PARADIGM SHIFT IN SOLID-STATE COOLING, HEATING AND TEMPERATURE CONTROL

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1.0 Abstract

The performance of thermoelectric materials and the systems that utilize them did not change appreciably between 1960 and 2000. The slow change and low efficiency muted interest in the technology. However, in the past two years, advances in the basic material and system-level thermodynamic cycles, have led to a projected four-fold increase in performance. This paradigm shift, new uses enabled by the improvements, and potential new markets for the technology are discussed. It is suggested that multi-billion dollar markets can result from the recent improvements.

2.0 Background

For the past forty years, thermoelectric (TE) and thermionic (TI) devices have shown great promise because of the obvious advantages derivable from the potential use of solid-state technology for cooling, heating and power generation. A paradigm shift, similar to that experienced by solid-state electronics with transistors and integrated circuits was expected. Certainly, some devices were enabled by the technology including sensor coolers for infrared and night vision systems, portable coolers, automotive seat cooler/heaters, remotely operated power generators, and a few others. Nevertheless, in the intervening years, the basic promise was not fulfilled to the extent anticipated.

The fundamental reason for the slow progress has been that in the 1960s, the intrinsic efficiency of TE systems was about one-fourth that of two-phase refrigeration systems (Freon 12, R134A and the like). It has barely increased since then. Unlike Moore’s Law, which chronicles the doubling of solid-state computer performance every eighteen months, TE and TI average performance has grown about 1.0% every four years! The lack of improvement, coupled with very low intrinsic efficiencies, has limited product applications to low-volume, high-cost niches and thus, discouraged funding of the technology by industry, military and university research organizations.

3.0 Recent Developments

In the early 1990s, the prospects for fabricating nano-size structures and creating engineered heterostructure materials led to a second look at creating more efficient TE materials. To this end, DARPA, ONR and DOE initiated and sponsored a long-term, multi-faceted activity with the goal of increasing TE system performance by a factor of about 3. Radical new approaches were taken by participating institutions and companies to achieve such performance increase. However, virtually no incremental gains were exhibited throughout the balance of the 1990s and progress appeared to be slow. Then, in 2001, Venkatasubramanian(1) at RTI announced in Nature, a heterostructure material system with substantial performance gains of 60% to 120%. This achievement was followed in 2002 by Harman(2) at MIT Lincoln Labs who presented in Science, improvements of about 60%. It is noteworthy that the two approaches, while exhibiting similar results, employed very different material systems and structures, so that within the two years, two independent (and significant) advancements came to fruition.

Performance of TE materials can be characterized in terms of a figure of merit called ZT. ZT is a direct, albeit complex, measure of material capability and efficiency. It also defines performance limits for TE devices (TI devices have a similar, related and comparable measure). Restating early results, between the years 1960 and 2000, the maximum value for ZT increased from about 0.9 to about 1.0. By 2002, values between 1.6 and 2.4 had been announced(1,2) in laboratory samples.

Recent reports suggest that other independent approaches, including quantum confinement(3) and TI(4,5) nanostructures, may yield comparable improvements in performance.

In parallel to the recent focus on material advancements, this author(6,7) and Diller(8) at BSST, Ghoshal(9) at IBM, and Echigo and later Tada(10) at Tokyo Institute of Technology have explored alternative thermodynamic cycles that can employ whatever TE materials are available to achieve higher overall system efficiency. Earlier this year, this author announced gains of 100% to 120% for systems such as air conditioning and Goshal announced 60% gains for applications such as chip cooling.

Table I presents a summary of these advancements. The Table includes incremental improvements, some of which have been realized for specific applications, as well as estimates for those that seem possible based on known losses in today's systems. Principal sources for the gains are the use of newer ancillary materials (such as heat pipes) and advancements transferable from the semi-conductor industry, including lower interfacial resistance and improved material processing.

Primary Sources of TE System Performance Gains	
Materials BiTe Thermoelectrics (1990s) Heterostructure (2000-2002)	 +60 to 160%
Thermodynamic Cycle Isolated Element (2000-2002) Convection (2001-2002)	 100 to 120% 30 to 80%
Materials/Design Incremental improvements (1960-2002) New ancillary materials and components (1960-2002)	 10% up to 10%

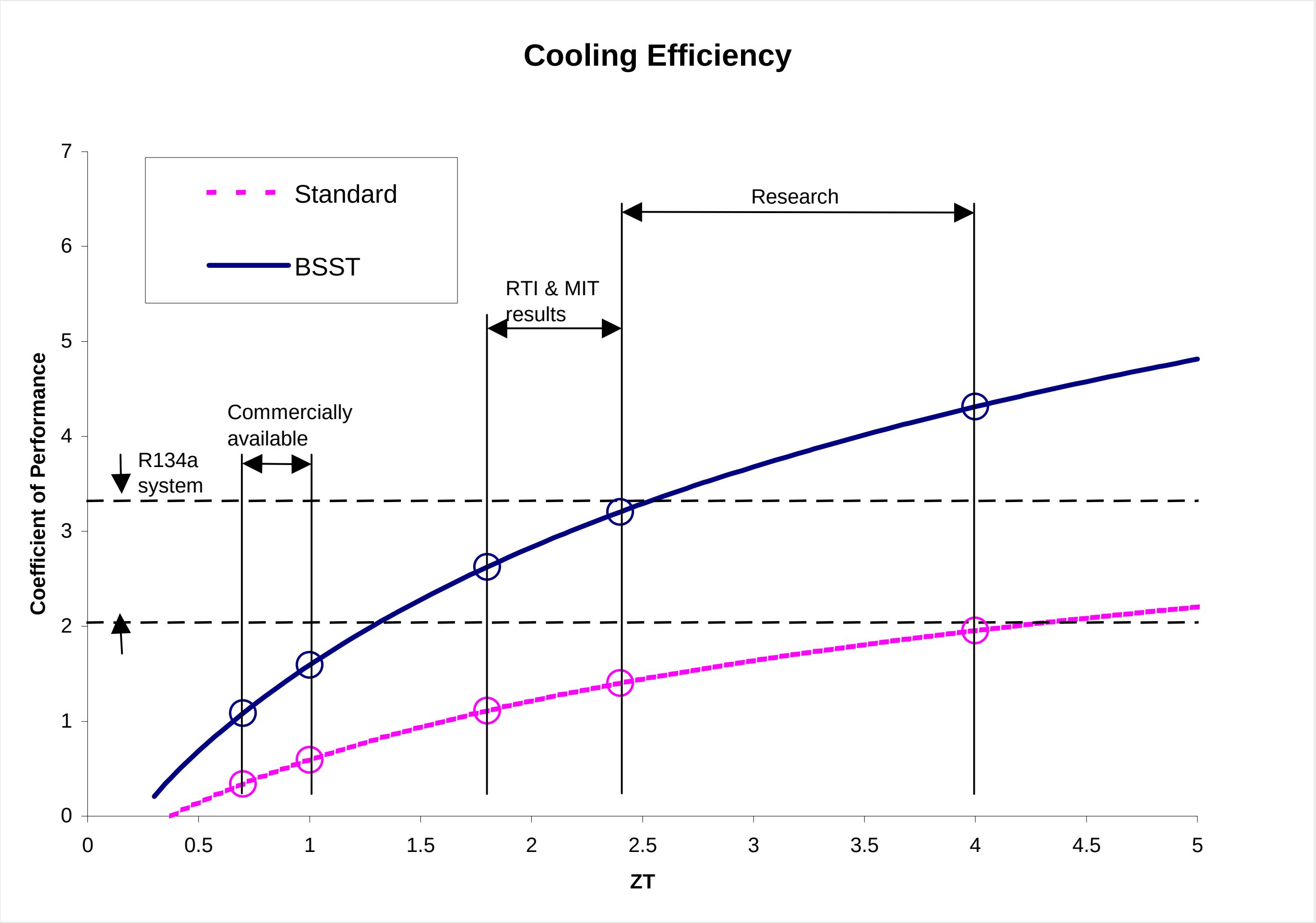
Table 1

The nature of the material advancements and thermodynamic cycle improvements are such that they can be combined so as to approximately multiply the gains. For example, in air conditioning systems, the combined performance should increase by about a factor of four and thus, prove to be comparable to that of today's compressor-based systems. Similarly, the advancements can be combined in power generation systems and have the prospect of leading to equally substantial performance gains. Verification of the expected performance gains awaits the availability of module-size TE devices made from the new materials.

Devices employing the new technologies can be expected to have characteristics that differ from their present counterparts that utilize refrigerants. They probably will be lighter, smaller, have fewer moving parts and fewer, if any, mechanical connections. They will interface more efficiently with other solid-state devices. Further, they are likely to be faster, their performance should be more adjustable, and they should be quieter. However, they will have somewhat larger and more complex heat exchangers. Also, it should be noted that performance for refrigeration applications (home and industrial refrigerators) unlike other usage, will be less efficient than that of present systems until a ZT of at least 5 is achieved.

Models exist from several industrial sources(11) and texts (12) that allow accurate prediction of TE performance. At BSST, such models have been developed and used to simulate TE system performance that incorporates both the effect of an increase in ZT and the BSST thermodynamic cycle.

Figure 1 shows the projected performance for an automotive HVAC system using these models as well as measured available input parameters. The benefits of the combined TE technologies are evident in the Figure. The horizontal axis is ZT. The vertical axis is efficiency (that is COP, the Coefficient of Performance of an air conditioner). Vertical lines indicate a particular value of ZT; for example, present materials have ZT between 0.7 and 1.0, and the RTI and MIT materials are about 1.6 to 2.4. The lower curve is for conventional TE cycle and the upper curve is with the BSST thermodynamic cycle.



The dashed horizontal lines labeled "R134 A System" bound the limits of today's automotive HVAC performance. A range performance for R134A is shown since under various automotive conditions, the performance of R134A and TEs of a specified ZT do not equate precisely, but result in the performance band shown. It is evident from Figure 1 that with existing commercial materials (ZT of 0.7 to 1.0) and the prior thermodynamic cycle, TE system performance is far off the mark. However, at a ZT of 1.8 and above with the BSST cycle, solid-state TE systems are projected to be competitive with today's HVAC systems.

The Figure indicates the potential impact of research now underway that targets still higher values of ZT, so that with time, there is the prospect of continued improvement in the performance of TE systems. Should such further improvements occur, the competitive advantage of the solid-state systems would widen over that of today's systems.

The combination of advancements described above, should enable TE systems to compete favorably, over the medium and long term, with present HVAC systems and their more environmentally friendly replacements that are now under evaluation and development in Europe and Japan.

A similar analysis can be applied to other market sectors to develop a more comprehensive understanding of the opportunity presented by advanced TE systems.

Table II presents a means of expressing some of the important market sectors that could be impacted by such advancements over time. The columns entitled "Cycle" are for the present cycle and the BSST cycle. The rows are for present TE materials, materials with a ZT of 2 (ZT2) and of 4 (ZT4). The cells indicate the combinations of ZT and cycle that enable TE-based devices to have performance competitive with existing technology, and thus, have the possibility of penetrating the named markets. It is apparent that if a material with a ZT larger than the value associated with a particular cell were to become available, the components in that cell (as well as cells above it) would achieve a further performance advantage by utilizing the improved material.

Cycle / ZT	**Present**	**New Cycle**
Present	· Infrared sensors · Refrigerators - Portable - Mini - Desk top · Bio-analysis · Vehicle seats	· HVAC - Vehicle auxiliary and spot (quiet) - Spot personal protective clothing - Industrial instruments - Computer - Telecommunications - Demist
ZT2	· Refrigeration - Small home (quiet) - Hotel room (quiet) · Temperature control - Communications - Electronic components · Biosynthesis	· HVAC - Home heat pump - Hotel room (quiet) - Industrial - Car - Commercial - Protective clothing · Humidity control · Power generation - Automotive waste/stationary waste - Military - Aerospace
ZT4	· Refrigeration - Small home - Hotel room	· HVAC - Energy-savings · Power generation - Co-cycle - Primary

Table II

An important consideration when evaluating TE technology, is to note that two unique characteristics, solid-state energy conversion and the ability to cool, heat and generate power with very small devices, allows such usage for localized (spot) as well as for wide-area (distributed) applications. Localized functionality is unique to TE (and possibly later, TI) systems. Thus, the technology provides new capability and the potential for use in important new applications, as designers become familiar with TE systems technology.

While the BSST advanced cycle can be designed into systems today, it will take time to realize the benefits of the new heterostructure materials. They will take the preparation, learning, and scaling up of specialized production semi-conductor-like processes and equipment. Also, significant development activities may be required to achieve the full predicted performance advantages. These issues will take some time to be resolved, so that the materials may take two to four years to become broadly available. Costs are uncertain until manufacture and usage are better understood. Nevertheless, it can be expected that, as with semi-conductor fabrication, costs will be driven more by processing and yields than by the intrinsic cost of materials, at least until the new technologies mature.

4.0 Summary and Conclusions

TE (and possibly TI) technology has taken a very significant leap in the past two years after being essentially stagnant for the previous forty years. This paradigm shift of up to a four-fold efficiency increase offers the prospect that the technology can enter the main stream for cooling, heating and certain power generation applications. Together, these uses constitute multi-billion dollar markets, and include the appliance, automotive, biotechnology, communications, consumer, industrial, medical and military markets, to name those most evident.

Long-term trends favor conversion from electromechanical systems with their complexity, reliability and environmental drawbacks, to solid-state systems with few or no moving parts and the associated ability to directly interface with electrical power systems. As a result, and with a sense of urgency, TE technology should be factored into the strategic planning process of businesses that could be impacted by such a shift.

As the invention of the transistor led to the semi-conductor revolution, and the laser to advances in data storage, medical processes and communication, in a more modest way, solid-state cooling, heating and power generation can lead to a new energy-conversion products and the long-term displacement of TE electromechanical systems that are produced today.

5.0 References

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