# Conductive Heating Technologies for Medical Diagnostic Equipment

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## Abstract

The medical diagnostic equipment industry uses discrete electric heaters in many of its products to provide localized heat to enable or enhance the operation of its equipment. A simple bench test comparison of polyimide insulated etched foil heaters, silicone rubber insulated wound wire heaters, thick film heaters, and cartridge heaters provides insight into the pros and cons of each heater type relative to the primary cares and concerns of the people who are responsible for the reliability and performance of medical diagnostic equipment. Ultimately, the polyimide insulated etched foil heaters stood out from the others in multiple areas.

## Conductive Heating

There are three mechanisms for heat transfer: thermal conduction, thermal convection and thermal radiation. Although there are applications within the medical diagnostics equipment industry that require convective and radiant heating, this paper will focus on heat transfer through conduction. Conduction can be described as the transfer of energy from the more energetic particles of a substance to adjacent particles that are less energetic due to interactions between particles [1].

## Medical Diagnostic Equipment Industry

Medical diagnostic equipment generally requires heating for one of three reasons. The first is to enhance the comfort of the patient undergoing the diagnostic procedure. An example of this would be the warming of the gel used in the performance of ultrasonic imaging. This type of heating does not require tight control, but must ensure that temperatures do not exceed patient comfort zones. The second reason for heating is to provide a repeatable condition for chemical analysis to occur. In these cases, the heat does not enable or accelerate the analysis itself, but may enable or accelerate the warm-up and stable operation of the diagnostic equipment. The third and most common reason is for heating the specimen being analyzed and/or the reagent being introduced as a reactant or catalyst for the chemical analysis. The heating may serve to preserve the specimen or to initiate, sustain or accelerate a chemical reaction or a biological process. The testing and discussion in this paper will most closely apply to this type of heating.

## Test Plan

We first identified the primary cares and concerns of the people who operate medical diagnostic equipment with regards to heating. We then identified the most commonly available applicable heating technologies. With this information, a test plan was devised that would directly examine some of the more relevant issues in question and provide the basis for discussion on the other issues.

The primary issues with regard to the integration of heaters into diagnostic equipment were identified as the thermal uniformity of the material being heated; the heat-up and cool-down speed; the compactness of the heater and heat-sink assembly; the unit cost of the heating element; the system cost of the heating, sensing and control system; and the reliability of the heater itself.

The identified commonly available conductive heating technologies were polyimide insulated etched foil heaters (Figure 1); silicone rubber insulated wire wound heaters (Figure 2); thick film heaters (Figure 3); and cartridge heaters (Figure 4).

A heat-sink geometry of 4“ x 5“ (102 x 127mm) was selected because it would accommodate the integration of readily available heater sizes and be reasonably transferable to medical diagnostic applications. Aluminum was selected because of its good thermal conductivity and machining properties.

A test temperature of 90°C (194°F) was chosen because it is a common medical diagnostic application temperature for denaturing nucleic acids such as DNA. Being on the high end it will also highlight any performance differences between heaters more clearly.

Four, ½” (12.7mm) thick aluminum heat-sinks were machined for mounting each of the heater types. The ½”thickness was chosen to accommodate the cartridge heaters. In addition, a separate ¼” (6.35mm) thick heat-sink was also machined for mounting an etched foil heater so that we could establish the impact of the heatsink thickness on heat-up and cool-down time.

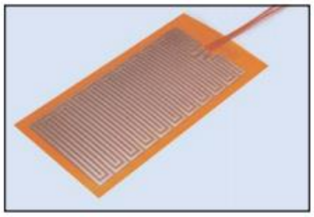

*Figure 1:* Polyimide insulated etched foil heaters

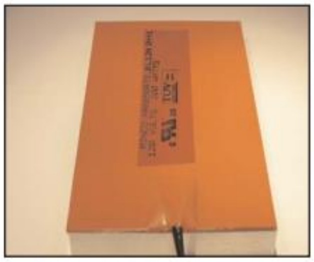

*Figure 2:* Silicone rubber insulated wire wound heaters

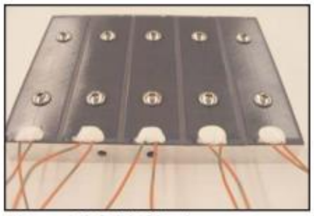

*Figure 3:* Thick film heaters

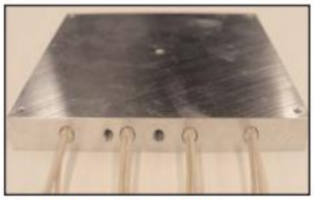

*Figure 4:* Cartridge heaters

The polyimide insulated etched foil and the silicone rubber insulated wire wound heaters were mounted to their heat-sinks with a pressure sensitive adhesive (PSA) film. The thick film heaters, which consisted of five separate heaters, were bolted to the heat-sink with two bolts per heater and the cartridge heaters, which consisted of four separate cartridges, were slid into holes that were drilled through the heat-sink. The holes had a slightly larger diameter than the cartridges, as specified by the cartridge manufacturer.

For temperature control, a Minco CT16 Temperature Controller was used with the PID parameters set to “normal”. The control sensor was a thermocouple potted into a case that was screwed into the heat-sink.

Testing consisted of observing the heat-up time, cool-down time and steady state thermal uniformity of each heat-sink with the same power input and same PID settings. An array of 20 thermocouples (Figure 5) was used to track the heat-up, cool-down and uniformity.

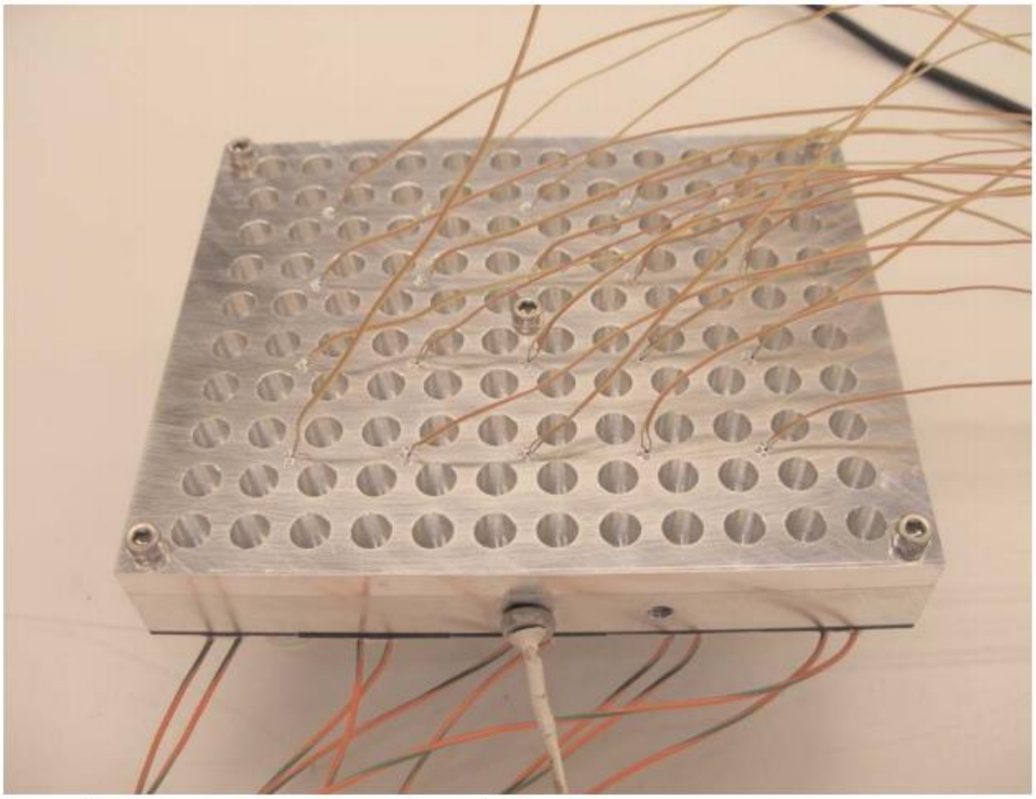

*Figure 5:* Thermocouple array attached to a heat-sink.

# Test Results

## Heat-up

Because the electrical resistance varied between each heating element, the input voltages had to be adjusted for each test to provide a maximum input power of 37.0 watts. The input voltage levels were calculated using the room temperature resistance of the elements. During the heat-up phase, the controller operated at 100% duty cycle until the heat-sink temperature neared the 90°C (194°F) set point.

There were clear differences in the heat-up rates of the ½” (12.7mm) thick heat-sinks. These differences can be accounted for by two factors: 1) the amount of heat lost to the air and, 2) the Temperature Coefficient of Resistance (TCR) associated with each heating element. When a heating element’s temperature increases its resistance will change proportionally to the TCR of the element. This change in resistance results in a change in power input to the heater (Table 1).

| | Room Temperature Resistance (Ohms) | Power @ Ambient (Watts) | 90°C (194°F) Resistance (Ohms) | Power @ 90°C (194°F) (Watts) |
|---|---|---|---|---|
| Wire-wound | 68.9 | 37.0 | 71.0 | 35.9 |
| Etched Foil | 52.1 | 37.0 | 52.6 | 36.7 |
| Cartridge | 37.9 | 37.0 | 38.2 | 36.7 |
| Thick Film | 38.7 | 37.0 | 42.5 | 33.7 |

*Table 1:* Although all the heaters had the same power input at room temperature, the power to the thick film heater dropped significantly due to its resistance increasing with temperature. The wire wound was also impacted, but to a lesser degree.

The cartridge heaters, which were embedded in the heat-sink, yielded the fastest ramp-up due to the near zero loss of power to the air and its low TCR. The etched foil heater had relatively lower heat loss to the air than the thick film and wire wound heaters, because of its higher percentage coverage and more intimate contact to the heat-sink. Combined with its low TCR, it yielded the next fastest ramp-up speed.

The wire wound heater, which had a higher TCR than the cartridge and etched foil heaters, but a lower TCR than the thick film heater, heated faster than the thick film even though the thick film has more coverage. The lag in the thick film heaters is due to the combination of a higher TCR, poor thermal conduction of the stainless steel substrates, and its poor contact to the heat-sink caused by a tendency to warp during heating.

The differences in heat-up times are shown in Chart 1. As expected, the ¼" (6.35mm) thick heat-sink with the etched foil heater had the fastest heat-up because it had significantly less mass to heat. It could have also been used with the wire wound and thick film heaters.

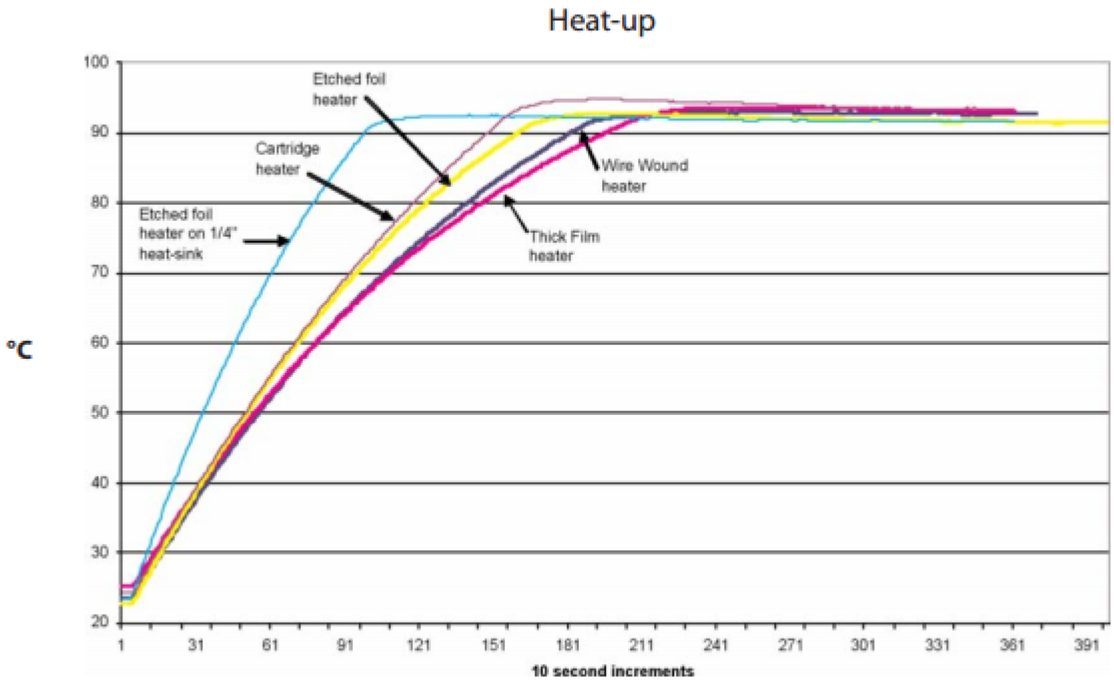

*Chart 1*: The cartridge and etched foil heaters provided the fastest ramp-up of the ½" heat-sinks. The cartridge overshot the set-point however. Also, the impact of reducing the mass of the heat-sink is made very clear by how much faster the ¼" heat-sink ramps-up compared to any of the ½" heat-sinks.

## Cool-Down

The cool-down phase consisted of removing the enclosure that was covering the heat-sink and cutting the power to the heater. Chart 2 shows that the cartridge heater displayed the most notable difference in cooling rates among the 1⁄2” (12.7mm) thick heat-sinks. It clearly lagged the others. This is partially accounted for by latent heat that is built up in the cartridge heater itself due to its construction. Cartridge heaters generate heat across a coiled wire inside the cartridge, which then has to conduct through a ceramic powder filler and a stainless steel sheath—both of which are poor thermal conductors. In addition to these thermal barriers between the element and the heat-sink, this construction results in a relatively small element that must operate at much higher watt density to supply the same power. The end result is a heater that operates at much higher element temperatures, which results in slower responsiveness and courser steady-state control. The other heaters, mounted external to the heatsink, operate at a lower element temperature and so have less energy stored resulting in faster cool-down The 1⁄4”(6.35mm) thick heat-sink cooled the fastest as expected due to its low overall thermal mass.

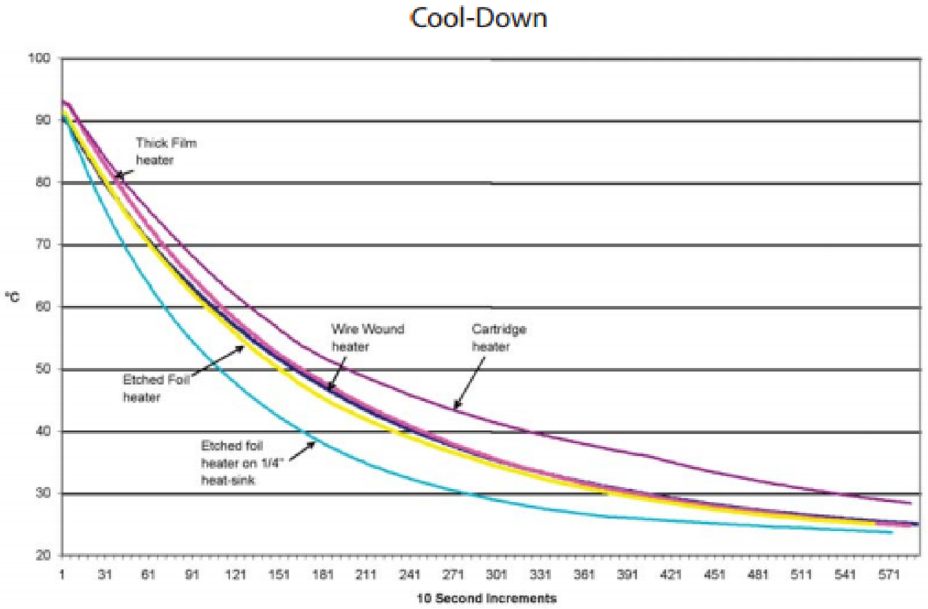

*Chart 2*: The cartridge heater stood out from the others in how slow it cooled, while on the other side the 1⁄4” thick heat-sink stood out from the 1⁄2” thick heat-sinks in how fast it cooled.

## Thermal Uniformity

The heaters chosen for this test were designed to supply uniform heat input to the heat-sink. They were not chosen to provide the optimal thermal uniformity across the working surface of the heat-sink however. While the results of this testing do not provide any indication which type of heater might provide the most uniform heat at the working surface of the heat-sink, they can serve as the basis for discussion of the possibilities.

When optimizing the working surface thermal uniformity, the geometry of the heatsink itself is as important as the heater. In our tests the etched foil, wound wire and thick film heaters were all mounted over the entire surface of one side of the heat-sink and were intended to input uniform heat into the heat-sink in one direction. Inevitably a 3-dimensional heatsink will have more surface area than a 2-dimensional, planar heater. This means that even if the heater supplies uniform heat into the heat-sink and the heat exits the remaining surfaces of the heat-sink uniformly, the temperature across the heat-sink cannot be uniform. In fact, it must be cooler in areas where more surface area is concentrated such as the sides and corners (Figure 6).

The effect of this can be seen in FEA modeling of our test blocks (Figure 7) and it is also visible in the infrared image of the 1⁄2” (12.7mm) thick heat-sink with the etched foil on it (Figure 8).

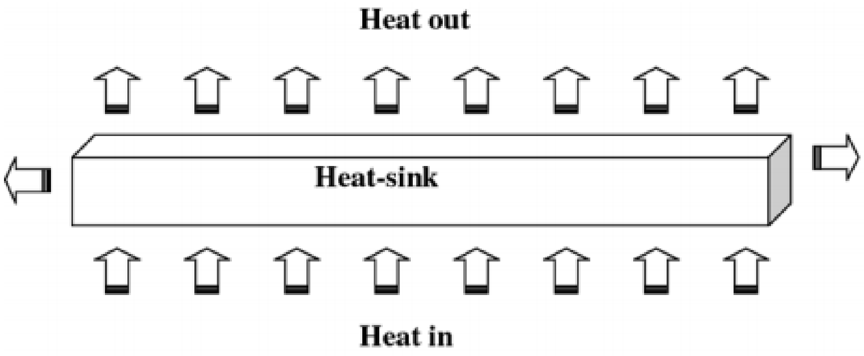

*Figure 6:* While the heat is uniformly entering the heat-sink on one side it is also leaving the heat-sink on the other five sides.

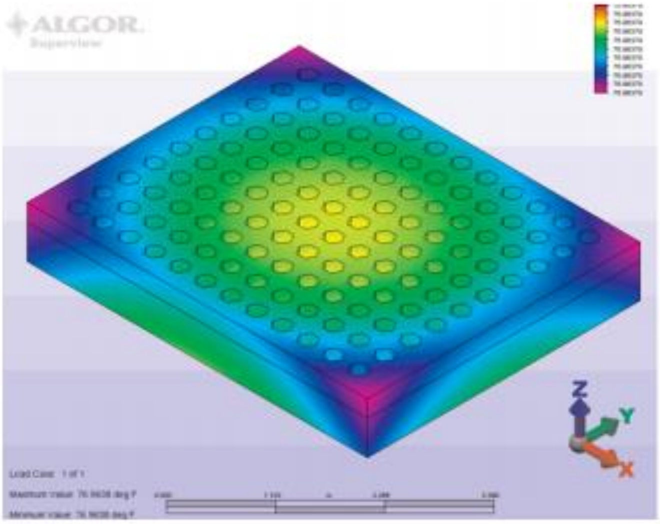

*Figure 7:* FEA modeling illustrates how uniform heat input in the bottom of a heat-sink does not result in uniform temperature at the top, due to more heat exiting at the corners where there is a greater concentration of surface area.

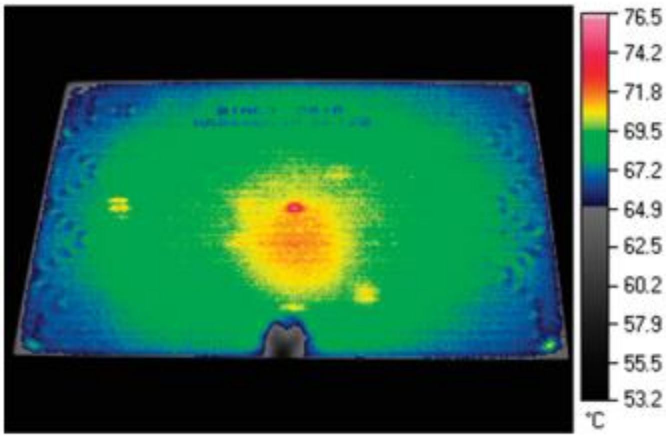

*Figure 8:* This infrared image of the functioning uniform watt density polyimide insulated etched foil heater on the ½″ heat-sink shows that the corners are indeed colder than the center of the heat-sink.

The non-uniform heat loss can be compensated for by inputting more heat in the areas that lose more heat. Heaters that do this are referred to as profiled heaters. Profiling is possible with all three of the planar heater types, however, the cartridge heater, due to its cylindrical geometry does not easily lend itself to profiling the heat input.

In addition to profiling the heater to match the heat loss of the heat-sink, uniform contact between the heater and the heat-sink must be ensured. When care is taken and the proper materials are used, both the silicone rubber and polyimide insulated heaters can be consistently mounted to most heat-sink materials. This may be achieved with a PSA film or by direct lamination with controlled heat and pressure. The latter approach minimizes the amount of thermal insulation between the heating element and the heat-sink.

Mechanically mounted heaters tend to be more susceptible to non-uniform contact problems. This showed up in an infrared image of the thick film heaters that were bolted to the heat-sink. If the heaters, which were designed for uniform heat input, were making uniform contact to the heat-sink, one could expect a heat pattern similar to that of the etched foil heater (Figure 8) or, at least a uniform pattern with the cooler edges less evident. However, the hot spots appeared to be at both ends of the heat-sink (Figure 9). This indicates that the heaters on the edges were not making as good of contact with the heat-sink as the center heaters. This could be the result of warping or bowing of the stainless steel heater substrate.

## Compactness

The medical diagnostics equipment industry, like many other industries, is always striving to reduce the weight and size of its products. Reduced weight improves the portability of the equipment and smaller size takes up less valuable laboratory space. Comparing the compactness and weight of the heaters we see that the etched foil with polyimide insulation requires the least amount of space, with a heater element thickness of 0.012” (0.3 mm) or less and a lead thickness of between 0.05”(1.3mm) and 0.09” (2.2 mm), depending on the wire gauge, it also introduces the least amount of weight at 6.5 grams. The wire wound and thick film heaters were essentially the same thickness with the heater element at 0.06” (1.5 mm) or less and a lead thickness of below 0.25” (6.4mm). The Thick film heater, however, weighed significantly more than the wire wound at 139 and 44 grams respectively. Also, the mounting of the thick film heater required bolts that added to the weight of the heater. The cartridge heaters, which had a diameter of 0.25” (6.35 mm) and an individual weight of 19 grams, required a heat-sink that could accommodate a 0.25” (6.35 mm) hole(s) without loss of structural integrity. This means that in many instances (including testing for this paper) the heatsink will have to be enlarged to accommodate cartridge or tubular heaters. This obviously has significant impact on the compactness and weight of the integrated heater and heat-sink.

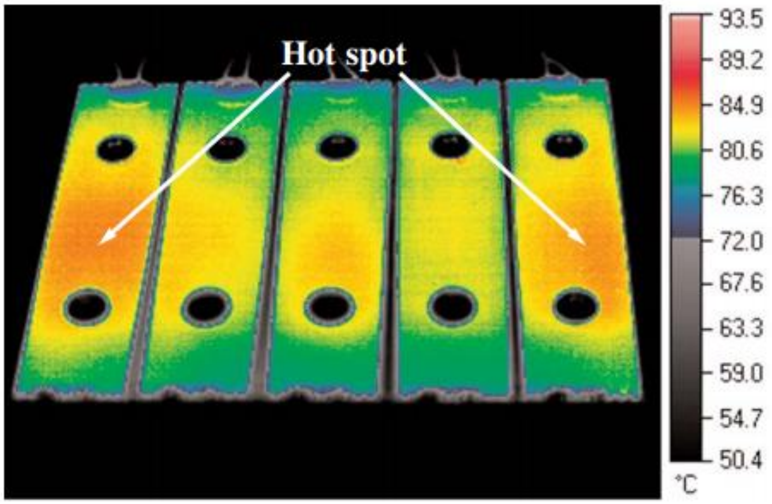

*Figure 9:* This infrared image of the functioning uniform watt density thick film heaters on the ½″ heat-sink does not show the colder corners we would expect. This is due to poor thermal contact between the heaters and the heat-sink.

## Unit Cost and System Cost

As mentioned earlier, the heaters used in the testing for this paper were readily available heaters and the heat-sink size was chosen to accommodate them. When designing the heat-sink for a medical diagnostics equipment application it would be better to have a heater designed to fit the heat-sink than to design the heat-sink to fit a heater. Although for optimal performance they should be designed in conjunction with one another.

Hot spot Figure 9: This infrared image of the functioning uniform watt density thick film heaters on the 1⁄2" heat-sink does not show the colder corners we would expect. This is due to poor thermal contact between the heaters and the heatsink. Copyright 2007, Minco Page 14 Comparing the quoted unit prices for the heaters used in these tests, for a 500 piece volume, it was found that, in this instance, the polyimide insulated etched foil heater was the lowest price, with the wire-wound and thick film heater priced slightly higher, and the cartridge heater being significantly higher priced for a single heater and more than eight times higher for the four heaters that were used in this test.

It should be noted that four cartridge heaters were used to provide better heat-up and thermal uniformity performance. However, a single cartridge heater could have been used to reduce heater cost at the expense of thermal uniformity.

It should also be noted that the etched foil heater was polyimide insulated which is a high temperature material and that lower cost insulations are available for lower temperature applications common in the medical diagnostic industry.

Although the polyimide insulated etched foil heater had a lower quoted unit price than the wire-wound and thick-film heaters, the prices were close enough that factors such as purchasing negotiation, custom design changes, or even something as minor as who generated the quote could change the order. In fact, in most instances, it would be expected that a silicone rubber wire wound heater would be less expensive than an etched foil heater, especially as the size of the heater increases.

System costs include the heater, the heat-sink, a temperature sensor, the controller and the cost to assemble into the final product. The most notable difference in cost would be heater and heat-sink cost. Therefore, a system using cartridge heaters would cost more than the others, because of the higher heater cost and the requirement for a larger and consequently more costly heat-sink.

## Reliability

The reliability of these various heating technologies is application dependent. Medical diagnostic applications generally operate at relatively low temperatures in the range of 37°C to 90°C (98.6°F to 194°F), which is well below the maximum operating temperature for each of these heater types. Therefore, reliability for all four types of heaters could be considered to be high. However, reliability could be impacted by the heat-up rate, which requires greater watt density and results in higher element temperatures.

## Conclusions

The cartridge heater provided the fastest heat-up of the four heater types under identical heating boundaries and control conditions; however, the mass of the heat-sink had to be increased to accommodate the cartridge heater geometry. Testing showed that the mass of the heat-sink was more important to heat-up speed than the heater type itself. Of the three heater types that could be used with a lower mass heat-sink, the etched foil provided that fastest heatup speed. These three heater types had similar cool-down characteristics, while the cartridge heater lagged behind them due to its thermal mass and high element temperature.

Working surface thermal uniformity is determined by how precisely you can profile the heat input to compensate for uneven heat output and the level and consistency of the thermal resistance between the heater and the heat-sink. Because of this, the etched foil heater has the potential to provide the best thermal uniformity. This is because it can be intricately patterned to provide profiled heat and will provide a consistent and low level of thermal resistance when properly laminated to a heat-sink. The wire wound heater cannot be as intricately patterned and the thick film heater cannot provide the consistent and low level of thermal resistance. Because the wire-wound and thick-film heaters lend themselves better to profiling than the cartridge heater, they could still provide better thermal uniformity than cartridge heaters.

## Comparison Table

| | Wire Wound Silicone Rubber insulated | Etched Foil Polyimide Insulated | Thick Film on Stainless Steel | Cartridge Heater |
|---|---|---|---|---|
| **Heating efficiency**<br>Compatibility with a minimal mass heat-sink and how well heat generated in a heater gets into the heat-sink | Average | Best | Average | Average |
| **Cooling efficiency**<br>The level to which a heater does not interfere with the cooling of a heat-sink | Average | Best | Average | Below Average |
| **Thermal Uniformity Potential**<br>How well a heater can be designed to compensate for a heat-sink's uneven heat loss | Average | Best | Average | Below Average |
| **Compactness**<br>How well a heater can be integrated with a heat-sink to take up the least amount of space | Average | Best | Average | Below Average |
| **Unit Economy**<br>Economy, of heaters used in this test, in terms of unit cost relative to one another (Note: rank would change with heater size) | Average | Best | Average | Below Average |
| **System Economy**<br>Economy in terms of complete heating system cost relative to one another (Note: rank would change with heater size) | Average | Best | Average | Below Average |
| **Reliability**<br>The reliability of the heater in medical diagnostic applications (<120°C) | While a <120°C operating temperature should be no problem for these heaters, other application specific factors that are outside the scope of this paper, should be discussed with an expert in heater design. | | | |

Table 2: Rankings of each of the four heater types tested, relative to one another, for each of the identified primary cares and concerns of the people who are responsible for the reliability and performance of medical diagnostic equipment.

## Summary

The medical diagnostic equipment industry uses discrete electric heaters in many of its products to provide localized heat to enable or enhance the operation of its equipment. Polyimide insulated etched foil heaters stood out from silicone rubber insulated wound wire heaters, thick film heaters and cartridge heaters in multiple areas of primary concern in a simple bench test designed to represent a generic medical diagnostic application.

### References

[1] Fundamentals of Engineering Thermodynamics, Michael J. Moran, Howard N. Shapiro, 1996, John Wiley & Sons, Inc.