The Laboratory Furnace Design Guide
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Preface

So how did I come to be building laboratory furnaces? I must give credit where credit is due. Laboratory furnaces were being built in the Department of Mining & Metallurgical Engineering at the University of Queensland before I came into the Department in 1968. The person largely responsible was Mr Thomas A. Shannon.

Tom was a Scott who was trained in and served in the Royal Signals Regiment of the British Army. His experience with furnaces, or the like, had been in making constant temperature enclosures to enable transmitter crystals to maintain a constant frequency. After leaving the Army he migrated to Australia with his wife and three daughters. He expected to find work in the television industry but instead wound up at the University of Queensland.

An example of Tom’s skills is that when still living in a village in England he came home when the Coronation was taking place to find that there were so many people in his house that he couldn’t get in the front door. They were all there to watch the Coronation on the only television in the village which Tom had made using a disposals ex-radar round green screen and showing figures about an inch tall.

As I said earlier Tom was making furnaces before I came on the scene. At the time I started he had not long made the first pot furnaces which were used for fire-assaying. Tube furnaces with the element wound on the tube and with brick insulation soon followed. A development from these were tube furnaces with the element internally cast so that furnace tubes could be changed without disturbing the element. Not long after there were higher temperature furnaces with Silicon Carbide (SiC) elements and also box furnaces.

I worked with Tom for about ten years until his retirement. I feel privileged to have worked with him and learnt so much not only about furnaces. It was hard to realise at the time that he was just working it out as he went along and was capable of coming up with so many original ideas that I am still using today. An example of Tom’s process of working on ideas would be that if we had just finished the design of say a furnace and I, with the enthusiasm of youth, would be ready to dash off and start building it post haste. Tom would sit back in his chair and look at nothing in particular and say, “Now what other ways could we do that”. I found this infuriating at the time but I now know better.

Bill Adams, 10 Oct 2014
1. Introduction

There are many types and sizes of laboratory furnaces and a number of different heating methods. For example: electrical resistance heating (direct and indirect), electrical induction heating, electrical radiant heating (i.e. with infrared lamps, etc), melting with an electric arc, gas and oil fired heating. This manual will only deal with electrical indirect resistance heating. Direct resistance heating involves an electric current being passed through the work piece to heat it whereas indirect resistance heating uses a heating element to heat by either conduction, convection or radiation or a combination of them.

2. Types of Furnaces

The most common types of laboratory furnaces are Tube Furnaces (horizontal and vertical), Box Furnaces, Muffle Furnaces and Vacuum or Controlled Atmosphere Furnaces. Resistance heating can also be used in laboratories to heat various shaped flasks and on tubes to maintain temperature between different parts of an experimental process.

Fig. 1. Small Box Furnace
3. Heating Elements

There are a number of different materials used for heating elements. The one chosen depends largely on the temperature required in the furnace. One of the earliest materials used is Nichrome™ wire, an alloy of nickel and chromium. Nichrome™ wire is easily identified because after being used for a while it develops a green oxide coating and usually coats any ceramic supports with a dark green colour as well. A more commonly used wire now is an alloy of Fe/Cr/Al which has a top wire temperature of up to 1400°C. This material is Kanthal™ wire. Other wires that are used for elements running at higher temperatures are platinum (which is not used often because of its cost and the great change in electrical resistance from when it is at room temperature to when it is at elevated temperature) and molybdenum which cannot be heated in air because it will decompose into molybdenum trioxide and therefore is usually heated in a hydrogen atmosphere which does rather complicate things. Tubular elements (like the type used in domestic electric stoves) are also used where possible. They are electrically safer because their sheath is at earth potential but they have a top temperature limit of only 600°C. They can also have the problem of absorbing moisture from the atmosphere that causes low electrical insulation resistance.

A number of non-metals are used for elements at higher temperatures. Silicon carbide, usually in rod form but also comes in other formats, is good for working temperatures up to 1500°C. Molybdenum Disilicide elements, which are in a ‘U’ shape are suitable for use up to 1800°C. The most common of these are made by Sandvik™ and are named Kanthal Super™. Also in the same high temperature league are Lanthanum Chromite elements. These are a rod element and are made by Pyrox™ in France. Graphite is also used as a heating element but like molybdenum oxidises rapidly in air and so must be used in a vacuum or an inert atmosphere.

4. Temperature Measurement (Thermocouples).

The most common method of measuring elevated temperatures is with a thermocouple. A thermocouple consists of two dissimilar metallic wires joined together at one end. This is the temperature sensing end which is usually referred to as the Hot Junction which isn’t strictly correct because it can also be used to measure sub zero temperatures.
When there is a difference in temperature between the hot junction and the other ends of the wires (usually referred to as the cold junction) a small voltage is developed across the wires. The magnitude of this voltage is dependent on the temperature difference and this voltage is used to determine the temperature via an appropriate measuring instrument.

There are a range of different standard materials used for thermocouple wires and there are thermocouple tables available which relate temperature to voltage. The important aspect of this is that they all require the cold junction to be at 0°C. Modern measuring instruments and temperature controllers have cold junction compensation built in so that the instrument will compensate for the difference between room temperature and 0°C.

Some of the most commonly used thermocouple types are listed below:

**Type “B”**  Platinum 30% Rhodium + / Platinum 6% Rhodium-. Use between 600°C and 1700°C.

**Type “R”**  Platinum 13% Rhodium + / Platinum -. Use between 0°C and 1500°C.

**Type “S”**  Platinum 10% Rhodium + / Platinum-. Use between 0°C and 1500°C.

**Type “N”**  Nicrosil + (Ni 14.2Cr 1.4Si) / Nisil – (Ni 4.4Si 0.1Mg) which was developed in Australia at the weapons research facility. Performance is slightly better than Type”K”. This thermocouple was expected to supersede Type “K” but that has not happened. Use between 0°C and 1300°C.

**Type “K”**  Chromel™+ (Ni 9.5Cr 0.5Si) / Alumel™- (Ni 5(Si Mn Al)). The most commonly used base metal thermocouple. Use between 0°C and 1250°C. The life expectancy of base metal thermocouples at temperatures above 1000°C is not good and it is better to use Type “R” or “S”.

**Type “T”**  Copper + (~99.95%Cu) / Constantan – (Cu 44Ni). Use between -190°C and 400°C.

**Type “J”**  Iron + (~99.95%Fe) / Constantan – (Cu 44Ni). Use between -190°C and 860°C.

**Type “E”**  Chromel™+ (Ni 9.5Cr 0.5Si) / Constantan – (Cu 44Ni). Use between -190°C & 1000°C.
5. Temperature Measurement (RTDs).

RTD stands for Resistance Temperature Device. Essentially an RTD is an electrical resistance which is placed where the temperature is to be measured. The resistance will change proportionally with temperature changes. A fixed voltage is applied across the resistor and the changes in current that will occur with resistance changes are used to determine the temperature.

RTD’s come in two, three or four wire versions. The most common being the three wire version. The extra wire/wires in the three and four wire versions are used to separate the wires that apply the voltage to the resistor from the measuring circuit wires.

Most RTD’s are made of platinum with the PT100 being the most common. The PT100 will have a resistance of 100 ohms at 0°C. RTD’s are used when greater accuracy, repeatability and stability are required but they can only be used up to about 250°C.


The most common refractory materials used are bricks, castable refractories and ceramic fibre. In all cases, the types of materials available are determined by manufacturers and local suppliers and the type of material used is determined by the application.

Bricks:

Two different types of bricks are regularly used. K23 or M23 bricks are suitable for use up to around 1200°C and are made from a fine, mainly silica material. They are easily cut and shaped using hand tools. K28 or M28 bricks are for use up to around 1500°C. They are made from a coarser material, once again mainly silica. These bricks have not come into the metric age and are still 9” x 4.5” x 3”, although more recently some other size variations have been supplied. Appropriate PPE should be worn when working with these bricks due to the silica dust. There are many other types of bricks available for specific purposes.
Castables:

There are many types of refractory castables. The choice of which one to use is determined by the application. For example, the refractory used to support a Kanthal™ wire element should have a high alumina content and be capable of working at a temperature higher than the element. Currently we are using Shiracast 180AR TS™ for this purpose. We also use other types of Shiracast™ for furnace ends, lids etc. and lower temperature applications. Moulds and casting techniques appear later in this manual.

Material cost and availability should be considered. Castable refractory manufacturers produce their products for industry and would usually receive bulk orders. As such, it can be difficult to source smaller quantities sometimes. The freight cost for a 20kg bag of refractory shipped from Victoria, for example, is the same as the cost of the material.

Ceramic Fibre:

Ceramic fibre materials owe their development at least partly to the American space programme and the need to protect space craft from the high temperatures encountered during re-entry. For us they are a light weight highly efficient insulating material that is available in bulk (like cotton wool), blanket, or board form. Like other refractory materials there are different varieties to select from depending principally on the required working temperature. Bulk ceramic fibre is the easiest to handle if it can be contained between other materials. Blanket can be used to line a metal furnace cabinet and be held in place with ceramic cones that are attached to the metal cabinet either with a bayonet fitting or bolts.

Board materials are usually available in sheet sizes of 1000mm x 500mm and a variety of thicknesses and can be cut with a sharp knife or other hand tools. When using board, allowance needs to be made for the fact that when manufactured it contains a binder which will shrink at elevated temperature. When it is first fired the binder will be burnt off at about 400°C and the material will then be less stable.
Furnace manufacturers have the facilities to make special ceramic fibre shapes for their furnaces, usually available as spare parts. Ceramic fibre materials were once regarded as harmless but have now been identified as a cause of respiratory and skin irritation problems and as such appropriate PPE should be used. Ceramic fibre that has been used is more hazardous than new material. Clean-up should be conducted using a vacuum cleaner with a hepa filter fitted.

7. Tube Furnaces

Tube furnaces can be of either horizontal or vertical orientation. Although similar in construction some allowance will usually need to be made for one or the other. For tube furnaces elements can be, wire (usually Kanthal™), silicon carbide, lanthanum chromite or sometimes molybdenum disilicide.

Wire elements are usually wound directly onto a suitable ceramic work tube rated to withstand the proposed working temperature of the furnace. The wire element is then coated with a high alumina setting cement to reduce the likelihood of the element moving on the work tube.

Fig. 2. Tube Furnace with element positioned for bulk ceramic fibre to be installed.
An alternative method is to wind the element onto a suitable mould and cast it so that the element is on the inside of a cast alumina tube. The element then radiates heat to the outside of the work tube without being in direct contact with it. This method has the advantage of making it possible to replace the work tube without needing to replace the element.

Fig. 3. Mould with winding, removed from lathe ready for casting

Because tube furnaces lose their heat predominately from the ends, wire elements are usually pitched so that there is more wire towards the ends in order to achieve a more even zone of temperature towards the middle where the job will be located. Vertical wire element furnaces may require more wire again towards the bottom to achieve the desired temperature profile inside the furnace.
Fig. 4.  Silicon Carbide Element

Silicon Carbide rod elements are suitable for tube furnaces up to 1500°C. The elements are located in a cavity around the work tube so that they can radiate their heat directly to the work tube. There are also silicon carbide tubular elements. These silicon carbide tubes are cut spirally to form the heating zone of the element. These elements are not very common and are rather expensive. The electrical resistance of all silicon carbide elements will increase as they age. For this reason there should be the possibility of increasing the power supply voltage to the elements to get the maximum life from them. There will come the time though when the elements will need to be replaced. Where silicon carbide elements are connected in series it will **ALWAYS** be necessary to replace all of the elements together rather one at a time otherwise there will be an imbalance causing the new element to age prematurely.

Fig. 5.  Lanthanum Chromite Element
For tube furnaces that are required to work above 1500°C, Lanthanum Chromite elements are the preferred choice. These elements and the furnaces that they are part of are made by Pyro™ in France. To date, no alternative manufacturer making Lanthanum Chromite elements has been identified. One point worth mentioning is that Lanthanum Chromite elements do not change resistance significantly with age, so that in a series circuit they may be changed one at a time. Molybdenum Disilicide elements, such as Kanthal Super™, may also be used for vertical tube furnaces but because of their ‘U’ shape and fragility are not as easy to handle as the rod type elements.

Fig. 6. Molybdenum Disilicide Element
8. Box Furnaces

There can be confusion between the terms “Box Furnace” and “Muffle Furnace”.

Fig. 7. Small Box Furnace

This manual defines a Muffle Furnace as a furnace where the work chamber is isolated from the heating element usually by the element being wound onto the outside of a ceramic muffle that is the chamber of the furnace.

Fig. 8. Muffle Furnace
For box furnaces with wire elements, the elements are usually in the side walls of the furnace. Elements are usually wound in a long spiral on a lathe and are then supported in either a cast ceramic refractory that becomes the side wall of the furnace or sometimes slots are cut in fire bricks that also become the walls of the furnace. Heavy gauge wire elements can also be supported on ceramic tubes along the side walls of the furnace.

Silicon carbide rod elements can be used in box furnaces. Placing these elements along the side walls of the furnace is considered the most suitable configuration. However, an alternative arrangement is to locate them above the work area near the roof of the furnace chamber.

9. **Muffle Furnaces**

The muffle of a muffle furnace is like a refractory box with an open front. Wire elements are wound on the outside of the muffle. The elements can be either wound straight on to the muffle or they can be wound into a small diameter spiral first and then wound onto the muffle. Either way they are then cemented onto the muffle with alumina setting cement. Because the elements wound on the outside of a muffle can distort with use, the elements that are spiral wound first tend to last longer.

10. **Vacuum & Controlled Atmosphere**

If the job size is small enough, the easiest way of putting it in a vacuum or controlled atmosphere is to use a tube furnace. An impervious ceramic furnace tube will be required along with the necessary end caps to seal the tube. The end caps are usually made of brass or stainless steel with ‘O’ ring seals. These endcaps are often water cooled as heat transfer from the furnace to the end caps is a problem.
Where a tube furnace can’t be used for vacuum/controlled atmosphere work, a vacuum chamber can be built in which a suitable furnace is constructed. Because the furnace is being constructed in a vacuum chamber, the materials used are limited so that they do not affect the integrity of the vacuum. For example, if castables or brick were used, being porous materials they can absorb moisture and air within, which is difficult for the vacuum pump to remove. It is better to use impervious materials and to make use of reflective heat shields where possible. The advantageous aspect is that because the furnace is working in a vacuum there is less need for insulation. However, it should be noted that the furnace should only be used when the chamber is evacuated. To reduce heating of the chamber walls, some vacuum chambers have water cooling tubes attached to the outside.
11. Temperature Control.

Early methods of temperature control used a thermocouple with its output connected to a special moving coil meter. These meters were fitted with a small flag on the meter indicator arm which passed through the gap between a small lamp and a PE cell as the temperature increased. The signal from the PE cell was used to turn the furnace on and off to control the temperature. Because the full range of the controller had to be compressed into the scale of a moving coil meter, these controllers could seldom achieve greater than ±20°C accuracy and setting them precisely was difficult.

In the latter part of the 20th century digital controllers made their appearance. Such has been the change that accuracies to one tenth of a degree are achievable. Many controllers will indicate to this level but the actual accuracy should be confirmed by measurement.

Improvements in temperature controllers have been brought about by such features as Cold Junction Compensation which automatically compensates for the difference between 0°C and ambient temperature at the thermocouple terminals of the controller. Also, built in Proportional Integral Derivative (PID) control and automatic tuning are features to improve accuracy and reduce temperature overshoot. Some furnaces combine temperature control with power level control to the furnace but these are not common.

Note: It is often assumed that the temperature the controller on a laboratory furnace is set to is the temperature around the job in the furnace. This is not necessarily true. The controller is simply controlling the temperature at the location where the control thermocouple happens to be in the furnace. The control thermocouple is often located close to the furnace element so that it responds quickly to element temperature changes and this location is often at a different temperature to the location of the job. For this reason it is important that where a specific temperature is trying to be achieved, a separate thermocouple is used to either calibrate the furnace in advance or monitor the job while it is in the furnace. For safety reasons, great care must be taken to ensure that thermocouples do not come near furnace elements.

The design of resistance wire heating elements involves firstly determining the power needed to carry out the process required whether it be to boil water, heat treat steel or melt aluminium etc. There are formulae available in the manuals provided by element manufacturers like the Kanthal™ Handbook, TEE (Thermal Electric Elements)™ catalogue or the Helios™ catalogue amongst others that enable this calculation to be made.

The power required to do the job is only a part of the picture. Allowance must also be made for heat losses from the external surfaces of the furnace which will be determined by the wall thickness and the type of insulation used. “Experience” and “Trial and Error” are methods often used to determine power requirements.

Let’s look at a real situation…….

A commercially made furnace comes in for repair. The element is burnt out. The only information available is what is on the furnace name plate which may or may not be accurate. The name plate may list the voltage and current ratings of the furnace and its maximum temperature. Additionally, the wire gauge used for the element can be measured using a micrometer.

The following is a typical example of this information;

240V, 10A, 18 B&S wire gauge.

The following calculation requires simple maths, knowledge of ohm’s law and the Kanthal™ wire handbook. The furnace is rated at 240V, 10A, 2400W, the element resistance is 24 Ω, the 18 B&S wire has a resistance of .5369 Ω/ft and the surface area of 18 B&S wire is 2.828 sq.in./Ω. The significance of the last piece of information will become clear later on. From the element resistance of 24Ω and knowing that the wire resistance is .5369 Ω/ft we work out that the length of the wire element should be about 45ft. That should be all we need to know to go ahead and make the element in whatever form the original was in.
BUT WAIT... There's one more thing to check. Wire elements have a surface load rating that should not be exceeded otherwise the element may well have a short and exciting life and the job may well land back on the bench sooner rather than later.

From the above it is known that 18 B&S wire has a surface area of 2.828 sq.in./Ω and the element resistance is 24Ω so the surface area of the element is 67.87 sq.in. using the formula and tables detailed above, this gives the W/sq.in. as 35.3.

Referring to the graph of permissible surface loadings for different wire types at different temperatures found on page 11 in the Kanthal™ hand book, it can be seen that Kanthal™ A1 wire at 1200°C the maximum wattage loading is shown as 12.8 W/sq.in. This is significantly different to the 35.3 W/sq.in. calculated in the last paragraph as being the wattage loading of our furnace. So what has gone wrong? It appears that the furnace manufacturer listed the incorrect current information on the name plate. From experience, 10 amps for this size tube furnace does seem excessive.

Using the same calculations but with 6A as the furnace current the following figures are obtained; 240V, 6A, 1440W, 40Ω element. Using the same wire, the wire length is approximately 75ft, the wire surface area is 113.12 sq.in. and the wattage loading is 12.7 W/sq.in. This is the information used when winding the element for a furnace with that specification.
13. Case Construction.

The type of furnace being constructed will have a large bearing on the type of material used for the enclosure. For example, a round tube furnace is most suited to machined aluminium ends and a sheet metal surround.

![Round Furnace with cast and machined aluminium ends and sheet metal surround](image)

**Fig. 10.** Round Furnace with cast and machined aluminium ends and sheet metal surround

Various boards are available for the walls of box furnaces. Hardie’s™ Fire Resistant (FR) board was the most suitable but due to its high percentage of asbestos, it is no longer available. However, less hazardous boards have now been developed. In particular, Modak Board™, which has been developed as a building material suited to bush fire prone areas, was tested but while the Modak Board™ appeared to handle the temperature, it does not handle the uneven heating of box furnace walls where the higher temperatures are exhibited at the middle of the sheet. This resulted in the sheets cracking and breaking. Another suitable product may be Mill Board but further research and investigation will be required to assess its suitability.

When constructing furnace enclosures, using galvanised steel or, where possible, stainless steel to construct them offers the most durability.

The most important part of the process of making castable refractories is having a well-made mould. The mould should be designed so that there is a slight taper (0.5° to 1°) on all sections that have to be removed to create a hole in the refractory required. However, where a long hole is required (e.g. through which an element may be threaded), a smooth well lubricated rod can be inserted but it must be removed before the castable refractory has dried fully (usually after no more than four hours). The cast refractory will shrink slightly as it dries and, as such, it is important to be aware of this when designing a mould so that the cast product can be removed easily from the mould when set.

Before casting, a suitable release agent must be applied to all surfaces of the mould. Typically, a mineral oil is used. The more viscous the oil, the more suited to the purpose. There are also specific release agents commercially made, but these are, as yet, untested in this application.
Traditionally, castable refractories have been mixed by hand. A suitable quantity of water is added to a mixing bowl and the dry material progressively added to it, mixing after each lot is added. A flat mixing tool/spatula can be used (e.g., a section of power hacksaw blade with the teeth ground off). The aim is to have the mix as dry as possible but moist enough not to separate. It should be noted that the drier the mix, the stronger the refractory will be.

The mix should be placed in the mould as quickly as possible after mixing, pushing it into all areas of the mould to eliminate entrapped air.
Some moulds may require a vibrator to be used to get the material into all areas of the mould. However, the vibrator should be used sparingly so that it doesn’t cause the components of the mix to separate.

![Image of levelling off material in mould]

Fig. 4. Levelling off material in mould


When designing wire elements, 1.5 to 2 times the gauge (diameter) of the wire should be left between adjacent turns where possible. It is most important not to have turns that are shorted together. With most element wires, after they have been in use for a time, an oxide coating will form on the wire which can help to insulate it from adjacent turns.

For this section imperial measurements are used mainly because the Hercus™ lathe used to form the elements in the EAIT Electrical Workshop is an imperial lathe and, in the authors opinion, for this application imperial measurements seem to work best.
SPIRAL ELEMENTS:

Wire elements can take a number of different forms, the most common of which is the spiral shape. Spiral elements can be fitted into a closed hole in the refractory wall of a furnace, into a slot in the furnace wall open on one side to radiate heat more effectively, or even made in a larger diameter and with a heavier gauge wire and hung off a refractory support tube.

Once the type of element wire, the wire gauge and the length of wire per element have been determined, it is necessary to work out the diameter of the mandrel to wind the element on. This generally has to be performed by trial and error. When the element is wound on the lathe it is under tension and when it is released the diameter of the spiral will increase significantly. One way of undertaking this is to use a couple of feet (approximately 60cm) of the element wire, put a likely size straight shank twist drill in the lathe chuck with the shank out and wind the short piece of element wire onto the drill shank. When using the lathe to wind an element always have the lathe running at or near its slowest speed and always ensure safety glasses are worn. After winding and when the tension is released you can then try this sample of your element to see how well it fits into the required slot or hole etc. When the mandrel diameter has been determined a suitable mandrel, long enough to suit the length of the lathe bed, will need to be identified or fabricated and a centre hole drilled in one end.

It is normal to close-wind spiral elements and stretch them later to give the required space between turns. Setting up the lathe for element winding is as follows:

- Set the lathe to run in reverse. It is easier to wind elements this way but take care with lathes that have a screw-on chuck that the chuck does not un-screw.
- Position and lock the tail stock at the right-hand end of the lathe bed and fit a centre into it.
- Fit the mandrel into the lathe between the chuck and the tail stock centre and tighten the chuck.
- Obtain a suitably sized piece of wood to mount in the tool post and position it so that it just touches the mandrel. It is there to support the mandrel when pressure is applied to it during the winding process. It is best to have a ‘vee’ notched in the wood where it bears on the mandrel to give better support.

- Work out how many TPI (turns per inch) there will be with the gauge of wire you are using and set the lathe so that the carriage will travel slightly faster. (I.e. if you calculate that the wire is 33 TPI then set the lathe to 32 TPI. Ensure that the lathe is configured so that the carriage will be travelling away from the headstock when the lathe is in reverse.

- When winding elements that exceed the lathe travel, more than one pass is made and the extra length is fed through the head stock. Therefore when winding long elements a length of PVC conduit should be mounted at the left-hand end of the headstock to support and protect the extra length of element.

- There are two ways of having the correct length of wire in a spiral element. The first is to measure and cut the correct length plus an allowance for connections and then wind the element. The other way is to work out how much wire per inch is on the mandrel when the wire is still tight on the mandrel and use this to work out how many CWI (close wound inches) are required and measure this as the element is wound.

The winding procedure is as follows:

- The wire should sit on a spool behind the operator as they stand at the lathe, ensuring that the spool is free running and that the wire cannot foul or tangle.
- Allow for end connections and excess then bend a right angle in the wire.
- Slide this bent length into the head stock so that the wire is held against one of the chuck jaws.
- Rotate the chuck by hand, winding on a few turns, remembering that the lathe will be turning backwards for this procedure.
- Position the carriage so that the piece of supporting wood is about 10mm to the right of the element on the mandrel and engage the lead screw.
The element wire should be held firmly with a suitable glove about 150 -200mm away from the mandrel and the lathe started.

When the carriage approaches the end of its travel, the lathe should be stopped but the tension on the wire should **NOT** be released.

At this stage, the length of element wound should be measured and noted whilst maintaining tension on the wire.

The lathe chuck should be loosened sufficiently to allow the tension on the wire to be released at the headstock end.

If a longer element is required, the wound element can be slid into the headstock. The chuck should then be tightened gradually, rotating the chuck by hand so that the element through the chuck is tightened on to the mandrel.

Continue following the same procedure until the required length of element has been wound.

**TUBE FURNACE ELEMENTS:**

There are several alternative methods used manufacture tube furnace elements. The two most common methods used to fabricate wire elements are detailed below.

Firstly, the simplest method used winds the element directly onto the ceramic tube. In the design stage, the following must be ascertained:

- The orientation of the furnace; either vertical or horizontal;
- The tube diameter;
- The properties of the material to be heated, including
  - Material/sample size;
  - Intended temperature it is to be heated to.

For example, a furnace is to be horizontal with a tube diameter of 38mm. The material being heated is a steel sample 50mm (2”) long that is to be heated to 600°C. The aim will be to have a tube furnace with an even temperature zone in the middle, greater than 50mm in length. To ensure this minimum requirement is met, a length of 75mm (3”) is chosen. Because tube furnaces loose most of their heat at the ends, more wire is used at the ends of the element than in the middle.
Usually when trying to achieve a certain length of constant temperature zone, an overall element length on the tube of three times that zone length will be required. In this example, this will result in a minimum of 225mm (9”)

The next parameters requiring calculation are the power required and the gauge of wire to use. From this information, the length of wire to be used to produce the power required and the pitch of the wire turns to be used on the tube can be established. As the process is affected by multiple variables, there is no fixed formula for determining these things and a certain amount of trial and error is often required.

As a further example, a furnace has the following parameters:

- Tube length 286mm
- Tube diameter 60mm;
- There is 19mm at each end of the tube left clear and therefore the element occupies 248mm of the tube length.
- Working from the centre of the element there is 12mm left clear in the centre usually for a thermocouple.
- Adjacent to that on each side there is 35mm with a winding pitch of 12TPI and outside those there are sections 83mm wide of 18 TPI.
- The wire used is Kanthal A1 1.04mm or 19 SWG or 18 B&S

To calculate expected resistance of this furnace element, the circumference of the tube is multiplied by the number of turns calculated from the information above. This will yeild the wire length. From the Kanthal handbook the resistance of A1 18 B&S wire is .5369Ω/ft. This then enables the resistance of the element to be calculated.

Once all the information above is ascertained, the element can be fabricated using the following technique;
Firstly the ceramic tube should be mounted in the lathe. This is best done by using a length of threaded rod, two nuts and two wooden cones or turned wooden pieces made to fit the ceramic tube so that the tube will be held centrally in the lathe. The threaded rod must have a centre drilled in one end. The whole assembly (nut, cone, ceramic tube, cone and nut all inserted on the threaded rod) are then mounted between headstock chuck and tailstock centre on the lathe.

At least three clamps will be required to hold the element in place during winding. These can be fabricated from a strip of metal, approximately 10mm wide with a hole in each end that wrap around the tube and are held in place with a nut and bolt.

To guide the element wire onto the tube, a piece of wood with a saw cut to act as a wire guide should be mounted in the tool holder. The saw cut should be from the bottom of the left side of the piece of wood through to the centre of the side facing the ceramic tube.

The start and finish positions, changes of pitch and any other relevant details should be marked on the ceramic tube with a pencil. This is best achieved by holding the pencil against the tube and rotating the tube by hand so that the markings are around the full circumference of the tube.

Set the winding pitch on the lathe for the first section of the element to be wound. In the example above, this is 18 TPI.
• The spool of wire used should be on a stand behind the operator so it can run freely.
• To start the winding process approximately 1m of wire should be run off the spool, ensuring sufficient is available to wrap around the tube at least twice and then bend the wire back on itself and twist double to provide the lead-outs for the power connection. This is best done using a battery drill and pliers to hold the wires at the end of the twist.
• At the end of the twist open out the two wires, the piece left to wrap around the tube and the wire on the spool so that the shorter piece can be wrapped around the tube as tightly as possible and then wrapped around the tail to secure it. Then, leading it out on the headstock side a clamp should be placed around the tube so as to hold the tail securely.
• The lathe saddle should now be moved along and the wire fed through the saw cut (mentioned previously). The saw cut is to be aligned with the element starting location marked on the tube. The lead-screw drive should then be engaged in preparation for commencing winding.
• The element wire must be held firmly with the right hand, wearing a suitable glove, and the lathe started.
• The element wire will then feed onto the ceramic tube evenly at the required pitch. When the wire reaches the first marked location point where the pitch changes, the lathe should be stopped, ensuring that the tension on the wire is NOT released. The lathe gearbox should then be set to the new pitch and the lathe re-started to continue the winding.
• Where a gap is required in the winding it is easiest to keep the lathe running and use the compound rest to advance the winding by hand.
• This process should be continued until the end of the winding. Upon completion, the lathe should be switched off WITHOUT releasing the tension on the wire. The wire should be looped around something so that tension is retained before the operator releases their hold on the wire.
• The second clamp should then be placed over the last section of the winding to hold it in place whilst the end power connection is made and the end of the winding secured. This is achieved through the same method used to secure the start of the winding. A third clamp is then added at the end to ensure the element windings are retained which should allow the second clamp to now be removed.

• The two remaining clamps should be left in place while the winding is coated with alumina (961) cement or similar and then dried out in a furnace at 100 to 120°C after which the clamps can be carefully removed. To fully fire the alumina cement it should be heated to 1000°C but if this is not possible the furnace itself can be used to complete the firing after the furnace has been assembled.

Fig. 6. Tube Furnace Element being cemented on tube
THE OTHER TUBE FURNACE ELEMENT:

To enable furnace tubes to be replaced without having to rewind the element each time, an alternative method can be used. The element can be internally cast in a tube of castable refractory. This technique requires the fabrication of a mould with a collapsible centre.

A collapsible centre can be achieved by using a piece of suitable size PVC tube and cutting it along its length. A piece of square section steel is then inserted in the gap to spread the PVC tube so that when the steel is removed the PVC tube collapses enough to slide easily out of the new element.

![Mould Parts](image)

**Fig. 7. Mould Parts**

The steel is drilled and tapped at the point where the element starts and finishes so that screws can be inserted to anchor the element ends while casting. The screws are removed from the cast element when the mould is dismantled. If a thermocouple hole is required
then a tapped hole in the steel can be used to secure a sleeve of the appropriate size to provide the aperture required.

To complete the mould, two stepped end pieces should be manufactures. These not only fit into the PVC tube with key steel but are stepped with the larger diameter of the outside diameter of the finished cast element. These are all held together with a threaded rod through the centre as for mounting the ceramic tube earlier. A casing is then made that fits around the outside with a gap suitable for filling with the castable refractory. This is held in place with at least two clamps similar to those used to hold windings earlier.

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**Fig. 8. Winding Element**

The element is wound in a similar manner to winding on the ceramic tube except that the end wires are wrapped around the screws as explained earlier rather than using clamps.

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**Fig. 9. End of Winding**
After the casting has dried the screws must be removed first and then the outer casing followed by the end pieces. This then allows the key steel to be pushed into the centre to release it from the PVC tube and then allow the PVC tube itself to be removed. The completed element must then be air dried and then fired before assembly into the furnace.

![Preparing for Casting](image)

**Fig. 10. Preparing for Casting**

16. Frequently Experienced Issues.

Furnace users often expect the process temperature on the temperature controller to be the working temperature inside the entire furnace. They need to be shown that this is not the case and that it is just the temperature where the control thermocouple is located. For accurately showing the temperature in a particular part of the furnace a probe thermocouple should be used. When a probe thermocouple is used, **great care must be taken** to ensure it does not get near the heating elements.

Brainchild 9090 temperature controllers are used commonly throughout the EAIT Faculty. Most of them use a relay output but others use an extra low voltage DC output to drive a solid state relay. The 9090 controllers are very convenient as they can be swapped from one case to another but when doing so their output configuration should be checked to ensure it is the same. Another option with 9090 controllers is to configure them as a single ramp and soak controller. This requires both alternative wiring and controller program configuration.
17. Requirements Questionnaire.

The following series of questions provides a useful method of ascertaining a client’s requirements for a furnaces operation. Obviously what questions are asked will be determined by answers to questions already asked (I’ve been asked for furnaces to do many unusual things (but no cremations to date!).

- Tell me as much as you can about what you are planning to do with the furnace?

- What type of furnace will be needed? Eg. Tube furnace (vertical or horizontal), box furnace, pot furnace, muffle furnace or other?

- What is the size and nature of the job to go in the furnace?

- What is the maximum temperature the furnace needs to work at?

- Does the work require a gas atmosphere or a vacuum?

- Will the furnace need to have a programmable controller?

- Do you need to be able to load and unload the furnace at elevated temperature?

- Will the process in the furnace generate fumes (toxic or otherwise) that will need to be extracted?
18. Glossary.

**AWG** - American Wire Gauge. An American system for identifying the size of wire.

**B&S** - Brown and Sharpe system which is the same as AWG.

**Box furnace** – Furnace with a box shaped heating chamber (hence the name) with an access door usually in one side but sometimes in the top or even in the bottom where the job is loaded into the furnace by placing it onto what is really the door.

**FR Board** - Fire Resistant board with an asbestos content, formerly manufactured by Hardie™ Ltd.

**Furnace** – Apparatus for subjecting metals etc. to heat.

**Kanthal wire™** - An alloy of Fe/Cr Al made by Sandvik™ used for heating elements.

**Lanthanum Chromite** – Material used for making heating elements that can be used up to a surface temperature of 1850°C. The elements are made in a rod shape. The elements are made by Pyrox™ in France.

**Molybdenum Disilicide** – Material used for high temperature heating elements up to 1800°C. The elements are formed in a ‘U’ shape. The most common ones are made by Sandvik™ and are called Kanthal Super™.

**Muffle furnace** – A furnace where the heating element is isolated from the work by having the heating element on the outside of a ceramic chamber and the work inside the chamber.

**Nichrome™** – An alloy of nickel and chromium used to make element wire.

**PID** - An algorithm of three parameters used to minimize error by adjusting process control inputs.

**Refractory** – Is actually an adjective relating to resistance to heat and/or corrosion but in the furnace world is regularly used as a noun to describe various insulating materials and furnace linings etc.
Silicon Carbide – A compound of silicon and carbon (SiC) used for furnace elements up to a surface temperature of 1550°C. Most commonly made in rod form but other shapes are also available.


RTD – Resistance temperature device. More stable and accurate than thermocouples at temperatures up to 250°C.

Thermocouple – Two dissimilar wires joined at one end used for temperature measurement. See section (4).

Tube furnace – Furnace where the work is contained in a tube (usually ceramic) and the tube is heated externally either by a resistance wire element wound directly onto the tube or by radiation from an adjacent heating element.
References


Helios Electroheat, C. 1990. Helios™ Product Catalogue, Mel, Australia