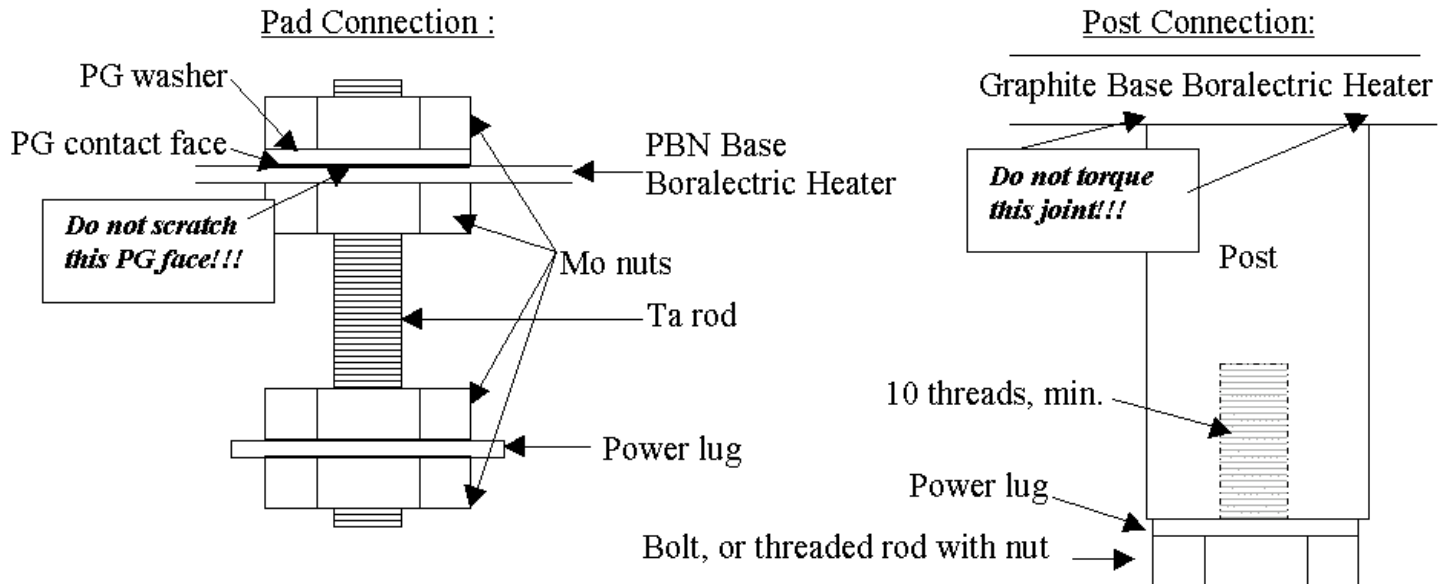


How do I install the heater?

Electrical connections to Boralectric™ Heaters are critical. The comparatively high power density and the high operating temperature of Boralectric™ Heaters make the connection more important than for conventional heaters.



Contacts to Boralectric™ Heaters are either on an exposed PG pad on the face, or on the threads of a post. For connection to pads, ACC recommends the user purchase one of our Heater Kits, in M2, M3 or M4 size. These are complete with Ta rod, Mo nuts and PG washers. The relatively high thermal expansion of PG helps insure good electrical contact during thermal cycling of materials with dissimilar thermal expansion. A few points to keep in mind:

1. Make connections finger tight, then +80 to 90°.
 - a. Less than 80° may have poor electrical contact.
 - b. Greater than about 100° may strip the threads.
2. Do not scratch the face of the PG pad. The PG is ~50 microns thick. Use a PG washer on the exposed pad to protect the conductive element surface.
3. Do not torque the joint between the post and the heater. This is a critical electrical connection. Hold the post by hand, or wrap the post with a cloth and hold lightly with pliers. Do not hold the heater body for leverage to make the post electrical joint.
4. Post connections require at least 10 threads of engagement for strength and electrical contact. The end of the post is coated for protection.
5. Check the heater resistance before and after connection. The connections should add no more than 1 ohm of resistance, but note 1.b.; take care to not strip threads.

Boralectric™ Heaters have inherent thermal uniformity due to the anisotropy of the CVD materials used in their construction. The best installation of a plate heater can be with the pattern on the bottom, the side opposite the product, with one or more thermal shields, to take full advantage of the heat leveling anisotropy.

Can multiple zones be used to improve thermal uniformity?

Yes. The losses from a heater are greater at the edges. There are two practical methods to mitigate edge losses. First, the heater can be made somewhat oversize. Losses vary greatly from installation to installation, but for free radiation from a Boralectric™ plate heater, most of the edge effect occurs in the outer 10 mm to 20 mm. If the heater is made oversize by this amount, the central portion is uniform.

But making a heater oversize can use extra power, and certainly costs valuable space in the system. A second method to combat edge effects is to increase flux where there are increased losses. Boralectric™ heaters can be made with multiple zones. An outer zone can be designed with a greater power density than the central zone. ACC has supplied heaters with up to 4, independently controlled, concentric heat zones; having a total of 8 electrical contacts. This is usually “over kill”, and two zones are shown to be very effective for most installations.

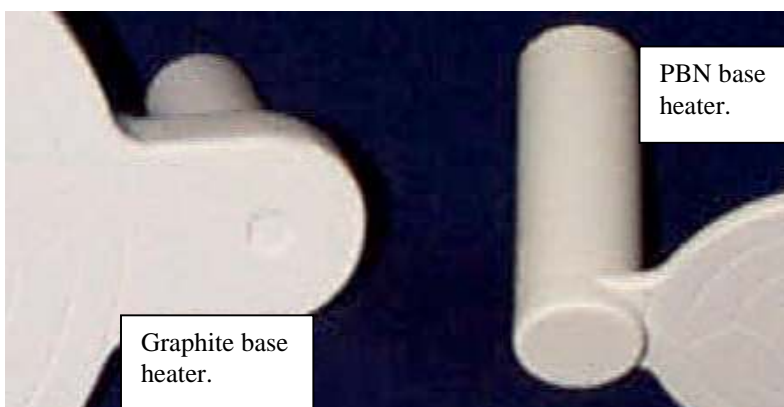
Multiple zones can be made in series, in which there is one set of contacts, or made with independent control using contacts for each zone. For series zones, the path resistance is greater where increased flux is needed, around the periphery of the heater. Series zones assume a given thermal relationship between the zones; the relative path resistance and therefore the relative power between the zones is fixed by the design.

Multiple zones are often most effective when separate contact, power supply, and control is used for each zone. Transients and system effects can be tuned in situ. The inherent limitations of thermal modeling have less impact on the final performance.

Can contacts be isolated from the heater on posts?

Boralectric™ Heaters are often used in environments where the electrical contacts need protection from the environment. This can be either a thermal or chemical need. Heaters can run very hot and melt contacts, or the environment may be oxidative and attack the contacts. In these kinds of applications, ACC offers a patented contact design that isolates the connection from the hot area; contacts are cooler and less susceptible to thermal and chemical attack. Heaters with these contact designs are called “Post Heaters”.

Two contact options are shown. In a graphite base heater, the mechanical connection is internal to the



Graphite base heater posts are $\phi 8.3 \times 25$, M2, or $\phi 9.3 \times 35$, M3, or $\phi 12.3 \times 50$, M4. Mx is the metric thread.

PBN base heater posts are $\phi 7.5 \times 25$, M3, or $\phi 11.5 \times 35$, M4, or $\phi 19 \times 50$, M6. Mx is the metric thread.

heater core, and the hot surface is flat. In a PBN base heater, the mechanical connection requires a nominal 3 mm

extension above the heater surface. A standard thread is in the cold end of the post for the electrical connection. The post is fully encapsulated with pyrolytic BN, except for the bottom face, so the only exposed graphite is at the cold end.

Can contacts be outside of the hot area, on tabs?

The two post designs shown above show the posts fastened to tabs outside of the hot area. This improves the thermal uniformity of the heater element. The electrical connection can often be a thermal heat sink. By moving the heat sink effect of the contact away from the hot zone, thermal uniformity is improved.

How is the pattern determined?

Pattern shape.

The only technical limitation to the pattern is machining capability, but different geometries can impact thermal uniformity. In any heater pattern, the current tends to channel at the inside of any tight corner. So, for adjacent webs in a series circuit, the current turns a sharp corner and can create a hot spot. The local hot spot may be some few mm diameter, and up to about 50 °C hotter.

For cylindrical and tube elements, the patterns are usually adjacent axial webs connected in series, with the current turning the corner at alternate ends. For the best uniformity, the turns should be outside the area of concern.

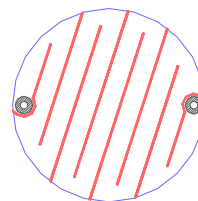
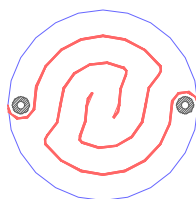
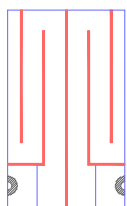
For flat, plate heaters, there are two typical heater patterns; double spiral paths and straight, adjacent series paths. The double spiral has relatively gentle turns, with only a tight corner at the center where the two spirals connect. This is the most common pattern.

Straight, adjacent series webs have no turns in the central area of the heater, all turns are near the periphery. But all turns are relatively tight. If there is sufficient space, where the turns are outside the critical area, this can be the most thermally uniform electrical pattern, but it may take up extra surface space for the turns.

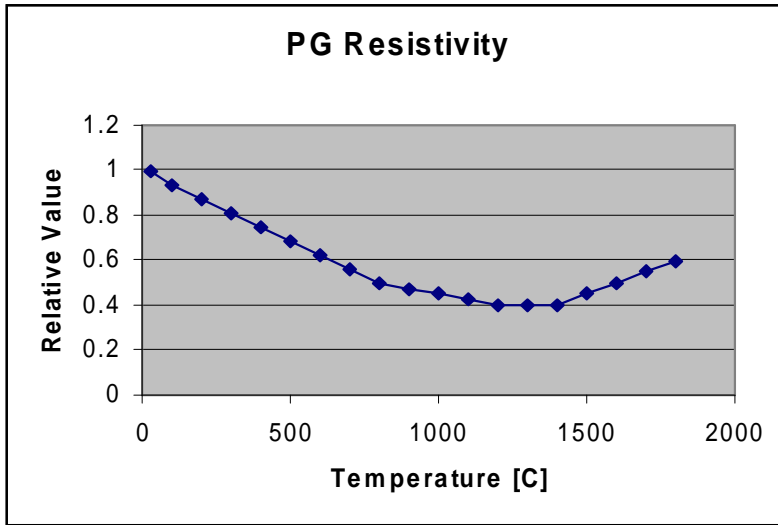
Electrical resistance calculations.

The room temperature electrical resistance, R, of any pattern can be estimated from $R = (0.21) \times (\text{path length}) / (\text{path width})$. The path width is the number of passes divided into the area they pass, less the gap. The length of the path is estimated as (heater area) divided by (path+gap) width. The gap is usually about .75 mm. So if the double spiral, below, is $\phi 50$ mm; the area is 1962 mm²; the width is $(\phi 50 / 7 \text{ passes}) - (.75 \text{ gap}) = 6.4$ mm; the length is $(\text{area of } 1962 \text{ mm}^2) / (\text{width of } 6.4 + .75 \text{ gap}) = 274$ mm. So R is estimated as $(.18) \times (274) / (6.4) = 7.7 \Omega$.

Adjacent axial webs for cylindrical heaters.	Double spiral webs for disk heaters.	Adjacent series webs for disk heaters.



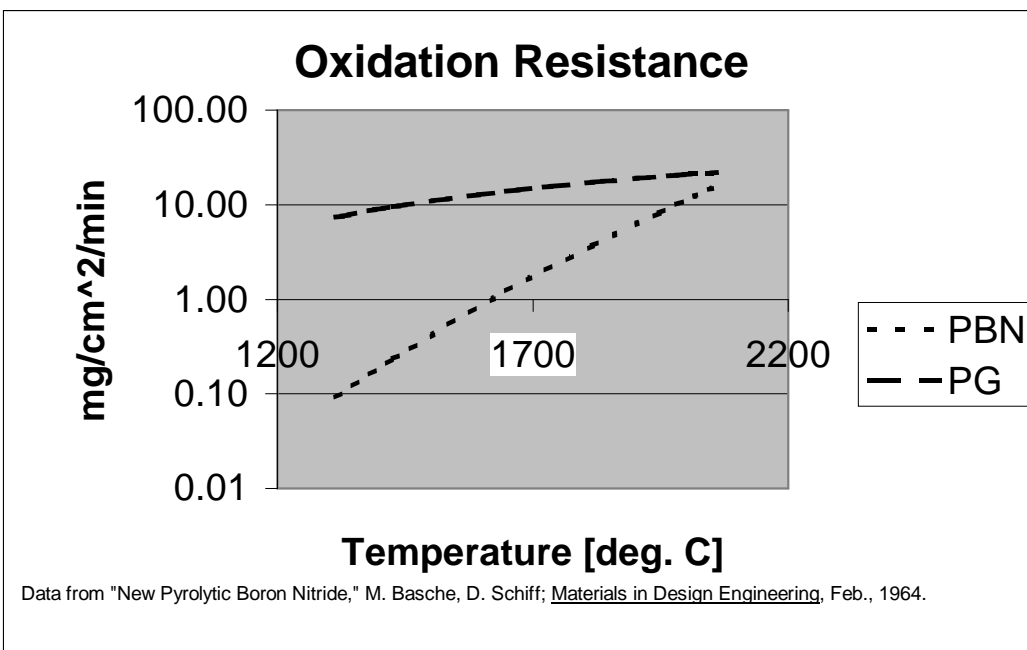
Does the electrical resistance change with temperature?



The resistivity of the PG conductive film in a Boralectric™ heater decreases with temperature, reaching a low point of about 40% of the room temperature value at around 1200 °C. This allows for a “soft start” capability, and requires less voltage as the temperature increases. Since resistance drops as the temperature increases, current also increases.

This must be taken into account in selection of the power supply. For constant voltage, current will start out low and increase as temperature increases. In transients, before steady state, it is possible to blow fuses if no thermocouple is used, or if the couple does not see temperature quickly and accurately.

What about environmental compatibility?



Oxygen.

At most heater use temperatures, the oxidation resistance of pyrolytic boron nitride protects Boralectric™ heaters, but the exposed graphite contacts may need protection. This is a very common failure of Boralectric™ Heaters.

Data from the cited reference were generated at 18.4 cc/min of air at 1 atmosphere. If oxidation is a concern, ACC recommends either of two solutions. A patented, PBN encapsulated contact post can be added. Pictures of “post heaters” can be seen on www.AdvCeramics.com, and in the section, “Can contacts be isolated from the heater on posts?” With the post, the exposed graphite can be below the oxidation threshold temperature. Or, success has been seen with an e-beam coating of platinum around 2000-2500 Å thick. For Pt coating, ACC refers you to Thin Films, Inc. at 978-692-9530.

Ammonia.

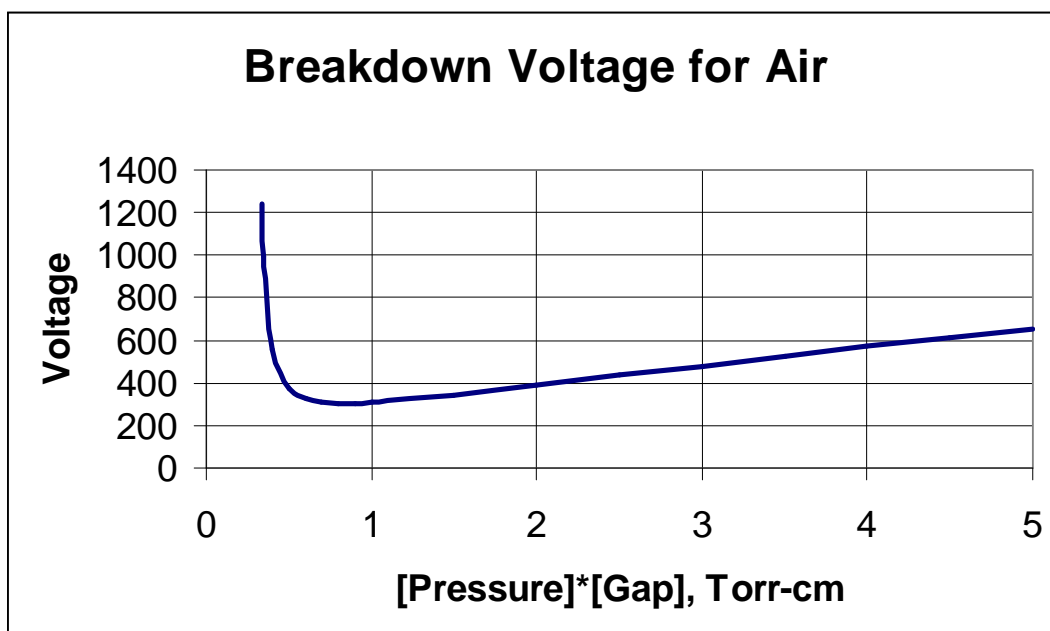
There may be reactions with ammonia. Gibb’s free energy calculations show a favorable reaction of carbon with NH₃ (ammonia) at about 1250 °K, 975 °C. Carbon is exposed at the contacts of Boralectric™ heaters. Any temperature above 975 °C is certainly a risk. Since many practical installations monitor a reference temperature, the heater temperature may be higher than the reference. Any installation should insure the heater contacts are below about 750 °C. Reaction rates progress rapidly with increasing temperature and are severe at 1500 °C.

Fluorine.

Boron nitride will react with fluorine plasma. ACC is developing an AlN coating, which will resist fluorine plasma. Please contact ACC for additional information.

What about voltage breakdown and arcing of the contacts and leads?

The PBN (pyrolytic boron nitride) capping layer on Boralectric™ Heaters has a strength of 200,000 volts/mm, so arcing within the heater is not a problem for any normal operation.



For the power leads and contacts, separation distance may be a concern. The graph is a plot of Paschen's Law as presented by Bazelyan, E.M. and Raizer, Yu. P. (*Spark Discharge*, CRC Press, Boca Raton, 1998). The break down voltage, V_{break} , for any gas is a function of gap distance, D , and gas pressure, P .

$$V_{\text{break}} = B * (P * D) / (C + \ln(P * D))$$

Where:

P = Pressure, Torr

D = gap distance, cm

$C = \ln(A / \ln(1 + 1/G))$

And, for air:

$A = 15 \text{ cm}^{-1}\text{Torr}^{-1}$

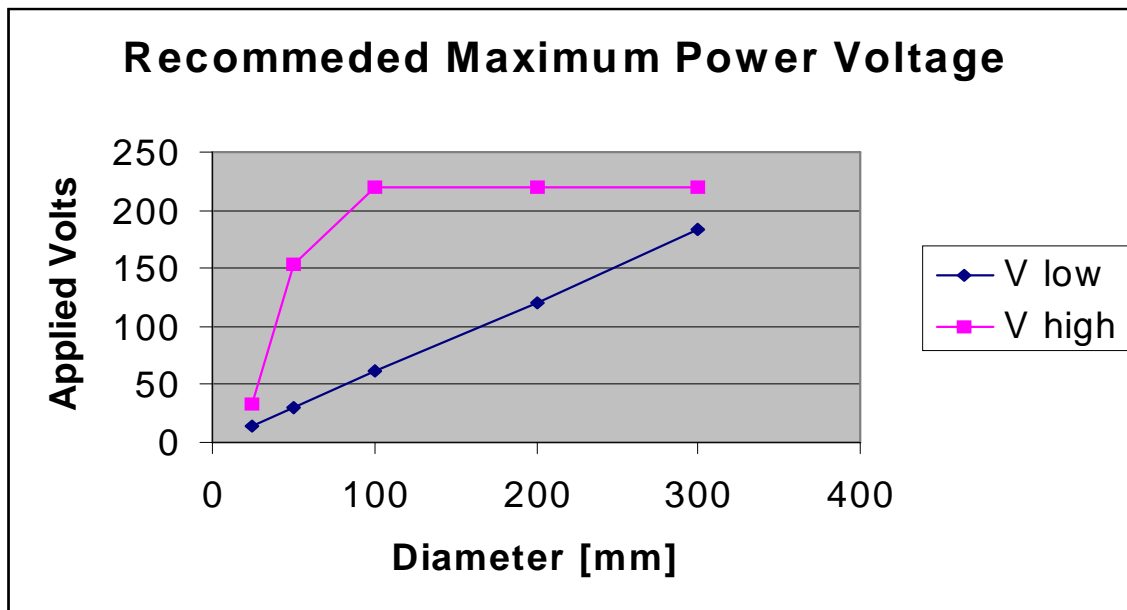
$B = 365 \text{ Vcm}^{-1}\text{Torr}^{-1}$

$G = .01$, a secondary ionization coefficient

So $C = 1.18$

This gives a minimum of about 300 volts at $P*D$ of 0.8 Torr-cm. For example, a 1 mm (0.1 cm) gap at 8 Torr will have a serious spark concern operating at 300 volts. These calculations are mostly empirical and also depend on geometry, temperature and gas. Staying below 220 volts is generally shown to be safe.

What Power Supply is Required?



For a typical maximum power of 50 watts/cm² (300 watts/in²), to achieve a temperature of 1000 °C:

For a heater of this area:		To give max. of 50 w/cm ²	At <u>least</u> this DC voltage is needed:		Above this is not needed (but is usually OK):		
Diameter (if Round)	Area	Max. Power	V low	I high (+20%)	V high	I low (+20%)	
[mm]	[in]	[cm ²]	[watts]				
25	1	5	200	14	17	34	7
50	2	20	1000	31	39	153	8
100	4	80	4000	61	78	220	22
200	8	310	15500	121	154	220	85
300	12	710	35500	183	233	220	194

Boralectric™ Heaters can be made utilizing a wide range of power supplies, but any heater must be matched to the supply. The higher the voltage, the more uniform the flux will be for any given power. This is because, for a higher voltage, a longer path, higher resistance pattern can be designed. The longer path will use a lower current, but will be more evenly distributed. If in any doubt, use a higher rated supply! Below V_{low} , the heater may not attain full power. Above V_{high} , there may be some excess power available. The data given are calculated on nominal, hot values, with a 20% margin. If the user knows the power supply available, they should provide this information to ACC for optimum design of the heater pattern. If the power supply will be matched to the heater after design of the heater, ACC can recommend appropriate power supply ratings.

Does AC versus DC matter?

Boralectric™ Heaters are passive resistors and are compatible with both AC and DC power supplies. Values given in the tables above are calculated for DC supplies, or for single-phase AC supplies using RMS (root mean squared) values. The RMS, single-phase AC value is what most “house supply” is rated at. For example, if the user has a “110V” wall outlet, this is understood to be 110 V, RMS.

What if my supply is over rated?

This is not a problem, but may need some extra precautions. The concern would be, can the heater be hit with the extra power? To prevent this, options are often available:

1. Set a current or voltage limit in the power supply so $V \times A$ is less than about 50 watts/cm². If a heater is designed to run at 50 V and 8 amps ($V \times A = 400$ watts), but is put on a 100 V supply, then a current limit at 4 amps could be set.
2. Insure the feed back in the control loop is closed relative to the heater. This means, the thermocouple (TC) that senses temperature must have very little off set and very little transient from the heater temperature. The opposite (bad) case is a TC remote from the heater and buried in a large block. In this case, the TC would call for increasing power, even though the heater is already quite hot, likely well above the TC sensed temperature.
3. Do not rely simply on only current or voltage feedback. A closed loop with temperature is much more desirable.

What about a 3-phase power supply?

Can this be used? Yes, probably. This question may come up on multiple zone heaters, obviously most likely on a 3-zone heater. These can be operated using a 3-phase supply, probably easiest in a Y configuration. The reason to use a multiple zone heater is to independently control power to each zone. The very purpose of a 3-zone heater, independent control of each zone, means the load on each leg will likely not be balanced. The user should check with their in-house engineering group, because they may recommend against this imbalance! If the heater is a small portion of the overall demand on the local power, this may not even be noticed. But this is an issue that should be looked at for each user.

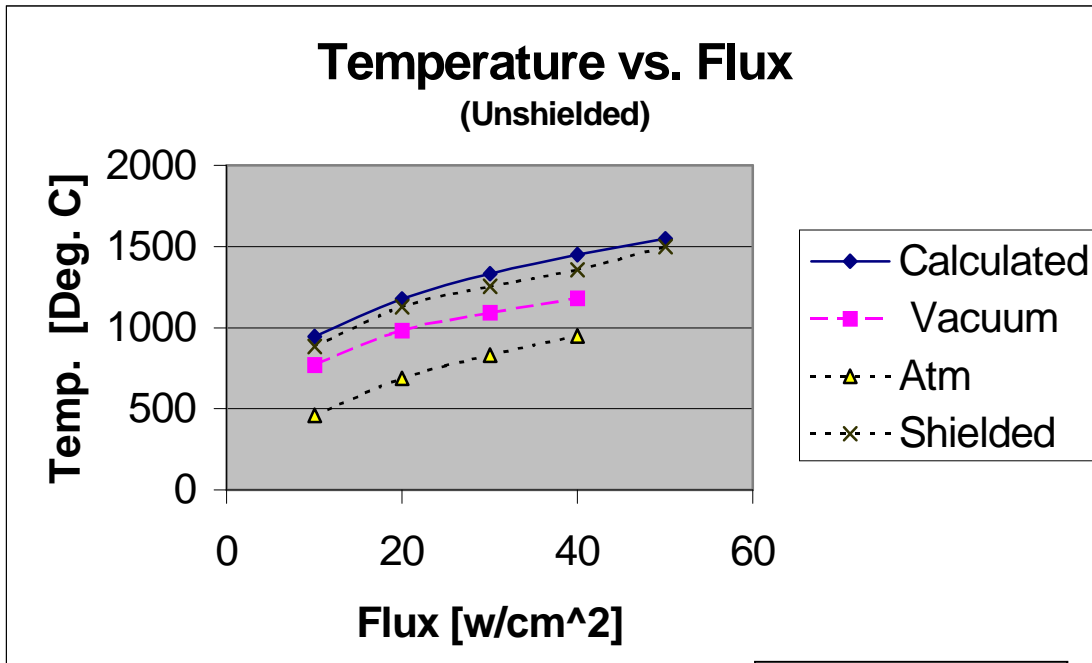
What are the voltage, current, and power in each leg? Calculations for this are only approximate, making the assumption that each zone is balanced, and there is no electrical phase angle between the current and the voltage. The power supply must be sufficiently over-rated to account for any errors introduced. The calculations for unbalanced legs are beyond the scope of this. If:

E_L = Voltage, E, Line I_L = Current, I, Line P = Power, total
 E_Z = Voltage, E, each zone I_Z = Current, I, each Zone P_Z = Power, each Zone

Then, for a Y circuit:

$E_Z = E_L / 1.73$, $I_Z = I_L$,
 $P_Z = (E_Z) \times (I_Z) = (E_L) \times (I_L) / 1.73$, $P = 3 \times P_Z = (E_L) \times (I_L) \times 1.73$

How hot is a Boralectric™ Heater?

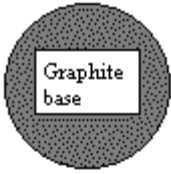


Boralectric™ heaters can reach 1500+ °C in steady state Steady State Conditions insulation. Free standing parts can reach 1000+ °C in steady state.

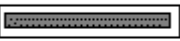
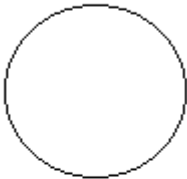
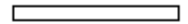
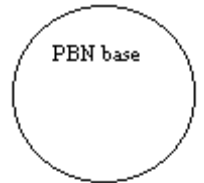
In a test chamber, with no shielding, “Vacuum” and “Atmosphere” data is collected, plotted above. The “Atm” atmosphere line is for nitrogen. The “Shielded” line is based on anecdotal information from customers. The “Calculated” line in the chart is from the Stefan-Boltzmann radiation equation for heat flux, $Q = \sigma \epsilon (T_{hot}^4 - T_{cold}^4)$, details are under the Stefan Boltzmann section. Any actual situation could deviate significantly from these data. Chamber insides may be water-cooled with a lower T_{cold} or may allowed to heat for a higher T_{cold} . A wafer over the heater may insulate the surface and increase the temperature and shielding under the heater is common, increasing temperature. Losses to power leads and mechanical support components can be 20 or 30 watts each. In principal, 1 watt with enough insulation will get to 1000 °C, yet 1000 watts with high losses will be cool.

For design, find your temperature, go across to the “shielded”, “vacuum” or “atm” line, and read down to the flux necessary. The most conservative approach is to use a maximum flux of about 50 watts/cm². This is more than adequate for most situations. Boralectric™ Heaters have been made with over 100 watts/cm². Use this value for the section ‘What power supply is required?’

How are Boralectric™ Heaters constructed?



First, size is determined. For heaters over about $\varnothing 100\text{mm}$, a machined graphite substrate is used. The substrate is typically 5-8 mm thick.. For parts under $\sim\varnothing 100\text{ mm}$, a PBN plate is used, about 1 mm thick.



Second, if a graphite substrate is used, it is Chemical Vapor Deposition (CVD) coated with Pyrolytic Boron Nitride (PBN). The coating is around 0.5 mm thick. This gives large, structurally sound, UHV tight parts, that can be used like a PBN plate.



Next, on the PBN plate or PBN coated graphite substrate, a thin conductive film of Pyrolytic Graphite (PG) is deposited by CVD and an electrical pattern is machined.



Finally, a CVD capping dielectric layer of PBN added. For electrical connections, contact points to the PG film are exposed. Contact posts for electrical connection away from the surface are an option

