VOL. 6. No. 11, p.p. 317-348 NOVEMBER 1941

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
N.V. PHILIPS' GLOEILAMPENFABRIEKEN

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, HOLLAND

TECHNICAL PROBLEMS IN THE CONSTRUCTION OF RADIO VALVES

by TH. P. TROMP.

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In this article several episodes in the history of the development of radio valves are discussed, particularly those concerned with the form of the valve. It is shown how the technical problem of whether glass or metal is the more suitable material for the bulb of the valve led to a complete revision of valve construction. The result is that radio valves can now be made either of glass or metal which satisfy all the requirements made by ordinary sets for the broadcasting region. The Philips key valves in glass or metal are finally discussed in detail. The conclusion is drawn that the difference in properties for the broadcasting region is so slight that neither of the two models is essentially preferable to the other. In the region of metre waves and shorter, however, the all-glass valves exhibit increasing advantages with decreasing wave length.

Introduction

The development which is observed in the form of every technical product, be it an electrometer, a lamp or an amplifier valve, is in general directed by two factors: first an ever-increasing insight into the physical laws which determine the function of a product, and second the problems and possibilities of manufacture. It may in general be said that for products which are manufactured only in small quantities the first factor is the more important, while in mass production the second factor also comes into prominence.

The question of which of the two above-mentioned factors determines the technical development also depends upon the nature of the product. If one considers a radio valve it may be said that the technical development of its electrode system is directed by a steadily increasing insight into the physical phenomena which determine its function. The external form of the radio valve, however, is quite a different question. As far as the function of the valve is concerned, the envelope, aside from providing contact in the socket, serves only to maintain a vacuum around the electrodes. From this point of view the external form of a radio valve would logically be a container which encloses the electrode system as closely as possible and through which mutually insulated connections are led. These connections would preferably be chosen in the form of short, straight wires, strong enough to be used as contact pins and far enough apart to cause no undesired couplings between the various electrodes.

In this article we shall give several details from the history of the development of radio valves which have indeed finally led to constructions of the simple character described [1]). The fact that this has occurred only after many years may not be ascribed to a lack of insight, but only to the difficulties which occur in the manufacture of a vacuum-tight container with sealed-in connections.

Historical survey

It would lead us too far if, in this article, we were to go into all the problems which are here encountered. It may be stated simply that the problem of the manufacture of a vacuum bulb with leads had previously reached an almost perfect solution in lamp manufacture, in the form of the so-called "pinch", so that it was obvious that this principle of construction could also be used for radio valves. The valves with pinch construction consist entirely of glass and are provided with a base with contact pins. The connecting wires to the electrodes must be soldered into these pins which are moulded or pressed in.

Although this construction by no means satisfies the above-mentioned requirement of smallest possible dimensions, and although the use of a base with pins to which leads must be soldered meant an undesired complication, this construction was

[1]) See Philips techn. Rev. 4, 162, 1939.

able to maintain its supremacy until the use of new materials for the envelope of the valve introduced a complete change in the form.

In 1935 in America metal radio valves appeared on the market (G.E.Co. and R.C.A.) [2]). Relatively soon after this, metal valves also appeared to a limited extent in some European countries. Philips manufactured a large number of such valves for European and overseas markets.

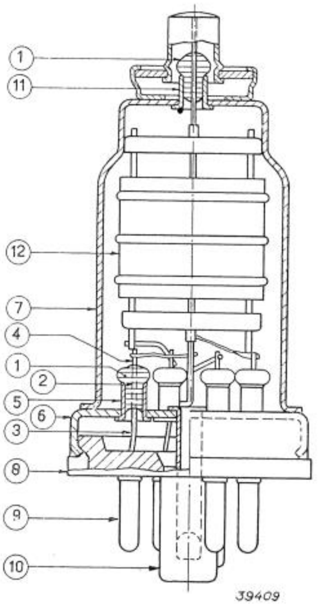

Fig. 1. Radio valve with metal envelope which appeared on the market in America in 1935.
1. Glass bead,
2. Molybdenum lead,
3. Nickel or copper connector,
4. Nickel support wire,
5. "Fernico" eyelet,
6. Metal header,
7. Metal bulb,
8. Bakelite base,
9. Hollow contact pin,
10. Bakelite spigot,
11. Eyelet of top lead,
12. Electrode system.

The first metal construction consisted of a fairly complicated arrangement, of which *fig. 1* illustrates a cross section. Briefly it is as follows. The "header" of the valve consists of a horizontal metal plate with a vertical cylindrical edge. In this header a number of holes are punched in which "Fernico" eyelets are welded. "Fernico" is an iron-nickel-cobalt alloy which can easily be welded to hard glass with a comparatively low coefficient of expansion [3]) — about $50 \times 10^{-7}/°C$. After welding, the eyelets are soldered with copper in order to obtain an absolutely reliable vacuum-tight joint. There is also a hole in the centre of the header in which a metal exhaust tube with a small flange is welded for the evacuation of the valve later on.

Lead-in wires are sealed into the "Fernico" eyelets (coefficient of expansion 48 to $50 \times 10^{-7}/°C$) with the help of the above-mentioned hard glass with low coefficient of expansion. These leads consist of three parts: an internal nickel support for welding the electrodes of the system, a short section of molybdenum wire for the vacuum-tight lead-in and a nickel or copper wire for the connection to the pins of the base, which in this case is constructed as a bakelite "wafer type" base plate with pressed-in pins. In this case a "holder" is therefore not superfluous, nor is the soldering of the leads in the pins. From the electrical point of view also this is a disadvantage, for instance with the high frequency losses and the frequency-drift during the heating-up period.

After the leads have been sealed in, a series of manipulations follows before the electrode system can be welded on the header, and only after that has been done can the iron envelope be welded to the base plate by means of a very heavy projection welder [4]) which produces a vacuum-tight weld. The valve is then ready to be exhausted.

It may be noted that the protection of the exhaust tube which is squeezed, welded and cut off, after the exhausting and de-gassing, is provided by a central spigot which at the same time locates the valve in the socket correctly.

A variant of this model, of which it was hoped that it would be less expensive than the construction described above, has the metal header replaced by a glass plate with sealed-in lead wires (nickel-iron core with copper covering). The glass plate is sealed into a chrome-iron ring which in turn is welded into an iron ring. The iron ring has the same function as the edge of the header of the model previously described, namely for the bulb to header weld. In this model the exhaust tube is not of metal but of glass; see *fig. 2*.

Originally in this model of valve the control-grid lead-out was at the top of the metal bulb as shown in the figure.

These valves were appreciably smaller than the glass valves previously manufactured with pinch construction, and due to the metal envelope a good

[2]) We do not consider here constructions in which the bulb serves not only as envelope but at the same time forms a part of the electrode system. Such constructions have long been used in high power transmitter valves, where the anode is constructed as a part of the envelope in order that it may be cooled more easily. In the case of receiver valves also such a construction, the so-called "Catkin" valve, was designed in England. This valve was, however, not manufactured on a large scale and after some time it disappeared from the market.

[3]) The coefficients of expansion of glass mentioned in this article refer to average values which are measured in the temperature range between 20 and 320 °C.

[4]) A projection welding apparatus is a resistance welding apparatus with which the parts to be welded can be joined on an accurately defined surface by a welding impulse of very short duration and considerable power.

shielding of the electrode system against external fields was automatically obtained.

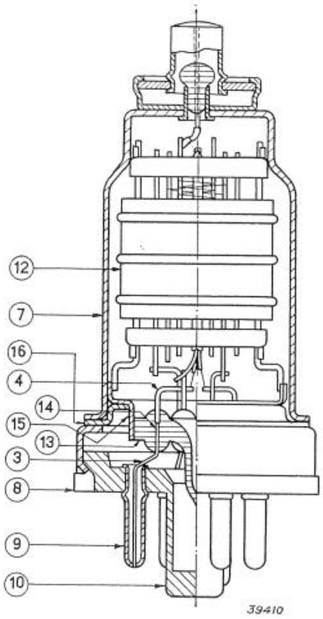

Fig. 2. Radio valve with metal envelope in which the metal header is replaced by a glass "button stem". For the meaning of the numbers see fig. 1, and further:
13. Glass button stem,
14. Lead-in wire,
15. Chrome-iron ring,
16. Iron ring.

In the meantime a new form of metal valve appeared in the European market (developed by "Telefunken"), in which the experience gained with the American construction was taken into account and several new ideas incorporated (see *fig. 3*). The principle of the metal header with "Fernico" eyelets and the insulated molybdenum leads through hard glass were here again used; a "base" in the form of a flat plate with moulded or pressed-in contact pins must also be used under this metal valve. The difference between this valve and the American model according to fig. 1 is that the electrode system is constructed h o r i z o n t a l l y, which permits a very solid construction, but with the accompanying (not inconsiderable) increase of the diameter. An advantage is that all the electrodes can have their leads on one side, namely to the bottom and without thereby increasing the anode-grid capacity [5]) (single-ended construction). In a series of valves this capacity is very important, since it may be the cause of an undesired coupling of anode and grid circuit. In modern set construction it is required that this capacity shall not exceed the extremely small value of 0.002 pF, a requirement which can immediately be fulfilled with the new form of metal valve.

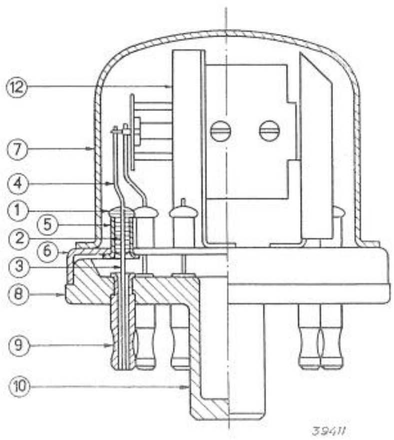

Fig. 3. European construction of the radio valve with metal envelope. The electrode system is placed horizontally. For the meaning of the numbers see fig. 1.

Technically this construction is satisfactory in all respects, it has, however, various disadvantages, for example the fairly large diameter and the fact that power-output valves and rectifier valves of the power as used in the broadcast-field cannot be made according to this design because of the limited length of the cathode (due to the horizontal construction). For these types of valves a vertical construction would again be necessary. It is for this reason that this metal range consists chiefly of radio-frequency, frequency-changing, intermediate-frequency, detector and low-frequency amplifier valves, while output valves and rectifiers belonging to this series are manufactured in the old familiar pinch technique, but with the same base as the metal valves.

The all-glass key valves

In the meantime work has been done at Philips on an improvement in the construction of the glass valve. The requirements upon which this improvement was based are briefly the following:
Small dimensions,
Good shielding,
Reproducibility in manufacture,
Good contact and firm fastening of the valve in the valve holder,
Low consumption of material and preferably use of materials which can be easily obtained.

In order to simplify the manufacture it is furthermore desirable that the valve should have no base, but the leads should be in one piece and serve also as contact pins.

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[5]) Later this design with all connections on the same side was also applied in America to the constructions represented in figs. 1 and 2. This was done by bringing the grid lead from the top to the bottom and introducing extra shielding in order to prevent the anode-grid capacity from becoming too large. This capacity is, however, much larger than that of the European metal valve construction described.

The result was the modern all-glass valve construction described in the article referred to [1]). It is chiefly distinguished by the use of pressed glass and thick chrome-iron contact pins, which make it possible to omit the "holder" which is in many respects so undesirable. In connection with the form and the function of the spigot these valves are called key valves (see *fig. 4*).

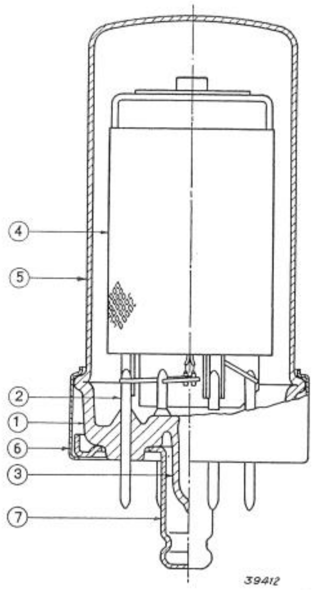

Fig. 4. Cross section of an all-glass Philips key valve. The sealed-in pins make direct contact in the socket; the bakelite base present in previous valves is eliminated.
1. Pressed glass base,
2. Chrome-iron pin,
3. Glass exhaust tube,
4. Electrode system,
5. Glass bulb,
6. Metal ring,
7. Metal spigot.

The model in which originally a series of special valves (particularly for television and other special purposes) were manufactured, still had a rather large diameter (envelope about 30 mm; largest diameter about 34 mm), but the use of these valves already meant a considerable saving of space on the surface of the chassis compared with the use of the metal valves with a diameter of 43 mm.

From this model with nine pins the modern glass key valve was developed with eight pins, an envelope diameter of about $27^1/_2$ mm and a largest diameter of about $31^1/_2$ mm. The central spigot in these valves is of metal and serves not only as centering and locating device in inserting the valve into its socket, but at the same time as shielding between anode and control-grid pin. This spigot is so arranged that the valve clicks into the socket, which is a great advantage for the locating device if the set is to be transported complete with valves; a requirement which at present is universal.

This construction also makes it possible to obtain a grid-anode capacity which is smaller than 0.002 pF in spite of the vertical assembly, the small diameter and the single-ended construction. The object of making smaller and smaller valves in connection with the demands of the set-makers is fully met by this construction. The development of the Philips midget receiver, type 203 U, which although equipped with four valves, has a volume of only 5 dm^3, was only possible because of the existence of such valves.

Properties of glass and metal valves

The advantages of the all-glass valve compared with the valves with a pinch have already been discussed in detail in the article cited [1]), and it is these properties which make them particularly suitable for use in the region of ultra short waves. The shorter the wave length, the greater the advantages. In the televison region (wave lengths of several metres) the properties are already important, at still shorter wave lengths (decimetre waves) they may even become of such value that a pinch construction need no longer even be considered.

We shall now compare several properties of the glass key valves with those of metal valves.

During the heating up period of the valves in a set, the capacity variations which occur due to the change in the dielectric cause a frequency drift of the set which has previously been pointed out. At broadcasting wave lengths this frequency variation may already be somewhat disturbing; but with the decrease in the wave length it becomes steadily more important. While with the glass key valves a decrease of the frequency variation by a factor 2 (at 15 m wave length) compared with the pinch construction was obtained, with the metal valves this advantage is again lost.

A second disadvantage of the metal valves is that in the construction described the leads sealed into the eyelets involve a rather large concentrated capacity, whereby at wave lengths shorter than 1 m an appreciable depreciation in the results, which can be obtained with the valves is noticeable, and below about 50 cm even makes their use impossible.

A third point of difference relates to the input and output damping. In the case of the glass valves this is lower than in the metal construction, since the dielectric losses of the capacities between the leads and the metal envelope furnish an extra contribution to this damping. Because of this a greater amplification can be obtained with glass valves at wave lengths in the metre region.

It is clear that all these points of difference relate to the short-wave properties. In the case of the ordinary broadcasting receivers, however, they are of no great importance.

As a matter of fact the metal valve has the advantage already mentioned of providing a better shielding against external fields. In the case of the glass valve this shielding must be obtained by building in a so-called cage of metal gauze (at least for those types where shielding is necessary), which encloses the whole system — a device which is satisfactory in all respects.

Another important point, which is of importance not only in the glass but also in the metal construction, is that of the high-frequency losses of the leads in the ultra short wave region. The D.C. resistance of the solid pin is hereby of secondary importance, because the high-frequency resistance depends mainly upon the condition of the surface layer. With given dimensions of the lead the following values were measured at a wave length of 90 cm:

silver wire	0.12 Ω
copper wire	0.12 ,,
aluminized iron	0.20 ,,
molybdenum	0.23 ,,
tungsten	0.26 ,,

A grade poorer are:

nickel	1.20 ,,
iron	3.60 ,,
"Fernico"	5.20 ,,
chrome-iron	6.00 ,,

From this it will be clear that if pins of the last mentioned materials are copper-plated or silver-plated, considerable improvement can be obtained. Thus, for example, with a given lead-in, thin silver-plating of the chrome-iron wire gave an improvement of the high-frequency resistance from 1.1 Ω to 0.13 Ω for $\lambda = 1.0$ m, while in another case an improvement from 1 Ω to 0.17 Ω was obtained by copper-plating the wire.

A metal key valve

From the above considerations it follows that in principle it must be possible to design a metal valve for the broadcasting field which satisfies the requirements specified in the introduction. Such a valve may be considered as equivalent in practical use to the glass key valve construction described. It is possible therefore to be more or less independent of the supply of a given raw material, factory equipment, etc. The solution of this problem is shown in the valve construction given in *fig. 5.* As to dimensions this valve is identical with the all-glass key valve described: the contact pins are also in the same relative positions to each other, there is also a spigot, its over-all dimensions are the same, and the same electrode systems can be used in it; briefly it is a design with which it is possible to make replicas of existing all-glass types. The components of this type are shown in *fig. 6.* The capacities between the electrodes (for instance input and output capacities) will of course differ slightly from those of a similar type in all-glass construction, but these differences are so small that they can be compensated very easily by trimming the set. In many cases it will even be possible to replace the valves in existing sets without any change.

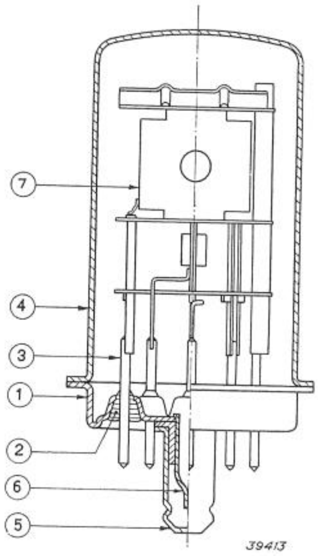

Fig. 5. Cross section of a metal key valve. The external dimensions, the arrangement of pins and the construction of the electrode system are exactly the same as in the glass key valves.

1. Metal header,
2. Glass bead,
3. Iron pin,
4. Metal bulb.
5. Metal spigot,
6. Metal exhaust tube,
7. Electrode system.

The new metal valve consists in principle also of a header (see figs. 5 and 6) with small holes for the vacuum-tight sealed-in leads, while there is an opening in the centre for welding the exhaust tube into the header. The advantage of this construction compared with that according to fig. 3 is, that due to the strong vertical construction in which, just as in the all-glass valves, several U-shaped supports provide the necessary mechanical strength, the length of the cathode may be chosen in accordance with the type of valve to be made. Power-output valves, rectifier valves, special combination valves, etc. can therefore also be made in this construction.

The iron header is subjected to several special treatments before the eight leads are sealed-in at a temperature of about 950 °C. A glass bead is previously fused around each pin, the glass of which is adapted to the lead wire and the iron header. The pins may then be of ordinary iron or of an iron alloy. In both cases they are subjected to a special surface treatment before sealing-in.

Upon comparison with the previously described metal construction it is obvious that the quality of this seal must be very high, not only with regard to vacuum tightness, but also to that of mechanical strength, accuracy and precision. The electrode system of the valve must be welded to the pins on the inside of the valve, and on the outside of the valve (when inserting it in its socket) fairly strong forces are exerted on the pins. The technical problems which are encountered in making those leads are not simple and require a thorough knowledge of glass-metal seals and wide experience. A brief comparison of the different techniques used in the constructions previously described gives the following picture.

In the case of the sealing in of a thin molybdenum wire (coefficient of expansion 51×10^{-7}) to give a vacuum-tight seal and to be insulated in a "Fernico" eyelet (coefficient of expansion 48×10^{-7}) a glass is used with a coefficient of expansion as close as possible to the above. A hard glass has been used with a softening temperature of about 540 °C [6]).

In sealing the solid chrome-iron pins in the glass key valve, the pin has a much higher coefficient of expansion, *viz.* about 103×10^{-7}, and it is fused into a soft glass with a slightly lower coefficient of expansion. This glass has a much lower softening temperature, namely about 475 °C.

Since this chrome-iron to glass seal satisfies high requirements as to quality and reproducibility, it would seem obvious that the header of the metal key valve as well as the pins should be made of chrome-iron. This would indeed be excellent were it not for the fact that the cost of such a header would be too high for normal use. Therefore an attempt was made to use cheaper and more easily obtainable metal. It was for this reason that iron was chosen for the new construction, with its appreciably higher coefficient of expansion: 125×10^{-7}. This makes it necessary that the glass should again have a higher coefficient of expansion.

Although in general soft glass is easier to work

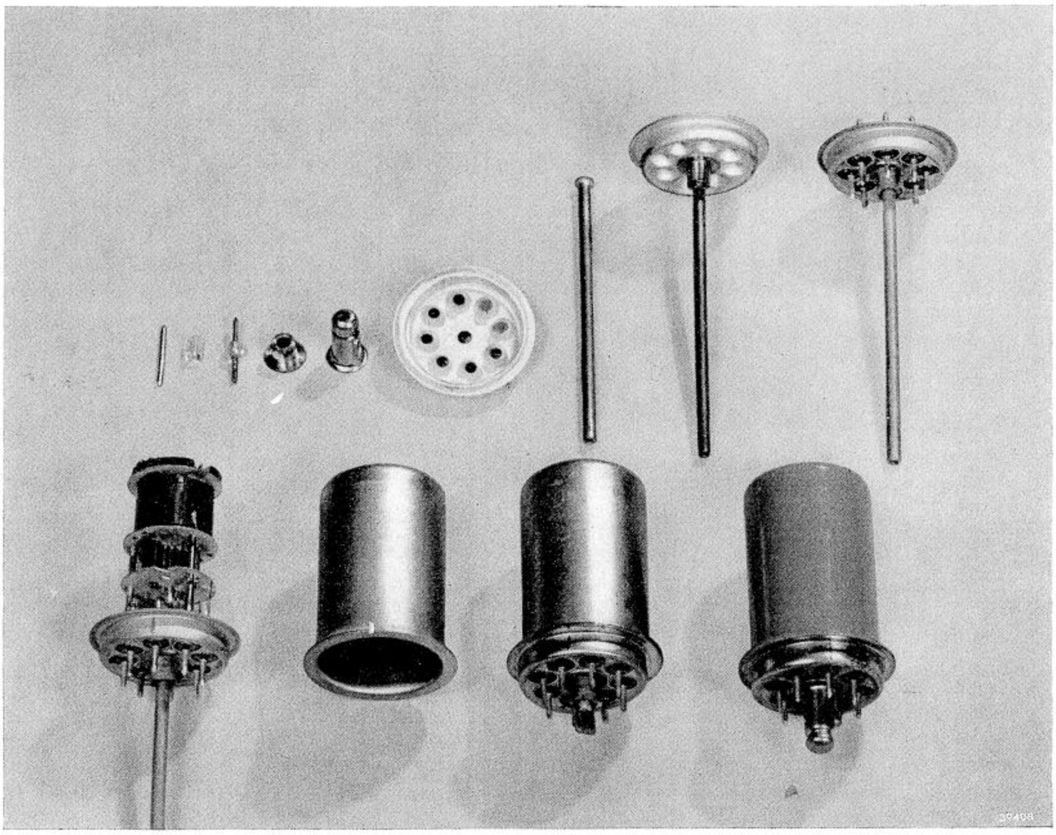

Fig. 6. The parts of the metal key valve in different stages of manufacture. Upper row, left to right: one of the 8 fused-in leads; glass tube to make bead; bead fused on pin; "cap" upon which the spigot is later welded; spigot; metal base plate with holes; metal exhaust tube; combination of base plate, exhaust tube and cap complete the base plate with fused-in pins. Lower row: electrode system assembled and mounted on the pins; metal envelope; valve after being exhausted and finally the completed valve.

[6]) The softening point is defined as the temperature at which a glass rod 30 cm long and 4 mm in diameter, supported at each end, bends 2 mm under a weight of 195.5 g. The melting point is much higher.

with than hard glass, soft glasses with such high coefficients of expansion introduce difficulties in manufacture among which is the chemical decomposition of these lead glasses during the life of the valve, not only by atmospheric influences but also by the formation of "lead trees" due to electrolysis of the glass. Moreover, in the short period during the sealing-process (at a temperature of about 950 °C) reduction of the lead oxide may occur resulting in surface conduction.

A satisfactory solution of these problems has been found and a manufacturing process worked out for the surface treatment of the metals and the sealing-process which meets these objections.

It is also important that the construction should be such that as far as possible the glass will be under pressure stresses only and under all conditions of use, since only under these conditions can an adequate guarantee be obtained of a mechanically strong and at the same time vacuum-tight seal (no cracks, no leaks).

When we study the stress diagram of such a complete header it will usually be evident that only pressure stresses do occur in the seal of glass to base plate, and at the pin, axial pressure and tangential pressure is combined with radial tensile stress. It may, however, also occur that the stress diagram of the axial and radial stresses along the pin is reversed (axial tension and radial pressure stress). The whole picture becomes more complicated when it is kept in mind that variations in the coefficient of expansion of the glass are inevitable and that the wire and the header do not behave in the same way, due to the fact that the influence of the surface layer on base plate and pin is relatively different.

After the metal exhaust tube has been welded on the header and the pins have been sealed in, the header is nickel-plated. On the bottom of the header a small "cap" is welded which is used afterwards for the fastening of the spigot which also serves to protect the iron exhaust tube. The metal bulb is then welded on the header with a heavy projection welding apparatus, after the electrode system of the valve has been mounted and welded to the pins and the connections between the various electrodes and pins have been made.

The following figures will give some idea of the power needed for such welding. While for the previously described metal valve with a diameter of 43 mm a projection welding apparatus of nominally 400 kVA must be used (the power impulse during welding is actually of the order of magnitude of 1000 kVA; primary 500 V, 2000 A, secondary about 110,000 A), for this construction a smaller apparatus can be used, of nominally 175 kVA (peak about 450 kVA). These welding machines are regulated by a special control device which makes it possible to vary the duration of the weld impulse continously from about $^1/_2$ to about 25 cycles, and to set the welding current in 16 different positions by primary regulation. The welding pressure can also be regulated between 100 and 17,000 kg. The welding electrodes are developed for this purpose and are water-cooled.

The welding method described has the advantage over any sealing process that the attachment of the envelope to the base header takes place at room temperature (it is only necessary to dissipate the heat developed at the weld and this is relatively little due to the short duration of the weld impulse). Undesired oxidations in the inside of the valve are thus *a priori* avoided. In the case of glass sealing, on the other hand, in certain cases precautions must be taken such as the protecting of the interior of the valve with inactive gases like nitrogen or mixed gas.

The valve thus constructed can be exhausted and de-gassed in the ordinary way. The exhaust tube is then squeezed and sealed by welding.

It is obvious that in the case of a metal valve direct heating of the internal parts by means of high frequency is impossible. The heating of the internal parts for de-gassing purposes must therefore take place indirectly *via* the metal envelope or by partial heating from the inside by heating the filament, with or without the combination of electron bombardment of the grids, etc. For external heating of the envelope (the header and leads must of course be cooled at the same time) high-frequency heating is, however, unnecessary, and the heating can more economically be done locally by means of gas.

The getter for binding the gas residues can be very easily flashed by heating with gas flames from the outside, or by the passage of current, and it is then deposited on the wall of the envelope with the advantage that the layer of getter is connected to zero potential (and thus does not form a "floating" capacity).

Summarizing, it may be said that it is possible in the broadcasting region to eliminate the problem of a choice between "metal" or "glass", so that the existence of this alternative need have no effect on the further development of set construction. Only considerations of a practical nature (equipment present in a given factory, the availability of certain materials or other special circumstances) need in the future determine the choice of the technique to be employed.