Estimating Power Requirements of Etched-Foil Heaters

Table of Contents

Abstract

When specifying a new etched-foil heater design, the first and often most formidable parameter to determine is heater wattage. How much power is needed to bring a part to temperature in a given time and how much to maintain it there? You can size a heater either by experiment or by calculating a theoretical value. The experimental approach gives the best answer, but a wattage estimate should be done before embarking on experiments. This white paper presents some numerical methods for you to use in estimating heater wattage. It is not perfectly accurate, as it is impossible to take into account all the variables acting upon a thermal system. What it does provide is an estimate to serve as a basis for ordering prototypes or starting lab experiments.

Basic Heat Transfer Theory

Two values must be calculated to determine wattage requirements: warm-up and operating heat. Assuming no lost heat, the power required to warm up a block of material is a linear function of the material's mass and specific heat, the degree of temperature rise and the desired warm-up time:

$$P = \frac{mC_p\ (T_f - T_i}{3.412t}$$

Where:
P = Heater power (watts)
m = Mass of material (lbs)
C_p = Specific heat of material (BTU/lb/°F) from Table 1
T_f = Final Temperature of material (°F)
T_i = Initial temperature of material (°F)
t = Desired warm-up time (hrs)
This formula will serve as a shortcut for power estimation if warm-up requirements are the dominant heat demand of the system and losses are small. The figure it gives is a minimum. Add at least 20% for unknown heat losses.
For best accuracy, you can estimate heat loss during operation and warm-up. Loss occurs in three forms; conduction, convection, and radiation.

Conduction transfers heat from a warmer object to a cooler one, usually through a solid medium. When speaking of etched-foil heaters, conductive loss generally refers to loss through insulation layers or heat sink mounting hardware. Conduction is a function of the temperature difference between the heater and its surroundings, the distance between hot and cool areas, and the cross sectional area and conductivity of conductive paths.

Convective loss occurs when the fluid medium surrounding the heater flows in currents and carries heat with it. For purposes of this white paper, the fluid is air. The two types of convection are natural, when heated air rises and creates air currents, and forced, when fans or wind drive air past the heater. Convective loss depends on the heat sink temperature relative to ambient, the shape and surface area of the heat sink, and the velocity of forced air.

Radiation is heat emitted as infrared energy. Radiant loss varies with temperature difference between the heater and ambient, heater surface area, and the nature of the surfaces radiating and absorbing the heat (emissivity).

Warm-up heat is the heat required to bring the heat sink to temperature in the desired time, plus extra heat to compensate for conductive, radiant, and convective losses during warm-up.

Operating heat equals the sum of steady state loses and process heat. Process heat represents work done by the heater to thermally process some material, for example, to melt a plastic film placed over the heat sink.

The total minimum heat required for an application is the larger of two values:
1. Warm-up heat, or
2. Operating heat including process requirements.

How to Use this White Paper

To estimate your wattage needs, follow the formulas in the next section "Heater Watttage Estimation Procedure" and reference values listed in Tables 1 and 2. For clarification see the example under "Sample Calculations". Note that some companies offer programs that will automatically perform all the calculations in this white paper.

Heater Wattage Estimation Procedure

I. Calculate steady state heat losses. Include conductive, radiant, and convective losses.

1. Conduction losses: Losses due to heat conduction through mounting hardware, insulation, and other material in contact with the heated part. Calculate separately for each conductive path.

Given the following:

K = Thermal conductivity of material from Table 1 (BTU•$/\mathrm{ft}^2/°\mathrm{F}/\mathrm{hr}$)

A = Cross sectional area of material (ft^2)

T_f = Heat sink temperature (°F)

T_a = Ambient temperature (°F)

L = Thickness of insulation = Length of conductive path (in)

P_{cd} = Conduction loss (W) = $\frac{KA(T_f - T_a)}{3.412\,L}$

2. Radiation Losses: Losses due to radiant transfer from the heat sink to surroundings.

Ignore insulated surfaces.

Given the following:

$\in$ = Emissivity of heat sink surface from Table 2

A = Area of exposed surface (ft^2)

T_{fR} = Final absolute temperature (°R=°F+ 460)

T_{aR} = Absolute ambient temperature (°R=°F + 460)

P_r = Radiation loss (W) = $\frac{\in A(0.1713 \text{ X } 10^{-8})({T_{fR}}^4 - {T_{aR}}^4}{3.412}$

3. Convection Losses: Loss to ambient air resulting from natural or forced air movement. Ignore with vacuum applications or well insulated surfaces. NOTE: These equations may be invalid for large heaters (longer than 2 feet) or high temperatures (above 500°F). Contact Minco for assistance in these cases.

a. Determine H (convection coefficient). Use one of two equations for H, depending on whether convection is natural (still air) or forced (fan, wind, etc.).

Given the following:

Natural Convection

F_C = Configuration factor from Table 3

T_{ave} = $(T_f + T_a)/2$ (°F)

L = Characteristic length from Table 3 (ft)

H = 0.03205 $F_c \left(\frac{T_f - T_a}{L}\right)^{0.025}$ exp $\left(\frac{-T_{ave}}{2900}\right)$

Forced Convection

U = Average air velocity (ft/sec)

L = Length of side parallel to air flow (ft)

H = 0.0675 $\sqrt{\frac{U}{L}}$

b. Calculate convection loss.

Given the following:

A = Area of exposed surface (ft^2)

T_f = Heat sink temperature (°F)

T_a = Ambient temperature (°F)

P_{cv} = Convective loss (W) = $\frac{HA(T_f - T_a)}{3.412}$

II. Calculate process heat requirements. If the heater is used for continuous processing (warming, melting, or vaporizing of materials other than the heat sink), calculate power lost to the processed material. For this formula, T_f and T_i are the initial and final temperatures of the processed material. Skip if the heater merely maintains temperature.

For continuous process, substitute the mass flow rate for m/t.

Given the following:

m = Mass of material in each process load (lb)

t = Cycle time for each load (hr)

C_p = Specific heat of material from Table 1(BTU/lb/°F)

h = Latent heat of fusion (melting) or vaporization from Table 1 if processed material will change state (BTU/lb)

T_f = Final temperature of material (°F)

T_i = Initial temperature of material (°F)

P_{CV} = Process heat (W) = $(\frac{m}{t})\frac{C_p\,(T_f - T_i) + h}{3.412}$

III. Calculate operating heat requirements. The total operating power (after warm-up) is the sum of conductive, radiant, and convective losses plus process power.

$P_p = P_{cd} + P_r + cv + P_p$

IV. Calculate warm-up requirements. Calculate the power needed to bring the heat sink to temperature in the desired time.

Given the following:

m = Mass of material (lb)

C_p = Specific heat of material from Table 1 (BTU/lb/°F)

T_f = Final temperature of heat sink (°F)

T_i = Initial temperature of heat sink (°F)

T_a = Ambient temperature (°F)

t = Desired warm-up time (hr)

P_{sl} = Steady state loss (W) = $P_{cd} + P_r + P_{cv}$

H_w = Warmup coefficient = $\frac{P_{sl}}{(T_f - T_a)}$

P_w = Warmup power (W) = $\frac{H_w\,(T_f - T_i)}{1 - \exp(\frac{-3.412 H_w t}{m C_p}} + H_w\,(T_i - T_a)$

Note: exp (x) = 2.718^x

V. Calculate total heater power. The total power requirement is steady state power or warmup power, whichever is larger. Specify actual wattage at least 10% greater than this figure.

P_t = Minimum total power required (W) = Maximum of P_o or P_w

CAUTION: These figures are estimates only. You must operate the heater in your equipment, under actual environmental conditions, to make a final determination of power.

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Table 1: Thermal properties of common materials

Typical values near room temperature. Contact your supplier for unlisted materials.

Material	Density $\frac{lbs}{ft^3}$	Specific heat $\frac{BTU}{lb°F}$	Thermal conductivity $\frac{BTU\ in}{hr\ ft^2°F}$	Latent heat of fusion $\frac{BTU}{lb}$
Aluminum 1100-0	169	0.216	1536	169
Aluminum 2024	173	0.209	1344	167
Beryllium	113.5	0.052	1121	
Brass (80-20)	535	0.091	960	
Brass (70-30)	525	0.10	840	
Chromium	450	0.11	484	
Constantan	555	0.09	148	
Copper	560	0.1	2736	
Gold	1206	0.03	2064	
Inconel	530	0.11	104	
Iron(Cast)	450	0.13	396	
Iron(Wrought)	480	0.12	432	
Lead	708	0.031	241	
Lithium	367	0.79	516	
Magnesium	109	0.25	1068	
Mercury	845	0.033	60.8	5
Molybdenum	638	0.061	980	
Nickel 200	554	0.11	468	
Nichrome (80-20)	518	0.11	104	
Platinum	1339	0.031	480	
Silver	655	0.056	2904	
Sodium	60	0.295	972	
Solder (50/50)	555	0.040	323	17
Solder (60/40)	540	0.045	355	28
Steel (Mild Carbon)	490	0.12	456	
Stainless Steel (300 series)	500	0.12	113	
Stainless Steel (430)	484	0.11	150	
Tin, Solid	456	0.056	468	
Titanium	281	0.126	138	
Zinc	445	0.095	188	

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Table 1 continued:

Material	Density $\frac{lbs}{ft^3}$	Specific heat $\frac{BTU}{lb°F}$	Thermal conductivity $\frac{BTU\ in}{hr\ ft^2 °F}$	Latent heat of fusion $\frac{BTU}{lb}$
Alumina	150			
Alumina Silicate	149	0.2	9.1	
Bakelite	81	0.36	118	
Brick, Common Clay	110	0.23	5	
Carbon	138	0.165	173	
Fiberglass (Duct Insulation)	0.75		0.28	
Fiberglass (Spin-Glas)	3		0.26	
Glass	165	0.20	7.2	
Ice	52	0.49	15.6	144
Mica	185	0.20	3	
Paper	56	0.33	0.84	
Paraffin (Solid)	56.2	0.69	1.8	63
Plastic:				
ABS	76	0.5	2.3	
Acrylic	74	0.35	1.0	
Epoxy	88	0.3	2.4	
Fluoroplastics	150	0.28	1.7	
Mylar	79	0.27	4.5	
Nylon	72	0.5	1.7	
Phenolic	124	0.35	1.0	
Polycarbonate	75	0.3	1.4	
Polyester	86	0.35	5	
Polyethylene	60	0.54	3.5	
Polyimides	90	0.31	6.8	
Polypropylene	57	0.46	2.5	
Polystyrene	66	0.32	0.96	
PVC Acetate	99	0.3	1.2	
Porcelain	156	0.22	10.8	
Rubber Synthetics	75	0.48	1.1	
Silicon	14.5	0.162	600	
Silicone Rubber	78	0.45	4.5	
Teflon	135	0.28	1.4	

Table 1 continued:

Material	Density $\frac{lbs}{ft^3}$	Specific heat $\frac{BTU}{lb°F}$	Thermal conductivity $\frac{BTU\ in}{hr\ ft^2°F}$	Latent heat of fusion $\frac{BTU}{lb}$
Acetone, 100%	49	0.514	1.15	225
Air	0.075	0.24	0.13	
Benzene	56	0.42	1.04	170
Butyl Alcohol	45.3	0.687		254
Ethyl Alcohol, 95%	50.4	0.60	1.3	370
Freon 12	81.8	0.232	0.49	62
Fuel Oil #1	50.5	0.47	1.0	86
Fuel Oil #2	53.9	0.44	0.96	
Fuel Oil #3, #4	55.7	0.425	0.92	67
Fuel Oil #5, #6	58.9	0.405	0.85	
Gasoline	43	0.53	0.94	116
Glycerine	78.7	0.58	1.97	
HCl, 10%	66.5	0.93		
Naphthalene	54.1	0.396		103
Oil, SAE 10-30, 40-50	55.4	0.43		
Paraffin, Melted	56	0.69	1.68	70
Transformer Oils	56.3	0.42	0.9	
Propyl Alcohol	50.2	0.57		295.2
Sulfuric Acid, 20%	71	0.84		
Sulfuric Acid, 60%	93.5	0.52	2.88	
Sulfuric Acid, 98%	114.7	0.35	1.8	219
Trichloroethylene	91.3	0.23	0.84	103
Turpentine	54	0.42		133
Vegetable Oil	57.5	0.43		
Water	62.4	1.00	4.08	965

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Table 2: Emissivities of common materials (∈)

Typical values near room temperature. Contact your supplier for unlisted materials.

Material	Emissivity
Blackbody	1.0
Aluminum, bright foil	0.07
Aluminum, heavy oxide	0.22
Aluminum, anodized	0.82
Brass, polished	0.04
Brass, heavy oxide	0.60
Carbon	0.95
Copper, polished	0.03
Copper, heavy oxide	0.80
Glass	0.90
Gold	0.02
Iron, cast heavy oxide	0.85
Paint (non-metallic)	0.98
Paper	0.90
Plastics (typical)	0.95
Rubber	0.95
Silver	0.02
Steel, mild polished	0.10
Steel, mild heavy oxide	0.85
Stainless steel, polished	0.17
Stainless steel, heavy oxide	0.85
Water	0.98
Zinc	0.25

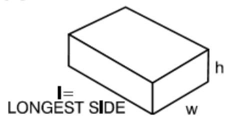
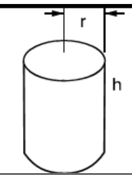
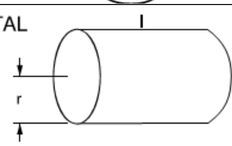
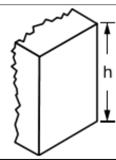
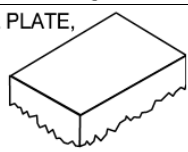
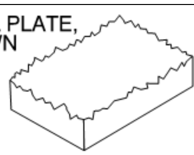
Conversion Factors

To get:	Use:
°F	= (1.8 * °C) + 32
°R (Rankine)	= °F + 460
BTU in/hr ft^2 °F	= 12 * BTU/hr ft °F
BTU in/hr ft^2°F	= 6.94 * W/m °C
BTU/lb	= 0.43 * kilojoules/kg °C
BTU/lb °F	= 0.239 * kilojoules/kg °C
in	= 0.394 * cm
ft	= 0.033 * cm
lb	= 2.205 * kg
lb/ft^2	= 0.0624 * kg/m^3

Disclaimer

There no warranty regarding the accuracy of information in this white paper. The user is cautioned that the procedures given here only yield estimates, not absolute values. You must make the final determination of the suitability of a heater for your application

Table 3: Volume, surface area and convection data for common solids

Shape	Volume	Surface area	Characteristic length*	Configuration factor
RECTANGULAR BLOCK 	V = lwh	A = 2(lw + lh + wh)	$L = \frac{lh}{l + h}$	0.93
VERTICAL CYLINDER 	$V = \pi hr^2$	$A = 2\pi r(r + h)$	L = h	1
HORIZONTAL CYLINDER 	$V = \pi lr^2$	$A = 2\pi r(r + l)$	L = 2r	0.90
VERTICAL PLATE 		Depends on shape	L = h	1
HORIZONTAL PLATE, FACING UP 		Depends on shape	$L = \frac{4 \text{ x Area}}{\text{Perimeter}}$	1.29
HORIZONTAL PLATE, FACING DOWN 		Depends on shape	$L = \frac{4 \text{ x Area}}{\text{Perimeter}}$	0.65

**Characteristic length is a factor relating convective heat loss to the shape and orientation of a surface.*

Assumptions

This white paper makes the following simplifying assumptions:

The heat sink, heater, and processed material are at a uniform temperature. This is of course not strictly true. Gradients exist. Outer surfaces are cooler than areas under the heater. But assuming that all temperatures are equal to the setpoint temperature spares us the iterative calculations needed to precisely characterize heat profiles.

All convection is laminar. The alternative is turbulent convection, a condition occurring with large heaters and high temperatures.

The convective fluid is air. Different equations are required if the heater is immersed in other media.
For radiant heat transfer, the surrounding environment is a blackbody at ambient temperature. This is usually a good assumption in large open areas but may not be in a small enclosure.

Values are conservative. Approximations are chosen to give values higher than the true value, ensuring that heaters will have more than sufficient power for the application.

Sample Calculations

Following is a typical heater application to illustrate the use of the estimation procedure.

For example, we are designing a reflow machine to melt solder on circuit boards. At the core of the machine is a rectangular aluminum block (Figure 1):

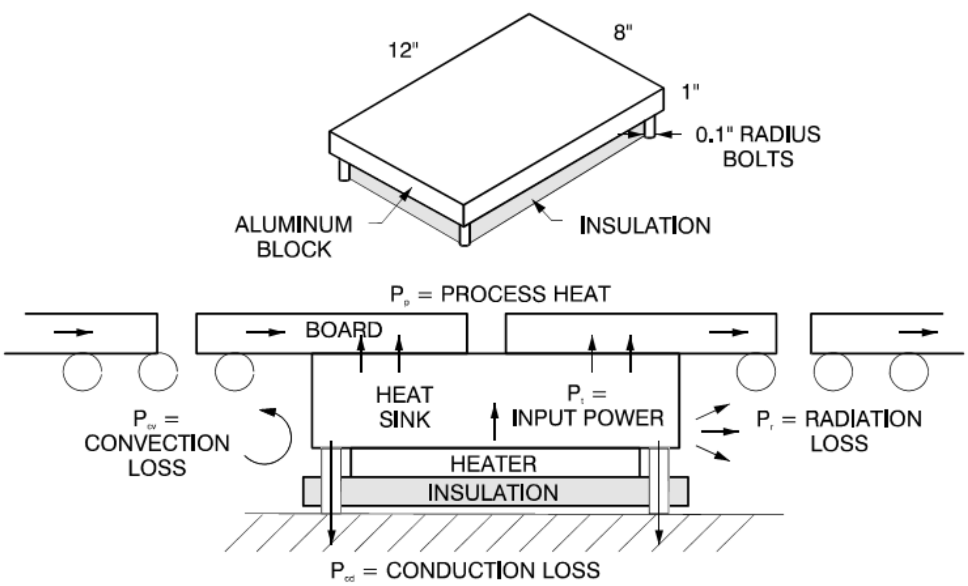


Figure 1

The block is mounted with 1" long steel bolts of 0.1" radius, and has 1" of fiberglass insulation beneath it. We want to bring it to operating temperature, 400°F, within five minutes of powerup. The initial temperature is equal to ambient, 70°F.

Once in operation, the machine deposits an epoxy-glass circuit board on the block every ten seconds. The dimensions of the board are 6" x 12" x 0.1", and it has 0.01 lb of solder on it to be melted. What is the heat required for warm-up, steady state maintenance, and processing?

I. Calculate steady state heat losses.

1. Conduction losses. We calculate conductive losses through the fiberglass insulation and mounting bolts.
Cross-sectional area (A):
Insulation: 0.67 ft x 1 ft = 0.67
Bolts: $4(0.1\ \mathrm{in})^2$ x π/(12 in/$\mathrm{ft})^2$ = $8.7 \times 10^{-4}\ \mathrm{ft}^2$

Thermal conductivity values (K):
Insulation: 0.26
Bolts: 456

Using the formula in "Heater Wattage Estimation Procedure" section I.1. for the conductive losses, the loss through the insulation is 17 watts and the loss through the bolts is 38 watts. The total conduction loss (P_{cd}) is 55 watts.

2. Radiation losses. We will ignore losses from the insulated surface.
The surface area (A) is the top plus the sides =
(1 ft x 0.67 ft) + 2(1 ft x 0.083 ft) + 2(0.67 ft x 0.083 ft) = 0.95 ft^2
Emissivity (ϵ) is 0.22 from Table 2.

From the formula in section I.2. on page 6, the radiation loss (P_r) is 49 watts.

3. Convection losses. We will ignore convective losses from the insulated underside. The top is a horizontal plate facing up; the sides are vertical plates. Configuration factors (F_c) come from Table 3.

Characteristic length (L):
Top: (4 x 1 ft x 0.67 ft)/[2(1 ft + 0.67 ft)] = 0.80 ft
Sides: 0.083 ft

Area (A):
Top: 1 ft x 0.67 ft = 0.67 ft^2
Sides: 2(1 ft x 0.083 ft) + 2(0.67 ft x 0.083 ft) = 0.28 ft^2

From the formula in section I.3. and the configuration factors from Table 3, the natural convection loss from the top of the rectangular block is 110 watts and from the sides of the block is 62 watts. The total convection loss is (P_{cv}) 172 watts.

II. Process heat requirements. We now calculate the heat needed to bring the board to temperature and melt the solder. The heat required to melt the solder, although negligible, is shown here as an example of calculating a state change.
The mass of the circuit board is the volume times the density of epoxy from Table 1.
(6" x 12" x 0.1")(88 lb/ft3)/(12 in/ft)3 = 0.37 lb.

From the formula in section II, the process heat required to heat the board is 3865 watts and the heat required to melt the solder is 45 watts. The total process power (P_p) required is 3910 watts.

III. Calculate operating heat requirements. The total operating power (P_o) required is the sum of the losses (conduction, radiation and convection) and the process heat requirement.
The total operating power is 4186 watts.

IV. Calculate warm-up requirements. The mass of the aluminum heat sink is the volume times the density.
(1 ft x 0.67 ft x 0.083 ft)(169 lbs/ft^3) = 9.4 lb.
From the formulas in section IV on page 9, the warm-up coefficient (H_w) is .84 and the total warm up power (P_w) is 2759 watts.

V. Calculate total heater power. Total input power (P_t) is the greater of warm-up power (P_w) or operating power (P_o). In this example, the process heat needed to warm the circuit board represents the largest share of the heat requirement. We will add an extra 10% for unknown losses to the operating power (4186 watts) to arrive at the specified heater wattage of 4600 watts.

Dividing the total wattage by the heater area gives a watt density of 4600 W / 96 in^2 = 48 W/in^2

Using a watt density chart, it's determined that only a mica insulated heater will withstand 48 W/in^2 at 400°F.

Determining Heat Requirements

By Experimentation

Calculations and theory are no substitute for experimentation when designing thermal equipment for optimum performance. Mathematical methods cannot account for all the variables acting upon the system. At some point you will have to mount a heater to your part and power it up to see how it works. If you have used this white paper to estimate power beforehand and have added a sufficient safety factor, your specified wattage should do the job. If not, you will have to redesign.

You can often save money by testing with standard etched-foil heaters before investing in a custom model. The usual procedure is to connect a variable power supply (Variac) to the heater and gradually increase power until the system performs as desired (or the heater reaches its maximum power rating). A proportional or on-off controller, placed in series with the Variac and heater, can simulate real-life control.

Standard heaters come in several resistances. You should specify a resistance low enough to give you the highest wattage you might need at your Variac's maximum voltage (W = E^2/R).

If you cannot find a standard heater with the correct physical dimensions, contact your supplier. All models with the same nominal voltage, all 28 volt heaters for example, have identical watt densities. If you make a mosaic of these heaters to emulate a larger one and power them in parallel, the watt density will be uniform across all the heaters. Using a 28-volt source gives 5 watts per square inch but heaters can operate at other voltages.

Finite Element Analysis

One other technique to estimate power requirements is to simulate the thermal system using computerized finite element analysis (FEA). FEA breaks a heater and heat sink into small nodes and analyzes the thermal profile of each node as shown in figure 2. It can model both steady state and transient situations in two or three dimensions.

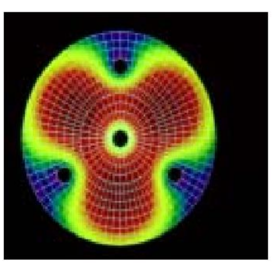


Figure 2: FEA thermal profile

Finite element analysis can handle many problems which resist theoretical or experimental solutions. You can use FEA to simulate extremely fast warm-ups, map thermal gradients across complex shapes, and determine watt density zones for profiled heaters.

Achieving Uniform Heat with Dual Element and Profiled Heaters Balancing loads with multiple elements:

What happens if warm-up heat is much greater than steady state loss (a common situation)? Once the heater reaches setpoint, its excess wattage overpowers the controller and causes temperature spikes.

One solution is to design a heater with two interwoven heating elements. The higher wattage element runs at full power until the controller shuts it off just below the setpoint. The second element, proportionally controlled, maintains setpoint temperature with an ideal duty cycle of 50%. Assuming the warmup heat requirement is P_w and steady state loss is P_{sl}, we will specify the warm-up element at (P_w - $2P_{sl}$) watts and the steady state element at $2P_{sl}$ watts. This technique also applies when process heat requirements exceed steady state requirements.

Profiling heater watt densities:

Our calculations have assumed that all areas of the heater and heat sink are at the same temperature. In reality, large gradients can develop across heat sinks. To obtain uniform temperatures at all points specify a heater with different heat levels in different zones, for example greater watt densities along the edges to compensate for loss. Contact your supplier for assistance when profiling heaters.

Summary

Determining heater wattage is a crucial step in specifying an etched-foil heater design. In most cases, the best approach is a combination of numerical methods and experimentation. By using the formulas presented in this white paper, you can determine an estimate of your wattage needs. Although they may not be absolutely accurate and cannot account for all the variables that act upon a system, they will provide you with a reasonable starting point from which you can begin your experiments. Finite Element Analysis (FEA) can be used in cases where numerical or experimental options are not adequate such as in extremely fast warmups or to map thermal gradients across complex shapes.

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