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# Heat-Induced Solid State Phase-Change Energy Production Technology

## ETM 571 – Managing Emerging Technology

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## WHAT

Systems and processes across the globe are inescapably subject to the second law of thermodynamics which states that the total entropy of a system will increase. Most commonly, the increased entropy takes the form of waste heat [1]. Researchers at the University of Minnesota led by Dr. Richard James have discovered a multiferroic alloy that can be used to convert heat directly into electricity due to its unique phase transformation properties [2]. This specific research is a young branch of the burgeoning phase-change technology field. Solid state phase-change technology research has been underway for a long time, but has only recently begun to gain traction over the last two decades (see figure 1).

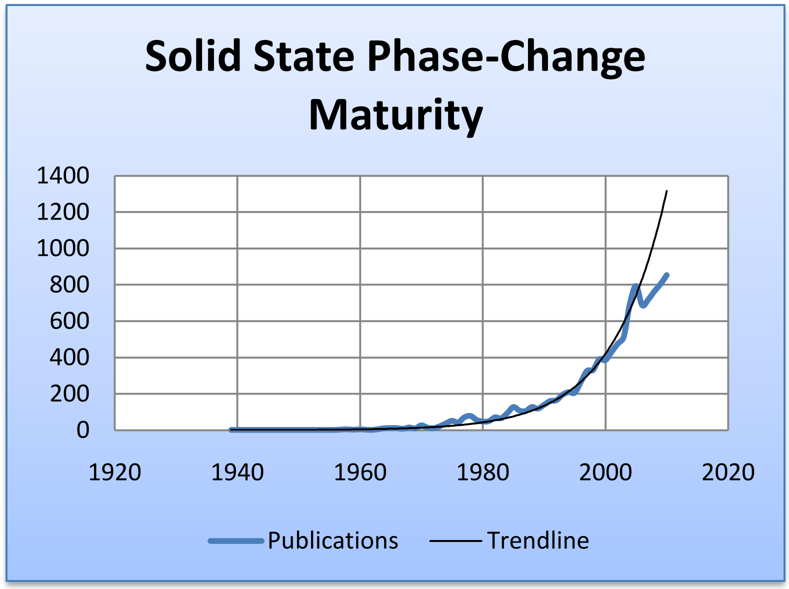


*Figure 1*

## WHY

Due to thermal inefficiencies and friction losses in mechanical elements, a typical internal combustion engine effectively uses approximately 20%-25% of the power produced by the combustion of the fuel [3]. Most of this loss is manifested as heat which, ironically, requires even more energy input in order to be managed (water pumps, etc.). Perpetual technological developments will continue to refine the traditional internal combustion engine; however, the loss of energy in the form of heat is an all but inescapable inherent characteristic of the vehicle as we know it. Although the internal combustion engine lends itself as an easy example of heat loss, the fact is that the laws of thermodynamics dictate that heat loss is everywhere. Considering the earth as a closed system (or the solar system in order to account for solar and tidal effects), the state of entropy will continue to increase. Mechanical, industrial, and chemical processes taking place globally experience losses in total efficiency as heat is spewed into the surrounding environment. This loss is generally accepted as unavoidable due to the impracticality and difficulty of converting heat into useable energy; however, heat-induced energy production holds the potential to harness a fraction of this lost efficiency and convert it directly into useable electrical energy [4]. Furthermore, waste heat is not the only possible source of energy for this particular application. As will be elaborated on later, the energy conversion requires a specific *change* in temperature, not exclusively a heat source. With this in mind, any natural environment that produces a thermal gradient has the potential to initiate the energy conversion process. Although battery technology and infrastructure have been early inhibitors of hybrid and electrical vehicle success, it is clear that there is a great deal of investment being made in the commercialization of improved vehicle efficiency [5]. It is apparent that consumers are growing ever more cognizant of their energy usage as oil prices increase and awareness of one's environmental impact continues to gain traction as a mainstream social sentiment. In light of these factors, the conversion of wasted heat into electricity possesses tremendous commercialization potential to all forms of consumers as a potential, incremental improvement to process and system efficiency.

## HOW

The science behind phase-change energy conversion is broken into two distinct processes: the heat-induced magnetization of the alloy, and the conversion of the magnetic state into electricity. The technological breakthrough aspect of this technology lies in the former process whereas the latter portion of the process utilizes existing knowledge/technologies.

The science of phase-change research lies in the inherently varying qualities of substances in various states. Although matter states are generally understood to be solid, liquid, and gas, the core of solid-state phase-change technology lies in the fundamental arrangement of molecules and the object's corresponding behavior. For example, researchers at IBM have found that applying a voltage across a specific alloy will cause it to change from a crystalline molecular structure to an amorphous state and vice versa. These two distinct states each possess a unique electrical resistance [6].

In this case, the researchers at the University of Minnesota have concocted a unique alloy made up of Nickel, Cobalt, Manganese, and Tin ($Ni_{45}Co_5Mn_{40}Sn_{10}$) that, when exposed to heat, converts from a low-magnetic (10 emu/cm$^3$) martensite phase to a higher-magnetic (1100 emu/cm$^3$) austenite phase. As alluded to earlier, this is the result of a subtle realignment of the molecular makeup of the object that directly influences its inherent characteristics. Specifically, the behavior of the martensite state "…suggests an inhomogenous structure containing a small volume fraction of ferromagnetic particles in an antiferromagnetic matrix" [4]. These varying states of lattice parameters are more commonly recognized in the context of common steel phase diagrams in which unique phases are achieved through a variation of compositions and heating/cooling phases. The transition between states in the $Ni_{45}Co_5Mn_{40}Sn_{10}$ alloy is similar; however, the different phases apparently hold respectively different characteristics from their corresponding steel phases. Furthermore, it should not be understated that a critical breakthrough factor of this alloy is in improved reversibility and the reduction of hysteresis (or the lag in the behavior of the material to the environment) [4].

The change in the alloy's magnetization leads directly to a change in the magnetic induction (or magnetic field). According to Faraday's Law {$\nabla \times \boldsymbol{E} = -\partial \boldsymbol{B}/\partial t$}, a change in the magnetic field creates an electric field normal to the magnetic induction vectors [7]. A copper wire is coiled around the alloy parallel to the electric field in order to produce a current. A schematic and actual image of the demonstration are shown in figure 2 [4].

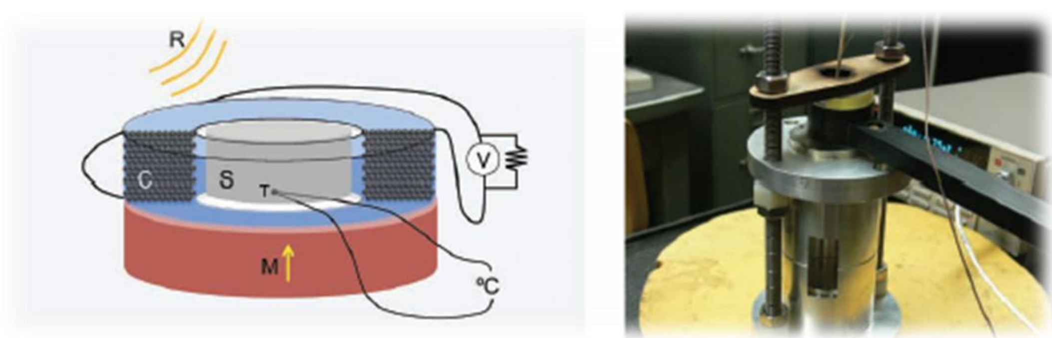


*Figure 2*

The result, as shown in figure 3, is a potential difference across the wire of .6 mV created by the heating of the material. The reverse potential difference appears to be caused by reaching the Curie point at which point magnetization of the specimen is lost and the fields reverse directions [4]. A major factor shown in figure 3 that may potentially prove advantageous is the discrete ΔT required to induce the transformation, in addition to the relatively low overall temperature at which the transformation takes place.

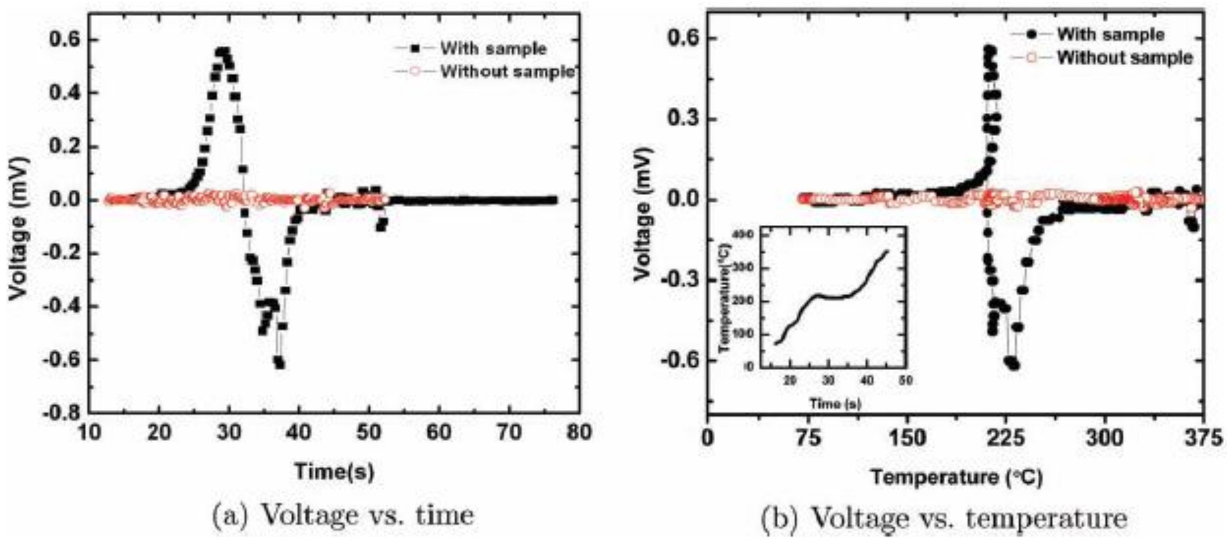


*Figure 3*

## WHEN

Determining the maturity of an emerging technology and its respective timeline for adoption and subsequent commercialization remains a largely speculative task. However, a handful of mechanisms help to hone in and identify where solid state phase change energy production lies on the general maturity model.

The first effort to identify technological maturity utilized a simplified bibliometric survey of solid state phase change research publications (Figure 1). However, a cursory review of the literature suggests that the research is saturated with a wide variety of differing scientific efforts, particularly in the field of solid state phase-change memory technology. In order to reduce the noise, a more refined survey produced the data shown in figure 4 [8]. A review of this data would suggest that that solid state phase change energy production, or at least magnetic alloy properties, has barely reached the first break point $\{f'(t) = 1\}$ on the maturity model. This would imply that the technology is transitioning from the early introduction stage and entering the rapid adoption phase. However, given that the effects of similar, but not directly applicable research publications were not entirely eliminated, and the fact that this bibliometric application lacked a degree of statistical and numerical rigor, a patent search analysis was performed.

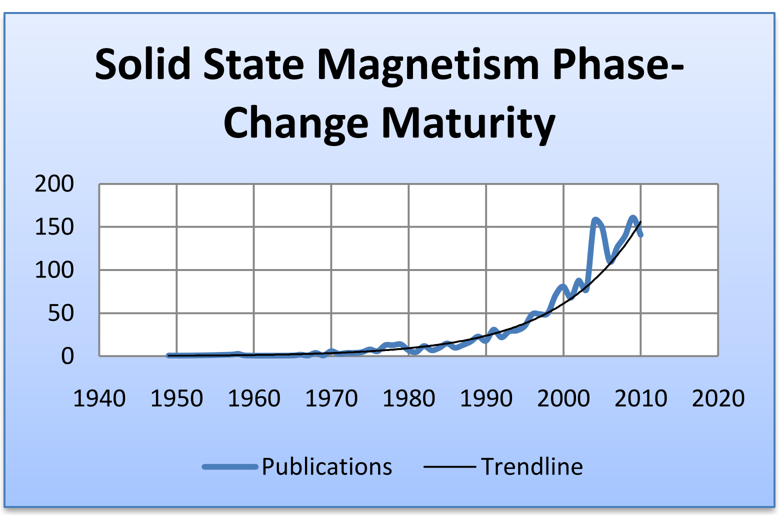


*Figure 4*

Using similar search criteria to the publication review, the patent search results to determine the relative maturity of solid state phase-change technology are shown in figure 5.

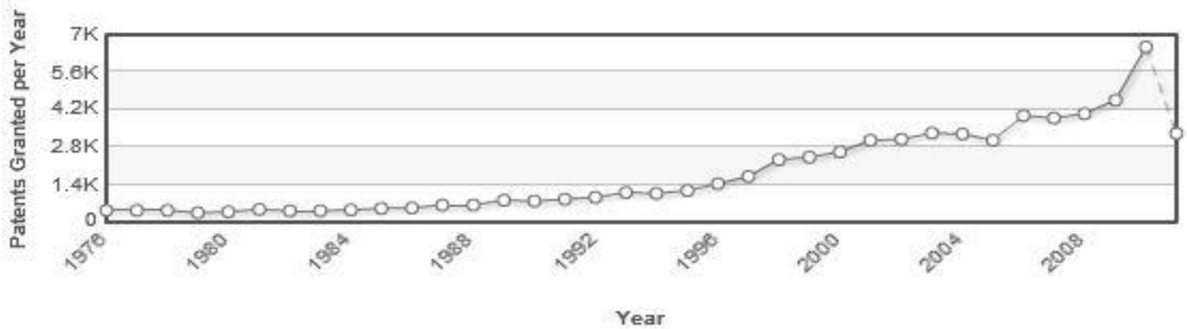


*Figure 5*

The results are similar; however, the case could be made that the first break point has not yet been reached. A number of factors could contribute to a slight patent lag; regardless, the same search noise was present as was experienced during the biblometric review. To account for the noise, a more refined patent search was performed leading to the graph shown in figure 6. [9]

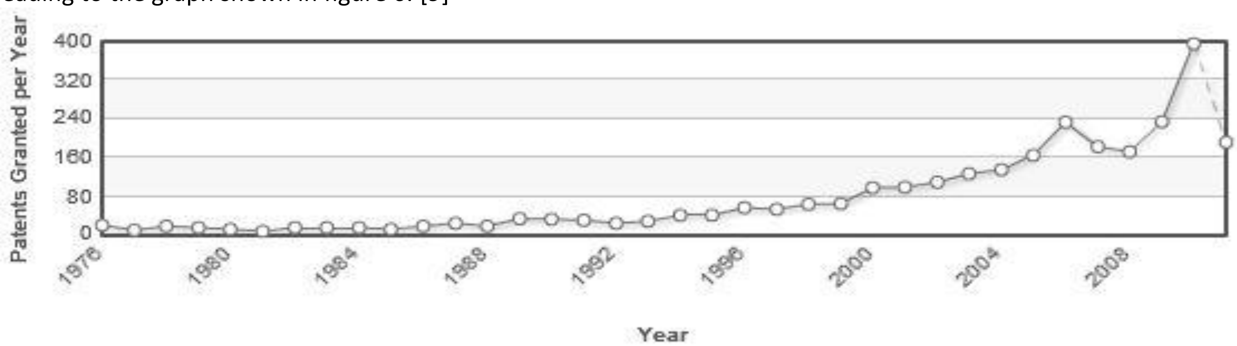


*Figure 6*

Although the curve maintains a similar shape and is shy of a break point, more notable is the overall decrease in applications. This striking decrease in patent applications versus those shown in figure 5 suggests that solid state phase-change energy production is, in fact, in its infancy and not as mature as the bibliometric review alone would imply. The speculative conclusion given these results is that solid state phase-change energy production remains in the introduction stage of the technological maturity model, but is perhaps poised to reach the first break point and thereby enter the early rapid adoption stage within the next five years (Figure 7). With an even greater degree of speculation and uncertainty, one could postulate to fifteen years of rapid adoption to match the approximate fifteen years of appreciable introductory growth, thereby placing technological maturity and respective market saturation at approximately twenty years away.

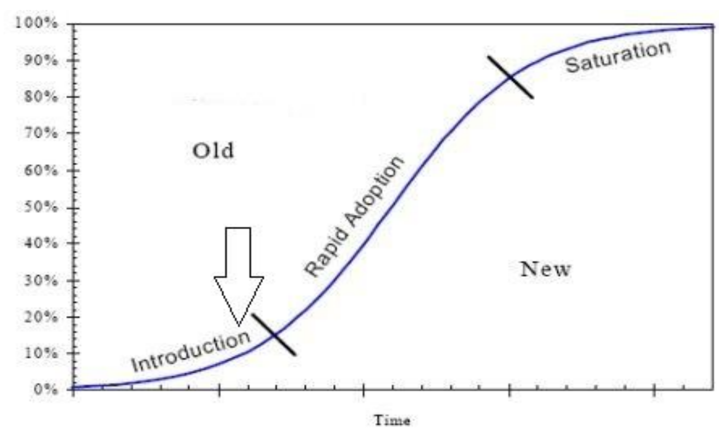


*Figure 7*

## WHO

Research being done at the University of Minnesota served as the catalyst for this report; however, there appears to be a number of current players. The publication results illuminated many academic laboratories across the world performing research in this area, heavily concentrated in the U.S., Japan, and China with substantial contributions to the field coming also from France, Germany, India, Russia, and Poland [8]. Specific institutions include the University of California, University of Tokyo, Bulgarian Academy of Sciences, and the Chinese Academy of Sciences. More enlightening; however, were the results from the patent searches. Although the University of California and its affiliates made an impressive showing in the patent results, they trailed behind Canon Kabushiki Kaisha and Shell Oil Company [9]. The presence of these two players in this particular field of research is fascinating due to the fact that they currently share very little, if any, mutual markets. This speaks to the potentially broad possibilities for future application.

Individually, three names tied heavily to comparable research are Harold J. Vinegar, Lowell L. Wood, Jr, and Roderick Hyde. Vinegar is naturally linked by association through Shell Oil Company having served as Chief Scientist, Physics, of Royal Dutch Shell. For 30 years, Vinegar studied and developed novel thermal recovery processes [10]. Similarly, Woods and Hyde are largely responsible for the University of California's position in this particular field of study and Woods is currently on the "Commision to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack [11]. Hyde is currently working with TerraPower after 32 years as a senior physicist at the UC's Lawrence Livermore National Laboratory [12]. Of particular interest, both men have also been heavily tied to discussions of a form of hypothetical space elevator called the space fountain [13].

Although Canon is best known for its cameras and other optical and imaging technologies, they also operate in medical devices and semiconductors, among other things [14]. It is highly possible that Canon recognizes commercial potential for this technology with their semiconductor branch in the field of consumer electronics. Specifically, Canon appears to be implementing comparable technology in ink jet recording devices [15].

Shell Oil Company, on the other hand, is self-described as being in the energy industry, not exclusively in the oil industry [16]. For this reason, it seems intuitive that Shell would invest heavily in the research of alternative energy sources. More specifically, Shell may have an interest in the potential application for improved vehicle efficiency. There is also the possibility that this is an element of game theory investment seen as a means to sustain the oil industry, Shell's core competency. Another potential application lies in the possibility that Shell may percieve an opportunity to augment offshore drilling technologies to harness naturally occuring temperature gradients in ocean waters to produce electricity or for other cogeneration mechanisms. Patents confirm Shell's interest in the possible integration of similar technology in complex subsurface formation heating procedures [17][18].

Current players aside, the potential future applications open a wide field for future players to join the race in solid state phase-change energy production. However, to even begin to postulate who may ultimately bring the technology to market, one must first speculate as to what the potential applications may be. The following are just a few speculative applications for this technology:

- As stated earlier, a device using this technology could be integrated into the exhaust system of motor vehicles. A great deal of heat is expelled from internal combustion engines that could be used to produce electricity. An obvious advantage in this application is the high number of auxilary systems in a vehicle requiring electricity which is currently being provided by the mechanically driven alternator. The electricity could be used to power these systems, or particularly in hybrid systems, recharge the batteries.

Many advancements have been made in vehicle efficiency over the last decade indicating both a willingness on the part of manufacturers to pursue such systems, and in turn on the customer's part to pay.

- Desktop computer units produce a great deal of heat, and this pales in comparison to far more powerful computers acting as servers. There will likely be a demand for a technology like this to be integrated into the computer architecture. The advantage of producing electricity from the waste heat will be enhanced by the effect the device could have as an additional heat sink.
- Along similar lines, current gaming systems such as the PS3, and in particular the XBOX 360, are hindered by an inclination to overheat and damage internal components. There is a sense that processing and graphic technology has outpaced the ability to economically cool the gaming systems. An application of the technology could have a similar effect on gaming systems as explained for general computers.
- Furthermore, smartphones and laptops experience similar effects under heavy use. Converting thermal changes into electricity would serve an especially critical purpose in these devices which is to extend effective battery life, which is a critical factor to consumers. Generally, all consumer electronics produce heat as even TVs and Blu-Ray players now possess powerful processing technology. Someday, the technology could be developed further to harness thermal gradients in devices all around us to improve energy efficiency. This suggests that organizations in the business of developing and producing semiconductors would be strong suitors for this technology.
- Phase transformation technology is already heavily speculated to be a part of the next revolution in memory storage technology, and this particular application may play a role. The necessary requirement for memory storage as we know it is ability to produce multiple logic states. For example, information could be assigned to discrete voltages, currents, or magnetic states that are heat activated. Seagate already appears to be researching in the vicinity of this technology.
- Industrial and manufacturing processes both consume tremendous amounts of energy and experience a high level of waste heat expulsion. On a macro scale, the technology could be integrated into industrial processes for cogeneration units in which energy is being produced as a byproduct of the core processes of the facility. This in turn would likely be used to supplement electrical useage elsewhere in the facility, or in some case, be sold back to the meters.
- Similarily, energy plants all over the world often produce energy through the process of heating fluids to power turbines which in turn produce electricty. This also is a relatively inefficient use of heat. Solid state phase-change technology could be used in concert with these production methods to supplement production.
- Offshore oil drilling rigs have direct access to one of nature's most abundant thermal gradients in ocean waters. This technology could be harnessed, as suggested earlier for the Shell Oil Company, to use the thermal gradients in the ocean to produce electricity to power electrical systems on rigs that are otherwise heavily isolated from support systems for electricity and fuel.
- Similarly, land based drilling and fracking operations are exposed to geothermal gradients that could be exploited to harness and produce electricity. Furthermore, a device could be developed to be durable enough to be integrated with drilling heads to return precise information regarding temperature. This possibility suggests that the potential of this technology lies beyond simple energy production, but in fact could be expanded to include durable and complex signal devices for extreme conditions.
- Along these lines, if heavily developed, the technology could serve as a thermostat signal under even more extreme conditions if an alloy is developed to transform at precise and extreme temperatures in the harsh outer space environment. This could lead to a new generation of durable, automated processers for satellites.

Given just this handful of potential applications, the following chart shows a small list of corporations that could ultimately bring a form of this technology to market in their respective domains:

| Potential Domains | Motor Vehicles | Electronics | Industrial |
|---|---|---|---|
| Potential Players | Toyota | Intel | Siemens |
| | Chevrolet | Samsung | General Electric |
| | Honda | Toshiba | Pelamis |
| | Ford | Texas Instruments | Chevron |
| | Volkswagen | Sony | BP |
| | Hyundai | Seagate | First Solar |

## WHAT IF

Although solid state phase-change energy production possesses promising characteristics, there are a number of risks, shortfalls, and competing elements that must be considered when evaluating future commercialization potential:

- The demonstration produced only a potential of 0.6 mV.  Although only a starting point, limited production could potentially limit possible applications substantially.  The authors hypothesize that 502 mV can be achieved from an optimized device using more appropriate geometries; however, this possibility remains theoretical.  Multiple devices, of course, could be wired in series to increase potential; however, this possibility raises questions regarding practicality and does nothing for improving the *efficiency* of the device. [4]
- Conventional metrics for gauging efficiency show that the efficiency of this device is deficient [4].  Although the application of converting waste heat into energy renders most metrics of device efficiency irrelevant, this is a potentially difficult spec to overcome if it reaches commercialization.
- Although an advantage of this technology is that there are no moving parts, this is offset by the notable stress experienced during the phase transformation to the material.  Over time, this will increase hysteresis thereby depleting performance [4].  These stresses will ultimately lead to failure, affecting the lifespan of the device.
- The current alloy, although made up of largely commodity metals, is a precise composition.  The cost of the metal is relatively minor; however, the cost of mass production could be adversely affected by the precision factor.
- Thermoelectrics are among a handful of technologies that are undergoing the same maturity process [3][4].  If a competing technology beats solid state phase-change production technology to the market with comparable price/performance (or follows with substantially improved price/performance), this technology may lose it relevance and any hope for a competitive advantage.
- The simple fact that $\Delta T$ is required to invoke a current means that it is not the new state the produces energy, but rather the transition itself.  This means for a voltage potential to be achieved, the device must cycle through the transformation.  As mentioned earlier, this will contribute to the eventual failure.  Furthermore, effective integration into a system will potentially require a degree of complexity in order to expose the device to frequent thermal gradients.

- The alloy ($Ni_{45}Co_5Mn_{40}Sn_{10}$) is experimentally shown to produce a voltage at approximately 220 °C (or 240 °C when cooling)* [4]. The specificity of the temperature requirement substantially limits the applicability of this alloy. For example, this may be a suitable temperature range in a vehicle's exhaust system, but will not be reached if applied to naturally occurring thermal gradients in sea water. This means that each application would possibly require a tedious trial-and-error process to determine precisely the correct alloy to reach the appropriate operating temperature range, adversely affecting the device's time to market across several industries. Furthermore, this potentially affects mass production abilities if each application requires a unique metallurgical makeup. **In the report, there is a noticeable discrepancy between the alloy's magnetization versus temperature in a controlled environment versus the experimental production of voltage. It's possible that this is a culminating effect of hysteresis and the possibility that the method of gauging the alloy's temperature during the demonstration lacked a certain degree of effectiveness, as the authors seemingly concede. The apparent Curie temperature for the alloy is 167 °C [4]. Regardless, the specificity factor remains in effect.*

## CONCLUSION:

At first glance, this technology appears to be hindered by a string of risks and technological shortcomings; however, these should not be construed as fatal. This technology possesses a great deal of promise for potential investors. There are a number of risks associated with solid state phase-change ferromagnetic activity that could hinder its potential to "cross the chasm" to successful commercialization [19]; however, many of these risks are hedged by the potential extensiveness of possibilities across a number of markets, only a few of which were identified here. The opportunity for commercialization is amplified by the breadth of potential applications across several, diverse markets. In turn, the risk of investment appears to be heavily mitigated.

Ultimately, this technology is in its infancy, and the true potential (and shortcomings) will not be clear without a great deal of further development. However, corporations in energy, electronics, semiconductors, memory storage, transportation, industrial, and even medical markets would be well-served to possess an element of this technology in their R&D portfolio, or at a minimum, keep tabs on its development.

## CITATIONS


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