Thermoelectrics
Panel Discussions

Panel Discussion I: February 18, 2004.

Moderator: Dr. John Stringer, Electric Power Research Institute

Topic: Are nanotechnology measurement capabilities and fabrication techniques useful to further develop quantum well thermoelectrics (QWT)?

The initial presenters in this panel discussion included Rhonda Willigan of United Technology Research Center (UTRC), Eric Kurman of JDS Uniphase Corporation, and Peter Martin and Suresh Baskaran of the Pacific Northwest National Laboratory (PNNL). Following a short presentation by each, other participants at the High Efficiency Thermoelectrics Workshop joined the discussion.

Rhonda Willigan's presentation related to the Cathodic Arc Deposition (CAD) capabilities at the UTRC. Pratt & Whitney, a UTRC company, has quite extensive capabilities in the area of cathodic arc deposition, potentially a new route for thermoelectrics (TE) utilization. It has three laboratories involved in this process, using two depositors, one or both of which are used for production facilities, probably involved in coating for turbine blades. In general, cathodic arc deposition technique is expensive and time-consuming and process speed-up is needed. Other problems, e.g., high material temperatures and different vapor pressures must also be overcome prior to adapting this process to thermoelectric devices. Eric Kurman presented an overview of the capabilities of JDS Uniphase. That company designs and manufactures products for fiber optic communications and other markets. Their coating laboratory in Santa Rosa, California has extensive experience in developing thin-film based devices, e.g., thin film filters, optical display and projection products, light interference pigments for security and decorative applications, gas and solid state lasers, and laser subsystems. Recent examples of products include electrochromic window specimens developed for the National Renewable Energy Laboratory (NREL), linear variable filters consisting of multilayer interference coatings vacuum deposited on rectangular substrates, which offer continuous spectral coverage within selected wavelength regions, and other products. Suresh Baskaran presented an overview of PNNL capabilities in large area sputter deposition and other related areas.

The open discussion focused on the following four areas:

- Measurement
- Fabrication
- Cost
- System

Measurements

John Stringer (Electric Power Research Institute) opened the discussion by asking the question: how precisely do we need to measure thermoelectric properties, and how could we make it objective? When we get to a point where the sophisticated methods discussed during the workshop get to be applied, we need to have the technology for applicability as well as the reproducibility of results. Do we need predefined standards? Current predictions of thermoelectric figure of merit can be coming from differ-

ent countries (for example, U.S., China, or Mexico). Many of the results are for customized equipment. It may be necessary to report direct results for "Z" or having standardized values for the temperature difference ΔT. Equipment used for measurements from different manufacturers may have different characteristics. Accuracy can become an issue. An accuracy of 1-2 parts per million is not comparable to one part in a thousand.

Hy Lyon stated that, in general, when the customers of the thermoelectric devices start making their own measurements, their results quite frequently do not agree with values reported earlier by the manufacturers of these devices. "Words have all kinds of meanings." So, it may take a while for the customers to come to the same exact definitions as the manufacturers, although eventually the two results do converge. The process of standardization must start with internal standardization, and we need extremely reproducible standards. During the conduct of the Defense Advanced Research Projects Agency (DARPA) thermoelectrics project, similar issues were encountered and it was suggested that a "round-robin" testing of devices be carried out to ensure accuracy of the reported results.

Another participant asked whether there existed any standards for thermoelectric measurements that may have been set up by technical societies?

Lon Bell stated that during the 1960's, certain thermoelectric standards did exist, which probably involved the National Institute of Standards and Technologies (NIST). Subsequently, individual commercial entities involved in developing thermoelectric devices were primarily concerned with addressing the needs of their own particular set of customers and there was not enough motivation for standardization among the companies.

Hy Lyon stated that, at one point, there was an attempt to get the International Thermoelectric Society (ITS) to come up with the relevant thermoelectric standards, but there was a lack of cooperation from that body.

Another participant stated that he had been watching the thermoelectrics industry for the past 2-3 years. The toughest problem he sees is whether any one believes any one else's data. This extends to the point that one company may question if another company is indeed making "big" progress on the ZT values.

Another participant stated that the biggest driving force for standardization may come from the marketplace itself as companies would compete so that their products could be sold to the same consumer on a comparable basis.

Lon Bell commented that the term "ZT" is meaningless for many industries, e.g., the power industry. On the other hand, the cooling industry would reference only the room temperature and would not be interested in the ZT value reported for a higher temperature. His advice was that one should look at the actual "Z" value rather than the "ZT" value.

John Stringer stated that one may need to have the equivalent of an ASTM standard, in order to ascertain the objectivity of the measurements.

Hy Lyon stated that if one is primarily interested in meeting the customers' needs, there currently are no standards. For

example, individual customers of power devices may be very concerned about such extraneous issues as the AC resistance, which may cause a degradation of 5% in the efficiency, but which may not apply to other consumers.

Fabrication

John Stringer asked the question whether there are any fabrication techniques available out there the experience from which could prove useful in the fabrication of thermoelectric devices.

Sarah Cooper (BioTE) stated that printing technology may be useful in thermoelectric fabrication.

Hy Lyon mentioned that thrmoelectrics is different in the sense that the directionality of properties (cubic versus anisotropic) is important for its application.

Rhonda Willigan (UTRC) stated that we need both faster and cheaper fabrication techniques and devices for thermoelectrics.

Cost

Suresh Baskaran asked the question whether techniques used in other transportation applications can be used in thermoelectrics to bring down the cost.

Eric Kurman stated that the thermoelectrics industry is not large enough to buy the raw material in sufficiently large quantities to bring down the cost. The situation is more like a car dealership, where the choices are limited to what is available. Over time, the material cost may come down, however.

Another participant stated that for the auto industry, over the past 25 years, there was a dramatic drop in cost. There are a lot of parallels between the thermoelectrics and the Micro-Electro-Mechanical Systems (MEMS) technology (the integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate). There is a lot of potential, if only people think creatively and independently.

Sarah Cooper (BioTE) stated that it is very difficult to find a system which will allow one to play around with the equipment, with a view to bring down the cost.

Gang Chen (MIT) stated that it is unclear how much the industry is willing to invest. So far, there has not been any serious industry investment.

David Lott (General Dynamics Land Systems) mentioned that the hybrid electric vehicle drive technology underwent a similar experience about five year ago (the components were too heavy, etc.) He himself was not aware of thermoelectric devices until the paper from General Motors came to his attention. Then he started seeing many thermoelectrics applications (for example, for the water cooling system) and many ideas came to his mind. The problem, as he sees it, is that a lot of people are unaware of this technology. He indicated that he will be in touch with individuals from the Hi-Z technology and others to investigate how the latest breakthroughs in the field could be leveraged most effectively. It will be interesting to find out whether we are looking at perhaps another 20 years of development or whether a lot of this technology is already usable? Regarding the question of whether “we are ready to move on to thermoelectrics” given the information so far, the answer is yes! Essentially, utilization thermoelectricity represents “money for nothing”. That is the

reason why companies such as GM, and others, are interested in this technology and attending the workshop.

System

Sarah Cooper (BioTE) stated that one obstacle that thermoelectrics faces is that many companies are still thinking "bulk" and the nano idea has not penetrated yet.

Another participant stated that he would be willing to bet a significant amount if someone were to prove that a good "system" can be constructed that can be of value to the army, navy, etc.

Terry Hendricks (National Renewable Energy Laboratory) stated that the thermoelectric systems would require a lot of components, contains a very involved design which can be very time consuming to produce.

Another participant stated that he personally believes in thermoelectrics, but the industry needs to be made into a believer, too.

Francis Stabler (General Motors) stated that, in the past, the auto industry had a lot of inertia in adapting a new technology. If a product were already available, the industry was very unlikely to go and develop it. If you were to get something that already works, they would be inclined to use it, but it is hard to convince the industry to change.

Hy Lyon stated that the number of guidelines for thermoelectric systems is not articulated and is difficult to define. The problem is that the failure modes are not defined. Customers would not be able to know if a new product like a thermoelectric device will not "blow up".

Francis Stabler agreed, stating that it does not take a lot of failings to cause an automobile recall.

Hy Lyon further stated that there are millions of thermoelectric products already out there, yet one still can not predict the failure modes accurately, for example, whether the heat sink will fail first or whether the wires would corrode, etc. All kind of "crazy things" can take place causing the system to fail. From the customer's perspective, it does not matter exactly what caused a device to fail, the customer tends to blame the vendor from which the product was purchased.

A representative from Caterpillar, Incorporated explained that Caterpillar looked at thermoelectrics for the past 1.5 years. From Caterpillar's perspective, the following needs to be done: the thermoelectric measurements need an independent verification and the efficiency of the devices needs to be represented as the true conversion efficiency at the module level. Once that is accomplished, one can look at integrating thermoelectric devices into systems. Then one needs to know how much the device is going to cost. It would be necessary to verify exactly how much the customer would be willing to pay for a few more percentage point increases in the thermal efficiency. For the thermoelectric technology to be acceptable to the customers, the cost definitely needs to be less than "1,000's of dollars per kilowatt."

After the above discussion, this panel discussion was concluded.

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Panel Discussion II: February 20, 2004.

Moderator: Dr. John Stringer, Electric Power Research Institute

Topic: What parameters would be necessary for acceptable risk for commercialization?

At the beginning of this discussion, Eric Kurman presented additional information regarding manufacturing facilities and techniques in use at JDS Uniphase. This was followed by open discussions.

The open discussion established the following items as necessary for commercialization:

- Parameters
  - Reproducibility
  - Durability
  - Capacity (second source qualification)
  - Size of Market
  - Suppliers' Risk
- Customer Stability
- Component Supplier
  - Security of Supply
- Small production versus large production
- "Push to the limit"
- Cost risk of failure
- Roadmap
  - Stakeholders
  - Destinations
  - Exchange between laboratory material science and device developer
  - Development of basic building block

The participants stated that stability, reliability, durability, etc. are all necessary for manufacturers to consider the commercial risk acceptable. Customers do not want proprietary solutions. Commodity solutions may be acceptable. Cost is of primary concern.

The security of the supply source is also of serious concern. For example, for products manufactured in Asia, unpredictable developments like outbreaks of the severe acute respiratory syndrome (SARS) may become concern for manufacturers who may be counting on the supply of items manufactured in the affected regions. Manufacturers like to have a fallback option or assurance that such an option may be available.

The lifetime of the component may also become important, depending on the application. For example, for automobiles, a shorter thermoelectric device lifetime may be acceptable than, for example, for space applications. The performance degradation (power loss) over time may also be of concern.

A certain minimum market size may be necessary to make a thermoelectric product viable from the manufacturer's point of view. In the past certain thermoelectric products may have had a degree of success in niche markets, but the requirements for success in the mass market are much more challenging. A mass manufacturer, unless he sees "the light at the end of the tunnel," is simply not going to take the risk of commercialization. The manufacturer requires a minimum market size. The avail-

ability of cost effective, high volume processes is also a must. In order that a manufacturer can get a clearer picture of the potential success of a novel thermoelectric device, he also must have a clear idea of what the competing technology is going to be.

Hy Lyon said that, even under the best of conditions, customers may want to push to limit, for example, by demanding the maximum coefficient of expansion, the maximum efficiency, etc. There is no "design market". Even if the customers get the already high "ZT" values of 2 or 3, they will still push for higher performance numbers wherever possible, eventually pressing every component in the assembly process.

Hy Lyon also stated that thermoelectrics is not necessarily always reliable. A thermoelectric device needs to be carefully designed for specific applications. However, even some of the best-designed devices can be considered unusable because they may not be reliable from the customer's perspective.

Another participant stated that commercial entities would like to see more empirical data related to thermoelectrics. However, large-scale commercialization may have to wait for years of development. There is a lot of fundamental work ongoing, but a considerable amount of verification testing may still be needed.

Another participant brought up the issue of intellectual property. Many developers may harbor an "illusion of richness" related to the potential of their research work, which may provide a commercial disincentive for them to share their research findings with others. It was suggested that it would probably be a good idea for the Department of Energy or other neutral thirds parties to independently evaluate all existing thermoelectric technologies and their potential. Unfortunately, the resources and time required for such an undertaking might prove stumbling blocks. The situation for thermoelectrics may be different from some other areas (e.g., fuel cells) where the industry heavily relies on the Federal government and its resources (the national laboratories) to provide guidance and to advance the science to make the product commercially feasible. For thermoelectrics, it is extremely important to ensure that independent test data is available and that the developers follow standards which are universally agreed upon. A suggestion was made that an excellent mechanism for accomplishing this could be via cooperative research and development agreements (CRADAs). The private sector can share in the cost and the government can assume the role of an intermediary/arbiter in such an agreement.

The above comments were followed by a discussion of how a possible roadmap could be developed to chart out further efforts to facilitate the commercial acceptability of thermoelectric devices and to reduce the commercial risks associated with them. It was stated that the roadmap would have to take into account diverse factors such as the stakeholders (manufacturers), destinations (consumer markets), interactions between laboratory material science and device developers, and the basic building blocks of development. In order to make such a roadmap acceptable, it needs to include a lot of comments from

everybody. Since such a document would be developed from the scratch, a number of cases and scenarios can be proposed. However, in order to make it credible, the draft needs to be shared by the peers in the high-efficiency thermoelectrics community and every one needs to be on the same page and seeing the same value in this work.

The specific example of dynamic random access memory (DRAM) chips and other related technologies was brought up by a participant, who stated that the successful market adoption of those technologies provide a paradigm for thermoelectric devices. It was stated that for thermoelectrics, all the necessary elements are indeed present, just as they were for the memory chip technologies. Many aspects of these technologies may be adaptable to thermoelectrics and used to make thermoelectric devices commercially feasible.

After the above discussion and an expression of thanks to the participants by John Fairbanks, the panel discussion session was concluded.