critical criteria to be proven, a rough assessment of whether laboratory results take us to or through the critical design constraints, and an estimate of the difference between laboratory ZT and device ZT for reduced dimension materials.

In the following presentation, entitled "Potential Applications of Quantum Well Thermoelectrics", Dr. Jack Bass (Hi-Z Technology, Inc., San Diego, CA) discussed applications of quantum well in the areas of cooling (using bismuth telluride or Si/SiGe) and power production (using B_4C/B_9C or SiC/Si). Cooling applications can include high voltage low current devices, micro-coolers for IC chips, CCD and IR laser diodes, refrigeration and HVAC systems. Power production applications could include 40 mW generator, low ΔT systems, thermal gradient generators, energy conversion in truck and auto exhaust, self-powered truck and car heaters, and self-powered appliances. Initial applications would be small because of limited material production capability, but will increase over time.

Dr. Francis Stabler (GM Powertrain, Pontiac, MI) made the next presentation, entitled "Automotive Applications for High Efficiency Thermoelectrics," and discussed the automotive thermoelectric applications in the areas of power generation and cooling and heating as well as the concerns and issues for each. Power generation applications could include electric power from exhaust or coolant energy to supplement or replace the conventional generator system, potential fuel fired auxiliary power unit (APU) applications, low power generators for wireless sensors, and solar power systems. Research has shown that while the potential for a thermoelectric radiator to provide 1-2 kW (typical of current day alternators) over a range of engine operating conditions is desirable,

even at low (engine) loads down to 25%, electrical power demands can be met. The low cost of present day alternators, a competing technology, can present a barrier. Concerns and issues include thermal management, start-up time for power generation, cost, interface with the vehicle electrical system (12 or 42 volt systems), shift to hybrid powertrains and engine-off-at-idle function, shift to diesel and lean-burn gasoline engines, and replacement of IC engines with fuel cells. The 1999 GM request for proposal for an electric power generator utilizing engine waste heat includes a list of specific requirements including those of energy source, location, output performance, size, cost, durability, and safety.

Subsequently, Dr. Lon Bell (Amerigon, Irwindale, CA) made a presentation entitled "High Efficiency Thermoelectric Application in Autos and Light Trucks". Amerigon is the world's largest supplier of TE systems for automobiles, currently supplying TE-based climate control systems (CCS) to Ford and Toyota, with production facilities in California, Mexico and China. The usage is expected to expand to most major automobile companies over the next three years (U.S., Europe, Japan, Korea), and the company is projected to become the world's largest commercial user of TEs within one year. It owns or controls 19 issued U.S. patents on TE systems for automobiles. Its CCS's are being used in such vehicle models as 2001 Lexus LS 430, 2003 Ford Expedition, and Infiniti CCS for 2003. Opportunities for advanced TEs include both cooling/heating/ventilation applications (present HVAC system replacement, auxiliary HVAC, HVAC for EVs and hybrids, quiet systems for trailers, vans, campers, defrost/demist, localized temperature control, e.g., instruments, on-board refrigerator, etc.) and power generation (exhaust waste heat recovery, engine coolant waste heat recovery, co-cycle generation, and alternator replacement). There are specific advantages to the use of TE systems in terms of high efficiency and system integration but any new system must be reliable, durable, light weight, cost effective at the system level, and help meet long-term environmental goals. He estimates that considerable opportunity can arise with two times today's figures of merit (ZT) but a real market breakthrough would require four times today's performance for these devices.

In a subsequent presentation entitled "Potential Applications of High Efficiency Thermoelectrics for the Army", Dr. John Prater (Army Research Office, Research Triangle, NC) presented an overview of the history and current status of the DoD Thermoelectric Program, including the paradigm-shifting concepts for TE Materials, e.g., bandgap engineering of electrical properties and phonon engineering. He also discussed the approaches under investigation for realizing improved thermoelectric properties in bulk systems. Army applications of TE devices include areas of cooling of electronics and optics (microelectronics/communications, IR detectors for night vision, temperature stabilization of optics), soldier body cooling (tank & helicopter crews and protective/survival suits), refrigeration & air conditioning (medical supplies), power generation from waste heat (vehicles/shelters/kitchens, remote power, battery recharging, blowers for heating units) and Chameleon IR Surfaces. Significant increase in thermoelectric figure-of-merit has been reported in recent years, in thin films and some bulk materials. New insights have been gained on thermoelectric behavior using a combination of theory and experimental data. However, there are still unexplored ideas and challenges in characterization, particularly for low-dimensional materials. With recent demonstration of high ZT materials, the potential exists for realizing systems with an efficiency of 20%. Continued material development will be required to translate these into practice.

Dr. Hylan Lyon (Marlow Industries, Dallas, TX) made the subsequent presentation entitled "An Overview of the Domestic and International Activities in Thermoelectric Cooling Markets". He discussed the evolution in bulk materials and devices for both domestic and international markets (Japan, FSU, Peoples Republic of China, and Western Europe). For cooling materials, he discussed the shift from Zone Refining to Bridgman furnace materials, as well as the shift by Marlow in 2000 to Micro Alloyed Material (MAM) because of various advantages. Domestically and internationally, device evolutions have occurred in refrigeration, electronic/optical component temperature stabilization/cooling, medical and military, and niche market applications. Dr. Lyon also quoted a communication from Professor Michael Rowe, past president of the International Thermoelectric Society, at the University of Cardiff, Wales, according to which the European Union is actively pursuing opportunities for thermoelectric research with openings in waste heat recovery and nanotechnology. These programs are somewhat like US programs and involve up to seven institutions and at least one industrial partner. The most recent budget across the range of

technology is more than 1 billion US dollars. Segmented and functionally graded materials have been successfully employed in unicouple fabrication and generating performance at least at par with reported US data. In miniature devices, generators, sensors and coolers, Europe may have the edge. Work is also believed to be progressing on a 500 watt isotopic powered thermoelectric generator for possible use by the European space agency. Also, the Japanese researchers are cementing strong bonds with European researchers.

Other Information

As a follow-up to the workshop, DOE invited and obtained from Sehoon Kwak (DaimlerChrysler Corporation) a write-up entitled "Thermoelectric Generators for Wasted Heat Energy Recovery" that presented the DaimlerChrysler perspective on this issue. He stated that current electrical systems for mid- and large-sized vehicles currently have average electrical power loads of 0.8 to 1.5 kW and peak power loads of less than 2 kW, which is projected to rise to 3 to 5 kW in five years. Hence, reclamation of the wasted energy, approximately 60% of the consumed fuel, must be considered for next generation vehicles. One way of accomplishing this energy recovery would be to incorporate thermoelectric devices into the exhaust system. To date, thermoelectric power generators have been primarily employed in space and military applications. Overall efficiency of 5% has made these devices somewhat impractical and expensive for automotive mass-production application. Porsche, General Motors, Nissan, and others have previously investigated thermoelectric power generation, and have concluded similarly. Most systems were based upon bulk Bismuth Telluride (Bi_2Te_3), Lead Telluride (PbTe), and Bismuth Antimony (BiSb). Current devices have improved only slightly over the years and the cost is about $4 to $5 per watt. Therefore, applications have been limited. Recent developments by JPL, Research Triangle Institute, and others, are enabling new applications to be considered. For a viable production application, the system should generate at least 1 kW of net energy in a packaging volume similar to a catalytic converter, and the cost of the system should be less than $0.10 per watt. Continued research in development of efficient thermoelectric materials is very important if thermoelectric is to be applied in the automotive industry. Furthermore, manufacturing and application studies must be carried out in conjunction with material researches to identify and evaluate necessary concepts that will allow efficient and cost effective application of thermoelectrics in the automobile industry. The thermoelectric devices also have the potential to be applied in waste heat recovery from high temperature fuel cell vehicles, directly integrating into the combustion engine for a power generation system, and replacing the refrigerant cycle with an environmentally benign HVAC system. An efficient thermoelectric device will make significant impact on the automobile industry, help reduce the transportation sector's dependence on foreign oil, and also allow an efficient transition of transportation systems from a petroleum to hydrogen base.

Subsequently, the DARPA/ONR MURI Review Panel provided a summary report on the 5th year program review. This report entitled "5th year MURI Review Summary," is included.