THERMOELECTRICS:
Energy usage reduction through Solid State cooling/heating and waste heat recovery

Submitting Organization

BSST LLC.

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AN AREA OF CRITICAL NATIONAL NEED

On June 26, 2009, the U.S. House of Representatives passed a landmark climate bill, the American Clean Energy and Security (ACES) Act of 2009. According to President Obama, if ACES passes the Senate, it "will spark a clean energy transformation," reducing "our dependence on foreign oil," and spur "the development of low carbon sources of energy"; most importantly, this legislation will "make possible the creation of millions of new jobs," making "clean energy the profitable kind of energy" (Obama, June 27, 2009). President Obama added that the bill's incentives "will lead to the creation of new businesses and entire new industries . . . [and] to American jobs that pay well and cannot be outsourced" (Obama, June 27, 2009). As the passage of the ACES in the House shows, clean energy, efficient energy use, and high quality domestic jobs are at the forefront of our nation's priorities and in the minds of U.S. policymakers.

One method for reducing emissions and oil consumption is to improve energy conversion efficiency in key energy consuming sectors. According to a report by the 2008 American Physical Society:

> *Whether you want the United States to achieve greater energy security by weaning itself off foreign oil, sustain strong economic growth in the face of worldwide competition or reduce global warming by decreasing carbon emissions, energy efficiency is where you need to start.* (Richter, p. S7)

The largest overall consumers of energy in the U.S. are commercial and residential buildings and transportation, which consume roughly 69% of energy; industry consumes the remaining 31% (U.S. DOE, "Annual Energy Review"). Building and transportation sectors also generate 70% of total domestic carbon emissions. Transportation itself represents more than 30% of our carbon emissions and 70% of the petroleum used for fuel (Richter, pp. S2, S21). Therefore, transportation not only contributes to global warming, it is also one of the largest contributors to our dependence on foreign oil.

Consequently, these two sectors offer the greatest opportunity for substantial improvement in the nation's overall energy utilization efficiency and emission reduction. Even moderate success would dramatically decrease our dependence on foreign oil in a relatively short time:

> *Of all policy and technology options, the one that has the greatest potential in the next two decades is improving energy efficiency, particularly end-use efficiency in buildings and transportation.* (Richter, p. S21)

A key way of significantly improving efficiency is by harvesting energy from the waste heat generated. More than 55% of the primary energy we generate in the United States is lost to waste heat (PCAST). Figure 1 shows the breakdown between the various contributing sectors and the energy flow from generation to final use. The Figure shows energy streams in terms of a common energy unit: quadrillion BTU (10^{15} BTU or 1.055 x 10^{18} joules of energy). The energy inputs are on the left, while the balance of used and wasted energy is on the right.

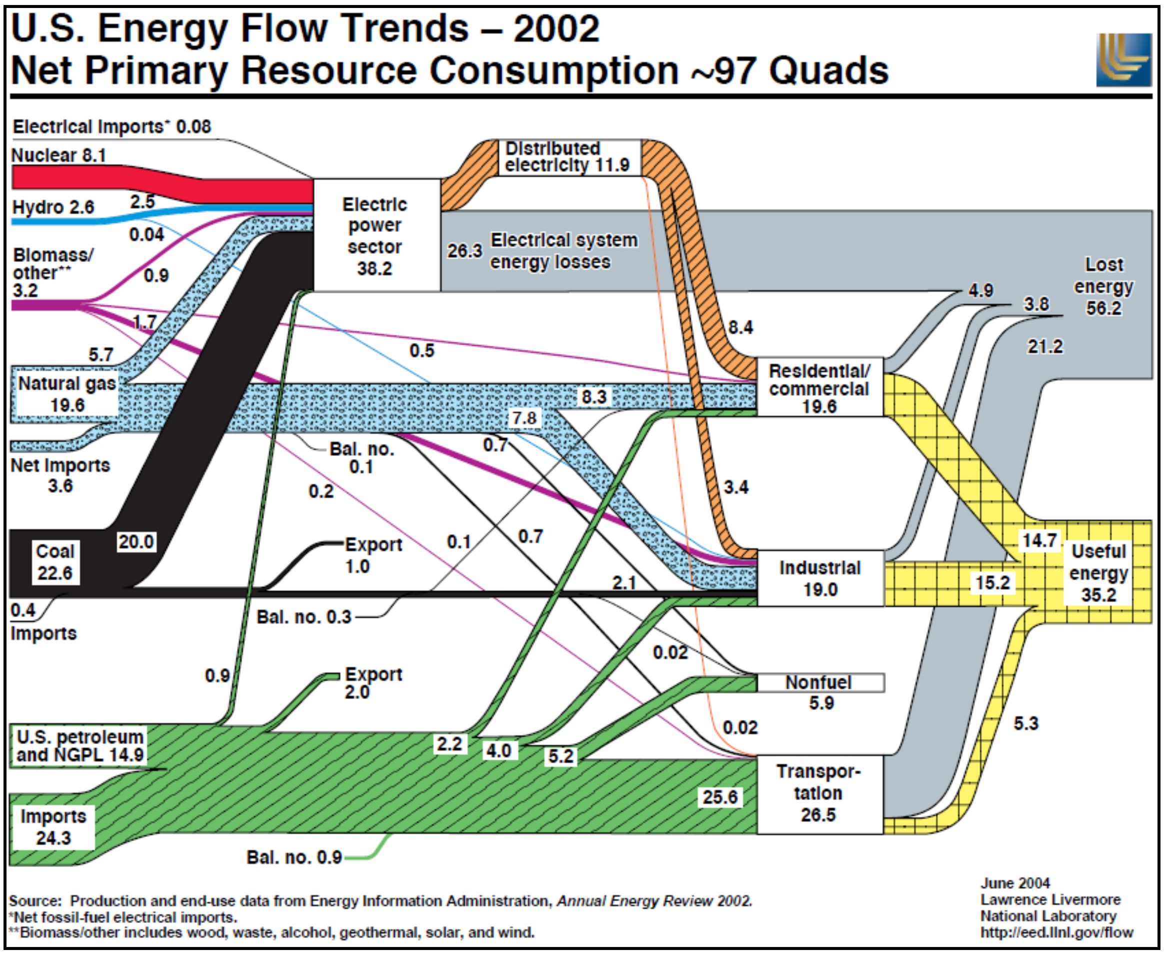

Figure 1. U.S. Energy Flow Chart summarizes energy streams across the national economy in terms of a common energy unit: quadrillion BTU (10^{15} BTU or 1.055 x 10^{18} joules of energy). The energy inputs are on the left, while the balance of used and wasted energy is on the right. (Kaiper)

As Figure 1 shows, of transportation's 26.6 quads of energy consumed, only 5.3 quads, or 20%, are converted to useful energy. For buildings, the apparent efficiency is 75%; however, 43% of the energy consumed in buildings is electrical. The electricity generation and distribution process is only 31% efficient. Therefore, the actual energy efficiency of buildings is closer to 38.

This white paper outlines an opportunity to address energy efficiency in transportation and buildings by effectively using thermoelectric (TE) materials in heat pumps that can provide more efficient temperature control and in heat engines that convert waste heat to electrical power. Recovery of energy from these sources of waste heat and energy usage reductions represent an opportunity for improving overall energy efficiency in the United States, and therefore, a path to reducing CO2 emissions and our dependence on foreign oil and providing pollutant-free climate control. This paper also describes the associated technical challenges that need to be addressed.

MAGNITUDE OF THE PROBLEM

Figure 2 shows a detailed breakdown of 2006 energy usage by industrial sector in the United States. In 2006, buildings accounted for 39% of the nation's primary energy consumption, 72% of the nation's electricity, and produced about 36% of the nation's total CO_2 associated with the annual energy consumption.

Transportation in 2006 represented more than 30% of our carbon emissions and 70% of the petroleum used for fuel (Richter, p. S28).

In the transportation sector alone, the United States uses 8 million barrels of oil a day for passenger vehicles. Each percentage point of improvement in fuel efficiency of cars is equivalent to saving 80,000 barrels of oil a day, or 29.2 million barrels of oil annually. If the fuel efficiency in passenger transportation is improved by 6.3%, the amount of saved oil is comparable to the estimated oil production at the Arctic National Wildlife Refuge if it is opened for drilling (U.S. DOE, "Analysis"). Saving 80,000 barrels of oil each day can greatly decrease the U.S. need for foreign oil.

In addition to decreasing our dependence on foreign oil, the United States needs to reduce CO_2 and other atmospheric pollutants. For example, R-134a (1,1,1,2-Tetrafluoroethane), a commonly used refrigerant, has 1,300 times the greenhouse gas effect of CO_2. A December 2008 report by the Energy Information Administration claims that vehicles in the U.S. leaked the amount of R-134a into the atmosphere equivalent to over 72 million tons of CO_2 . Eliminating or reducing the usage of these refrigerants will significantly reduce total greenhouse gas emissions (U.S. DOE, "Emissions") Therefore, transportation not only contributes to global warming, it greatly increases our dependence on imported oil. Improving energy efficiency in the transportation sector is vital to reducing the production of greenhouse gases and to reducing overall oil consumption.

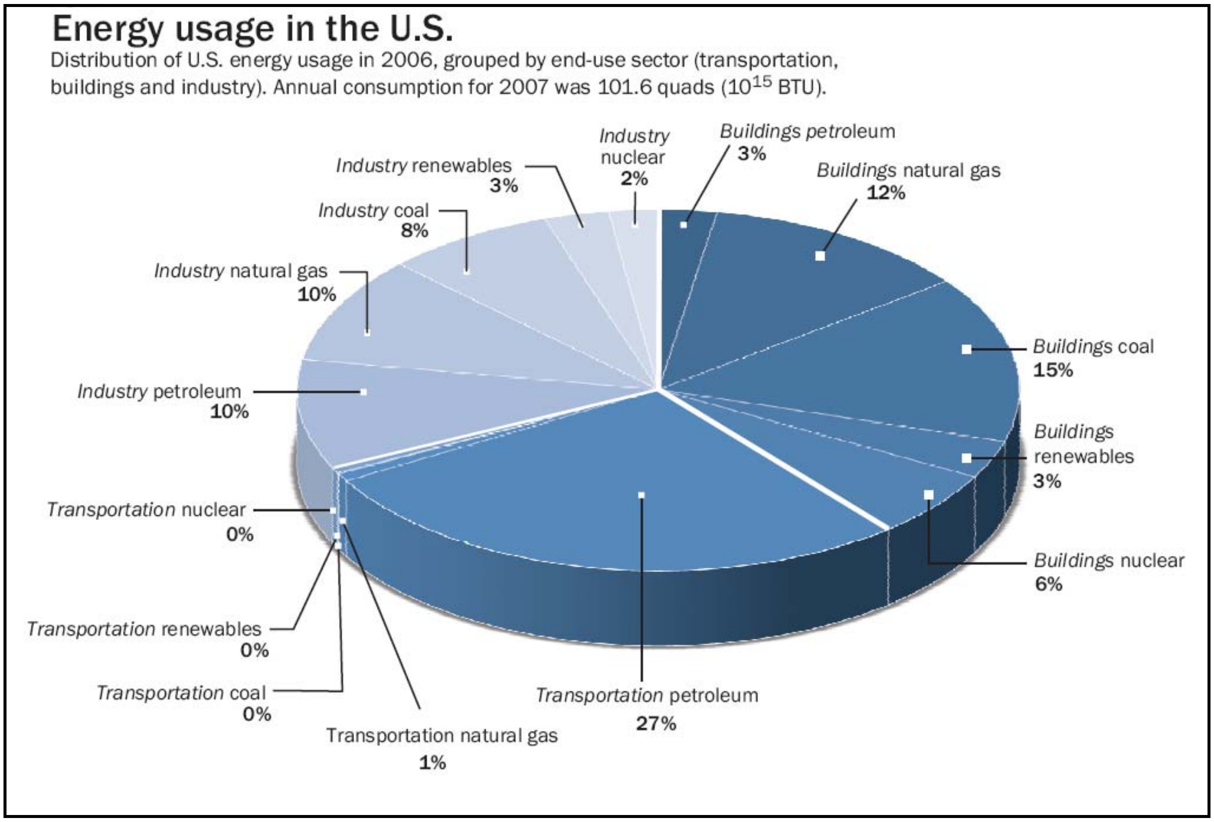

Figure 2. Energy usage in the U.S. This chart shows a detailed breakdown of energy usage by sector in the United States in 2006. According to the chart, the largest consumers of energy in the United States are commercial and residential buildings and transportation. (Richter, p. S21)

MAPPING TO NATIONAL OBJECTIVES

TE devices work by generating electricity when a temperature differential is applied across the device; this power generation mode is based on the *Seebeck effect*. Alternatively, TE devices can work as heat pumps to produce cold and heat when electric current is passed through the device; this reverse process is called the *Peltier effect* (Bell, "Science").

To date, TE materials have proven highly reliable in niche applications, such as remote power generation in harsh environments on land and in robust, dependable, maintenance free power sources in space. These uses have been enabled by the superior stability and reliability properties, and, in spite of TE system efficiency below 5%, due to the performance limitations of commercially available TE materials (Hendrics). However, TE materials research has resulted recently in a series of fundamental breakthroughs in high performance bulk nanostructured thermoelectric materials. (For more detailed information about recent successes in the materials field, see a recent review by A. J. Minnich, M. S. Dresselhaus, Z. F. Ren, and G. Chen.) These results enable the potential to recover 10-15% of the energy from waste heat in a variety of processes. With these improvement gains, TE can become the technology of choice for many new heat engine applications.

The performance of TE materials is characterized by a dimensionless parameter, ZT. The figure of merit, Z, is a function of the physical properties of the material; T is the absolute temperature. Higher ZT translates into higher device efficiency, both for climate control (heat pump) and power generation (heat engine) devices. Modern commercially available heating/cooling and power generation TE materials have ZT in the range of 0.8 to 1.0, and have a material energy conversion efficiency of roughly 1/6 of the possible maximum (Carnot) efficiency. Recent developments in TE materials demonstrated improvement of ZT to ~1.5 and an energy conversion efficiency rising to ~1/4 of the Carnot limit, a vast improvement over commercial state-of-the-art devices.

Historically, progress in TE materials has lagged behind that in other domains of solid-state technology, such as microelectronics, photovoltaics, and lighting. If technology is transitioned into manufacturing rapidly and efficiently, however, the recent advancements in bulk TE materials for power generation enable attractive and practical waste heat recovery solutions. Additionally, the fundamental principles behind recent breakthroughs in power generation materials are currently being applied to lower temperature TE materials, which are commonly used for heating and cooling applications. If successful, advanced TE technology will mature rapidly to address the challenges of energy-efficient climate control in tomorrow's buildings and cars. Advanced TE materials provide a high-reward program area that can noticeably increase energy efficiency in many different applications. Even with the demonstrated performance improvements, there are still formidable challenges for migration of TE technology into mainstream applications. The challenges involve transferring technology to the private sector, scaling up of manufacturing processes, and solving a variety of materials and engineering problems that are associated with integrating materials into devices that function under strenuous thermal and mechanical conditions. An additional challenge currently is the worldwide economic crisis, which has resulted in an uncertain business environment; therefore, companies and investors, who are normally proactive in technology development, have subordinated their R&D initiatives to address the seemingly more immediate need of short term operations. In such a difficult economic environment, targeted investment by government is more important than ever.

MEETING A TIMELY NEED NOT MET BY OTHER TECHNOLOGIES

Other government agencies, such as the DOE and DOD (mostly through DARPA and ONR), have provided significant investment in advanced TE materials research. However, gaps still exist that prevent commercialization of the advanced TE materials. As stated previously, new high-efficiency TE materials have been fabricated in research laboratories. Now two issues must be addressed to effectively capitalize on the successful research and apply it in the private sector. First, an efficient, rapid process must be employed to bridge the gap between laboratory success and large scale commercial production:

> *The time it takes for new thermoelectric materials to make the transition from first announcement in peer reviewed publications to*

> *commercialization is undesirably long. As a result, universities, laboratories, government agencies, commercial users, and venture funding providers throughout the world have not supported research in the [TE] field to the level that would be expected for such an otherwise promising technology.* (Bell, "Addressing")

Second, without proper and reliable funding, many of the considerable societal benefits from the pioneering R&D done in the United States may be lost to better financed opportunistic foreign competitors. Worldwide, basic and applied research in advanced thermoelectric materials and vehicle applications, including waste heat conversion to power, heating, and cooling, is taking place at an unprecedented level. China, Japan, Europe and Russia already have programs to synthesize new TE materials and to develop subsystems for applications in the automotive and other markets. Russia's Rusnano Project, for example, includes funding for development of advanced thermoelectric materials. The EU project, HeatReCar, reduces energy consumption by massive thermoelectric waste heat recovery in light duty trucks (Fairbanks). A Japanese team recently visited the U.S. DOE and "selected U.S. companies to debrief the results of their five-year national project in waste heat recovery" (BSST). The program's results were "positive" and the "second five-year program" is scheduled to start soon, with increased participation from industry (BSST). Japan's program of power generation from automotive exhaust gas, with an advanced TE material developed in 2007, promises a payback period of fewer than seven years.

As Figure 3 illustrates, there are two high-reward TE applications: waste heat recovery and climate control. The advanced, bulk mid-temperature TE materials used in the waste heat recovery applications have been proven in the academic laboratories. Superior properties have already been demonstrated in the laboratory for the TE materials that are best suited for waste heat recovery; these TE materials, therefore, are closer to the manufacturing stage and to commercial success in the private sector. These successful TE products enable a $29 billion industry, and, based on their advanced state of material readiness, have a lower associated risk than the advanced TE materials that climate control applications need.

Because high-efficiency, bulk lower temperature TE materials for climate control are trailing the progress of the higher temperature TE materials of power generation, climate control's commercialization risk is higher. However, verifiable performance improvements of the lower temperature TE materials will enable a massive $31 billion industry *in the automotive sector alone.*

Advanced TE materials open up new, highly lucrative, markets to a broad cross section of industries. The following entities should be encouraged to develop proposals within the identified areas, either individually or preferably teamed in consortia with broad charter to take the technology to commercial readiness:

Type of the organization	**Potential use of TIP funds**
Academic entities	• Facilitate technology transfer to commercial sector • Expand existing innovations in material science to wider

	variety of materials with emphasis on low cost, environmentally friendly material systems • Expand research into applications and system demonstrations
Electronic material manufacturers	• Diversify into thermoelectrics as a field adjacent to existing businesses • Validate academic results • Scale up manufacturing processes • Address device integration needs such as mechanical robustness and low loss electrical interfaces • Early-on establish recycling procedures for materials of concern
Companies presently operating in thermoelectric market	• Validate academic results • Apply existing manufacturing techniques to new materials • Address device integration needs such as mechanical robustness and low loss electrical interfaces • Design advanced materials into devices and applications • Model the device performance • Manufacture components and sub-systems
System integrators, such as automotive OEMs and Tier-1 manufacturers, and providers of climate control solutions	• Specify the end-user requirements for TE materials and sub-systems • Incorporate device models into system models, assess the system-level impacts, provide feedback to developers • Incorporate devices into systems, test comprehensively • Design the devices into products

If it is in the interest of the U. S. to remain a leader in advanced TE technology, and in TE's over $50 billion commercial potential, the U.S. government must continue funding TE research, and facilitate bridging the gap between this research and the needs in the private sector's for TE-material based products.

SOCIETAL CHALLENGES ADDRESSABLE BY ADVANCED TE MATERIALS

The increased energy efficiency that advanced TE materials provide through waste heat recovery and the reduced CO_2 emissions through solid-state cooling can greatly assist in mitigating global warming as discussed above. In addition to helping our environment, these improved TE materials can help the U.S. to maintain a strong technological leadership position. More efficient TE materials, with increased ZT, will provide helpful societal benefits, including more efficient use of energy, more energy efficient buildings, improved climate control, and elimination of environmentally harmful gases for HVAC systems. Government funding of these beneficial TE materials will provide long-term benefits to our environment.

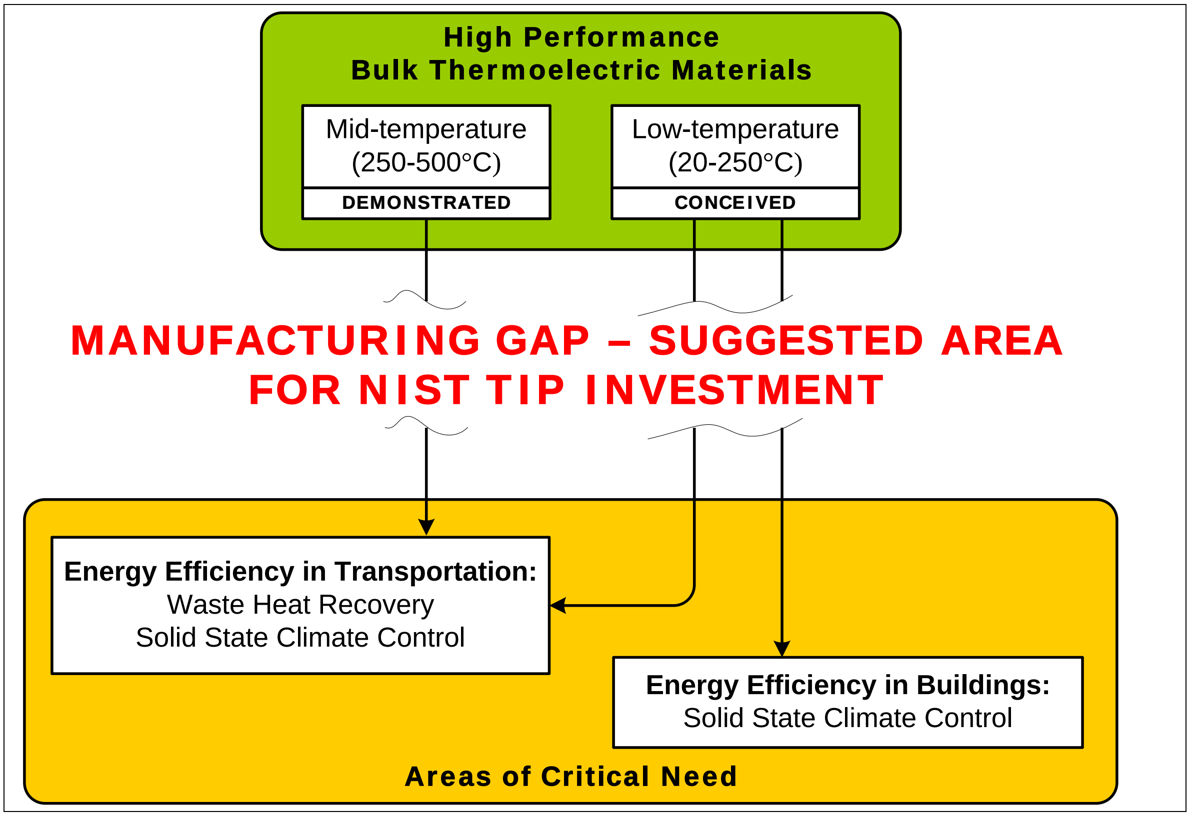

Figure 3. Proposed TIP investment areas for high-performance TE materials

Another critical payoff of improving TE materials is green job creation, as Table 1 shows. For example, a 10% market penetration of auto waste heat recovery systems can provide 21,454 U.S. jobs in manufacturing, engineering, sales, and administration. Most importantly, these are net jobs created since the waste heat recovery system is a new component to the automotive sector, so that no jobs are displaced by its introduction and usage. Similarly, a 10% penetration of these advanced TE materials into the automotive solid-state HVAC market can result in the creation of 11,467 green U.S. jobs. In this case, about half the jobs replace compressor systems currently imported, and the other half displace parts from U. S. manufacturers. However, the new jobs provided by advanced TE materials are much-needed sustainable, green jobs for U.S. workers.

Table 1. Creation of Jobs by U.S. Auto Waste Heat Recovery Systems* (market analysis by BSST LLC)

Market Penetration	Manufacturing Labor Jobs (1960 hrs/yr)	Engineering, Sales, and Admin. Jobs	Total Direct Employment
1%	1,480	666	2,145
3%	4,439	1,997	6,436
10%	14,796	6,658	21,454
30%	44,388	19,974	64,362

* In 2009 dollars, based on a $29 billion market size

Table 2. Creation of Jobs by U.S. Automotive Solid-State HVAC** (market analysis by BSST LLC)

Market Penetration	Manufacturing Labor Jobs (1960 hrs/yr)	Engineering, Sales, and Admin. Jobs	Total Direct Employment
1%	791	356	1,147
3%	2,372	1,068	3,440
10%	7,908	3,559	11,467
30%	23,724	10,676	34,401

** In 2009 dollars, based on a $31 billion market size

Note: In Table 1 and Table 2, jobs created and recovered reflect new jobs created to produce TE subassemblies and jobs recovered for foreign sourced traditional HVAC designed subassemblies.

ALIGNMENT WITH NIST TIP OBJECTIVES

The problems outlined previously in this paper and the proposed solutions, are closely aligned with the strategic mandate of NIST TIP program. The high risk, high reward technological approaches based on solid state energy conversion will result in high quality manufacturing jobs in new, sustainable green industries, benefiting society as a whole. Developments in advanced TE materials will help to maintain the technological leadership role of the United States, and will leverage federal investment in fundamental research by enabling an efficient technology transition from academic laboratories into the manufacturing sector.

SUMMARY

Increasing the efficiency of energy utilization in the United States by waste heat recovery and more efficient solid state cooling/heating offers tremendous opportunities to reduce emissions of greenhouse and other gaseous pollutants. Thermoelectric (TE) materials hold the potential to greatly enhance our ability to both harness waste heat by turning it directly into electrical power, and by providing emission free temperature control. However, TE usage has been limited by poor energy conversion efficiency. High performance TE materials with greatly enhanced capabilities have been demonstrated in academic laboratories. However, converting these high performance materials into products that address critical needs of our society, has become a nearly insurmountable challenge for the private sector in the face of the worldwide economic downturn. Policy makers in Japan, Europe, and Russia recognize the potential of TE technology and already have put advanced TE material programs in place that both rival, and in some cases exceed, those based on U. S. Government support to date. U. S. Government funding is essential to bring these promising and sustainable advanced TE materials from the laboratory to the private sector. If this is done well and quickly, a trajectory will be set to improve energy utilization efficiency, reduce consumption of foreign fossil fuels and create a generation of sustainable green jobs.

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