# Prospects for High Temperature Cryocooling with Improved SWaP-C Enabled by Advanced DTP Solid-State Thermoelectrics

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## ABSTRACT

Conventional thermoelectric (CTE) systems can provide temperature differences up to 140K, which is not sufficient for most cryocooling applications. Distributed Transport Property (DTP) thermoelectrics, thermoelectric material systems with properties that vary optimally throughout the material, exhibit significant gains in cooling capacity, efficiency, and maximum temperature difference. Initial empirical test results and numerical modeling indicate that temperature differences greater than 220K are possible with DTP, opening up a broad range of new opportunities for cryocooling applications.

DTP solid state devices present a new and attractive SWaP-C benefit package not attainable with other cryocooling options. In this paper, we show where temperature control systems based on DTP materials can meaningfully impact commercial cryocooling applications, such as cryosurgery and cooling of electronic devices. We compare the performance and other critical characteristics of CTE, DTP, and traditional cryocooler technologies and identify applications where DTP systems create the option of compact solid state temperature control in the higher operating temperature range of cryocoolers.

## INTRODUCTION

Distributed Transport Property (DTP) solid state devices bring thermoelectrics (TE) into the upper operating temperature range of cryocooling applications. While conventional TE (CTE) technology is unlikely to get to the deepest cryocooling ranges, DTP has pierced the applicability threshold of allowing cryocooling in applications like IR cameras/sensors, cryosurgery, and cooled electronic and power devices.

One cryocooling application example is for cooled IR cameras, which provide significant benefits over uncooled IR cameras in speed, spatial resolution, sensitivity, synchronization, and spectral response [1–5]: “If you want to see the minute temperature differences, need the best image quality, have fast / high speed applications, if you need to see the thermal profile or measure the temperature of a very small target, if you want to visualize thermal phenomena in a very specific part of the electromagnetic spectrum, or if you want to synchronize your thermal imaging camera with other measuring devices…a cooled thermal imaging camera is the instrument of choice” [6]. Cooling reduces thermally-induced noise to a level that is below that of signals from imaged scenes [6].

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Cooled IR cameras include those based on photon detector arrays such as indium antimonide (InSb) and mercury cadmium telluride (HgCdTe or MCT) [7]. These materials typically require cooling to liquid nitrogen temperatures (77K) for most effective operation. Liquid nitrogen and Stirling coolers are the most common thermal management systems used to achieve such temperatures. Liquid nitrogen systems, stored in a vacuum flask and controlled with a cryostat, can provide long operating life and at relatively low cost. However, these systems are large and bulky and require regular liquid nitrogen replenishment, all factors which limit applications [8].

Stirling-based cryocoolers are another deep cooling option. However, these mechanical systems with moving parts present vibration and long-term durability issues and are relatively large, heavy, and expensive. They are often the limiting factor in terms of size, weight, power, and cost (SWaP-C) for a given cooled IR camera system. TE solid-state cooling is an option for operation down to 190K. TEs have the benefit of no moving parts, no refrigerants, no vibration, smaller size and weight, and lower cost. Some IR cameras that use indium gallium arsenide (InGaAs) as the focal plane array successfully use TE cooling [8]. However, for the majority of applications below 190K, conventional TE systems cannot operate effectively because of limitations to the maximum temperature differential attainable, the amount of power needed to operate at those temperatures, and the limited cooling capacity of TE devices.

More recently, high operating temperature (HOT) IR cameras based on new focal-plane array technologies, such as strained-layer superlattice (SPS) and nBn quantum infrared sensors, have been developed that provide performance similar to InSb focal plane arrays at about 80K and HgCdTe at 95K, but operate at considerably higher temperatures [7]. Cooling these sensors to around 150K provides faster response time, higher spatial resolution, greater measurement accuracy, greater sensitivity, and broader spectral response compared to uncooled microbolometer-based IR cameras.

## TE CASCADE SYSTEMS

With a hot-side temperature of 300K, single-stage conventional CTE devices achieve a maximum temperature difference (DT) in cooling mode of 73K [9]. Multiple single-stage devices can be stacked on top of each other in a cascade or multi-stage configuration to increase maximum DT. For conventional devices, the maximum DT achievable with zero heat load is 107K for two stages and 130K for four stages [10]. DTP TE technology utilizes TE materials in which the transport properties (Seebeck coefficient, electrical resistivity, and thermal conductivity) vary with position. These structured materials can improve critical performance metrics to create DTP TE devices and cascades that will outperform today's commercial CTE systems.

To facilitate an understanding of the contributions DTP technology can make to improved performance, it is helpful to first describe several factors that govern TE cascade capability. Figure 1a is a schematic of a typical TE temperature control cascade. The TE array Stage 1 is in good thermal contact on its cold side with a control volume in which sensors or other objects are maintained at a specified temperature, $T_C$. Heat produced by active sensor components plus sources of parasitic heat such as

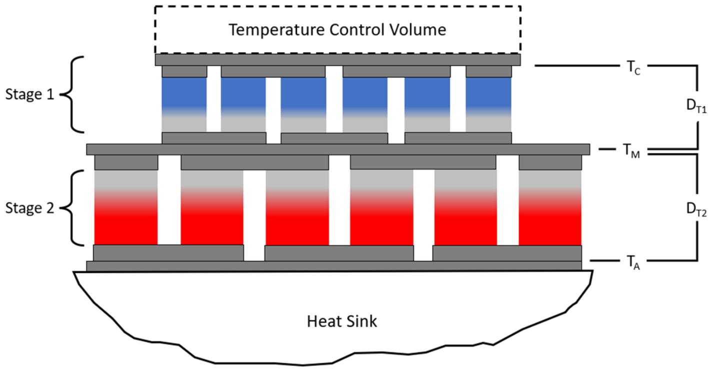

**Figure 1a.** Schematic of a typical TE temperature control cascade.

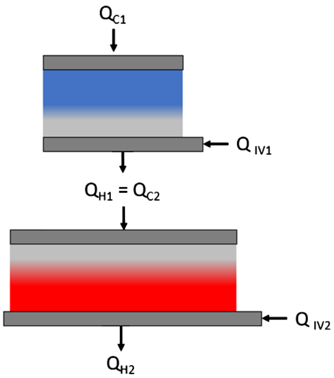

**Figure 1b.** Exploded view of a two-stage cascade showing flow of thermal and electric power within the cascade module of Figure 1a.

radiation and conduction from the environment together constitute the heat load to be removed from the temperature control volume. TE Stage 1 operates at a DT of $D_{T1}$, with a hot side $T_M$. The cold side of the Stage 2 TE array, at temperature $T_M$, is in very good thermal contact with the hot side of Stage 1 and removes the waste heat that accumulates there. Stage 2 operates at a temperature differential of DT2. Its hot side, where the waste heat from Stage 2 is rejected, is at ambient, $T_A$. $T_C$ is chosen to be the temperature required for cold-side operation, and $T_M$ is designed to be the temperature that optimizes TE temperature control system (cascade) performance.

Figure 1b shows an expanded view of the cascade and defines thermal and electrical power flow during steady state operation. The operating thermal load at the cold side is $Q_{C1}$. Electric power, $Q_{IV1}$, is the external power required to operate Stage 1. The sum, $Q_{C1} + Q_{IV1} = Q_{H1}$, is the heat rejected at the hot side of Stage 1. $Q_{H1}$ is the thermal load, $Q_{C2}$, for the cold side of Stage 2. As with the first stage, $Q_{C2} + Q_{IV2} = Q_{H2}$, and the heat is rejected to ambient. For cascades with more than two stages, each added stage operates in a similar fashion. Waste heat from lower temperature stages adds to input electrical power, and the sum is rejected to the next stage. The same condition applies when the last stage is reached. Present commercial TE cooling and heating materials limit stage efficiency to less than 1/6th Carnot efficiency. Thus, for operation near maximum DT, for each added stage, maximum efficiency is limited to at most a sixth that of a system with one fewer stage. Further, efficiency of each stage decreases as DT increases and the minimum number of stages is governed by the rate of efficiency decrease with temperature within each stage.

While other factors also influence efficiency, having fewer stages allows for higher efficiency. As a result, to produce higher performance, the stages of TE cascades require higher maximum DTs (to increase operating DTs), higher coefficients of performance (COPs) (to increase efficiency), and greater heat pumping capacity (to reduce size and parasitic losses).

We have performed theoretical [11] and numerical [12] studies on the feasibility of producing DTP TE elements from available commercial TE materials that exhibit performance gains which can lead to better performing TE cascade systems. To validate DTP TE capabilities, we have produced and characterized basic DTP TE devices for comparison with corresponding CTE TE designs.

## DTP AND CTE PERFORMANCE

A set of experiments was conducted to validate the analytical and numerical results described in [11, 12]. To simplify interpretation of test results and eliminate some of the parasitic losses present in more complex devices, DTP and CTE TE couples of the type shown in Figure 2 were fabricated. High thermal and electrical conductivity electrodes connect the TE materials. Electrons (induced from an applied current) passing from p-type to n-type cool, and electrons passing from n-type to p-type reject heat. TE modules are composed of TE couples, the smallest fully functional unit. Comparable CTE and DTP couples were evaluated. Each couple was made of one p- and one

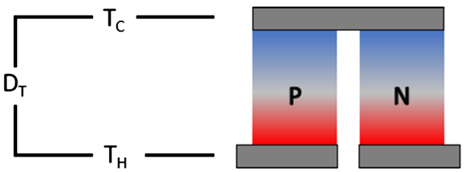

**Figure 2.** TE systems are composed of multiple TE couples that form the basic unit of TE devices.

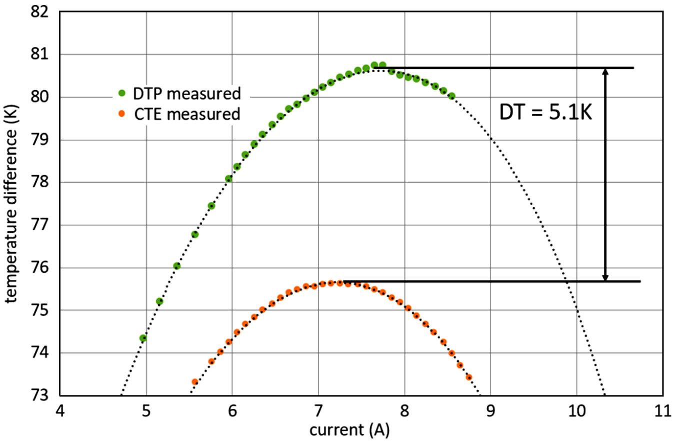

**Figure 3.** DTP design shows a 5.1K greater maximum DT compared to that of a comparable CTE design.

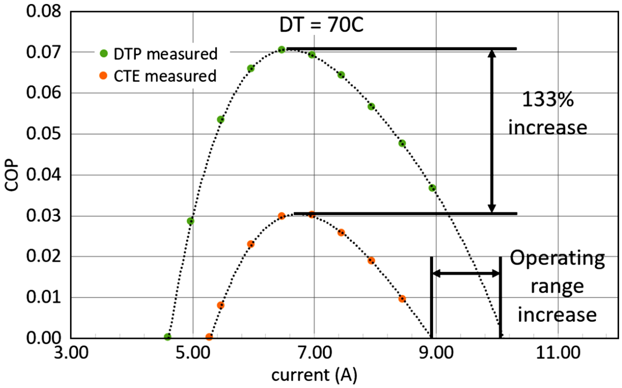

**Figure 4.** The DTP design exhibits higher efficiency (COP) and a broader operating current range than the corresponding CTE design.

n-leg of the same aspect ratio (i.e., TE material cross-sectional area divided by length). To avoid the complexity of fabricating DTP TE element legs with fully optimum properties, the experimental DTP couples were each fabricated from two segments of TE materials with advantageously different transport properties. Thus, the parts did not express the maximum performance possible with DTP technology, though they did have properties that exhibit the character of DTP devices and could be numerically modeled using properties available from TE material manufacturers.

Figure 3 shows the test results comparing CTE and DTP DTs as a function of electrical current. At a 300K hot side temperature, the DTP design produced a maximum DT of 80.7K, which is 7% higher than the 75.6K of the corresponding single-material CTE design.

Figures 4 and 5 show test results for the same two couples at the same hot side temperature of 300K and tested at a fixed DT of 70K. The benefits of DTP in terms of increasing maximum cooling efficiency or COP can be seen in Figure 4. The DTP design had a measured 133% increase

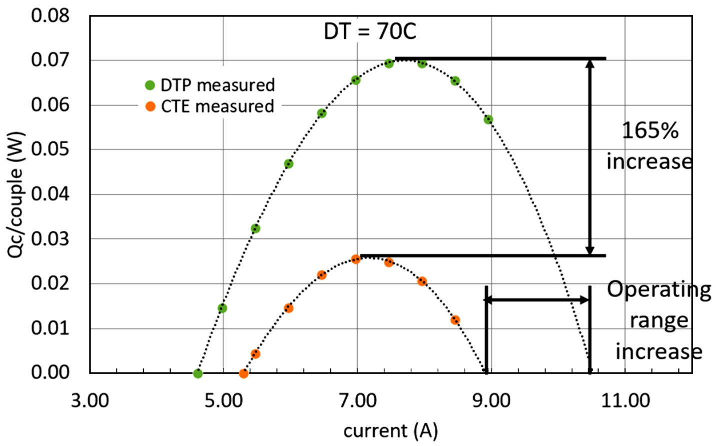

**Figure 5.** The DTP design has higher cooling capacity ($Q_C$) over a broader operating current range than that of the corresponding CTE design.

in maximum COP compared to the CTE design. The benefits of DTP in terms of increasing maximum heat pumping, $Q_C$, can be seen in Figure 5. The DTP design had a measured 165% increase in maximum $Q_C$ compared to the CTE design. Figures 4 and 5 also show the expanded operating range for the DTP design compared to that of the CTE design.

The performance gains achieved with the DTP two-material composite TE leg design are shown in Figures 3, 4, and 5. Greater performance improvements can be realized with material systems that better approximate optimum material properties along each TE leg, as described in [11]. With TE materials that are similar to those commercially available, but optimized for DTP rather than CTE properties, gains greater than 35% in maximum DT, 150% in COP, and 200% in heat pumping capacity are projected in single-stage designs at large DTs.

DTP expands the range of operating currents beyond that of CTE under off-nominal conditions, a property that is critical for systems with cooling loads that change during operation. The numerical analysis in Figure 6 shows COP as a function of DT and electrical current for a CTE and DTP device optimized for similar maximum DTs, 98.9K and 97.9K, respectively. A single-stage CTE device cannot achieve this level of temperature differential, so a two-stage cascade is required. However, with commercially available TE materials optimized for DTP properties, a single-stage DTP device will be capable of operating at this temperature differential. Off-nominal COPs over a broad range of DTs and electrical currents are greater than two times higher for DTP devices compared to that of the two-stage CTE design [11, 13].

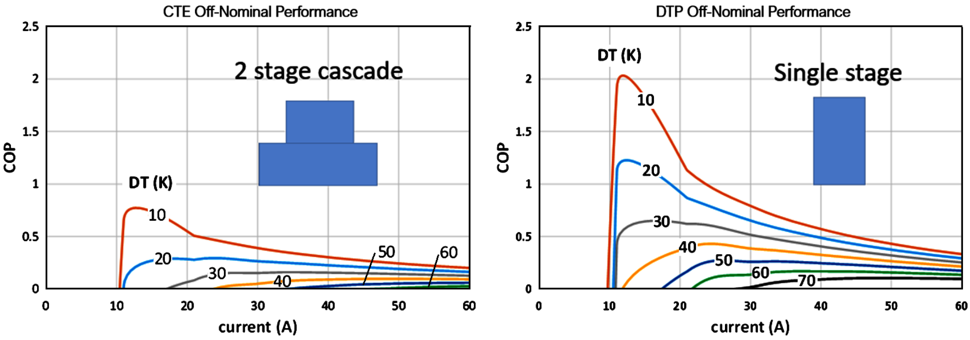

**Figure 6.** DTP single-stage design performance numerical modeling demonstrates for off-nominal DTs and applied currents a >2X increase in COP over that of a two-stage CTE design at the same maximum DT of about 98−99 K [11, 13].

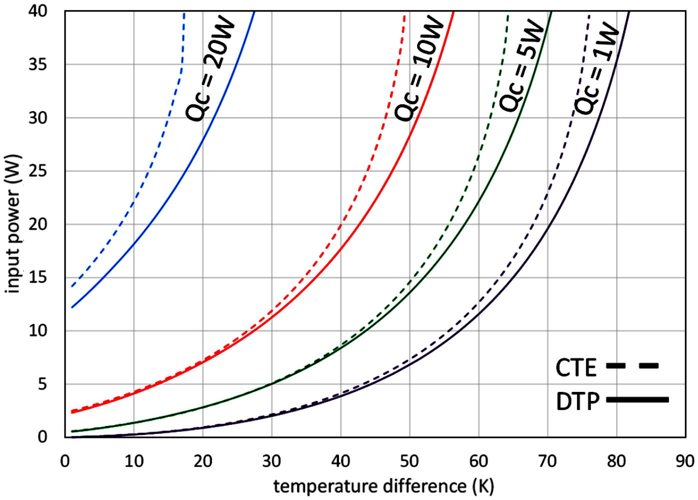

**Figure 7.** For DTP and CTE devices of the same fixed size, input power can be less, and achievable DT can be greater for DTP designs over a broad range of cooling loads ($Q_C$) [13].

The differences between DTP and CTE performance metrics that influence cascade design are summarized in Figures 7 and 8. Figure 7 presents results of a numerical analysis for DTP and CTE devices of the same size and same heat load ($Q_C$). The DTP design operates at lower power and/or a higher DT compared to CTE devices. In this example, DTs can be increased by greater than 50% and/or input power can be reduced by greater than 35%.

Adding stages to a TE cascade can increase the maximum DT, but the increase is compromised by the efficiency loss associated with each added stage. Thus, to generate a fixed required cooling power, adding stages results in a substantial reduction in efficiency and hence a significant increase in total power input. This and other trade-offs, and the complexity of producing multi-stage TE cascades, limits commercial cascades to six stages. The best available six-stage devices have maximum DTs of about 140K [14].

Figure 8 presents a comparison of present CTE cascades with numerical simulations of corresponding DTP cascades. The DTP projections account for the loss mechanisms that are comparable for DTP and CTE commercial devices. Numerical results of our simulations for CTE cascades accurately match the performance specifications of commercial designs, so our DTP simulations should be an accurate basis for comparing the relative performance of the two

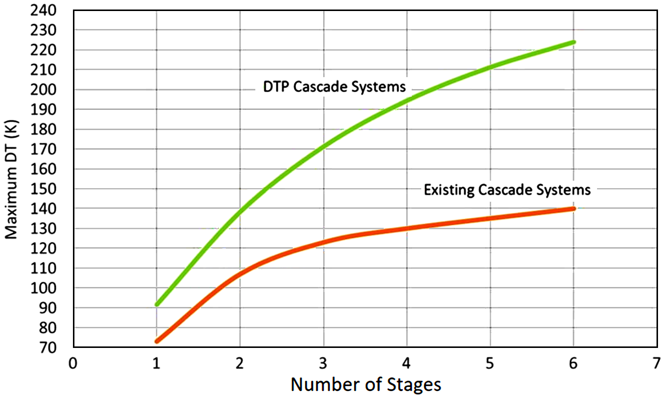

**Figure 8.** Maximum DT achievable with multi-stage DTP cascade systems is projected to be much greater than that of CTE systems with the same number of stages [13].

technologies. As expected, the simulations show that DTP systems outperform their CTE counterparts by larger margins as the number of stages increases.

Present commercial TE materials do not have good performance at the coldest operating temperatures in three-, four-, five-, and six-stage DTP systems. For these stages, TE materials that are described in the literature and have been produced were used in our numerical simulations. These TE materials are not commercially available and therefore will require production specifically for DTP multi-stage TE cascade fabrication.

The compounding benefits from DTP technology shown in Figure 8 should enable maximum DTs of about 220K with similar six-stage cascades. With DTs of 220K, liquid nitrogen temperatures (77K) could be achieved with a hot side temperature of 300K, and thus enable solid-state deep cooling suitable for use in HOT IR cameras, IR cameras that require even further deep cooling, and other high temperature cryocooling applications.

## CONCLUSION

The validation test results shown in Figures 3, 4, and 5 demonstrate meaningful and applicable benefits of DTP today compared to CTE. Quantifiably improved DT, COP, and cooling capacity plus superior device size, weight, ruggedness, cost, and vibration-free operation can impact performance in today's high temperature cryocooling applications.

Beyond the relevance to current applications, with further development and optimization, in part as described in Crane and Bell [11], further performance improvements can be achieved with greater than 35% gain in maximum DT in a single-stage device, 150% gain in COP, and 200% gain in cooling capacity. Near future multi-stage DTP devices will permit maximum DTs greater than 220K while size, weight, power, and cost (SWaP-C) are optimized.

DTP permits deeper cooling and solid-state thermal management to a greater level of performance and with less complexity and enables improved SWaP-C for existing and future high temperature cryocooling applications.

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