

## SERIES 49UL HEATER JACKETS

### INTRODUCTION

Thermal management or heater systems can be found in myriad applications throughout the industrial and consumer sectors. Raw materials extraction and processing, heavy industry, chemical production, and many advanced technological industries require systems that can precisely control temperature during operations. Oil extraction, for example, requires large heater systems to maintain the viscosity of crude oil low enough for treatment and transportation of the liquid. In the chemical industry, heater systems are used to maintain reaction vessels at temperatures appropriate for a given chemical reaction. Heater systems are required to both promote phase change such as sublimation of a solid and evaporation of a liquid. Heaters prevent phase change of gases to liquids allowing control for transportation and delivery, avoiding condensation that affects equipment proficiency. The semiconductor industry generally employs electrically resistive heaters to control deposition and etch temperatures within process tools. As well, thermal management systems are needed for precise control of the delivery of liquids and gases to process chambers and to control the deposition of solid waste material in exhaust lines that can produce excessive particle contamination in the process chamber and reduce line conductance.

Heater systems normally consist of a power supply, an electrically resistive heating element, an insulating heater jacket, a temperature sensor, and a control system that maintains the system at a pre-set temperature. The element can be configured as an immersion heater or as metal strips, pads, or more complex designs for contact surface heating of the walls of pipes, process chambers,

and reaction vessels. Contact heating elements may be wound about the surface that requires heating, directly placed on the surface, or embedded in a customized, conformal, insulating jacket that surrounds the surface. Insulating jackets, in a heater system, can be as simple as a ceramic thermal blanket wrapped around a pipe with a heating element, use a sewn outer shell with insulation and heating element, or be as complex as the custom-molded jackets with embedded heating elements. This Technical Note is the second in a series of three describing the Series 49UL Thermal Management System. In this note we describe MKS Instruments' sewn construction heating jackets with embedded heating elements (Figure 1).



Figure 1. MKS Instruments' S49UL Thermal Management System showing Teflon (white) and polyimide (gold) heater jackets.

### Heater Jacket Construction Physical Configuration

Heater jackets contain several functional components: a flexible heating element; a temperature sensor, an insulating layer, and a fastening device to secure the heater to the substrate. Some systems may also have

a thermal fuse. The heating element is a critical system component. It must be made of a durable material that responds to electrical power input in a precise and known manner that permits good temperature control. It must be configured so that it distributes the heat it generates in an even manner, leaving no cold spots on a substrate. Finally, it must be operationally safe, representing no fire or injury hazard in the work environment.

Flexible heating elements are normally fabricated using a high resistivity metal in the form of a wound wire bent into a pattern that provides relatively uniform heating over the entire element. Typically, wire-formed elements are constructed using tungsten, nichrome (nickel-chrome) alloy, or Kanthal (iron-chrome-aluminum) alloy wires with nichrome being the most common. Less commonly, stainless steel, copper, or titanium may be employed, typically for corrosive immersion heater applications. Alternatively, etched foil (printed) heater elements may be used. In printed heater elements, a thin, flexible foil of a specific metal alloy is patterned to create a conductive element over the entire foil surface. This type of printed heater has extremely high watt densities that are effective for rapid heating of bulky or high heat-dissipating materials and for effective heating under low heat transfer conditions. Both types of heater elements provide a tailored watt density in a flexible package that can be formed to specific shapes. MKS Instruments' heater system employs a configuration in which a wire is stitched into a fiberglass sheet to form the heating element. Figure 2 shows a thermal image comparison of a conventional wire heating element vs. the MKS stitched wire heater. The conventional element displays inconsistent filament density and temperature that can result in cold spots in the heated substrate. MKS' heater jacket with a stitched heating element exhibits temperature uniformities of about  $\pm 5^\circ\text{C}$ .

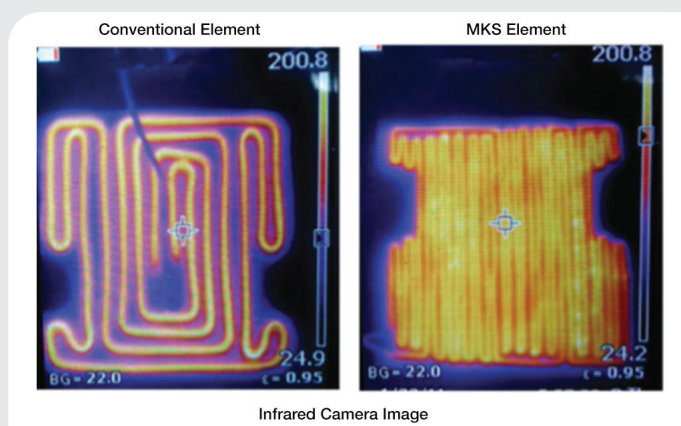


Figure 2. Infrared camera image of two heating elements. Left is conventional heater wire on a substrate and right is the MKS Instruments' stitched heater element.

### Sizing a Heater Element

Relatively simple Second Law physics considerations determine the size of the heater element needed for an application. The heat equation for changing the temperature of the substrate is:

$$Q = Cp \times m \times \Delta T \quad (1)$$

where  $Q$  is the thermal energy (Joules, J) needed to raise the temperature of the substrate by an amount  $\Delta T$  ( $^\circ\text{C}$ ).  $Cp$  ( $\text{J/g}^\circ\text{C}$ ) is the specific heat capacity of the substrate and  $m$  (g) its mass.

A practical example is a comparison of how much thermal energy is needed to raise the temperature of a valve to  $100^\circ\text{C}$ . Two materials are compared. One is 304 stainless steel and an equally sized valve made from aluminum. The  $Cp$  of aluminum is  $0.921 \text{ J/g}^\circ\text{C}$  while that for 304 stainless steel is  $0.502 \text{ J/g}^\circ\text{C}$ . If the stainless-steel valve has a mass of 5 kg, an identically sized but lower density aluminum valve will have a mass of 1.72 kg. Assuming that both valves are at an ambient temperature of  $20^\circ\text{C}$  prior to heating, per equation (1) the stainless-steel valve will require 200.8 kJ (55.8 watt-hours) of thermal energy to reach  $100^\circ\text{C}$  while the aluminum valve will only require 126.7 kJ (35.2 watt-hours) to achieve the same temperature. If a heater jacket with the same watt density is used, it will take nearly 1.6 times longer to raise the stainless-steel

valve to 100°C than required for the aluminum valve. Conversely, the two valves can be heated in the same amount of time if a heater jacket with a higher watt density is used for the stainless-steel valve vs. that used for the aluminum valve.

Another example of how equation (1) can be used to determine heater jacket parameters is provided by the situation in which a single controller and a single temperature sensing point is used for controlling two heater jackets on two stainless-steel objects having different mass and volume characteristics. We will assume that the temperature sensor is located on the object having greater mass. The larger object is not solid, has a mass of 5 kg, and a volume of 3 m<sup>3</sup> while the smaller object is also not solid and has a mass of 1 kg and a volume of 1 m<sup>3</sup>. Equation (1) can be used to show that the energy needed to raise each object to a temperature of 100°C from ambient (20°C) is 200.8 kJ (55.8 watt-hours) for the larger object and 40.2 kJ (11.2 watt-hours) for the smaller object. Thus, a heater with a watt density of 55.8 watts can heat the larger object to 100°C in an hour and one having a watt density of 11.2 watts can do a similar job for the smaller object. This represents a problem if identical heaters are used on both objects since the time required to provide enough thermal energy to raise the larger object to 100°C will result in 5 times the thermal energy needed to reach 100°C being supplied to the smaller object. Therefore, the smaller object will overheat relative to the larger object (assuming both objects start at 20°C and that 55.8 watts is supplied to both heaters for one hour, the larger object would reach 100°C while smaller object would be heated to 420°C according to Equation (1)). Additionally, once the setpoint temperature has been achieved, the temperature of each object must be maintained by providing enough continuous thermal energy to compensate for heat losses. The larger object, having greater surface area, will suffer heat loss at a higher rate than the smaller object, assuming that equally effective insulation is present for both objects. The heater for the larger object must therefore supply a greater amount

of continuous thermal energy than the heater for the smaller object. These problems can be addressed by reducing the watt density of the heater for the smaller object so that it supplies only as much energy as is needed to raise the temperature of the smaller object to the desired temperature in the amount of time required for the larger object and then to maintain the object at temperature. While it is possible to configure a series of many heaters with variable watt densities so that objects of different thermal characteristics can be heated and controlled by a single controller and sensing point, this is both time consuming and expensive. Furthermore, safe operation requires that the heater power must be applied in series in these configurations. This means that the failure of one heater in the series produces a complete heating system failure. MKS can provide this type of heater jacket configuration and has done so for some customers, however, the added cost required to execute and tune the heater system far exceeds the cost of having an individual controller, temperature sensor and heater on each object. Since electronic controllers are relatively inexpensive, it is more efficient to configure heaters in parallel with individual controllers so that the failure of one heater does not affect any other in the system. It should also be noted that the location of the temperature sensor is important in systems having multiple heaters. If the heaters are mounted on substrates having uniform mass, the placement of the temperature sensor is not critical, however, the sensor placement is of paramount importance when substrates of differing mass are involved. Ideally, each heater should have its own temperature sensor and controller for the best temperature control.

Heater elements for large objects can have quite complicated physical configurations. This is necessary to ensure intimate contact between the element and the substrate as well as to supply the correct energy density to different areas of the substrate. Difficult-to-heat shapes include those with protruding thin sections as well as large mass volumes where the heater element watt density needs to vary considerably. Heat tape is

not a solution with complex shapes since tapes are of uniform watt density and cannot be wound over themselves to increase their watt density. The best designed heaters vary the element watt density where needed with the best solution being a fitted heater incorporating variable element watt density.

### Insulation

Substrates being heated require enough thermal energy to raise and maintain their temperature to a setpoint plus additional thermal energy to compensate for heat loss during these processes. Any heating element that is applied to a substrate transfers thermal energy to both the substrate and to the surrounding air; as well, the substrate itself will transfer heat to the ambient air. How the transfer of the thermal energy available from the element is partitioned between heating the substrate and loss to ambient depends on factors such as the intimacy of contact between the element and the substrate, the effectiveness of insulation, and the conditions of the surrounding ambient air (i.e. temperature and humidity, air velocity over the heater/substrate surface, etc.). Obviously, the optimal arrangement for effective and efficient control in heating a substrate is one in which heat transfer to the substrate is maximized while heat losses to ambient are minimized. While heat transfer to the substrate is determined by the characteristics of the heating element (see above), heat losses to ambient are primarily determined by the effectiveness of the insulation surrounding the element and substrate.

Effective insulation should limit the exposure of the heated substrate and the heating element to ambient air and minimize heat transfer through itself to the ambient air. Two properties determine the ability of insulation to reduce heat transfer to ambient. One is its thermal conductivity and the other is the thickness and integrity of the insulation. The thermal conductivity of a material is a measure of its ability to transfer thermal energy from hot to cold regions. In classical thermodynamic terms, this means that the thermal energy,  $Q$ , moving from a hot to a cold region within a material obeys the relationship

known as the Fourier Law:

$$Q = kA \frac{\Delta T}{\Delta x} \quad (2)$$

where  $A$  is the cross-sectional area through which the heat flows,  $\frac{\Delta T}{\Delta x}$  is the temperature gradient between hot and cold areas, and  $k$  is the proportionality constant for this relationship, known as the thermal conductivity. Thermal conductivity is a characteristic material property, unique for each material phase and formulation. It is normally defined in terms of heat flux with units  $\frac{\text{Watts}}{(\text{mK})}$ . While dry air has a very low thermal conductivity (0.026 W/mK) which, at first glance appears to make it a good insulator, convective and other types of air motion in the vicinity of the substrate promote heat loss from the substrate and element to the point that air is ineffective as insulation. Efficient insulators such as silicone foam have low thermal conductivities ( $k = 0.1$  to  $0.15$  W/mK, depending on foam density) and are effective in limiting heat transfer from the element and substrate to ambient air. Many of the best insulators take advantage of the low thermal conductivity of air by trapping it (motionless) within their structure. For example, Balsa wood has a thermal conductivity of about  $0.04$  W/mK, largely due to the presence of air in its structure (dense woods such as maple have higher thermal conductivities ( $k = 0.35$  W/mK)). Similarly, fibrous materials such as fiberglass have much lower thermal conductivities than their constituent material would suggest, owing to the presence of trapped air within the fiber matrix. This is reflected by the fact that the thermal conductivity of fiberglass ( $k = 0.045$  W/mK) is much closer to that of air than to glass ( $k = 1.05$  W/mK). Of course, the thermal conductivity of fiberglass will vary between these two values, depending on how densely the fiberglass is packed. Table 1 provides a short list of the thermal conductivities of some common insulating materials.

The form and thickness of insulation determine the quality of heater performance; in thin film process operations, this can often be equated with both increased yields and increased system uptime. For example, thin film processing equipment requires

Material	Thermal Conductivity (W/m*K)	Notes
Silicone foam	0.1 to 0.14	Varies with composition [1]
Polyurethane foam	0.03	[2]
Fiberglass	0.04	[2]
Polyimide foam	0.045	[3]
Air (at 293K temperature)	0.0262	[2]

Table 1. Thermal conductivities of some common insulating materials.

uniform temperature in the precursor delivery lines to prevent clogging and condensed material and to ensure a constant vapor delivery rate. Constant delivery rate means constant pressure in the process chamber and fewer defects in the film process. Downstream of the chamber, exhaust line heating reduces the accumulation of process byproducts. Poor heater performance in either of these applications contributes to particulate production and an increased need for system cleaning. Proper heating in these applications thus reduces the downtime required for equipment cleaning and operating costs for the system can be reduced with only a small increase of energy usage.

Another important consideration for heater insulation is safety, most importantly the need to avoid a burn hazard to operators and others working around the heater jackets. SEMI safety guideline S2-0200 stipulates that that the external temperature of heater jackets should be no more than 95°C.

MKS' heater jackets are available with either polyimide foam or fiberglass insulation. Both insulating materials have low thermal conductivity, about 0.045 W/mK. The thick tubular heater jackets are constructed with flat end shapes that mate snugly to one another (Figure 3), ensuring little thermal leakage at the joints, avoiding

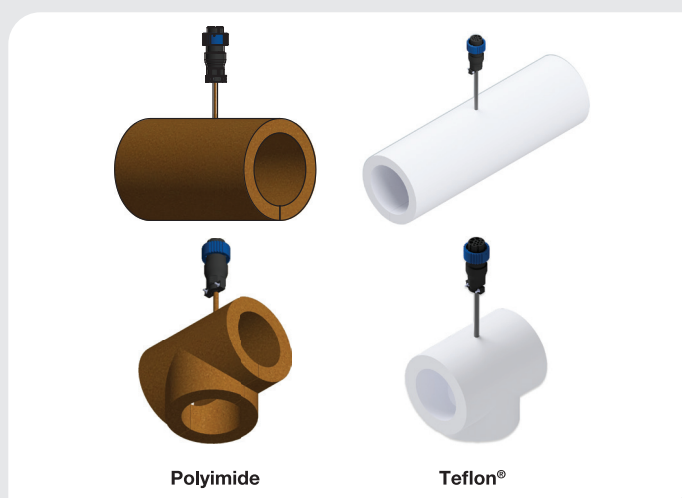


Figure 3. Polyimide and PTFE (Teflon®) heater jacket forms.

excessive heat loss between heaters. This facilitates more precise temperature control, with optimal temperature uniformity from center to edge and between each heater in a series.

The form and insulation thickness of MKS' heater jackets produce the highest quality heater system available for various heating applications, including exhaust line heating requiring temperatures up to 200°C (with possible heating to 250°C upon request). The uniform and tight temperature control provided by these heaters produces reliable temperature control that minimizes deposits in system exhaust lines for multiple process applications. The versatility of sewn heater jackets allows for applications of many different shapes where other heaters cannot be applied. As well, the thickness of the advanced materials of construction of these heater jackets and the tight joints produced by their design significantly reduce operational energy costs (Figure 4). Energy costs are further reduced by the advanced power management features of the Series 49UL Thermal Management System described in the first Technical Note in this series. The thickness and tight joints of MKS heater jackets also ensure compliance with the SEMI S2-0200 safety guideline.

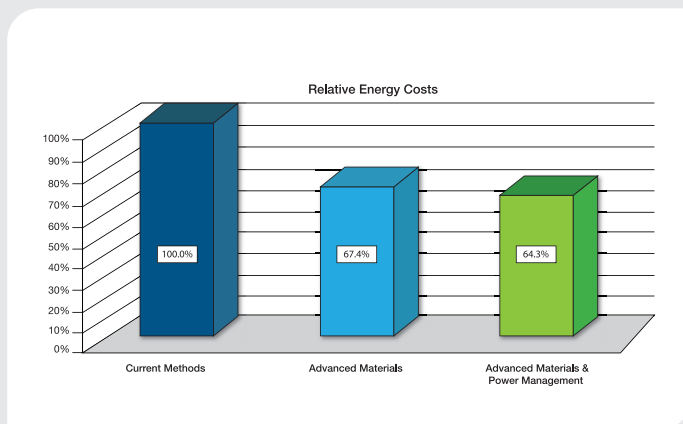


Figure 4. Energy savings possible with advanced materials and power management.

### Shell Material

The shell material of the heater jacket encloses the heating element, temperature sensor(s) and insulation. It must be compatible with the heater temperature and operating environment within which the heater system is placed. MKS Instruments S49UL Thermal Management System offers heater jacket shell material of either polytetrafluoroethylene (PTFE -Teflon®) which operates at temperatures up to 250°C or in low-particulate or PTFE-coated polyimide material. The property of low particle emission is, of course, critical for any heater jacket employed within a cleanroom environment. If the heater shell material is porous it can allow particles from insulation material (i.e. materials such as fiberglass) to escape into the cleanroom environment. Heater jackets are typically built in a non-cleanroom environment and since there are particles from handling, packaging, and other factors, a heater can eject hundreds of thousands of particles for the first hour or more following initial startup. Additionally, oils, solvents, and other materials employed during the fabrication of heater jackets can remain within the insulation matrix. When the heater is first operated, these materials will be emitted as volatile organic chemicals (VOCs) into the clean room environment. VOCs are detrimental to device yield and are strictly controlled in modern fabs. To mitigate these issues, MKS provides customers with the option of having S49UL heater jackets preconditioned in a

cleanroom environment until particle and VOC emissions have abated. The product is then packaged in a clean environment and shipped.

NEMA, the National Electrical Manufacturers Association, sets the standards for safe operation of electrical equipment within industrial environments. If heater jackets are used in biopharmaceutical or other healthcare-related manufacturing processes, a NEMA certification could be required. MKS has heaters specially designed and tested to NEMA 4X standards levels and has been supplying NEMA 4X certified heater jackets and controllers for more than a decade.

### Closures

Fit is an important parameter for heater jackets since a good fit ensures intimate contact between the heater and the substrate and effective insulation. The best possible fit would be achieved if the heater and insulation were part of, or physically bonded to, the entire surface of the substrate. This is normally not possible, however, since heater jackets must be periodically removed for maintenance and cleaning of the substrate. For these reasons, heaters are commonly fitted with fasteners to close and hold the heater in intimate contact with the substrate. There are several mechanisms in use for heater closures. Common closures include snaps, Velcro™, and strings or laces. Each type of closure has some difficulty associated with it. Snaps are mounted on straps that can stretch over time. Conversely the heater diameter may shrink with time. Both situations leave snap fasteners loose on the heater. Velcro loses some of its holding loops every time it is opened eventually resulting in holding failure or loss of tightness to the substrate. Laces are relatively old technology for fastening heaters and it is often difficult to get the heater jacket tightly bound to the substrate when



Figure 5. MKS heater jacket showing button strap closures.

making the final tie. All of these closures are problematic in terms of particle generation. MKS offers a unique solution for heater jacket closures, using a strap made from Viton™ which loops over a button (Figure 5).

### Applications

Within the semiconductor and other coating and etching industries, one of the main areas of application for heater jacket systems is the heating of process exhaust lines. These deposits are sources of particle and chemical contamination that can migrate upstream (backstream) into process chambers and damage product. As well, heavy deposits in constricted zones of exhaust lines (i.e. valves, sharp bends, etc.) can reduce the pumping speed achievable in the process tool which can have a negative impact on the reaction environment within the process chamber, also impacting yield of the process. Heater jackets are highly effective in reducing the condensation of deposits on internal exhaust line surfaces. Heating the exhaust lines causes less material to deposit over time, which, in turn, increases the tool uptime and reduces maintenance costs for the process tool. Heated exhaust lines are especially important in deposition processes that use tetraethylorthosilicate (TEOS), titanium nitride (TiN), carbon-doped low-k films, and epitaxy. The byproducts of these processes are condensable and rapidly produce thick deposits in unheated exhaust lines.

Other applications such as tanks, vaporizers, manifolds, parts attached to chambers and exhaust lines and other shapes can be heated. Many shapes can be heated with the sewn construction heater jackets.

### Costs

The cost of purchasing and operating a heater system is trivial when compared to the cost incurred from increased maintenance time, energy consumption and product loss when the heater system is not in place or is not of sufficient quality. Consider an unheated or poorly heated exhaust line that requires regular maintenance every 4 months at a cost of about \$1200 per maintenance cycle or \$3600 per year. Good working heaters have a lifetime of more than 5 years. MKS

has heaters installed in several installations that have operated trouble-free for over 6 years and in general, MKS heaters have an expected lifespan of at least 10 years. If installation of efficient heaters on the exhaust line costs \$8,000, over a 5-year period the cost per year for heaters is \$1,600 per year. If installation of heaters on the exhaust line doubles the clean cycle time to 8 months, the yearly cost for maintenance and heaters would be \$2,400 resulting in an annual savings of \$1,200 per year. Not included in this estimate is the cost of electricity, which depends on the item being heated and on heater quality, and the cost of cooling the building from the heat added by the heaters. Heaters with less efficient insulation add to building temperature control loads. Therefore, the added cost per year for good quality heater systems is offset by the savings in cleaning, energy costs and increased production. The cost of heater installation and operation is typically less than half the cost of maintenance without heaters.

### Conclusion

The most cost-effective heater systems for applications such as exhaust line heating are not the least expensive. Using low quality heater systems results in low energy efficient operation, poor uniformity of temperature control, and excessive emission of particles and VOCs from the heater system. These failures of poorer heater systems result in higher operational costs as compared with a more expensive, higher quality system. Furthermore, poor quality heaters contribute to increased downtime and maintenance requirements in process tools. MKS Instruments S49UL Thermal Management System is a high-quality heating system for applications such as thin film process exhaust lines. Installation of the S49UL system can produce significant cost-savings in terms of operational and maintenance costs for process tools such as deposition and etch systems.

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