SEMINAR FOR BOILER INSPECTORS
Design Calculations for Copper Boilers. (as used in most published designs)

At the present time there are no nationally agreed boiler design formula for the hobby of Model Engineering. Almost all boilers designed by or for the model engineer have followed the practices that have been used by all the major published designers in the model engineering press.

It has been suggested by many that the Australian boiler design code be adopted in the UK, but at the present time there are no formal proposals to do so or for any equivalent document produced by any of the hobby's UK umbrella organisations. Until such time as a design code is written and adopted by all parties concerned, we can only work to what is considered as 'Custom and Practice'.

Designers such as Henry Greenly, with the first published design for a passenger hauling 5" gauge coal fired locomotive the 'Halton Tank' together with his designs for Bassett Lowke all date from the first decade of the last century. L.B.S.C also used the same basic design criteria for his many published designs in Model Engineer, English Mechanics etc. Similar principles have also been followed by K N Harris, Tubal Cain, Martin Evans and Don Young.

None of the designs published in the model engineering press have failed in service through bad design. Even Martin Evans 'Simplex', much criticised for its lack of crown stay attachment to the outer wrapper has, as far as is known, never failed. He did publish a similar alternative for his the LN.E.R. B1 design 'Springbok', and there are reports of problems with one boiler for a B1 where the crown came down slightly during the initial hydraulic test. On further examination it was noted that the builder had mixed the old design of a flat-topped Inner firebox with the modified round top outer wrapper without fastening them together. Fortunately the boiler inspector spotted this very quickly and the crown was pushed back into shape. Rod stays were then fitted through both inner and outer plates and silver soldered in position.

Until such time that nationally agreed design proposals are available, we suggest that the design calculations as used in the past be applied when a hobbyist wishes to build a boiler of their own design.

The Code of Practice produced by the Model Engineering Lision Group (MELG) on the Examination & Testing of Miniature Steam Boilers 2018 recommends in the section on design verification, that

- *The constructor of a boiler to other than a recognised design available through the model engineering trade and/or press shall produce design drawings and demonstrate to the satisfaction of the inspector, either by calculation or by well-proven example, that the design and materials used have adequate strength.*
- *If no working pressure is stated on the drawings, or published accompanying text, the boiler shall be treated as a new design and calculations shall be produced and validated.*
- *If a boiler is being made to a published or established design but is intended to be used at a higher pressure than that specified by the designer, it shall be treated as a new design. The decisions taken by boiler Inspectors shall be taken as final (see section 19).*
- *Consideration should be given to the use of a build record sheet.*

It is essential when any of your members are considering the construction of a boiler, that the club inspectors are fully involved at key stages of design and construction. This so that the boiler inspector is able to make sure that it is being made to the agreed design, using the correct materials for plates, tubes and jointing materials, and most importantly, to make sure that the correct penetration of the jointing material has occurred.

You will see on the following pages of this note that all the calculations are very simple and straightforward and answers often include rounding up to nearest available size.

Boiler Barrel

For a given thickness and diameter, a length of seamless solid-drawn tube will make the strongest barrel. When a barrel is made from flat sheet rolled to a cylindrical form with the joint lapped and riveted or brazed, the strength will depend on the type of joint used. For double riveting it is customary to take a figure of 70% of the strength of the solid drawn tube. For a single rivetted joint 50% is taken while for brazed or silver soldered joint 80% is generally accepted.

To calculate the right thickness of metal to be used for the boiler barrel, the following formulae can be recommended;

$$P = \frac{D \text{ x } F \text{ x } WP}{TS \text{ x } R \text{ x } C \text{ x } T \text{ x } 2}$$

Where P is plate thickness in inches

- D is boiler diameter in inches
- F is the safety factor. (this is between 6 and 10 but usually a factor of 8 is used)
- WP is the working pressure in lb/in^2
- TS is the tensile strength of copper (a suggested figure is 25,000 lb/in^2)
- R is the riveting allowance (this is when a rolled and riveted barrel is used. Single row 0.5, double row 0.7, and for riveted and silver soldered 0.8. It is suggested that all copper boilers include this figure as an added safety factor.)
- C is the corrosion allowance (no allowance is usually made for copper)
- T is the temperature allowance (copper diminishes in strength at high temperatures. An allowance of 0.8 for pressures between 60-100 lb/in^2 and 0.7 for pressures from 110 to 150 lb/in^2)

Consider an example of a copper boiler with a barrel diameter of 4", working pressure 80 lb/in^2 rolled from flat sheet and with silver soldered seam;

The barrel thickness required = $\frac{4 \text{ x } 8 \text{ x } 90}{25000 \text{ x } 0.8 \text{ x } 0.8 \text{ x } 2}$ = 0.090”, 13 S.W.G.. 3/32”, 2.5mm

To change the calculation around, barrel thickness x tensile strength x riveting allowance x temperature allowance x two, over diameter x safety factor will give the maximum working pressure

Maximum working pressure = $\frac{0.090 \text{ x } 250000 \text{ x } 0.8 \text{ x } 0.8 \text{ x } 2}{4 \text{ x } 8}$ = 90 lb/in^2

Flue/Fire Tube sizes

The above formula is not appropriate for a tube subjected to external pressure.

A firetube or superheater flue must be made thicker than given by the formulae above because an externally loaded tube will collapse by buckling at a far lower load than that at which it would burst when subjected to internal pressure.

Note: Only solid drawn copper tubes should be used. Rolled and seam welded tubes must not be used for external pressure applications.

Recommended Minimum Wall Thickness of Flue Tubes For Copper Boilers working at 80 to 120 lb/in².

The following list is for the recommended minimum wall thickness for a copper flue tube;

Tube OD	Wall Thickness	Tube OD	Wall Thickness
¼”	24 S.W.G.	5/16”	22 S.W.G.
3/8”	20 S.W.G.	7/16”	20 S.W.G.
½”	20 S.W.G.	5/8”	20 S.W.G.
¾”	18 S.W.G.	7/8”	18 S.W.G.
1”	18 S.W.G.	1-1/8”	18 S.W.G.
1-1/4”	16 S.W.G. (or 1/16")	1-3/8”	16 S.W.G. (or 1/16")
1-1/2”	16 S.W.G. (or 1/16")		

There is a definite relation between the diameter and length of a flue tube, whatever the size of the boiler. An examination of the most successful locomotive boilers shows that the length of the flue tube divided by the square of the internal diameter works out at between 50 and 70. For model boilers at all scales the following formula is recommended;

$$d = \sqrt{\frac{L}{65}}$$

Where d is the internal diameter of the tube and L is the distance between the tubeplates, both being measured in inches.

The formula cannot of course be used exactly as tubes are usually only available in increments of 1/16”

Example; for a tube of 7” length;

$$d = \sqrt{\frac{7}{65}} = 0.33”$$

The nearest standard tube to meet this would therefore be 3/8” diameter x 20 S.W.G. wall thickness

---

Superheater Elements and Flue Sizes.

The size of superheater elements is governed by the considerations of the diameter which must be small enough to ensure that all the steam passing through the element is properly heated and that there is sufficient area through the elements to accommodate the required steam flow without significant pressure drop. This problem is referred to in some publications as ‘wire drawing’.

Once again, reference to successful designs is helpful with shorter barrels generally giving the least trouble as far as superheat temperature is concerned. In most cases the fraction of length divided by diameter is between 230 and 280.

For model boilers at all scales the following formula is recommended;

$$d = \sqrt{\frac{L}{275}}$$

Where d is the external diameter of the tube and L is the overall length of the element, both being measured in inches.

For practical purposes the overall length of the element may be taken as twice the distance between the tube plates

Example; for a boiler where the distance between the tube plates is 8”;

$$d = \sqrt{\frac{16}{275}} = 0.242”$$

So in this case, elements of ¼” outside diameter would be satisfactory.

To find a suitable size of superheater flue for the elements, it is only necessary to add sufficient clearance for the passage of the gases around the element while bearing in mind the need to sweep the flues.

The following table gives recommended sizes for elements and associated flues.

Element size	Flue inside diameter	Element size	Flue inside diameter
3/16”	½”	7/32”	9/16”
¼”	11/16”	9/32”	¾”
5/16”	27/32”	3/8”	1”
7/16”	1-1/8”	½”	1-1/4”

Thickness of Copper for Boiler Plates - Fireboxes and Stays

Where the outer firebox wrapper is made separately to the barrel the material should be of the same thickness or, in the case of the Belpaire type it may be a little thicker with advantage.

The inner firebox wrapper should be between $^2/_3$ and $^3/_4$ the thickness of the outer wrapper.

The firebox flanged plates, throatplate, smokebox tubeplate and backhead should all be of the same thickness as the barrel.

Plate crown stays should be at least the same gauge as the firebox wrapper covering and attached to the whole length of the inner firebox crown including the flanges of the tube and backplate.

Fitting of Firebox Side, Longitudinal Backhead, and Throatplate Stays

The general principle underlying the staying of a boiler is that all flat surfaces in the boiler must be properly supported and that all surfaces not self-supporting will require stays.

In locomotive boilers there are three principle types of stay;

- Side stays – to support the flat side, front and back of the firebox
- Longitudinal stays - to support the flat ends of the boiler (smokebox tubeplate and backhead)
- Crown stays - to support the top or crown of the inner firebox

Side Stays.

These may be screwed, nutted, riveted and caulked with soft solder using copper, gunmetal or monel metal for the actual stays. This method, although tedious is perfectly acceptable being a mechanical fixing using the soft solder as a sealing medium. This has the advantage of being suitable for the average model engineer to successfully complete a boiler without the use of oxy-acetylene equipment.

More commonly seen is the use of round head rivets inserted from the inner firebox with a small countersink on the outer firebox wrapper to assist the brazing process.

The following table gives recommended sizes for screwed stays for Firebox Side, Throatplate and Backhead stays (based on thread root diameter)

Thickness of inner firebox	Stay diameter & thread.	Thickness of inner firebox	Stay diameter & thread.
3/64” or 18 S.W.G.	5 BA	1/16” or 16 S.W.G or 1.6mm	5 BA
3/32” or 13 S.W.G or 2.5mm	4 BA	1/8” or 10 S.W.G. or 3mm	3/16” x 40 tpi
5/32” or 8 S.W.G. or 4mm	¼” x 40 tpi	3/16”	5/16” or 3/8” x 32 tpi
1/4”	3/8” or 7/16” x 26 tpi	5/16”	½ “ x 26 tpi

The pitch of side stays can be calculated by the following formula;

$$\text{Pitch} = \sqrt{\frac{D^2 \text{ x T x } 3}{\text{P x F x } 4}}$$

Where D is the minimum diameter of the thread in inches

P is the maximum working pressure in lb/in²

F is the safety factor. (this is between 6 and 10 but usually a factor of 8 is used)

T is the ultimate tensile strength of the stay

For copper T may be taken as 25,000 lb/in², gunmetal as 38,000 lb/in² and monel metal as 60,000 lb/in²

As an example for a 3/16” x 40 tpi Gunmetal threaded stay, and a maximum working pressure of 100 lb/in²

$$\text{Pitch} = \sqrt{\frac{5 \text{ x } 5 \text{ x } 38000 \text{ x } 3}{32 \text{ x } 32 \text{ x } 100 \text{ x } 8 \text{ x } 4}} = 0.96 \text{ inches}$$

Note: The 3/16” diameter stay is shown as 5/32” diameter in the calculation being the root diameter of the thread.

Silver soldered plain rivet type stays without threads can be calculated on full diameter.

The same formula is applicable in calculations for throatplate and backhead stays.

Longitudinal stays

These are used in boiler where the firebox wrapper is separate from the barrel, the two being joined by a throatplate.

The number used is dependent on the size of the boiler, one of which can be the thick walled copper tube used to pass steam to the boiler’s blower, or on locomotives with hydrostatic lubricators, a second hollow stay may be used to get the oil to the steam header in the smokebox.

Usually there is an even number of stays at around one inch pitch across the top of the firebox the centre being left clear for any girder stay in the centre of the crown and also to clear the regulator valve or rod. The stays may be silver soldered or screwed using blind nipples. They can be made from either copper or bronze and should be not less than the diameter of the side stays. The same applies to the cross staying to be found on Belpaire type outer fireboxes.

Crown Stays

There are four distinct types of crown stay used in model locomotive boilers;

- The direct or rod stay
- The fabricated plate girder stay
- The girder stay not connected to the outer wrapper e.g. in Simplex
- The sling girder stay

The direct rod type is probably the best to use in Belpaire fireboxes, best made from monel or drawn bronze. There are several methods of fitting involving threading and/or silver soldering, details of which are in the books recommended for further reading at the end of this note.

Rod stays although often used are not ideal for round top fireboxes as it is desirable that they be located radially so that the threaded holes in the plates are normal to the stay centre line.

The fabricated plate girder stay is often used in boilers up to 1 ½" scale where a pair of shaped plates of the same thickness as the outer wrapper are rivetted and silver soldered to both inner and outer wrappers.

When using plate crown stays it is vital to carry them along the full length of the inner firebox assembly so that they lie over the flanged edges of the inner firebox tubeplate and the firebox backplate.

Girder crown stays which are not connected to the outer wrapper have been used from time to time, but only on round top boilers and must be silver soldered along their length to the crown of the firebox.

The sling girder type are not recommended for copper boilers. Such stays are difficult to make and only suitable for large scale round top boilers where there is sufficient space between the inner and outer wrappers for easy assembly of the parts.

Boiler Test Code - Design Verification.

The subject of design verification is covered in the Boiler Test Code 2012 edition in section 4 and will become section 5 in the 2018 edition.

This section of the code has caused some concerns to boiler inspectors as to what constitutes a modification and under what circumstances are design calculations required. There have been examples where inspectors feel that verification is required for minor alterations to a published design such as the placing of feed water clacks on the front ring of the barrel because the original drawings showed backhead mounting. This of course is not the intention of this section of the test code.

When the NAME boiler sub-committee compiled and published the original Northern Association Test Code it was felt that this section should be included for those Instances when a prospective builder wished to build a boiler of non-standard construction such as the boilers designed by the Lancashire and Yorkshire Railway for their 0-8-0 goods engines which had no side firebox stays as the plates were corrugated The use of such would require the appropriate calculations as would other such as the boilers for the L.M.S. 'Fury' or the L.N.E.R. 4-6-4 'Hush Hush'.

Such conversions as the lengthening or shortening of a boiler barrel or increasing or decreasing the length of firebox, providing the stay size and pitching is no greater than that of the unmodified published design are acceptable without further assessment.

Any increases in material thickness, larger silver soldered flanges, thicker and closer pitched stays will have no detrimental effect on the safety of the boiler.

A case was brought to our attention of an inspector who requested stress calculations on the boiler for a 3 1/2" gauge Juliet because the barrel had been made from 3/32" thick copper tube instead of the specified 1/16". This clearly was not necessary a safety had not be compromised by choosing a thicker material.

Further reading and sources of information

There are many publications covering the design and manufacture of miniature boilers by well-respected model engineers such as Henry Greenly, K N Harris, Tubal Cain, Martin Evans, Alec Farmer and Don Young.

Of particular value to the authors of this note are Model Locomotive Boiler Making by Alec Farmer and Model Locomotive and Marine Boilers by Martin Evans.

Tips and Suggestions

1. Great care should be exercised if asked to increase boiler pressure above the design pressure because any such increase will reduce the factor of safety which is included to allow for any wastage or build-up of scale which can cause burning of the boiler plates.
2. Although cadmium containing filler metals were banned from sale in 2010, many model engineers retain useful stocks of such material or having used nothing other than Easy Flow No.2 and equivalent products for many years, still think about the temperature working range in terms of the Johnson Matthey materials.

   The following may be of use to you when asked which grade of silver solder should be used.

JM Brazing Alloy	Melting range ^{o}C	JM Silver-flo melting range ^{o}C	CUP Alloys melting range ^{o}C
Type 5	698 to 788		
Easy-flo	620 to 630		
Easy-flo No.2	608 to 617	JM Silver-flo 55 - 630 to 660	CUP 455 – 630 to 660
Argo-flo	605 to 651	JM Silver-flo 56 - 618 to 652	CUP 445 – 640 to 680
Argo-Bond	616 to 735	JM Silver-flo 38 - 650 to 720	CUP 438 – 650 to 720
B6	790 to 830	JM Silver-flo 40 - 650 to 710	CUP 430 – 665 to 755
D3	700 to 740	JM Silver-flo 24 - 780 to 800	CUP 424 – 740 to 780

   The above table has been constructed for comparison purposes to the original Johnson Matthey materials. It does not include all material ranges available. For further information on the ranges of materials please check;

   http://www.jm-metaljoining.com/products/silver-flo

   http://www.cupalloys.co.uk/for-model-engineers/

   Included with your seminar notes you will find a leaflet kindly supplied by CuP Alloys Ltd. which lists the appropriate ISO Standards for the various grades of silver solders with the temperature melting ranges and rod sizes available from them.

3. It is often recommended in articles on the construction of copper boilers that Johnson Matthey 'Easy-flo Flux' be used. However, if the data sheets from Johnson Matthey are consulted, we find that they do not recommend this flux for applications requiring prolonged heating. Anyone who has built a large sized copper boiler will know that the prolonged heating required will exhaust the flux often before the temperature for brazing has been reached. The Tenacity range of fluxes are suitable for extended heating and higher temperature . A large range of fluxes are available with Tenacity No.5 and its working range of 600 to 900 ^{o}C being popular with Model Engineers.

   For a complete information visit http://www.jm-metaljoining.com/products/tenacity

4. When boilers are presented for hydraulic test, the onus is on the boiler owner or operator to provide any necessary blanking plugs and also a suitable thread adaptor to fit the society's test pump. The details of the thread of the test pump fitting should be available to all boiler owners on a notice board or in the operating procedure.
5. Care should be exercised when inspecting boiler fittings. Dependent on water quality the life of some boiler fittings containing any zinc can be very short. This is caused by the dezincification of the fittings. A simple explanation is that the zinc is sacrificed to protect the copper and is caused by any acidity present in the boiler water, which can create a battery effect which etches out the zinc. Threads are particularly vulnerable to this decay. It can and has caused check valves and other fittings to blow out when the boiler is in steam. Boiler fittings ideally should be made from bronze or gunmetal and not brass.

   Some years ago the Northern Association asked the commercial manufacturers to use suitable zinc free brass for the production of boiler fittings but unfortunately there was no response from them.

   Recently, some boiler fittings made from bronze have appeared on exhibition stands of some of the specialist suppliers, but in general they continue to be manufactured from brass.

   The part of the fitting which always corrodes is the part which is screwed into the boiler. Accordingly it is recommended to use bronze for this part. The rest of the fitting can still be made from ordinary brass if required, as the body of a valve is not in direct contact with the copper of the boiler.

If in the future and need help or advice on boiler matters, please contact either the Secretary of Safety Officer of your affiliated body. Your club secretary will always have these contact details.
