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About Tellurex | The 12 Most FAQ | Cooling Products

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The 12 Most Frequently Asked Questions About Thermoelectric Cooling

1. How does this technology work?

The basic concept behind thermoelectric (TE) technology is the Peltier effect —a phenomenon first discovered in the early 19th century. The Peltier effect occurs whenever electrical current flows through two dissimilar conductors; depending on the direction of current flow, the junction of the two conductors will either absorb or release heat. Explaining the Peltier effect and its operation in thermoelectric devices, is a very challenging proposition because it ultimately keys on some very complex physics at the sub-atomic level. Here we will attempt to approach it from a conceptual perspective with the goal of giving readers an intuitive grasp of this technology (i.e., without getting too bogged down in the minutia).

In the world of thermoelectric technology, semiconductors (usually Bismuth Telluride) are the material of choice for producing the Peltier effect—in part because they can be more easily optimized for pumping heat, but also because designers can control the type of charge carrier employed within the conductor (the importance of this will be explained later). Using this type of material, a Peltier device (i.e., thermoelectric module) can be constructed—in its simplest form—around a single semiconductor 'pellet' which is soldered to electrically-conductive material on each end (usually plated copper). In this 'stripped-down' configuration, the second disimilar material required for the Peltier effect, is actually the copper connection paths to the power supply.

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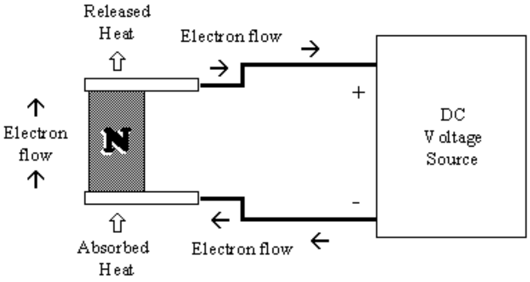
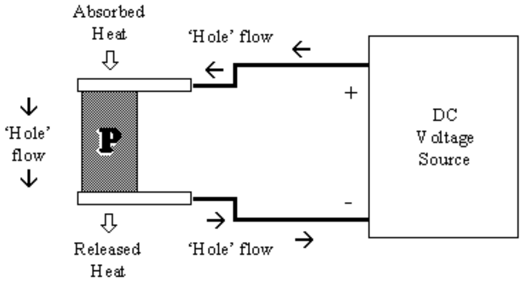


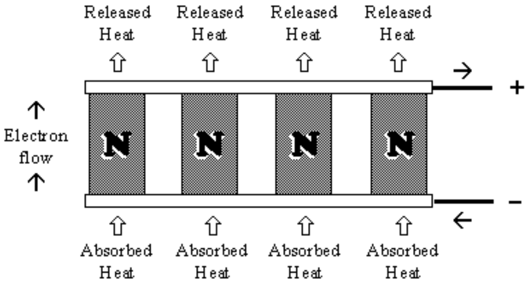
It is important to note that the heat will be moved (or 'pumped') in the direction of charge carrier movement throughout the circuit (actually, it is the charge carriers that transfer the heat). In this example, 'N-type' semiconductor material is used to fabricate the pellet so that electrons (with a negative charge) will be the charge carrier employed to create the bulk of the Peltier effect. With a DC voltage source connected as shown, electrons will be repelled by the negative pole and attracted by the positive pole of the supply; this forces electron flow in a clockwise direction (as shown in the drawing). With the electrons flowing through the N-type material from bottom to top, heat is absorbed at the bottom junction and actively transferred to the top junction—it is effectively pumped by the charge carriers through the semiconductor pellet.



In the thermoelectric industry, 'P-type' semiconductor pellets are also employed. P-type pellets are manufactured so that the charge carriers in the material are positive (known in electronics as 'holes'). These 'holes' enhance the electrical conductivity of the P-type crystaline structure, allowing electrons to flow more freely through the material when a voltage is applied. Positive charge carriers are repelled by the positive pole of the DC supply and attracted to the negative pole; thus 'hole' current flows in a direction opposite to that of electron flow. Because it is the charge carriers inherent in the material which convey the heat through the conductor, use of the P-type material results in heat being drawn toward the negative pole of the power supply and away from the positive pole. This contrasting heat-pumping action of P and N-type materials is very important in the design of practical TE devices (as will be explained in the next FAQ). While the illustration here—for simplicity's sake—shows 'hole' flow through the connections to the power supply, in reality, electrons are the charge carriers through the copper pathways.

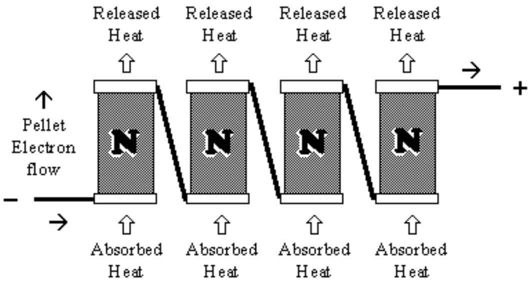
2. Why are two types of material (P and N) required?

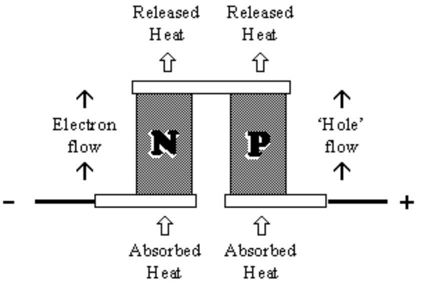
Unfortunately, while you can make a simple thermoelectric device with a single semiconductor pellet, you can't pump an appreciable amount of heat through it. In order to give a TE device greater heat-pumping capacity, multiple pellets are used together. Of course, the initial temptation would be to simply connect them in parallel—both electrically and thermally—as shown in the accompanying drawing. While this is possible , it does not make for a very practical device. The 'fly in the ointment' here, is that the typical TE semiconductor pellet is rated for only a very small voltage—as little as tens of millivolts—while it can draw a substantial amount of current. For example, a single pellet in an ordinary TE device might draw five amps or more with only 60 mV applied; if wired in parallel in a typical 254-pellet configuration, the device would draw over 1000 amps with the application of that 60 mV (assuming that the power supply could deliver that sort of current).



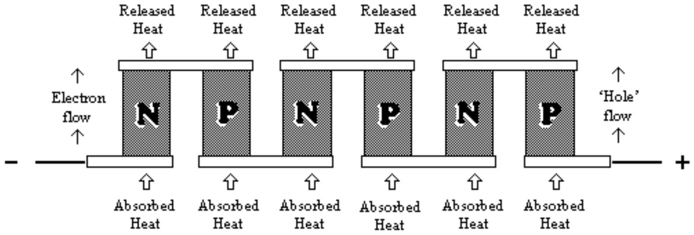
The only realistic solution is to wire the semiconductors in series, and doing so in a way that keeps them thermally in parallel (i.e., pumping together in the same direction). Here, we might

be tempted to simply zig zag the electrical connections from pellet to pellet (see illustration) to achieve a series circuit. This is theoretically workable, however, the interconnections between pellets introduce thermal shorting that significantly compromises the performance of the device. Fortunately, there is another option which gives us the desired electrical and thermal configuration while better optimizing the thermoelectric effect.



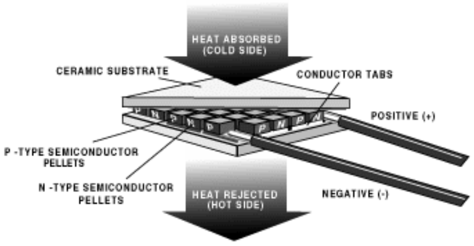


By arranging N and P-type pellets in a 'couple' and forming a junction between them with a plated copper tab, it is possible to configure a series circuit which can keep all of the heat moving in the same direction. As shown in the illustration, with the free (bottom) end of the P-type pellet connected to the positive voltage potential and the free (bottom) end of the N-type pellet similarly connected to the negative side of the voltage, an interesting phenomenon takes place. The positive charge carriers (i.e, 'holes') in the P material are repelled by the positive voltage potential and attracted by the negative pole; the negative charge carriers (electrons) in the N material are likewise repelled by the negative potential and attracted by the positive pole of the voltage supply. In the copper tabs and wiring, electrons are the charge carriers; when these electrons reach the P material, they simply flow through the 'holes' within the crystalline structure of the P-type pellet (remember, it is the charge carriers inherent in the material structure which dictate the direction of heat flow). Thus the electrons flow continuously from the negative pole of the voltage supply, through the N pellet, through the copper tab junction, through the P pellet, and back to the positive pole of the supply—yet because we are using the two different types of semiconductor material, the charge carriers and heat are all flowing in the same direction through the pellets (bottom to top in the drawing). Using these special properties of the TE 'couple', it is possible to team many pellets together in rectangular arrays to create practical thermoelectric modules. These devices can not only pump appreciable amounts of heat, but with their series electrical connection, are suitable for commonly-available DC power supplies. Thus the most common TE devices now in use—connecting 254 alternating P and N-type pellets—can run from a 12 to 16 VDC supply and draw only 4 to 5 amps (rather than 1000 amps at 60 mV).



Multi-couple configuration increases heat-pumping capacity

Of course, in fabricating devices with multi-pellet arrays, you must have a means to mechanically hold everything together. A solution is to mount the conductive tabs to thin ceramic substrates (as shown in the illustration); the outer faces of the ceramics are then used as the thermal interface between the Peltier device and the 'outside world'. Note that ceramic materials have become the industry standard for this purpose because they represent the best compromise between mechanical strength, electrical resistivity, and thermal conductivity.

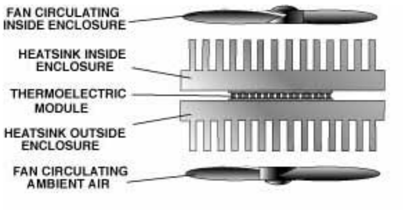


3. Do these P and N couples function like diodes?

No. It is easy to see why many people expect couples to work like diodes, given the pairing of P and N materials, but there is a crucial difference. In the manufacturing of diodes, a depletion region is created between the P and N layers. When the diode is forward-biased, charge carriers are drawn into the depletion region and the diode becomes conductive; when reverse-biased, charge carriers are drawn away from the depletion region and the diode acts like an open circuit. Without a depletion region, a TE couple cannot act like a diode; the couple will conduct in both electrical polarities and there is no fixed voltage drop across the couple (unlike the nominal 0.6 to 0.7 VDC typically dropped across a forward-biased silicon diode).

4. How is a typical thermoelectric (TE) system configured?

Let's look conceptually at a typical thermoelectric system designed to cool air in an enclosure (e.g., picnic box, equipment enclosure, etc.); this is probably the most common type of TE application. Here the challenge is to 'gather' heat from the inside of the box, pump it to a heat exchanger on the outside of the box, and release the collected heat into the ambient air. Usually, this is done by employing two heat sink/fan combinations in conjunction with one or more Peltier devices. The smaller of the heat sinks is used on the inside of the enclosure; cooled to a temperature below that of the air in the box, the sink picks up heat as the air circulates between the fins. In the simplest case, the Peltier device is mounted between this 'cold side' sink and a larger sink on the 'hot side' of the system. As direct current passes through the thermoelectric device, it actively pumps heat from the cold side sink to the one on the hot side. The fan on the hot side then circulates ambient air between the sink's fins to absorb some of the collected heat. Note that the heat dissipated on the hot side not only includes what is pumped from the box, but also the heat produced within the Peltier device itself (V x I).



CONCEPTUAL DRAWING OF AIR-TO-AIR THERMOELECTRIC COOLING SYSTEM

Let's look at this in terms of real numbers. Imagine that we have to pump 25 watts from a box to bring its temperature to 3°C (37.4°F) from a 20°C (68°F) ambient. To accomplish this, we might well have to take the temperature of the cold side sink down to 0° C (32°F). Using a Peltier device which draws 4.1 amps at 10.4 V, the hot side of the system will have to dissipate the 25 watts from the thermal load plus the 42.6 watts it takes to power the TE module (for a total of 67.6 watts). Employing a hot side sink and fan with an effective thermal resistance of 0.148 C°/W (0.266F°/W), the temperature of the hot side sink will rise approximately 10°C (18° F) above ambient. It should be noted that, to achieve the 17° C drop (30.6°F) between the box temperature and ambient, we had to create a 30° C (54°F) temperature difference across the Peltier device.

5. Can Thermoelectric systems be used for heating as well?
Yes. One of the benefits of TE technology is that you can switch the direction of heat pumping by simply reversing the polarity of the applied voltage—you get heating with one polarity, cooling with the other. Thermoelectric modules make very efficient heaters—in fact, because of the unique properties of Peltier devices, any given TE system will have a greater capacity for heating a load than cooling it.

6. Are TE systems used only for heating or cooling air?
No. Systems are often designed for pumping heat from both liquids and solids. In the case of solids, they are usually mounted right on the TE device; liquids typically circulate through a heat exchanger (usually fabricated from an aluminum or copper block) which is attached to the Peltier unit. Occasionally, circulating liquids are also used on the hot side of TE cooling systems to effectively dissipate all of the heat (i.e., a liquid-to-liquid system). Note that liquid cooling is never achieved by immersing the Peltier device in the fluid—thermoelectric modules are not the equivalent of 'electric ice cubes'.

7. Do I have to use a heat sink in my design?
Whether heating or cooling a thermal load, you must employ some form of heat sink to either

collect heat (in heating mode) or dissipate collected heat into another medium (e.g., air, water, etc.). Without such provisions, the TE device will be vulnerable to overheating; once it reaches the reflow temperature of the solder employed, the unit will be destroyed. When the heat sink is exchanging heat with air, a fan is usually required, as well.

8. Can these devices be immersed?
Only for cleaning purposes and never while under power. TE devices should always be dry when under use to prevent thermal and electrical shorting.

9. What type of products currently use this technology?
There are an increasing number and variety of products which use thermoelectric technology—from picnic boxes to water coolers, laser applications, and highly-specialized instrumentation and testing equipment. The compatibility of many TE's with automotive voltages, makes them especially suitable for small cooling jobs in that industry. With each new year, the imaginations of design engineers widen with the immense possibilities of thermoelectric heating and cooling.

10. Why would I want to use a thermoelectric system instead of compressor-based technology?
Both technologies have their advantages and disadvantages, but where thermoelectric technology really shines, is in making it feasible to do very small cooling jobs—ones which would be wholly impractical with a compressor-based system. Can you imagine cooling an individual integrated circuit with compressed gasses? What about thermally cycling a test tube or cooling a very small enclosure? TE's are also strong in products which demand both heating and cooling in the face of a changing operating environment; here a simple switching of TE current polarity allows the system to shift to the mode required. In addition, unlike compressor technology, TE system components can be mounted in any physical orientation and still function properly. Of course, one other advantage of TE systems, is that they do not require evaporative chemicals which may be harmful to the environment. Thermoelectric devices open up a whole new world to cooling and heating possibilities.

11. Are there situations where compressor-based systems make more sense?
Yes. Generally, whenever a small compressor-based system would clearly be 'overkill' in providing a cooling solution, TE systems become the most viable choice. You find a 'gray area' amidst the medium-sized cooling jobs; here decisions ultimately come down to critical cost/benefit or design engineering considerations which are unique to each application. Given the present state of technology—unless there are unique overriding concerns—the compressor-based approach has distinct advantages in larger cooling systems such as standard-sized refrigerators and air-conditioning systems for buildings & vehicles. However, ongoing research into materials may one day make thermoelectrics practical for many of these larger applications.

12. For heat-only applications, do thermoelectric devices have advantages over resistive heaters?
Yes. Resistive devices create heat solely by virtue of the power dissipated within them. TE devices, on the other hand, not only provide this I 2R heating, but also actively pump heat into the thermal load; this, potentially, makes them much more efficient than resistive heaters. Unfortunately, the need for a DC power source and the generally higher cost of TE systems compared to resistive heaters, precludes their use in most heat-only applications. Furthermore, Peltier devices have a far more limited temperature range than most resistive heaters. Generally, TE devices are only used for heating in systems that also require cooling

The 12 Most Frequently Asked Questions About Thermoelectric Power Generation

1. How does this technology work?
This gets complicated—but then if it was easy, everybody would be explaining it. We'll just take it one small step at a time.

First, we need to understand the relationship between the flow of electricity and the existence of charge carriers. According to electron theory, electricity is the movement of electrons in a circuit. It occurs whenever there is a continuous conductive path across an applied voltage. The voltage provides an electromotive force which sets the electrons into motion. The resulting electrical current is measured in terms of the number of electrons moving past a given point in one second, where one ampere (or 'amp' for short) equals the movement of 6.25 x 10^{18} (ten to the 18th power) electrons per second.

Charge carriers are the physical components of a material which allow it to conduct electricity. The precise nature of these carriers, is a function of the material's atomic structure. In the simplest examples, like copper, the material is a pure element which has only a single valence electron in its outer shell (see Figure 1). The fewer the number of electrons in an element's outer shell, the more loosely bound it is to the atom's nucleus, and the easier it is to make it flow with the application of a voltage. Other elements with a single outer electron include silver and gold and they are excellent conductors.

Conductivity takes a somewhat different form when it comes to semiconductor material. For electronic applications, semiconductor materials are 'grown' into crystalline structures which are given conductive properties by virtue of the impurities (or dopants) which are added. In their purest form (i.e., without dopants), the base semiconductor materials form crystalline lattices which become very stable by sharing electrons among the constituent atoms. Figure 2 shows such a configuration for a silicon crystal. In looking at the shell mapping, be aware that the electrons (shown in red), are actually in constant motion as they orbit the nuclei in the lattice. The shared electrons, however, are continually pulled into the orbits of adjacent nuclei to maintain the structural stability of the lattice. In this pure state, the material is not very conductive.

Once the impurities are added to the mix, however, the conductive properties are radically affected. For example, if we have a crystal formed primarily of silicon (which has four valence electrons), but with arsenic impurities (having five valence electrons) added, we wind up with ‘free’ electrons which do not fit into the crystalline structure (see Figure 3). These electrons are thus ‘loosely bound’ and when a voltage is applied, they can be easily set in motion to allow electrical current to pass. The loosely bound electrons are considered the charge carriers in this ‘negatively doped’ material (which is referred to as ‘N’ material).

It is also possible to form a more conductive crystal by adding impurities which have one less valence electron. For example, if Indium impurities (which have three valence electrons) are used in combination with silicon, this creates a crystalline structure which has ‘holes’ in it—that is, places within the crystal where an electron would normally be found if the material was pure. These ‘holes’ make it much easier to convey electrons through the material upon the application of a voltage. In this case, ‘holes’ are considered to be the charge carriers in this ‘positively doped’ conductor (which is referred to as ‘P’ material).

It is critical here to understand that the existence of charge carriers is entirely a property of a given material. The vast, vast majority of conductors—including those employed to make electrical connections—use electrons as the charge carriers and would be considered ‘N’ material. ‘P’ material can only be fabricated within crystalline structures.

Okay, now that we have a basic understanding of electricity and the nature of charge carriers, we need to come to grips with an important concept in power generation. Sometimes it is possible to set charge carriers in motion through interaction with other energy sources. For instance, if a magnetic field is moved along a conductor, the effect of that field upon the electrons (assuming that there is a complete path), will cause electrical current to flow. In essence, if you can force charge carriers to move, you can create voltage and current flow. This is not only true when there is an interaction between charge carriers and magnetic fields, but when those carriers are set in motion by the flow of heat.

Thus we come to the nitty gritty of Seebeck technology. Whenever an electrical conductor is strung between two different temperatures, the conductor is capable of transferring thermal energy from the warmer side to the colder one. Furthermore, the physical process of transferring that heat, also tends to move electrical charge carriers within the conductor in the same direction as the heat. Conceivably then, this charge carrier movement can be used to generate electrical current—if we can find a way to effectively complete the circuit.

Here, however, we run up against a major issue. If the conductor which completes the circuit is identical to the first conductor, the flow of thermal energy will create a potential for equal charge carrier movement in both conductors. Furthermore, the potential for current flow in one conductor is in complete opposition to that in the other conductor. The result is no net current flow.

If we employ two dissimilar conductors, on the other hand, we get quite a different result. With differing capacities for moving charge carriers in response to thermal flow, the current level in one conductor will overcome (or in some cases, complement) the potential for thermally-generated current flow in the other conductor. The net effect is a continuous current level which is equal to the generated current capacity of the primary conductor (for the given temperature difference) minus the generated current capacity of the second conductor. The existence of this net current flow, indicates that a voltage is created through the movement of heat and we can get a direct measurement of this voltage level by breaking the circuit and measuring across the opened terminals with a voltmeter. Note that the ability of two dissimilar conductors to produce a voltage when a temperature difference is applied, is called the Seebeck effect. The voltage which results is referred to as Seebeck voltage.

Probably the most well-known example of this phenomenon, is the common thermocouple. For example, with a K-type thermocouple made of two wires—one composed of a nickel-chromium alloy and the other from nickel-aluminum, if one junction is at 100° C and the other junction (the so-called ‘reference junction’) is at 0° C, a voltage of approximately 4.096 millivolts is produced. In general, the voltage generated by a thermocouple is a function of two things: 1) the temperature difference (DT) between the two thermocouple junctions, and 2) the nature of the conductors employed (including their temperature dependencies).

Of course, thermocouples are used primarily for temperature measurement—not power generation. Thermoelectric power generation (TEG) devices typically use special semiconductor materials which are optimized for the Seebeck effect. The circuit shown in Figure 10 demonstrates the simplest possible example. It shows a single ‘N’-type semiconductor pellet connected across a voltmeter.

As the heat moves from the hot to the cold side of the pellet, the charge carriers (i.e., electrons from the dopants) are carried with the heat. Heat also effects charge carrier movement in the return path (typically copper wire). Because the heat movement can carry far more charge carriers in the semiconductor material than in the circuit’s return path, however, a significant potential difference (i.e., Seebeck voltage) is generated. In this example, the Seebeck voltage would be about 20 mV.

In thermoelectric power generation, ‘P’ pellets are also employed. Figure 11 shows a basic configuration. Note how the flow of electrons goes in a direction opposite to that of hole flow.
It is through the use of both N and P type materials in a single power generation device, that

we can truly optimize the Seebeck effect. As shown in Figure 12, the N and P pellets are configured thermally in parallel, but electrically in a series circuit. Because electrical current (i.e., moving electrons) flows in a direction opposite to that of hole flow, the current generating potentials in the pellets do not oppose one another, but are series-aiding. Thus, if each pellet developed a Seebeck voltage of 20 mV, this combination of an N and P pellet would generate approximately 40 mV rather than zero volts.

Of course, in truly practical TEG’s, many such P & N couples are employed to bring the Seebeck voltage up to useful levels. The illustration in Figure 13 shows a three-couple device (more typically, a Seebeck module would have 127 couples or more). Note the direction of electrical current flow in the N/P series configuration (assuming a load is connected across the Seebeck device).

2. Do TEG’s employ silicon-based semiconductor material?
They can. Tellurex, however, uses bismuth/telluride structures to optimize performance. While similar dopants are employed in both semiconductor technologies, the crystalline latices which form from Bismuth/Telluride, are far more complex. The same principles of ‘N’ and ‘P’ material

apply, though.

3. How is a typical TEG system configured?
Fundamentally, there are four basic components: a heat source, a TEG module (i.e., a thermoelectric generator—also known as a Seebeck device), a ‘cold-side’ heat sink, and the electrical load. The system may also include a voltage regulation circuit, or a fan for the heat sink. The illustration in Figure 14 shows one example.
In this case we have a burner box with a propane fuel source. It is shown with the burner box open on one end, but in reality, it would be enclosed. The TE module is then sandwiched between the heat source and the cold-side sink. While this example shows only a single TEG module, in reality, several modules might be deployed in whatever series/parallel electrical arrangement best served the load.

4. Do I have to use a heat sink in my design?
It would be virtually impossible to get an adequate DT without some type of heat sink. However, you can sometimes reduce the size requirement for the sink (i.e., fin surface area) if you can find a way to insure good air flow.

5. Are any special precautions required for the hot side of the system?
Yes. First and foremost, you want to prevent the hot-side temperature of the TE device from exceeding the melting temperature of the solder employed to secure the semiconductor pellets to the copper tabs. It is recommended that the temperature be kept below 200° C. Toward this end, it is a good idea to use some type of ‘heat spreader’ to prevent hot spots at the hot-side module interface. Usually this means employing a relatively thick casting or extrusion between the heat source and the module.

On the mechanical side—especially when using multiple devices—you need to find a means of applying compression between the hot and cold sides, which will apply even pressure across

the modules and, most importantly, prevent the hot-side interface from bowing. If there is too great an expanse between compression points, the hot side interface can distort to the point where some modules are crushed or the thermal interface is compromise.

6. What does the specification, THot, mean?
This is the temperature at the mounting surface of the module, which comes in contact with the heat source (i.e., the hot side of the system).

7. What does the specification, TCold, mean?
This is the temperature at the mounting surface of the module, which comes in contact with the cold-side heat sink.

8. What does ‘no-load voltage’ (VNL) mean?
This is the voltage output of the TEG system when no electrical load is connected.

9. What does ‘load voltage’ (VL) mean?
This is the voltage output of the TEG system when an electrical load is connected.

10. What does internal resistance (RInt) mean?
This is the electrical resistance of the TEG module (or module array).

11. What does ‘power conversion efficiency’ mean?
It is the ratio of power output to power input, expressed as a percentage. In this case, power output would be the wattage dissipated in the electrical load and power input would be the rate of energy use (e.g., watts, BTU’s/hr) to create the necessary DT.

12. What does ‘electrical efficiency’ mean?
It is the ratio of electrical power dissipated in the load to the total amount of power generated (including the dissipation in the internal resistance).

BACK TO TOP

z-max technology | power generation products | cooling products | design manual | faq
about Tellurex | ordering | contact