Thick Film Heaters

Heatron
Complete guide to
Thick Film Heaters

Heatron Thick Film Heaters
(March 29, 2021)

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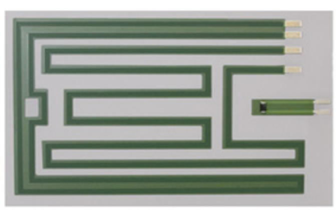
Introduction

When considering a surface heating solution for your project or process, how about a heater that can be described as Lighter, Thinner, Smaller, and Faster? Well, if these are music to your application designers or project engineers, then, Heatron has made it possible by providing a wide range of highly customizable Thick Film Heaters (TFH) that is ideal for heating applications and can be the game changer to solve the problem!

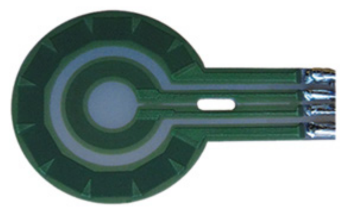
This article is to introduce the technology and concept of Thick Film Heaters (TFH) and specific developments by Heatron that offers four major categories of variety of unique TFH products include: Ceramic Core Alumina (Al2O3), Ceramic Core Aluminum Nitride (AlN), Thick Film Aluminum (Al), and Thick Film Stainless Steel. Each of these can be customized to suit applications for industries such as Medical & Life Sciences, Aviation and Transportation, Security, Food Service, Printing, Industrial, and Semiconductor, name just a few.

Thick Film Heaters are built by using a deposition process by screen printing resistive or conductor traces on top of a substrate. The deposition process allows for close control of thickness and width of the resistor, thus accurately controlling the heater resistance, wattage, watt density, and uniformity of the heated part.

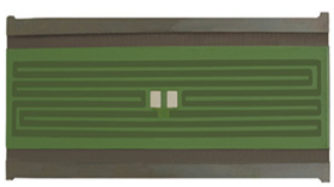
The nomenclature for a Thick Film Heater is determined by the substrate used. For example, "Ceramic Thick Film Heater" has its name from the ceramic being the substrate. Heatron's ceramic TFHs are, thus, Ceramic Core Alumina (Al2O3), Ceramic Core Aluminum Nitride (AlN), in addition to Thick Film Aluminum (Al), and Thick Film Stainless Steel that are made with substrates of Aluminum and Stainless Steel, respectively. The photos below demonstrate the samples of four types of TFHs, based on the substrate or core used, as provided by Heatron.



Ceramic Core
Alumina (Al2O3) Heater



Ceramic Core
Aluminum Nitride (AlN)



Thick Film Stainless Steel

Thick Film Aluminum (Al)

Basic Components and Structure of a Thick Film Heater

A typical TFH consists of several components or layers and is illustrated by the diagram at the end of this section. The selections of dielectrics, conductor, and resistive ink, and determination of their combinations are dictated by the properties of these materials and thermal-electrical requirements of the end TFH products, also by the application or process compatibility with the operating temperature and cycle rates, watt density, and environment.

1. Substrate

The substrate is the surface on which the heater is to be built. The substrate is the surface facing the object to be heated.

Base substrate materials commonly used are divided into a few classes: (1) Ceramics, such as aluminum oxide (AL2O3), aluminum nitride (AlN), beryllium oxide (BeO), and zirconium oxide (ZrO2); (2) Stainless steel, such as types 304 and 430; (3) Aluminum, (4) Glass or Mica, (5) Surface treated rubber and plastics.

Substrate material is selected based on the choices of resistive pastes and conductor materials which are all important components of a TFH. Compatibility with the application conditions or operating environment, operating temperature, power requirements, and cost are important factors to consider for the selection of substrate. Heatron design engineering team is experienced in analyzing the applications and proposing an optimized plan that are focused on boosting performance and containing costs in a timely manner.

2. Dielectric Layer

The dielectric layer separates between the metallic substrate and the printed traces. The dielectric layer can be printed, coated, or laminated. The dielectric materials are generally glass and ceramic based and are not conductive. This layer is particularly necessary if the substrate is metallic, such as stainless steel or aluminum. The metal substrate must be electrically insulated from the printed traces of either resistive pastes or conductor material. The dielectric layer restrict leak current and ensure the electric integrity of the heater.

If an electrically non-conductive base substrate is selected, such as ceramic or non-metallic in nature, the dielectric layer may not be needed.

3. Heating or Resistive Traces

The resistive ink or paste is to be printed or coated onto the treated substate to form heating traces or paths; therefore, it is called “functional material” as it is responsible generate heat in a TFH. The formula determines partially the resistivity or wattage of the heating traces or elements. The choice of materials and their concentrations have been investigated and optimized through extensive effort of research and development at Heatron. Heatron’s proprietary knowledge on the chemistry of the paste formula and electric engineering allows high compatibility and strong adherence between the ink and chosen dielectrics or substrates.

The functional resistive materials can be printed in two ways on the surface of the non-metallic substrate or the dielectric layer on top of the metallic substrate: printing the heating traces or pattern that are lines or circuits; or coating the underlying surface with full coverage. In the first case, the conductor traces, to be discussed next, may not be needed, but in the second case, the conductor traces must be printed to allow electrification.

The pastes or inks can be developed to exhibit three different relationships between the resistivity or power output and temperature under which the device operates:

(1) ZTC – zero temperature coefficient of the resistance. The power output or watt density of heaters made with ZTC formula does not change as a function of temperature. ZTC material is most used in most type of TFHs. Examples of the ZTC ink or paste are by mixing ceramics or glasses with metals and metal oxides such as silver and ruthenium in various combinations to obtain inks with different resistance values. This article addresses mainly the ZTC heaters.

(2) PTC – positive temperature coefficient of the resistance. The PTC heaters can self-decrease the power output when the temperature is increased, and the opposite is true: output increases automatically when the object to be heated becomes colder. PTC heaters can be divided into two classes based on the materials or application temperatures. The high-temperature class is made using polycrystalline ceramics containing key ingredient such as barium titanate ($BaTiO3$) which exhibit a PTC property above the Curie point of about 120^{o}C. In low-temperature class of the PTC TFHs, the formula of PTC paste is prepared by mixing conductive particles such as carbon black with semicrystalline polymers such as polyethylene or per-fluorinated ethylene and their oligomers in either solvent-based emulsion state or molten state. The polymer and carbon based low-temperature heaters exhibit PTC effect monotonically between relatively low glass transition temperature (-40^{o}F or lower) and the melting point of the semicrystalline polymer. Heatron has developed prototypes of the low-temperature polymeric PTC heaters and can be used in medical diagnostics. The heater heats the blood sample with diminishing power as temperature rises. To facilitate the diagnostics, the temperature plateaus within a narrow range at so-called “limit temperature” as determined by the melting point of the polymer.

(3) NTC – negative temperature coefficient of the resistance. This type of device is known as thermistor, derived from the term thermally sensitive resistors, can be used as a cost- effective sensor for very accurate temperature measurement. This class is out of this article.

4. Conductor Traces

The conductor traces are typically precious metal particles such as silver, palladium, gold or platinum and their respective alloys.

Conductor traces are printed to apply voltage onto resistive traces to generate heat. As mentioned above, sometimes, the voltage may be applied directly onto the resistive traces, therefore, the preparation and printing of conductor traces are not required. However, if the heater substrate or the dielectric layer is coated continuously with a layer of resistive material, then, conductor traces are necessary to apply voltage.

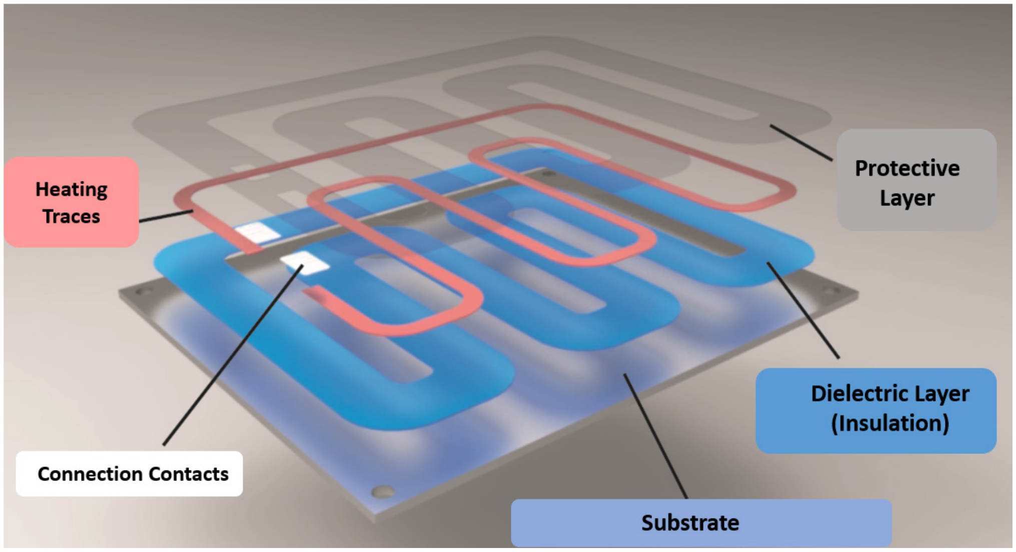
5. Protective Layer

Commonly used non-metallic materials for protective coatings include polymers, epoxies, and ceramics, depending on application conditions and environment. The protective layer for TFHs is printed or coated continuously to cover the heater assembly as the sheath of the heater with several intents: electrically insulating the heating traces, mechanically protecting physical damage, chemically inhibiting or preventing corrosion along with water resistance, and thermally withstanding maximum application temperatures.

6. Connection Contacts

The contact points or areas allow for attachment of lead wires by soldering, clamping, or welding. The contact points or areas can be the conductor materials described above. Metals with high electric conductivity can reduce contact resistance and create heat.

The diagram below is modified based on illustrations by Heatrod, which is a Sister company under NIBE Element: (https://www.heatrod.com/heating-elements/thick-film-elements). Note that the Conductive Traces are not present since the electric contacts can be made directly with the Heating Traces.



Steps of TFH Fabrication

The process of TFH fabrication involves steps described below and illustrated by the diagram at the end of this section:

Step 1: Substrate Cutting

The shape or geometry of the substrate is dictated by that of the surface for the specified form factor. Depending on the substrate, the cutting is done by laser or diamond saw, which is according to the engineering drawing of the shape and dimensions as well as the sequence of the cutting action. The information or requirement on cutting is stored in the computer that controls the cutting.

Step 2: Dielectric or Insulation Printing or Coating

The glass or ceramic based dielectric material is prepared or emulsified into the form of ink or paste having right viscosity by using an organic carrier or solvent. The dielectric emulsion is printed, coated, or spayed over the metal substrate.

In case of non-metallic substrate such as ceramic, this step may be skipped. Certain surface activation treatment may, however, be necessary to promote and enhance the bonding between substrate and printed traces.

Step 3: Ink Development or Formulation

Pastes or inks are commonly prepared by mixing or compounding the required ingredients, such metal or metal oxides and ceramics, with a solvent to produce a paste for printing described in next step. The mixing is typically done on a two- or three-roll mill machine. The mixing must be microscopically dispersive so that a high degree of homogeneity between the mixing ingredients can be achieved. High paste homogeneity can eliminate hot spots and burnout of the finished parts.

The conductor material will also need to be made into the liquid state or in the form of paste or ink for printing if needed.

Step 4: Stencil or Mask Fabrication for Screen Printing.

Stencil for screen printing on the substrate is usually a thin sheet of material, such as plastic and metal, with the pattern of heating traces cut from it. By using a squeegee to force the paste or ink through the cut-out patterns in the stencil, heating traces or conductor traces are transferred over to the surface of underlying substrate.

The stencil determines the arrangement of heating traces and ultimately the pattern of heat distribution. It is designed to allow heating according to the surface where heat is needed. The power density can be adjusted area by area by changing the pattern of stencil to form a multi-zone TFH.

Step 5: Printing

The printing process is to deposit resistive and/or conductor traces onto the non-metallic substrate or the dielectric layer on metal substrate. Many technologies to print films for electronics or heaters have been developed, this article focuses on the screen-printing technology. Other interesting printing technologies will be briefly described.

Screen-printing has a long history and is the most simple, flexible, and economic method. Screen-printing is still the most widely used process to make TFHs as of today. Printing is done by forcing the pastes or inks through engineered stencils using a squeegee onto a flat or cylindrical surface of substrate. There are different methods to print:

1. The resistive traces are printed using the stencil onto the top of the precoated dielectric layer of the metallic substrate or directly onto the non-conductive substrate. Conductor traces may not be needed as the connections can be made directly onto the ends of resistive traces.

2. After printing the resistive traces, conductor traces are printed to make connections with the resistive traces to form circuit. The printing sequence maybe be reversed. Obviously, this method requires two different stencils or masks, one for resistive traces and one for conductor traces.

3. Coat the resistive paste to cover the substrate completely, then, print the conductor traces to form circuits. The electric current flows though pathways with the least resistance.

The resistive traces or coating are responsible to transform electric current into heat, and the conductor traces apply voltage onto the resistive traces.

The deposition process using screen-printing allows for close control of thickness and width of the traces or heating elements, thus accurately controlling the heater resistance, wattage, watt density, and uniformity of the heated part.

Other printing technologies to print films is listed below based on research reviews (Reference: M. Prudenziati *et al*, "Technologies of Printed Films", in "Printed Films, Material Science and Applications in Sensors, Electronics and Photonics" ed. by M. Prudenziati & J. Hormadaley, published by Woodhead Publishing Limited, 2012, ISBN 978-0-85709-621-0).

- Direct-write deposition using filament or liquid dispensing system, in which the electric circuits or traces are dispensed or written directly onto treated surface of a substrate.
- Ink-jet printing, which is also a direct-write process to deposit droplets of functional pastes or inks onto the substrates.
- Direct gravure off-set printing process, in which the functional material is transferred from the gravure, which is engraved with groves identical to the circuit pattern and filled with the ink or paste, to the surface of the substrate.
- Rotogravure printing, in which the transfer of ink or paste is done by dynamic contacting between the rotating cylindrical gravure and the traveling sheet of substrate. The substrate is constantly pressed against the gravure roll by another roll to make the ink stain on the substrate.
- Offset lithography, this technology involves the use of a plate roller that has a smooth surface but has contrastingly different wetting properties on different areas. Upon contacting with the ink or paste, only certain lines or areas are wetted to form the patterns the surface of the plate roller. The surface pattern is then transferred to a counter-rotating printing roller, which in turn transfers the pattern onto the moving substrate which is impressed by a third roller on the opposite side of the substrate.
- Flexographic printing – similar to offset lithography, but the surface of the first roller has been engraved with the desired pattern which is filled with the ink or paste. The pattern is transferred to the printing roller which, in turn, transfers the pattern onto the traveling substrate.
- Other techniques – a wide range of printing technologies have been developed including laser-based processes and plasma or thermal spray.

Step 6: Curing or Firing

In this step, and printed heater undergoes heat treatment to make strong bonding between the substrate or dielectrics and the printed traces. The early stage of curing or firing evaporate any liquid that is used in the step of paste preparation. During the firing process, the metal and metal oxide particles in the ink are bonded by virtue of sintering in the solid state. The bonding forms a morphology in which a network of a large number of nanoscales electrically conductive pathways are formed, which becomes the permanent heating traces or elements. Also, during the firing process the glass particles are melted and the molten glass fills up the interstitials between traces, between the traces and substrate, and to bond the entire structure to attain high mechanical strength. At the same time, the structure remains certain degree of bendability because of the ratio between thickness and lateral dimensions is very small.

Heatron developed temperature profiles that are optimized for the processes of bonding involving various pairs of substrate and ink.

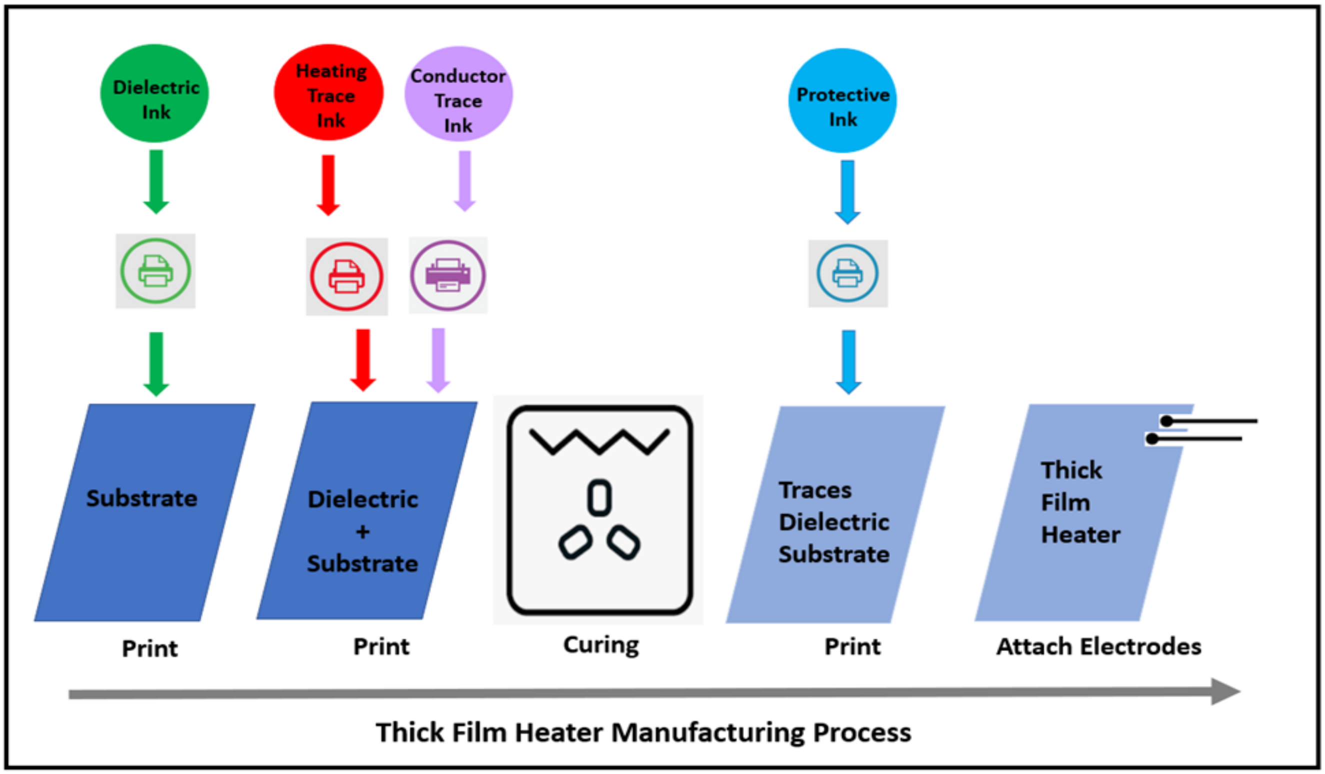
Step 7: Finishing steps - Protective Layer and Electric Termination

The protective layer on top of the heating traces is a dielectric material which insulates the heating traces. The non-metallic protective later, such as polymer or epoxies, maybe printed, coated, or sprayed on.

Various metals and alloys can be used for making the termination, including silver, platinum, gold, and silver alloys. The attachment of lead wires can be done by spring contacts, soldering, and ultrasonic wire bonding. The connection points or areas can be encapsulated using epoxy or silicon RTVs.

Step 8: Final quality inspection typically consists of tests such as:

- Resistance of the heater which determined the power output or total wattage.
- Insulation resistance (IR) between electrodes and ground such as the metal substrate using a voltage between 500 to 1,000 Vdc depends on intended application.
- Dielectric test or hi-pot between electrodes and outer metal substrate or ground with an applied voltage of 2 times rated application voltage plus 1000 Vac
- Performance active testing to measure the current and wattage under the rated voltage.
- Thermal imaging to determine surface temperature and uniformity.
- Service lifetime test which is an accelerated performance active aging test by cycling the temperature and voltage on/off for a specific duty cycles and duration of the test.



Unique Advantages and Benefits of TFH

For surface heating, there are other choices of heaters. Heatron provides Flexible Silicon Heaters, Kapton® Polyimide Etch Foil heaters, and Etched Mica Heaters. The question is why Thick Film Heaters? This section lists and explains the unique advantages and benefits that TFH can offer, and sometimes, cannot be replaced by other form of surface heaters.

- Heating Pattern: TFH are made with screen printed heating traces which can be tailored to applications to deliver even heat for thermal uniformity across a surface, or different power densities (heat) in different areas, i.e., more power can be targeted in particular areas to meet the needs of the application. This is done by the combination of three factors: (1) designing pattern of heating traces that intensify heating at cold spots or areas on the surface; for example, multiple independent heat zones can be designed into one heater; (2) formulating the pastes with a wide resistance range to deliver sufficient wattage, (3) adjusting printing width and depth to supplement the resistivity of the paste. The end result is the capability of TFHs to apply heat with very predictable heat distribution across the surface or just in certain areas, uniform or concentrated on cold spots, and to accommodate the features of surface area and optimize the amount of heat transfer by virtue of conduction.

- Odd Form Factors: Unlimited unusual heater shapes and geometry to fit target areas for unique heating patterns. The intention is to fit custom profile or area. At Heatron, ceramic (Al_2O_3 and AlN), aluminum, and stainless-steel substrates are cut with precision laser into almost any 2-dimensional shapes, a great solution to situations where custom form factors exist but other heaters will not fit or do not perform effectively. Heatron's sales and application team is available to understand customer's application and design a TFH as the right choice.

- Design Versatility: As shown in above, the versatility in design of TFHs, shapes and heating distribution, enables value engineering to shorten development cycle and reduce costs.

- Low Profile and Small Footprint: The most distinguishing character of TFH is its low profile and can made with very small dimensions. As thin as 0.010", the THFs minimize the space requirements and is ideally suitable for thermal coupling to flat heat sinks, circuit boards and bulk heads etc. This is clear advantage when compared to bulky wire wound type heaters such as flexible silicone laminated heaters, as the wires have to be either very long or the AWG of the wire has to be very small. TFHs overcome the space issue by selecting an ink of a particular resistivity value from a wide range.

- Substrates Choice: Various substrate materials can be utilized to be compatible with objects to heated and environments under which TFH operates. Refer to Step 1 under the Section "Process of TFH Fabrication", the ceramic substrates have excellent corrosion resistance property. Stainless has moderate corrosion resistance, and aluminum offers a high resistance to corrosion once the surface oxide is formed. Thermal conductivity, which intrinsically the heat transfer from heater to object, varies for different substrates. Stainless steel has the lowest value of about 15 W/mK, aluminum nitride (AlN) has the highest value up to 220 W/mK.

- Light Weight: The TFH is thin and light weight, excellent for applications need rapid heating and uniform temperature. The low mass also lowers energy consumption and boost performances.

- Low Thermal Mass or Heat Capacity: The low thermal mass is ideal for rapid thermal response or fast temperature cycling. Having a low heat capacity, the temperature can be increased quickly by using low amount of energy.

- Maximum Heat Transfer: Due to the direct surface contact, a TFH ensures efficient heat transfer via conduction through thermally stable substrates and precise resistance trace patterns.

- No Electrical Complication: The printed pattern can reduce or eliminate potential electrical inductance and capacitance inherent in wound resistance wires. The inductance and capacitance currents may cause issues of nuisance ground-fault that is unacceptable.

- High Operating Temperature: Ceramic TFHs have maximum operating temperature up to 1832°F, such as Heatron's high temperature ceramic TFHs (Al2O3 and AlN).

- High Watt Density: Standard products range between about 20 W/in² and 40 W/in², but Heatron can provide 75 to 1000 W/in², depends on the substrates.

- Corrosion Resistant: Ceramic TFHs have excellent corrosion resistance and perform well under corrosive conditions where acid and alkali solutions exist. Aluminum TFH, after forming a layer of oxidation by gaseous acids present in the air, which serves a corrosion-resistant layer, can perform well in most corrosive environments. Stainless steel substrate can, however, tolerate only modest corrosions.

- Long Life: Service life of TFHs can be very long if the application conditions are met according to instruction of operations. Heaters tend to last longer if the temperature is kept below its designed maximum temperature rating, as high temperature accelerates deterioration of the heating traces, the dielectrics and protective layer.

Industries and Applications of TFHs

- Medical and Life Sciences - Dialysis, CPAP, DNA analysis and testing, blood diagnostics, surgical devices, vessel sealer, blood and fluid warming, instrument warming, MRI equipment, temperature therapy, sterilization

- Aviation & Transportation - Instrumentation, personal comfort, deicers, over the road truck and railcar freeze protection, oil and battery heating, auto and motorcycles.

- Automotive – cold weather battery warming on electrical and hybrid vehicles, motor heating, fuel cell temperature maintenance, mirror defogging, cabinet comfort heating, steering wheel and seats heating, door handle de-freezing, coolant heaters. Refer to our article "*HEATRON ELECTRIC HEATING SOLUTIONS AND ELECTRIC VEHICLES*" for more details of applications.

- Security - Chemical detection, explosives detection, alcohol detection, cameras lens defogging

- Food Service - Warming holding cabinets, display shelves, prep stations, heated dishware, fryer systems, grilling platters, appliances.

- Health and Beauty Appliances – Personal hair styling and drying tools, skin spa and facial steamer, heating pads and blankets, heating body and foot massager, sauna belt.

- Printing - 3-D Printers, Laser Printers, Card Printers, Thermal Printers, Commercial and Industrial Printers. A practical example is the Thick Film Nozzle Heater offered by Heatron. By printing the heater traces or circuit directly onto the aluminum block of the nozzle, the heat is directed precisely when and where it is needed (https://www.heatron.com/products--services/thick-film-heating-elements-and-circuits/thick-film-nozzle-heater).

- Industrial - Packaging lines, electronic enclosures, freeze protection, motor heaters, plastic fabrications (extrusion, molding, calendaring), water heating, hot plates.

- Semiconductor - High temperature burn-in boards and testing equipment, wafer chuck heaters, water heating.

- Analytical Instruments and Advanced Research Institutions – Thermal analysis, spectrometers, chromatography, imaging equipment, separation and membrane sciences.

- Food and beverage equipment - holding cabinets, hot food displays, warming trays, storage warming, brewing temperature maintenance, portable food delivery.

Why Heatron?

Over the past 36 years, Heatron has emerged from a small private heating component and manufacturing company to an industrial leader in a full-service heating element supplier to OEMs with proficiency in thermal management, heating element design and application, and design for manufacture. In 2014, rapid expansion of the Thick Film product line required the addition of manufacturing and warehousing space at the facility in Erie, Pennsylvania, USA.

Heatron has developed a variety of TFHs to cover the widest spectrum of applications and industries. There are currently four major standard types of TFHs offered by Heatron:

- Ceramic Core Alumina (Al_2O_3)
- Ceramic Core Aluminum Nitride (AlN)
- Aluminum (Al)
- Stainless Steel

TFHs using other substrates as required by application can be developed quickly, and custom design is the core competency at Heatron.

Common features and benefits for all four types of TFHs offered by Heatron are listed in the following, which can be a game changer for many custom heating applications:

- Precision and Repeatability of Printing ensures products conform to specifications.
- Precision engineered, precise sizing, shape capability, repeatable pattern of low profile can fit tight spaces and tolerances.
- Well controlled wattage distribution leads to uniform or gradient surface temperature.
- High thermal conductivity, low mass, and low heat capacity TFHs enable fast response of heat transfer resulting in fast ramp up and cooling down, and very uniform temperature and controlled wattage distribution on surface.
- Precisely controlled heating for high-temperature applications over a wide temperature range, up to 1000°C maximum.
- High insulation standoff per unit thickness or excellent dielectric properties which result in low leakage current and make product safe.
- No outgassing, clean, non-contaminating heat source is a critical requirement for applications of clean environments.
- Facilitate high heat resistance and high thermal conductivity applications.
- Resistance to moisture and corrosion, suitable for most application environments.
- Excellent hardness and wear resistance ensure the integrity of the TFHs.

The unique features and benefits of the Heatron TFHs are listed in the table below. The unique characteristics for each type of TFHs can be used as a preliminary selection guide.

	Ceramic Core Alumina (Al2O3) Heater	Ceramic Core Aluminum Nitride (AlN)	Thick Film Aluminum (Al)	Thick Film Stainless Steel
Max Application Temperature (°F)	662 - 1832	1832	302	1202
Max Power Density (W/in^2)	75	1000	400	200
Max Ramp Up Speed (°F/sec)	122	572	302	302
Thermal Conductivity (W/mK)	35	220	173	15
Density (g/cm^3)	3.75	3.26	2.70	7.80
Thermal expansion coefficient (10^{-6}/°C)	8.1	2.56	24	5.8
Substrate thickness (inch)	0.25 -0.50	0.05 - 0.20	0.0014 - 0.75	0.004 - 0.12
Typical Maximum Dimension (inch)	6 x 12	5 x 11	12 x 24	12 x 24
Theoretical Total Wattage (W)	5,400	55,000	115,200	57,600
Unique Characteristics	Ideal for small to mid-size Uniform temperature Highest insulation standoff High-temperature 1832°F Low mass Low leakage current Excellent dielectric strength Flexibility and Bending Excellent corrosion resistance	High-density nonporous AlN High-purity AlN Fast response Very uniform temperature Size and shape capability Clean, non-contaminating High thermal conductivity Prevents cracking Excellent corrosion resistance Highest-performing TFH	Low-heat applications High-degree of control 3-dimensional installations Anodization as insulator Good corrosion resistance	Superior structural properties Fast ramp up High temperature applications Low-profile Tight tolerances Tighter form factors drive design Many voltage and wattage combination

For detailed design of TFHs and information on other surface heating products offered by Heatron, such as Flexible Silicon Heaters, Kapton® Polyimide Etch Foil heaters, and Etched Mica Heaters, please visit Heatron website and contact our engineering team at: https://www.heatron.com/about-us/request-a-quote.

HEATRON

ENDLESSLY INVENTIVE

Heatron transforms your vision
into higher performing products.

sales@heatron.com
(913) 651-4420
Heatron.com

3000 Wilson Avenue
Leavenworth, KS 66048
USA