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# Frequently Asked Questions About Our Power Generation Technology

## 1. How does this technology work?

This gets real 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 $10^{18}$ 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.

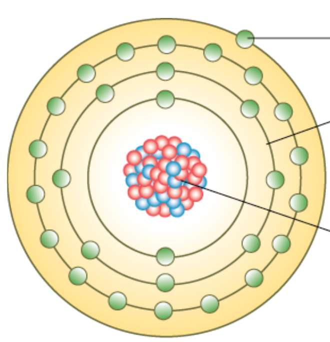



*Figure 1: Structure of the copper atom*

Conductivity takes a somewhat different form when it comes to *semiconductor* material. For electronic applications, semiconductor materials are 'grown' into crystalline structures that 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 green), are actually in constant motion as they orbit the nuclei in the lattice.

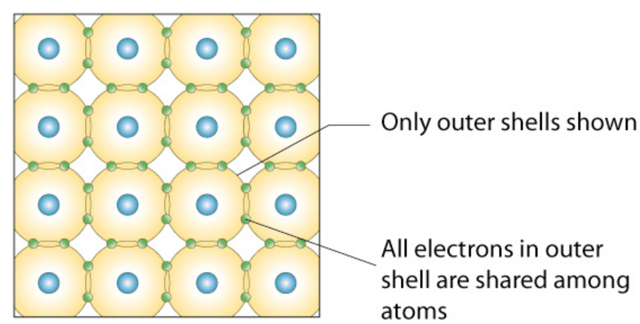



*Figure 2: With four electrons in the outer shell, silicon atoms form a stable crystalline lattice by sharing electrons with each other.*

The shared electrons 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).

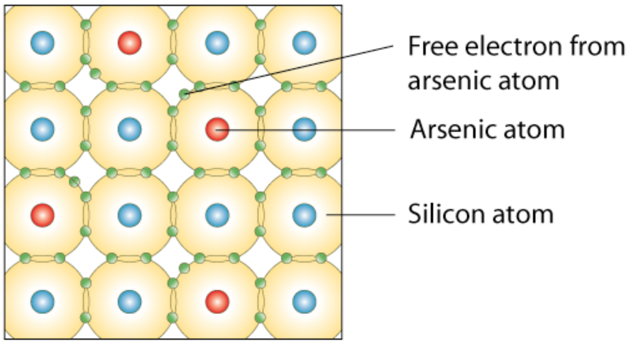



*Figure 3: Arsenic dopant adds free electrons to the crystalline lattice, making it more electrically conductive, creating 'N' material.*

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 (see *Figure 4*). These holes make it much easier to convey electrons through the material upon the application of a

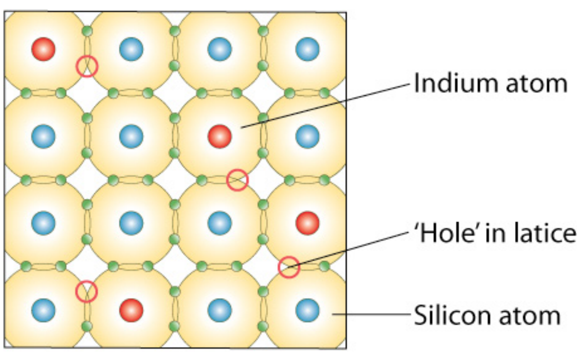



*Figure 4: Indium dopant leaves "holes" in the crystalline lattice, making it more electrically conductive while creating 'P' material.*

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 (see *Figure 5*). Conceivably then, this charge carrier movement can be used to generate electrical current—*if* we can find a way to effectively complete the circuit.

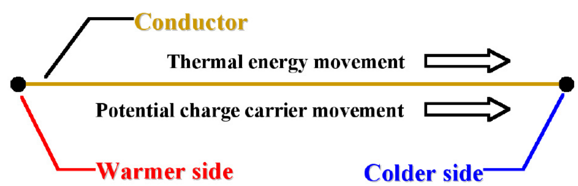



*Figure 5: The capacity for charge carrier movement is created whenever thermal energy moves through an electrical conductor.*

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 (see Figure 6). Furthermore, the potential for current flow in one conductor is in complete opposition to that in the other conductor.

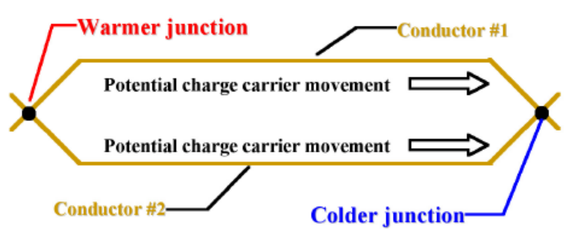



*Figure 6: When identical charge carriers are employed, there is a complete circuit, but the two potential differences cancel one another (resulting in no net current flow).*

The result is *no* net current flow. If we employ two *dissimilar* conductors, on the other hand, we get quite a different result (see *Figure 7*). With *differing* capacities for moving charge carriers in response to

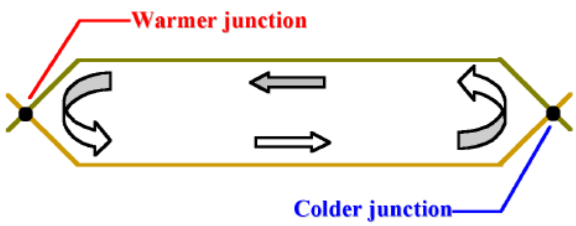



*Figure 7: Use of two dissimilar conductors creates a complete circuit which allows for continuous current flow. The conductor with the greatest capacity for charge carrier movement will determine the direction of current flow.*

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

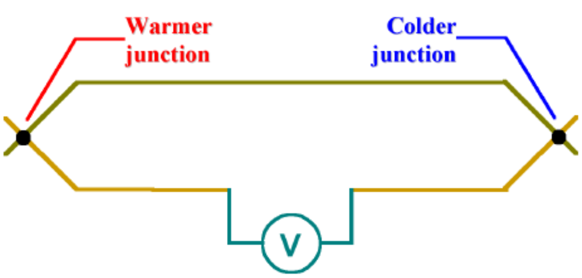



*Figure 8: Breaking the circuit, allows for the measurement of the Seebeck voltage which is produced.*

opened terminals with a voltmeter (see *Figure 8*). 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 (see *Figure 9*). 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 (ΔT) 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.

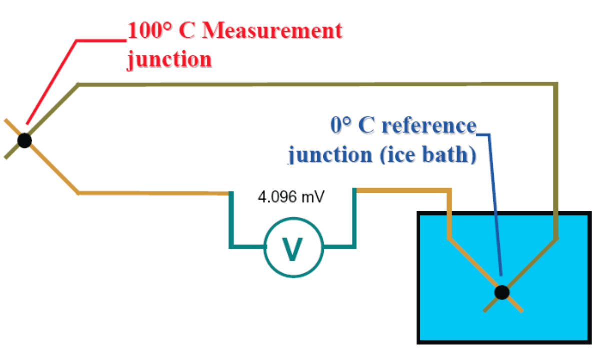



*Figure 9: Thermocouple using 0° C reference junction.*

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

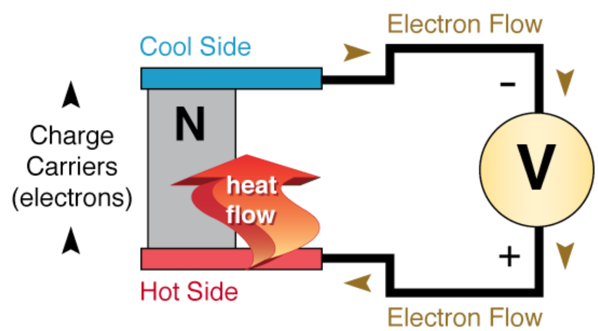



*Figure 10*

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 pellet than in the circuit's return path, however, a significant potential difference (i.e., Seebeck voltage) is generated. In this example, the Seebeck voltage might be about 20 mV.

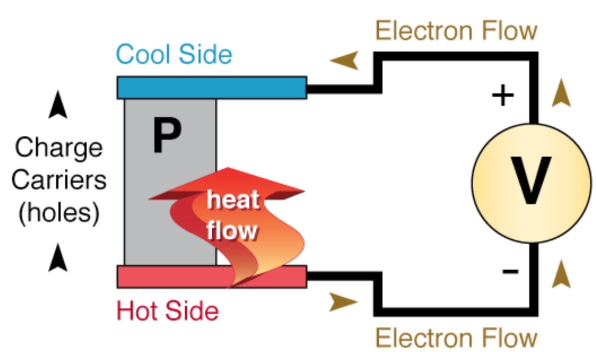



*Figure 11*

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

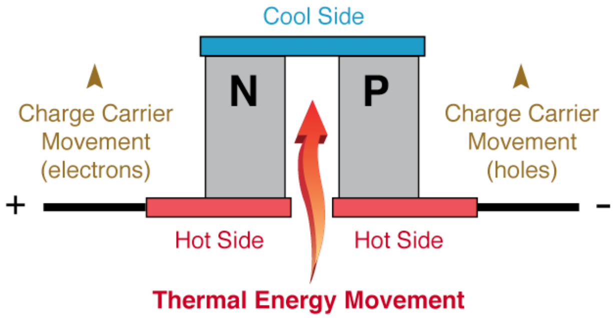



*Figure 12*

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 semi-conductor material?

They could, but don't. Tellurex uses bismuth telluride structures to optimize performance. While similar dopants are employed the crystalline lattices which form from bismuth telluride, are far more complex than those of silicon. 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.

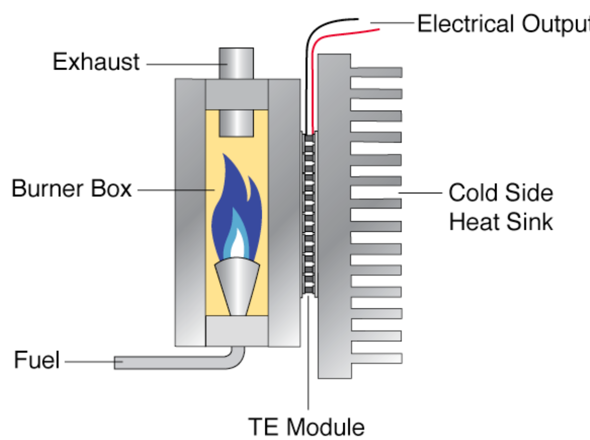



*Figure 14*

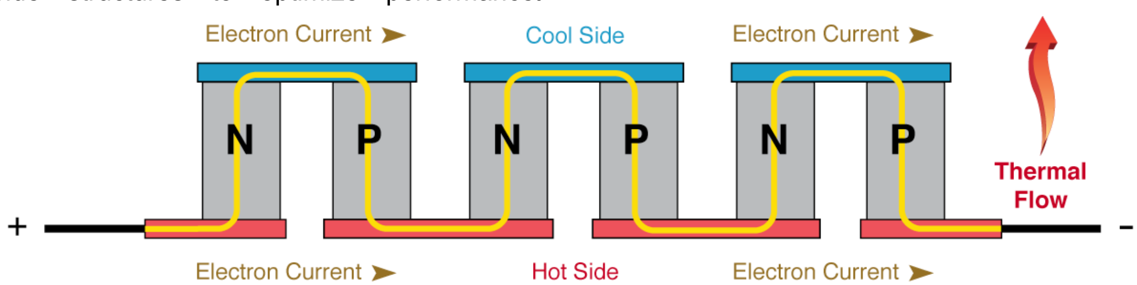



*Figure 13*

**4. Do I have to use a heat sink in my design?**

It would be impossible to get an adequate ΔT 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 in constructing the modules. It is essential, therefore, that the temperature be kept below the rated high temperature for the device. 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.

**6. What does the specification $T_{Hot}$ mean?**

This is the temperature at the mounting surface of the module, where it comes in contact with the heat source (i.e., the hot side of the system).

**7. What does the specification $T_{Cold}$ mean?**

This is the temperature at the mounting surface of the module, where it comes in contact with the cold-side heat sink.

**8. What does “no-load voltage” ($V_{NL}$) mean?**

This is the voltage output of the TEG system when no electrical load is connected.

**9. What does “load voltage” ($V_L$) mean?**

This is the voltage output of the TEG system when an electrical load is connected. It will be less than $V_{NL}$ and its amplitude will depend, in part, on the resistance of the load.

**10. What does “internal resistance” ($R_{Int}$) 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 ΔT.

**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).

**13. What does “worst case operating point” mean?**

Within the range of operating possibilities, the worst case will occur at the point where the generating system can *just meet* the expected demands of the electrical load. In most systems, this will be when: 1) the generator is at the lowest expected ΔT, *and* 2) the load requires the greatest expected current draw. Some systems may have a worst case operating point under other unique conditions, however. The key concept is that the load requires everything that the generator can produce.

**14. What sort of efficiencies typically result from TE power generation?**

To put it bluntly, TEG’s are not used for their incredible power conversion efficiency. When your primary design goal is maximizing efficiency, you’re plainly going to choose another technology. Generally, if you’re getting 2 to 3% between power in and power out on a bismuth telluride TEG, you’re doing pretty well.

As for the efficiency of any *specific* TEG system . . . well, that depends. The properties of thermoelectric modules are quite temperature dependent and efficiencies can vary widely depending on the operating parameters of the system at hand. Generally speaking, the higher the ΔT the more efficient your system will be.

**15. Why, then, would I want to use a thermoelectric generator (TEG) as opposed to some other approach?**

Thermoelectric power generation is definitely a niche technology. TEG use is most viable in applications where *waste heat* can be converted into usable electric power. In these situations, the input power is essentially *free*—heat that is a by-product of some other necessary process. As long as the opposite side of the module can be effectively cooled (usually with a passive heat sink) to create a ΔT across the TEG, there is the potential for extracting DC to power an electrical load. When the source heat comes at no cost, inefficiency is hardly an issue.

Another common justification for using TEG's, is when there is an overriding reason precluding the use of other technologies. For example, the remoteness of a use site may make it impractical for someone to maintain a gas-powered mechanical generator. As long as a source of fuel is readily available, a properly-operated thermoelectric generator can run for a very long period without human attention. The need for a low-noise solution might also tip decision making in favor of thermoelectrics.

## 16. What is "maximum power transfer" and why is it so important in designing TEG systems?

It's too bad there's not a short answer to *this* question, but alas. People are so accustomed to working with regulated power sources these days, that they hardly pay attention to this very fundamental concept of electronics. With a regulated power supply, you can connect all kinds of different loads (within *some* limits), and the voltage will stay relatively constant. You can even buy constant current sources that will keep the *current* steady despite variations in load.

TEG's just don't work like regulated power supplies. At any given ΔT, as the load resistance decreases, so does the output voltage; as the load resistance increases, the output voltage will follow suit. There is no inherent output regulation (although it can be provided with additional circuitry). Why? Because TEG's have appreciable "internal resistance". This means that as more current is drawn by the electrical load (e.g., as load resistance decreases), more of the available power is dissipated *within the TEG*; furthermore there is an appreciable voltage drop across this internal resistance.

To understand the electrical model for a TEG system, imagine the no-load voltage (i.e., the open-circuit voltage output of a TEG) applied to a series circuit consisting of the module's internal resistance ($R_{INT}$) and the electrical load ($R_{Load}$)—see *Figure 15.* As in any series circuit,

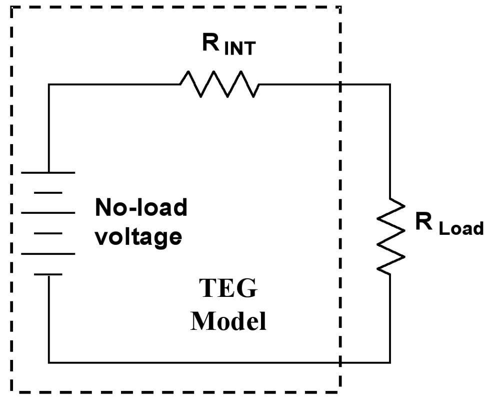



*Figure 15*

the voltages will 'drop' in proportion to the resistances. Thus, if the no-load voltage was 3 VDC, the internal resistance was 3 Ω, and the load was 6 Ω, there would be a 2 VDC drop across the load.

$$V_{Load} = V_{NL} \cdot \frac{R_{Load}}{R_{INT} + R_{Load}}$$

$$V_{Load} = 3\,VDC \cdot \frac{6\,\Omega}{3\,\Omega + 6\,\Omega} = \mathbf{2\ VDC}$$

So how does "maximum power transfer" fit into all of this? Here's the deal. For *any* electrical circuit, you will transfer the most *power* to the load when the resistance of the load *equals* the internal resistance of the voltage source. Note we are not saying that this point of operation will give you the maximum amount of voltage or current—that is simply not true—but you will derive the greatest *power* output at that point. For example, in the circuit with the no-load voltage of 3 VDC and 3 Ω of internal resistance, we could use the following formulas to determine load voltage, current, and power for various load resistances:

$$V_L = V_{NL} \cdot \frac{R_{Load}}{R_{INT} + R_{Load}} \qquad I_L = \frac{V_L}{R_L}$$

$$P_L = V_L \cdot I_L$$

*Table 1* shows what would result for a range of load resistance values between 0.5 and 8 Ω. While the load voltage increases with load resistance and load current increases as the load resistance decreases, it can be seen that the maximum amount of *power* is transferred to the load when the load resistance *equals* the internal resistance of the TEG. This is an immutable principle which can actually be proven as the general case using advanced mathematics. It can also be demonstrated empirically in the lab. Ironically, at this operating point, you will dissipate equal amounts of power within both the load and the internal resistance

| RL | VL | IL | PL |
|---|---|---|---|
| 0.5 | 0.43 | 0.86 | 0.367 |
| 1 | 0.75 | 0.75 | 0.563 |
| 1.5 | 1.00 | 0.67 | 0.667 |
| 2 | 1.20 | 0.60 | 0.720 |
| 2.5 | 1.36 | 0.55 | 0.744 |
| 3 | 1.50 | 0.50 | 0.750 |
| 3.5 | 1.62 | 0.46 | 0.746 |
| 4 | 1.71 | 0.43 | 0.735 |
| 4.5 | 1.80 | 0.40 | 0.720 |
| 5 | 1.88 | 0.38 | 0.703 |
| 5.5 | 1.94 | 0.35 | 0.685 |
| 6 | 2.00 | 0.33 | 0.667 |
| 6.5 | 2.05 | 0.32 | 0.648 |
| 7 | 2.10 | 0.30 | 0.630 |
| 7.5 | 2.14 | 0.29 | 0.612 |
| 8 | 2.18 | 0.27 | 0.595 |

*Table 1*

of the generator (i.e., your *electrical* efficiency will be 50%). This, no doubt, seems less than ideal, but if you want to get the maximum power output from your generator, you can only do so with a matched load.

Okay, so we just need to match our generator and load, right? Matching loads, however, can get fairly tricky. It is most easily done when sales quantities can justify a *custom* TEG module; then the pellet configuration can be optimized for the specific application. When employing off-the-shelf options, on the other hand, the designer is left to arrive at a series/parallel module combination that can do the best job of load-matching with the fewest devices. Further complicating matters in many cases, will be the fact that operating conditions may change over time and your design may be matched for one set of circumstances but not for another. If the ambient environment is dynamic and/or the load resistance is variable, therefore, the engineer must design to the worst case and then manage surplus capacity with a regulatory circuit.

There will be some cases where you may not want to design for maximum power transfer, especially in those systems which do not run on waste heat. Here power conversion *efficiency* (which occurs at a somewhat different operating point) may be the greater issue. Even then you may want to compromise a bit toward enhancing power transfer—a little bit of efficiency sacrifice can translate into a significant power output boost.

Practically speaking, most TEG system designs will be at least somewhat mismatched. When you're dealing with discrete building blocks (i.e., individual TEG modules), you can only *approximate* a given resistance with series/parallel combinations. Generally, it is better to err on the side of having load resistance *exceed* internal resistance (efficiency is a much more slippery slope when it is the other way around).

## 17. Is a TEG's resistance fairly constant over its operating range?

These devices are significantly temperature-dependent and that presents us with additional challenges in arriving at design solutions. For example, a module that has an internal resistance of 5 Ω at an average temperature of 100° C, might reach 6.1 Ω at 150° C. This can result in significant shifts in output voltage, current, and power as operating temperatures change. With that module for instance, if the average temperature was 100° C, the no-load voltage was 8 VDC, and the load resistance was 5 Ω, the resulting load voltage would be 4V with a current draw of 0.8 amps ($P_L$ = 3.2 W). If the average temperature then drifted to 150° C while holding the same no-load voltage, the load voltage would decrease to 3.6 V with a current draw of 0.72 amps ($P_L$ = 2.6 watts—nearly a 19% decrease). Therefore, if there is any potential for variation in operating conditions, you have to look at the range of module resistance values that may result and make sure that you can accommodate them. This usually means designing to the worst case—making sure that you get sufficient power when ΔT is low and current demand is high—and manage the excess generating capacity at all other operating points.

## 18. What sort of ΔT is required to generate power?

Any ΔT at all will result in power generation. The greater the ΔT, however, the more power can be derived at the greatest efficiency—all other things being equal. Put differently, the greater the ∆T you achieve, the fewer TEG devices it will take to power a given load.

### 19. How big can these devices get?

Theoretically, there is no limit, but practicality does impose some restrictions. Issues related to thermal expansion/contraction—and cost—tend to keep module sizes down to a moderate size. Typical devices range up to 50 mm (1.97") square and about 4 mm thick, but there are exceptions. In the general case, when extra generating capacity is required, multiple TEG devices will be employed rather than fabricating some sort of gargantuan module.

### 20. How small can these devices get?

Here again, the theoretical limit goes far beyond what is practical. One issue is manufacturability. At a certain point, smaller devices become more expensive to make because they are less adaptable to automated techniques and require more hand assembly under demanding conditions.

### 21. Is there any advantage to be gained from using multi-stage TEG's?

Only if you are dealing with stages that employ dissimilar types of semiconductor material that are also optimized for different temperature bands. This approach also demands a large enough ∆T so results will more than makes up for the structural complexities and losses in this approach.

A related technique that is in development, is to layer thermoelectric *pellets* with materials that are formulated for accommodating temperature gradients across the element. Thus a material employed at the colder end of the pellet can be optimized for that part of the spectrum while another material can be utilized for the warmer range. This yields greater efficiencies.

Doing staging with modules of the same material type, however, offers no advantages at all. This sort of series thermal configuration would actually lower the ∆T applied to each stage (halving it in the case of two layers). This, in turn, would reduce the power output of each stage. It is a lose-lose proposition.

### 22. If I need more voltage than can be provided by a single device, what are my options?

If the electrical current level from a single device is adequate, but the voltage is insufficient, you usually place additional modules electrically in series.

### 23. If I need more current than can be provided by a single device, what are my options?

If the voltage level from a single device is adequate, but the current level is insufficient, you usually place additional modules electrically in parallel.

### 24. What if I need more voltage and current?

Here there is no one clear answer. This requires circuit analysis on various series, parallel, and series/parallel combinations of TEG's until one is found which best matches the load conditions. Of course, you need to keep the temperature dependence of the modules in mind as you explore this.

### 25. How can I determine the optimum series/parallel configuration for a given load?

Frankly, this is probably best done by presenting your design needs to a Tellurex sales representative. At Tellurex, we employ computer models to help us converge on a solution that will meet your worst-case requirements and give you extra capacity at other times. To help you with your application, we will need to know:

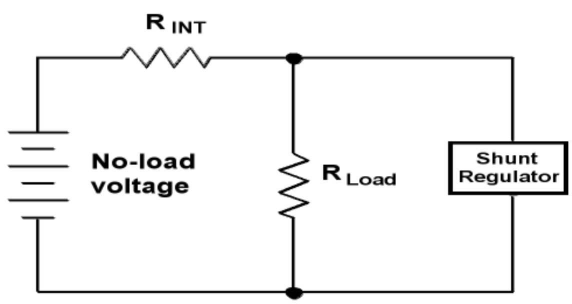
1) The expected range for $T_{Hot}$,
2) The lowest expected ∆T,
3) The desired voltage level,
4) The greatest expected current draw at that voltage level,
5) Any physical limitations which might impinge on the number of Seebeck devices employed,
6) Whether or not voltage regulation is important (i.e., whether your load can withstand fluctuations in voltage and current), and

7) Whether quantities could justify the use of a custom device.

## 26. If I need a steady output voltage, do I need some sort of regulator?

Unless your operating conditions are *absolutely* constant, you will need a regulator. The instinctive response in this kind of situation, is to employ a series regulator. Naturally, according to Murphy's Law, that is precisely the *wrong* thing to do. The problem with series regulators, is that their input voltage must be at least 1.5 to 2 V higher than the desired output. This means that you might have to use additional generator capacity just to deal with the voltage drop across the regulator. Ideally, you would like a regulator that would allow you to use every last bit of available voltage if it's required.

Fortunately, there is a regulator circuit which can deliver on this frontier—the *shunt* regulator. A shunt regulator uses a power semiconductor component (usually a transistor) placed in *parallel* with the load. Here it works much like the overflow drain on a bathtub—if you fill the




tub to the overflow drain, it begins to siphon off water to keep the tub from overflowing. With the shunt regulator, if the TEG is producing power that would normally take the load voltage beyond the desired operating point, the regulator will begin to conduct. By drawing additional current, it can drop more voltage across the internal resistance of the TEG module.

The shunt regulator can provide two types of regulation—line and load. In providing line regulation, the shunt circuit conducts current as necessary to hold the load voltage constant in the face of changes in no-load voltage. It can also provide load regulation—that is, altering its conductive properties to compensate for changes in load resistance. If the load requires more current, the shunt regulator conducts less; if the load requires less current, the shunt regulator conducts more. There is one "fly in the ointment", however. The shunt regulator can only provide regulation as long as it is drawing current. Once the circuit load resistance draws all of the available current at the desired voltage, the regulator can no longer respond to further reductions in either load resistance or no-load voltage. If you design your system to this worst case, however, you should not have any problem with regulation.

A DC-DC converter can also be used as a regulator in these situations although it tends to be a more expensive alternative. There are situations where it is the only option, however, such as in micropower generation where very low voltages must be stepped up to a useable level. A shunt regulator would be incapable of doing this. The trickiest part about using DC-DC converters, however, is in matching the input impedance to the internal resistance of the TEG(s).

It is important to note here, that the use of a regulator will decrease the power-conversion efficiency of the system. The power dissipated in the regulator is generated output that is not delivered to the load. This is simply part of the price of regulation, however.

## 27. What is impedance?

Impedance is very similar to electrical resistance only it also involves other effects which can have a diminishing effect on current levels. Impedance also includes capacitance (dealing with the charging and discharging action of components) and inductance (which arises from the expansion and contraction of magnetic fields). When you match an input and output impedance in a circuit, you try to get all of these characteristics in concert to bring about either maximum power transfer or optimize efficiency. Steady-state DC does not have capacitive or inductive issues, but DC-DC converters pulse the output of TEG's and that does create impedance matching concerns that go beyond resistance.

## 28. Why not just control the heat source to get a regulated output?

This would be a terrific way to go if it was practical. With this approach, if a generator was using excessive energy, you could just cut down on the input power (e.g., fuel flow). The problem is that this would typically be done with an electrically-controlled valve. Unfortunately, the power demands of these valves and the support circuitry to control them, would consume most (and perhaps all) of the generator's potential output. An electronic regulator is usually more cost-effective.

### 29. Is there a limit to how many devices I can use in a TEG system?

Theoretically, no, although at a certain point, it can get a little clumsy mechanically.

### 30. Are there any special considerations which apply to clamping a device?

The biggest challenge is finding an effective way to maintain fairly even compression across all of the modules employed. In doing this, you must provide enough compression screws (i.e., the fasteners which draw the hot and cold sides toward the module) to assure a good thermal interface, yet avoid any distortion of the metal stock (heat sinks, burner boxes, etc.). If the expanse is too great, the metal can easily bow and compromise the thermal interface (and mechanical integrity) in the process. Also, when assembling the generator, it is important to bring the compression up gradually on these screws so that modules are not crushed from the collapsed fulcrum effect {see "Mechanical Clamping Method", in the *Introduction to Thermoelectrics*}.

### 31. Do I need to be concerned with the rate of temperature change when powering up my system?

You will certainly enhance the longevity of your system if you ramp it up (or down) slowly. Very rapid changes in temperature can cause damage to the module due to differential rates of thermal expansion and contraction. While some thermal variation is expected in a TEG system and the devices must withstand this, it is still prudent to minimize these dynamics whenever possible. Try to keep the rate of change under 1° C per second

### 32. How can I determine what my heat sink needs are?

This is probably best done by using a rule of thumb and inferences. Proceed as follows:

1) Based on the expected ΔT, you can make a guess on the system's power conversion efficiency. For bismuth telluride with a fairly high ΔT, this would be in the range of 2-3%.
2) Take your worst case (i.e., greatest) electrical load in watts and divide it by the estimated efficiency. This will approximate the number of watts that must be dissipated in the sink.
3) Subtract the expected ambient temperature from the expected cold side of the thermoelectric device. This will be the ΔT for the heat sink.
4) Divide the expected heat sink ΔT by the total number of watts that will be dissipated in the sink.

For example, if we suspected an efficiency of 2% in an application delivering 5 W to a load, with a temperature difference of 30° C between the cold side of the module and ambient air, we could determine the required heat sink resistance (1/*K*) as follows:

$$1/K = \frac{\Delta T_{Sink}}{\left(\frac{P_L}{\eta_{T\arg}}\right)} = \frac{\Delta T_{Sink} \cdot \eta_{T\arg}}{P_L}$$

$$1/K = \frac{30° \cdot 2\%}{5\,W}$$ **= 0.12° C/W**

### 33. Would it be helpful to include a fan on the "cold side"?

With any heat sink, proper air movement will dramatically enhance the performance. Thus, if you can provide active ventilation to your cold-side sink, you should be able to improve your ΔT. The big question is whether the improvement in performance will be more than enough to offset the power demands of the fan. Sometimes it will be feasible, sometimes not.

### 34. Do I have to insulate between the hot and cold sides of the system?

If you can find an insulating material which will withstand your highest temperatures, it will improve the power-conversion efficiency of the system. Aerogel™ and Pyrogel® blanketing are good for such applications, but they can be difficult to obtain in small quantities.

**35. How can I measure no-load voltage directly when the system is connected to an electrical load?**

Simply put, you can't. The only way to measure the no-load voltage, is by disconnecting the load and measuring the voltage which results. You'll find, however, that as soon as you remove the load connection, the no-load voltage will quickly change. This occurs because the sudden loss of current flow decreases the effective thermal conductivity of the module. This, in turn, disrupts the thermal balance of the system because heat from the source cannot flow to the cold side sink as easily.

**36. What happens if I design a system which provides more electrical power than I need?**

If the system *always* provides surplus power, try decreasing your ΔT. This can be done by either decreasing input power (if possible) or by using a less efficient heat sink on the cold side. On the other hand, if your power surplus occurs on an intermittent basis and your load cannot withstand the variability, you may need to manage the excess with a shunt regulator or DC-DC converter.

**37. Does Z-Max® offer any advantages over other thermoelectric power generators?**

Yes. With our unique, patented, hybrid metallurgy, Z-Max® devices yield power outputs which are unsurpassed in the industry for bismuth telluride technology.

**38. What are the temperature limits for your TEG's?**

Our G1 series bismuth telluride devices have an upper limit of 175° C on the hot side and 100° C on the cold side. The G2 series can run at temperatures as high as 320°.

Meanwhile, Tellurex researchers are working in conjunction with universities and other collaborators, to develop new technologies which can operate at—and are optimized for—much higher temperatures. This will pave the way for designs which will function at significantly greater ΔT's than have been possible in the past. With system efficiencies being highly correlated with ΔT's, substantial improvements in material efficiency may be yielded. This is especially true in designs which use layered semiconductor elements to optimize material performance within the temperature gradient. Prototype devices have been produced and development is progressing to bring these devices to commercialization.

**39. What kind of efficiencies are expected from these new materials?**

Under best-case conditions, using layered thermoelectric elements, *material* efficiencies over 10% may be achieved. This assumes a very high ΔT (e.g., 400° C). As ΔT decreases, so does efficiency. High ΔT's and the formulation of materials which are optimized at high temperatures, allow for greater efficiency. If you used the new materials with the same kind of temperature drop that is typical of bismuth telluride systems, you would probably get an efficiency comparable to that $Bi_2Te_3$ technology (give or take depending on the actual temperatures used).

It is important to note that we are talking about *material* efficiency here. As we introduce mechanical and thermal interfaces into the equation—which are not insignificant—the actual module efficiency will be less. At this time, we are evaluating the extent of these effects in our research.

**40. I am having a lot of difficulty designing a power generation system using the graphs provided on the Web site. How should I begin?**

The absolute best thing you can do is to contact our sales department (231-947-0110 or sales@tellurex.com). The design of thermoelectric generator systems, requires an extensive, specialized knowledge base and is a very challenging proposition—even for very experienced engineers and scientists. It is much more demanding than dealing with the cooling side of thermoelectrics (i.e., Peltier technology). There are a lot of variables and everything is inordinately temperature dependent. With the addition of the need for load matching, it gets tricky very quickly. To be frank, *we* need a computer model to cope with it. With our proprietary computer-based tools to converge on a solution, we can cut through calculations in a split-second that would take hours of laborious work any other way. In the process of setting up the model, we can identify the kind of information that is needed to evaluate your power generation needs (see question 25)—and you may require more specific estimates than you anticipate in order to get meaningful answers. Work with us and you will certainly get farther faster.

**41. My results seem to vary significantly from what is predicted on the graphs at your Web site. What would account for this?**

Like other manufacturers, Tellurex bases its specifications and performance graphs on modules tested under laboratory conditions. Great care is taken in the preparation of samples. We especially try to insure consistency in thermal interfaces and insulation between hot and cold sides of the test system. Key temperature readings are taken right at the surface of the TE modules. Using these methods, we find that we get very good repeatability.

Results within a customer's system are very dependent upon the details of the design and environment, from selection of a cold-side heat sink, to worst-case ambient conditions, nature of interfaces, use of insulation, and so on. Placement of temperature sensors can often go a long way toward explaining discrepancies.

The best way to insure close correspondence between expectations and results, is to communicate with our sales staff from the outset (231-947-0110 or sales@tellurex.com). We can often spot problems that you may not see and make recommendations that can substantially improve your design.

**42. Are these modules tested before shipment?**

All Tellurex TEG's are subjected to quality testing before shipment.

**43. Can I check a TEG with an ohmmeter?**

No. The vast majority of ohmmeters apply DC to the resistance being measured. This will generate a Seebeck voltage which makes the measurement inaccurate. To measure internal resistance directly, you must use a meter which applies a true AC waveform (i.e., one which varies in polarity every half-cycle). With the continual polarity reversals in this type of meter, little or no Seebeck voltage will be created (although some self-heating may result if you hold it under test for a prolonged period). To get this kind of operation, you will probably have to locate a high-quality LCR meter. There are a few handheld meters on the market which can do this, too—check B & K).

**44. Can I use an ohmmeter which applies a pulsed DC?**

No. This, too, will result in Seebeck voltages which make measurement inaccurate. The meter must apply a waveform which reverses polarity every half cycle.

**45. Are all thermoelectric modules on the market essentially the same?**

No. Each company takes its own approach with manufacturing processes and material formulations, some to assure the highest quality and others to deliver the lowest price.

**46. What sorts of differences are seen?**

There are two major areas of difference and each impacts performance:

a) Workmanship: In good quality devices, manufacturers strive for superior alignment of semiconductor pellets, strong bonds between pellets & conductor tabs, strong bonds between tabs & substrates, and superior cleanliness. In poor quality devices, electrical and thermal shorting can be created by bad alignment and debris; furthermore inadequate bonds can compromise strength.

b) Material technology: Each manufacturer jealously guards its formulation of semiconductor material. Some companies, like Tellurex, have become international standards for the benchmarking of their materials. In fact, Tellurex has exclusive worldwide licensing to the highest performing power generation materials. Other companies are not as successful in the development of semiconductor material and the differences in performance can be highly significant.

**47. There are thermoelectric modules available from third party sources at highly discounted prices. Are these different from other thermoelectric modules?**

Yes. Low budget thermoelectric modules, in addition to the problems noted above, may be scrap or defective products that a reputable company would never release to a customer.

**48. I purchased a thermoelectric module with the same specifications as the Tellurex product but it does not perform as well. Why is that?**

We have seen specifications from another company that make it appear that a device has an incredible capacity for heat-pumping as expressed in watts. Upon closer examination, we have found that their published data actually describes the heat that the module dissipates in its own resistance while running at VMax. We recommend that you discuss all published specifications with their sales support staff. If that experience disappoints you, call us.

**49. Is Tellurex still the global leader in new thermoelectric materials, engineering and technology?**

Yes.

**50. How long has Tellurex been in business?**

Since 1986.

**51. How can I order products from Tellurex?**

You can call us at 231-947-0110 or order from our Web site at www.tellurex.com.

**52. Do you have a minimum order requirement?**

Tellurex direct sales requires a minimum of $75. Exemptions may made for academic institutions.

**53. How can I get more information?**

The best place to get information is from our website—www.tellurex.com. You can also call us at 231-947-0110 or write us at 1462 International Avenue, Traverse City, MI 49686. Email may be directed to sales@tellurex.com.

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