USE, APPLICATION AND TESTING OF Hi-Z THERMOELECTRIC MODULES

(The HZ-14 is used as an example. The other modules should be evaluated in a similar way.)

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Abstract

The HZ-14 is a thermoelectric module that converts low grade, waste heat into electricity. To obtain optimum performance from the HZ-14 it is important to address several key points when using the module in an application. These key points in the use of the module are discussed, and methods of identifying the causes of inferior performance are addressed. The performance characteristics of the module are also described.

1.0 Introduction

The HZ-14 is a thermoelectric module that is intended to target the waste heat market. The module uses bismuth telluride based alloys and consists of 98 couples as shown in Figure 1. When applied to any heat source, the module requires a heat flux of about 8 watts per cm^2. With a temperature difference of 200°C the module converts 5% of the thermal energy that passes through it into electricity, generating a minimum of 14 watts of electrical power. When properly installed, it will run for tens of thousands of hours.

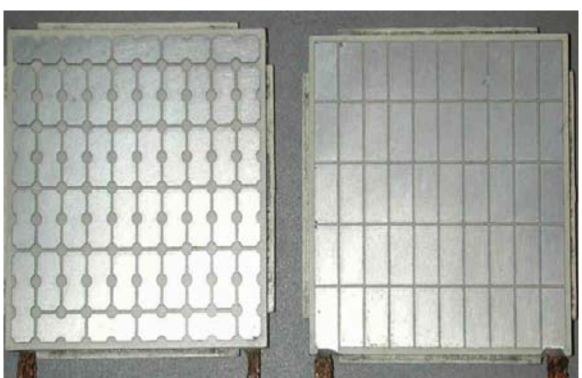

Figure 1 – H Z-14 Thermoelectric Module Showing the Cold Side (right). The hot side (left) shows dots of the "egg crate" material.

It has been observed, however, that unless special attention is paid to certain details, satisfactory performance from the module is not achieved. The purpose of this article is to address these key points and to discuss some solutions that have been found to yield good results.

2.0 Mounting of the Module

The best method of using the module is to compressively load it between the heat source and the heat sink. A minimum load of 200 psi has been found to yield the best results. It is very important to uniformly distribute the load over the surface of the module to achieve optimum power performance and avoid damaging the module. A well designed mounting system needs to address the following issues:

1) Compressive Loading
2) Thermal expansion
3) Uniform load
4) Overhang
5) Thermal spreader
6) Flatness and thermal transfer compound
7) Thermal bypass
8) The hot side of the module is the side showing dots

2.1 Compressive Load

Putting the module under a compressive load helps in two ways: 1) it ensures that the module always remains in compression (where it is the strongest), and 2) it maximizes heat transfer across the interfaces. Experimentation shows that most of the beneficial effects on heat transfer are achieved with a 200 psi compressive load.

2.2 Thermal Expansion

In determining the compressive load, it is important to accommodate the large thermal expansion of the module which is about 20 x 10^{-6} °C^{-1}. The best way to do this is to use springs to apply the load. If the system is simply bolted together, then the expansion of the module will apply too much pressure, or conversely, any yield in the bolts or threads will rapidly lose pressure. A typical system that can be used to mount a thermoelectric module to a hot surface is shown in Figure 2. The Belleville springs used in this example apply a large amount of force in a very compact space and at the same time they allow for thermal expansion.

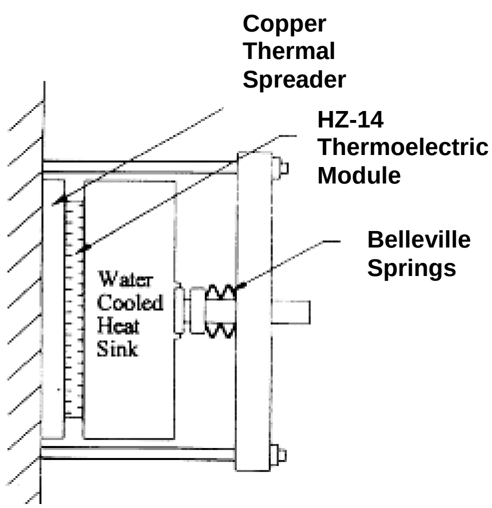

Figure 2. Module Pressure System

2.3 Uniform Load

The clamping system used to hold the heat sink and heat source onto the module can have a significant effect on the module performance. If the module is clamped to the heat source and the heat sink by simply bolting along the edges of the heat source and heat sink, then bowing can occur, since the edge of the module acts as a pivot pin as shown in Figure 3.

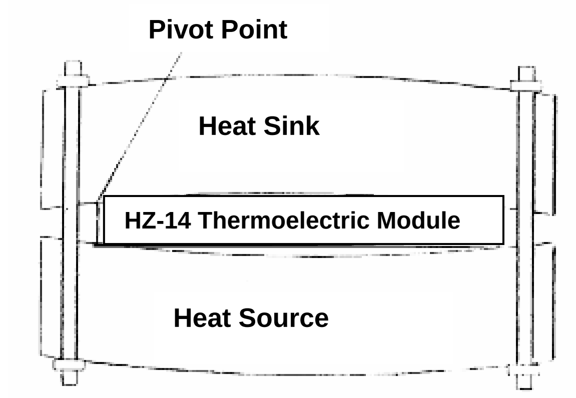

Figure 3. Bowing of Heat Sink/Source

Bowing of the heat sink will cause excessive forces on the perimeter of the module and a gap in the center of the module. This type of mechanical loading is to be avoided since it will result in non-uniform temperatures across the face of the module and, therefore, poor performance from the module. Also, if the forces around the circumference of the module become too large, this may result in permanent damage to the module caused by micro-cracking of the thermoelectric material. Thicker heat sinks and heat sources will help minimize this bowing effect.

2.4 Heat Source Overhang

The maximum performance from the module is achieved when the temperature difference across the face of the module is zero. Since the heat source will cool near its edges, the edge of the heat source should extend well beyond the edge of the module. In a laboratory test setup an overhang of at least 0.5 inch is necessary to avoid most of the cooling effects caused by the proximity of the edge of the heat source. In an actual generator it may not be possible to allow for this 0.5 inch overhang.

2.5 Thermal Spreader

To further assist in uniform temperature distribution across the face of the module, it is helpful to place a copper or aluminum plate between the module and the heat source. If the heat sink is not copper or aluminum, then a copper plate should be placed between the module and the heat sink as well. The copper plate should be at least 0.25 inch thick.

The copper plate acts as a thermal spreader and helps to minimize hot spots and cold spots and provide a uniform temperature to the face of the module.

2.6 Flatness and Heat Transfer Compound

For maximum heat transfer across the interfaces, it is important that the surfaces to which the module is to be applied be as flat as possible. A flatness of ±0.001 inch is necessary but a flatness of ±0.0005 inch is recommended. If the heat sinks are being clamped from the sides then a very slightly convex surface will help compensate for any bowing that may occur.

In any interface, no matter how smoothly machined it is, microscopic irregularities on the surface (See Fig. 4) limit the amount of contact area that can be achieved between the two surfaces.

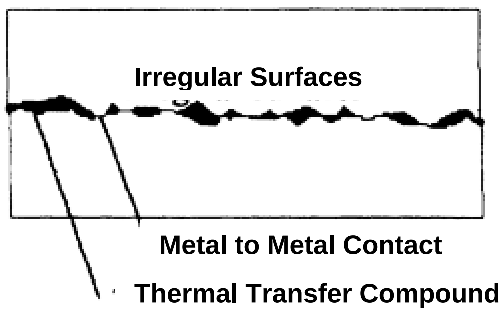

Figure 4. Interface with Irregular Surface

Filling the voids in the interface, that are caused by the irregular surfaces, with a heat transfer compound can greatly improve the thermal conductivity across the interface. Using too much thermal transfer compound, however, will prevent metal-to-metal contact, and the thermal conductivity will actually be reduced. Conventional silicone greases, using a ZnO filler that are commonly used to heat sink transistors, work very well. If maximum performance is necessary heat transfer greases filled with AlN or BN will decrease the thermal resistance.

Thermally conductive adhesives are available that could be used to bond modules to heat sinks and heat sources, but they do not yield satisfactory results. Even though the bulk advertised properties appear to be good, the filler material often pulls away from the interface surface leaving a layer of unfilled adhesive with a very low thermal conductivity.

Another disadvantage with adhesives is that the module may not always be held in compression as it is with spring loading. If the adhesive allows the module to be subjected to tensile or shear forces, it then becomes susceptible to damage.

2.7 Thermal Bypass

A significant loss of efficiency in the thermoelectric systems that is often overlooked is thermal bypass. Thermal bypass is defined as thermal energy that passes from the hot side to the cold side without passing through the thermoelectric material. About 2% of the thermal energy passing through the module bypasses the thermoelectric material by passing through the module structure.

A much larger portion of the thermal energy can bypass the module by passing through the metal support structure outside the module and through the air gap between the hot and cold sides. Referring to Figure 2 it is obvious that a large amount of thermal energy will pass from the heat source to the cold side through the mounting rods. This can be minimized by making the mounting rods as small as possible, choosing low thermal conductivity materials and by increasing the length of the thermal path. One method for increasing the length of the thermal path is shown in Figure 5. The use of Kapton washers at the interfaces will help minimize thermal bypass.

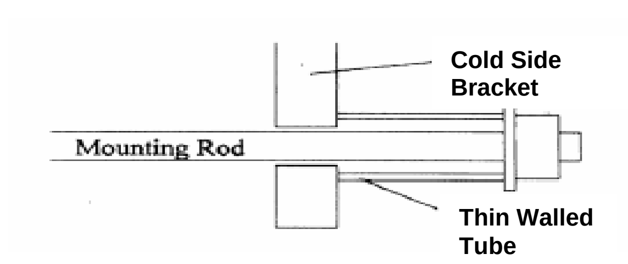

Figure 5. Increased Thermal Path

To avoid any support structure that can conduct heat from the hot side to the cold side, it is suggested, where possible, to mount a thermoelectric module on both sides of the heat source. This allows the mounting rods to go from one cold side to the other cold side without touching the heat sources as shown in Figure 6.

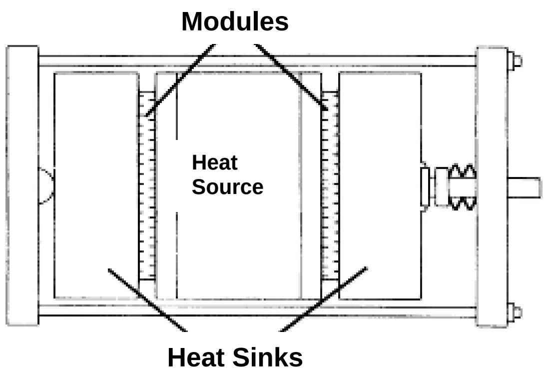

Figure 6. Double Sided Arrangement

This arrangement forces all of the thermal energy to pass through with the exception of the thermal energy that is lost to the surrounding atmosphere. Good thermal insulation will minimize the heat losses to the atmosphere.

3.0 Interfaces

The interface between the module and the heat source and the interface between the module and the heat sink are very critical components of any thermoelectric system. The surface of the module consists of the metallic, electrical conductors that join the “N” and “P” elements of the module. It is essential that these conductors are not electrically shorted together.

Since most heat sources (and heat sinks) are also electrically conductive, an insulating material must be placed between the module and the heat source or heat sink. If the heat source (or sink) is not electrically conductive then, of course, this is not necessary.

Several options for an electrical insulator exist and they each have their advantages and disadvantages. Some of the more common alternatives are:

1) Impregnated silicone pads
2) Hard anodized Al_2O_3 coatings
3) Sputtered coatings
4) Ceramic wafers
5) Kapton
6) Mica

All of these alternatives require the surface to which the module is to be mated to be extremely flat. A minimum tolerance of ±0.001 inch is suggested for the flatness of the mounting surface but a tolerance of ±0.0005 inch is recommended. The 14 watt modules are surface finished to this tolerance. Where possible, any deviation from flat should be towards the formation of a convex surface as discussed in Section 2.6.

3.1 Silicone Pad

Silicone pads are commonly used in mounting power components in electronic circuits. They are easy to work with and because of their flexible nature they can compensate for irregular surfaces. The very best pads that were available however still allow a temperature drop of 25°C when the module was a ΔT of 200°C. Further, these pads are not recommended for use above 210°C.

3.2 Hard Anodized Coatings

Aluminum hard anodized coatings have worked well in some cases. It is essential that good silicone based heat transfer grease be used and that the pads are held in compression. The aluminum hard-coatings are easily scratched however, making the use of hard-coatings unreliable. Some “extra hard” hard-coatings have recently advertised but these coatings have not been evaluated.

3.3 Sputtered Coatings

Ceramic coatings sputtered onto the module or onto the heat sources (or heat sinks) are very promising. In order to be strong enough to provide reliable results, the coatings become quite expensive. While this method may provide good results, they remain to be evaluated.

Sputtered coatings still require the use of a good heat transfer grease and compressive loading to achieve a low resistance interface.

3.4 Ceramic Wafers

The most flexible system that yields the best results and is cost effective is to use a thin ceramic wafer in between the module and the surfaces to which it is being mounted. With the proper use of heat transfer compound in all interfaces and compressively loading the arrangement, temperature drops from the heat source to the module can be as low as 15°C with a module ΔT of 200°C. A similar temperature drop between the modules to the heat sink can be realized.

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Suitable ceramics that are relatively inexpensive are 96% Al_2O_3 wafers that are 0.010 inch thick and available commercially from several sources including Hi-Z. If BN filler heat transfer compound is used in the interfaces, temperature drops of less than 10°C have been achieved.

4.0 Troubleshooting

If all of the above steps are carefully followed, a satisfactory thermoelectric system should result. If, however, the system does not perform as expected, the problems can be quickly identified by following the steps described below and using Table 1.

4.1 Module ΔT

The first step is to determine what temperature difference has been obtained across the module. This can be estimated by bringing the module to the operating temperature and allowing it to stabilize. This should be done with the electrical load attached to the module. If no electrical load is available, connect the outputs from the module together using a jumper cable.

Next, connect the leads from a voltmeter to the outputs of the module so that the voltage can be read on the display. The voltage reading with current flowing through the module is called the load voltage (V_L). Disconnect the module from the load and quickly read the voltage on the voltmeter. The reading should be taken about 1 second after the electrical load is disconnected. The voltage on the module with no current flowing is called the open circuit voltage (E_O). Record this value in Table 1 on line 1.1.

When the load is disconnected, the module temperature will increase and the open circuit voltage of the module will rise. The open circuit voltage reading must be taken before the temperature rises significantly from the steady state condition.

Once the open circuit voltage has been measured refer to Figure 7 and obtain the module ΔT. Record this value on line 1.2. Similarly, from Figure 8, the available power from the module can also be found. Record this value in Table 1 on line 1.3. Compare the actual power that you are generating from the module with the value that you recorded on line 1.3. If you are obtaining this amount of power but it is lower than what you think you should be generating, you may have a heat transfer problem at the interfaces with your heat source and/or heat sink. Proceed to section 4.3 for a discussion on this topic. If you are not generating as much power as is indicated on line 1.3, then continue on to section 4.2.

4.2 Module Integrity

The integrity of the module can be determined by measuring the value of the internal resistance (R_i) of the module. If the measured value of R_i is less than the value in Figure 9 that corresponds to the measured open circuit voltage then the module

Table 1. Module Evaluation Work Sheet

1.0	Determine Module ΔT					
	1.1	Measure module open circuit voltage		E_O	= ________	V
	1.2	Predict module ΔT	(see Figure 1)	ΔT	= ________	°C
	1.3	Verify obtainable power	(see Figure 2)	P	= ________	W
2.0	Verify Module Integrity					
	2.1	Select precision load		R_L	= ________	Ω
	2.2	Connect precision load				
	2.3	Measure resistor voltage		V_R	= ________	V
	2.4	Measure loaded voltage		V_L	= ________	V
	2.5	Measure open circuit voltage		E_o	= ________	V
	2.6	Calculate module current	$I = V_L/R_L$	I	= ________	amps
	2.7	Calculate internal resistance	$R_i = \frac{(E_O - V_L)}{I}$	R_i	= ________	Ω
	2.8	Maximum allowable R_i from Figure 9		R_i	= ________	Ω
3.0	Measure Interface Temperature Drop					
	3.1	Measure hot side temperature		T_H	= ________	°C
	3.2	Measure cold side temperature		T_C	= ________	°C
	3.3	Calculate overall temperature drop		ΔT	= ________	°C
	3.4	Calculate temperature drop across interfaces ($\Delta Ti = (T_H - T_C) - \Delta T$)		ΔTi	= ________	°C

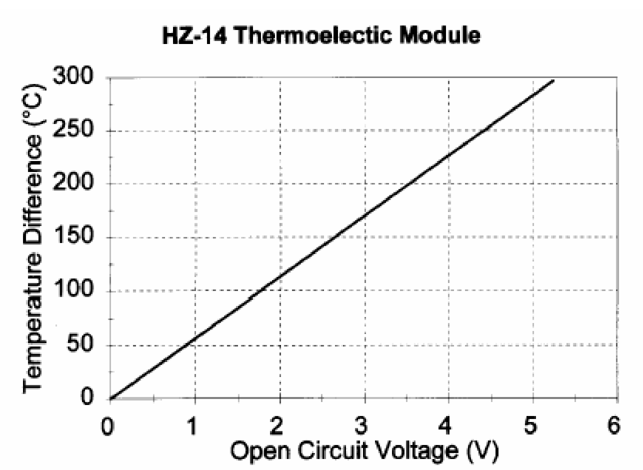

Figure 7. ΔT vs Open Circuit Voltage

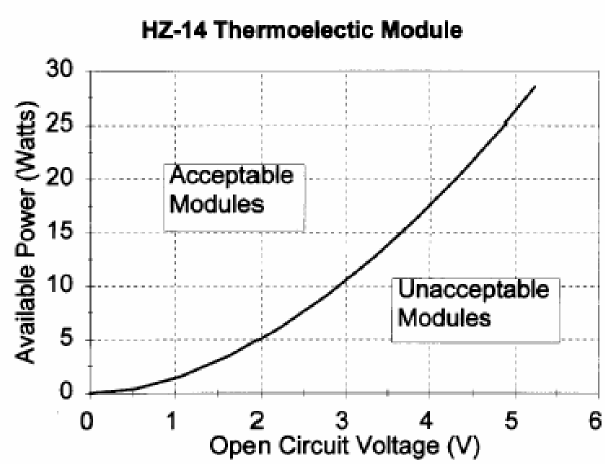

Figure 8. Power vs Open Circuit Voltage

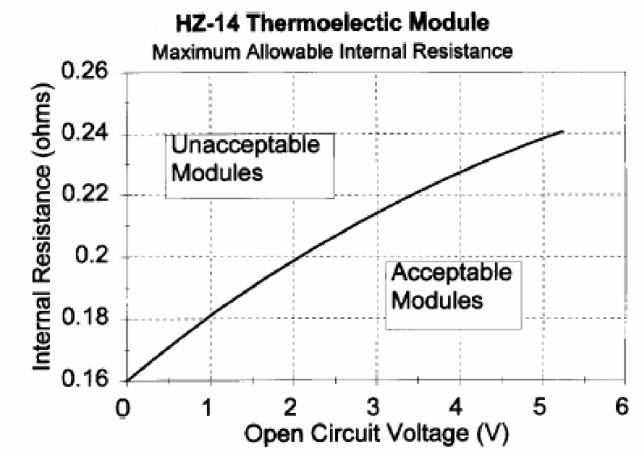

Figure 9. Internal Resistance vs Open Circuit Voltage

is making the power rated for that ΔT and E_o. If you are not sure what the internal resistance of your module is, this section will describe how it can be measured.

It is important to understand that maximum power cannot be obtained from the module unless the load resistance is closely matched to the internal resistance of the module.

The load resistance is equal to the internal resistance of the module when the load voltage is one half of the open circuit voltage. Figure 10 shows how much power is available from the HZ-14 module at different current levels (or in other words, at different loads).

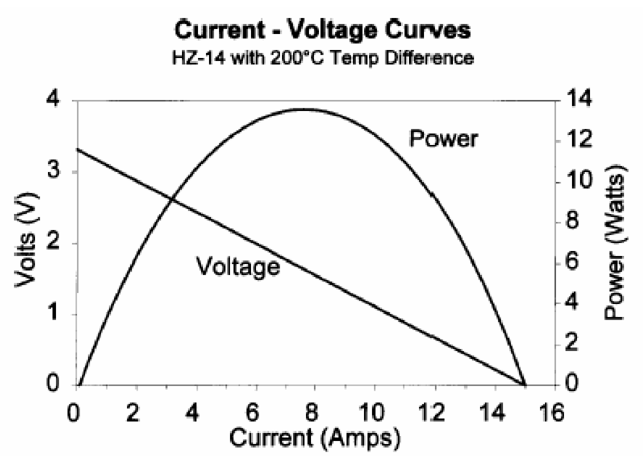

Figure 10. Current vs Voltage

4.2.1 Precision Electrical Load. In order to accurately determine how much power the module is generating it is important to connect the module to an electrical load that can accurately measure the power being dissipated. The value of the electrical load must be close to the value of the internal resistance of the module in order to obtain maximum power from the module.

Unfortunately, the internal resistance of the module is a function of temperature. For the sake of this evaluation a load resistor that is between 0.15 Ω and 0.25 Ω is suitable. The load resistor must be capable of dissipating at least 20 watts of power and have at least 5% accuracy. Record the value of the selected load resistor on line 2.1 of Table 1.

4.2.2 Connect Precision Electrical Load. The precision load that was selected in section 4.2.1 must be connected to the power leads of the module. A switch that is capable of switching the potential 15 amps of current needs to be placed in the circuit.

It is preferable to solder all connections to prevent loose or high resistance joints. A 14 awg wire or larger should be used. Heat sink the resistor in an appropriate manner.

4.2.3 Measure Resistor Voltage. With the load resistor connected to the module, heat the module to the operating conditions and allow the temperatures to stabilize. Measure the voltage drop across the load resistor. This is the "resistor voltage" (V_r). Record V_r on line 2.3 of Table 1.

4.2.4 Measure Loaded Voltage. Measure the voltage of the module **on the module leads**. This is the "loaded voltage" (V_L). Record the V_L on line 2.4 of Table 1. It is important to **measure the voltage on the module leads**.

4.2.5 Measure Open Circuit Voltage. With the meter leads still connected to the module leads, break the circuit by opening the switch discussed in section 4.2.2 and quickly measure the open circuit voltage (E_o). This value should be measured about 1 second after disconnecting the load. Record this value on line 2.5 of Table 1.

4.2.6 Calculate Module Current. Using Eq. (1) calculate the current (I) and record it on line 2.6 of Table 1.

$$I = V_R / R_L \tag{1}$$

R_L is the value of the resistor in ohms.

4.2.7 Calculate Internal Resistance. Knowing the open circuit voltage (E_O) from line 2.5 of Table 1 and the loaded voltage (V_L) from line 2.4 and the current (I) from line 2.6, calculate the internal resistance of the module using Equation (2). Record the R_i on line 2.7 of Table 1.

$$R_i = (E_O - V_L) / I \tag{2}$$

The measure value of R_i can be compared to the maximum allowable R_i as shown in Figure 9. If the measured R_i is less than the allowed R_i then the module is producing more than specified power. Using the E_o from line 2.5, determine the maximum allowable R_i from Figure 9 and record this value on line 2.8 of Table 1.

4.3 Interface Temperature Drop

If the module is known to be a good module but you still can't get rated power from the module, then the module is not operating at the temperatures that it needs to be at.

When measuring the temperatures of the hot and cold side it is important to position the thermocouples as close to the module as possible. It is ideal to drill a thermocouple well into the thermal spreader plate and the cold side heat sink and position the thermocouple in the thermocouple well.

Measure the hot side temperature (T_H) and record this value on line 3.1 of Table 1. Similarly, measure the cold side temperature (T_C) and record this value on line 3.2 of Table 1. To measure the temperature drop from the hot surface of the module to the cold surface of the module follow the steps described in section 4.1. This is the estimated module ΔT.

Now that the temperature drop from the hot source to the cold sink is known and the temperature drop across the module is known, the temperature drop across all of the interfaces (ΔT_i) can be calculated from Equation (3).

$$\Delta T_i = (T_H - T_C) - \Delta T \tag{3}$$

Record the ΔT_i across the interfaces on line 3.4 of Table 1. The temperature drop across all of the interfaces should be around 30°C to 50°C but due to variations in material properties the value should be used as a guide only. If large values for ΔT_i are obtained (greater than 50) then the interfaces of the system may need to be improved. Following these guidelines should help lead to an optimally efficient system.