SILICA AS A VALVE-ENVELOPE MATERIAL

The common feature of all transmitting valves is, of course, a high power-dissipation in the electrodes. This power must be lost mainly through the envelope. Until the development of metal-to-glass technology, where the heat could be transferred by direct conduction to a cooling fluid, all heat loss was by radiation through the glass or silica bulb. Neither material has high transmission in the infrared, and the bulb absorbs this radiation. Comparing the two materials, fused silica transmits heat up to a wavelength of about 7 microns, while even boro-silicate glass cuts off at about 3 microns. For a particular electrode temperature a silica bulb will therefore absorb less, and will run at a lower temperature. At the same time the softening point of silica is about 1000°C, compared with about 600°C for glass, so a silica bulb can be allowed to operate at a much higher temperature than a glass one.

A further advantage of silica is its low coefficient of thermal expansion. This is only about 10 per cent that of glass, so it is much less likely to crack due to temperature variations or thermal shock. It is also much stronger mechanically than glass, and so better able to withstand the shock and vibration found in Service environments. Further, it is a very good material electrically. It has high resistivity, four or five orders of magnitude higher than glass. It has high dielectric strength, and a dielectric constant about half that of glass.

This is an impressive list of advantages, but there are disadvantages also. It is chemically inert, making it very difficult to devise vacuum-tight seals with metals. It is a far more expensive material than glass. The actual 'working' is more difficult, requiring higher working temperature, and it takes longer than glass. Valves were therefore relatively expensive, although the high initial cost was largely offset by the fact that they could be repaired simply and cheaply in the event of filament burn out or electrode damage.

SILICA-VALVE TECHNOLOGY

Silica-valve technology was developed in Signal School at the end of World War 1 with the help of the Thermal Syndicate Co, both in the supply of parts and instruction in the art of silica working. It was based on simple manual construction and assembly. Later the same methods were used by Mullard and other companies for factory production. These manual methods were adequate for the small numbers needed for Naval wireless between the wars. However the technology was not amenable to mass-production methods. The huge increase in demand for all types in 1940 for radar applications could only be met with difficulty, and the use of unacceptably large numbers of highly skilled technicians. This certainly contributed to the demise of silica valves in favour of easily mass-produced metal-to-glass types.

The technology for all types was essentially the same: hand-made electrodes were assembled and mounted in a set of fused-silica components made by Thermal Syndicate. The lead-out seal rods were first bound to electrode ribs. The whole envelope was then sealed together, first the main body flanges, then the lead-out seals and filament-tensioning spring tube. An oxyhydrogen torch is necessary to fuse silica. The completed unit was then sealed to the pumping unit. The detailed stages are described below.

The Electrode System

The anode, usually cylindrical, was formed by winding molybdenum tape 2-mm × 0.1-mm on a wooden mandrel, and weaving longitudinal strips of the same tape into the winding to produce a basket structure. Three or four molybdenum ribs were also woven in to make the structure more rigid, and also to leave tails to locate in the envelope and make a connection to a lead-out seal. This type of construction allowed new or modified designs to be made up very quickly. It was also better thermally than a solid cylinder, in that a significant proportion of the filament radiation passed through the basket's interstices and did not contribute to the temperature rise of the anode.

The grid also was wound on a wooden mandrel, on which a lightly-engraved spiral was cut. The grid winding of molybdenum wire, typically 0.2-mm or 0.3-mm diameter, was wound in the spiral over three or four molybdenum ribs, and each turn was laced to the ribs with fine molybdenum wire. The ends of the ribs were located in narrow tubes fused to the end-caps, one rib being bound to a lead-out seal. In some of the much later designs the grid spiral was spot-welded to the ribs.

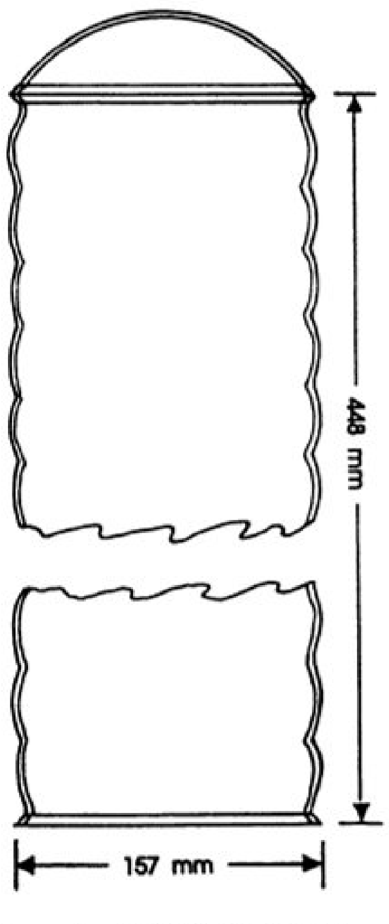
Until 1939 the filament was always of pure tungsten, usually in hairpin form, but in a few types as a number of parallel wires. The filament ends were bent for insertion in holes drilled in the lead-out seal rods, to which they were then bound. The filament was tensioned by a spring at the loop end of the hairpin. Some experiments had been done in 1922, apparently successfully, on a thoriated-tungsten filament, but surprisingly it was never applied to an operational type.

In 1939 the need for very high peak-emission currents in radar valves led to new research on thoriated tungsten. T. J. Jones, in Signal School, developed a system that would withstand the high processing and operating temperatures in silica types. Before evacuation the filament was heated in naphthalene vapour, tungsten carbide being formed to a depth of about one third of the filament diameter. Thorium is relatively tightly bound to tungsten carbide, and so gives an electrically robust emitting surface.

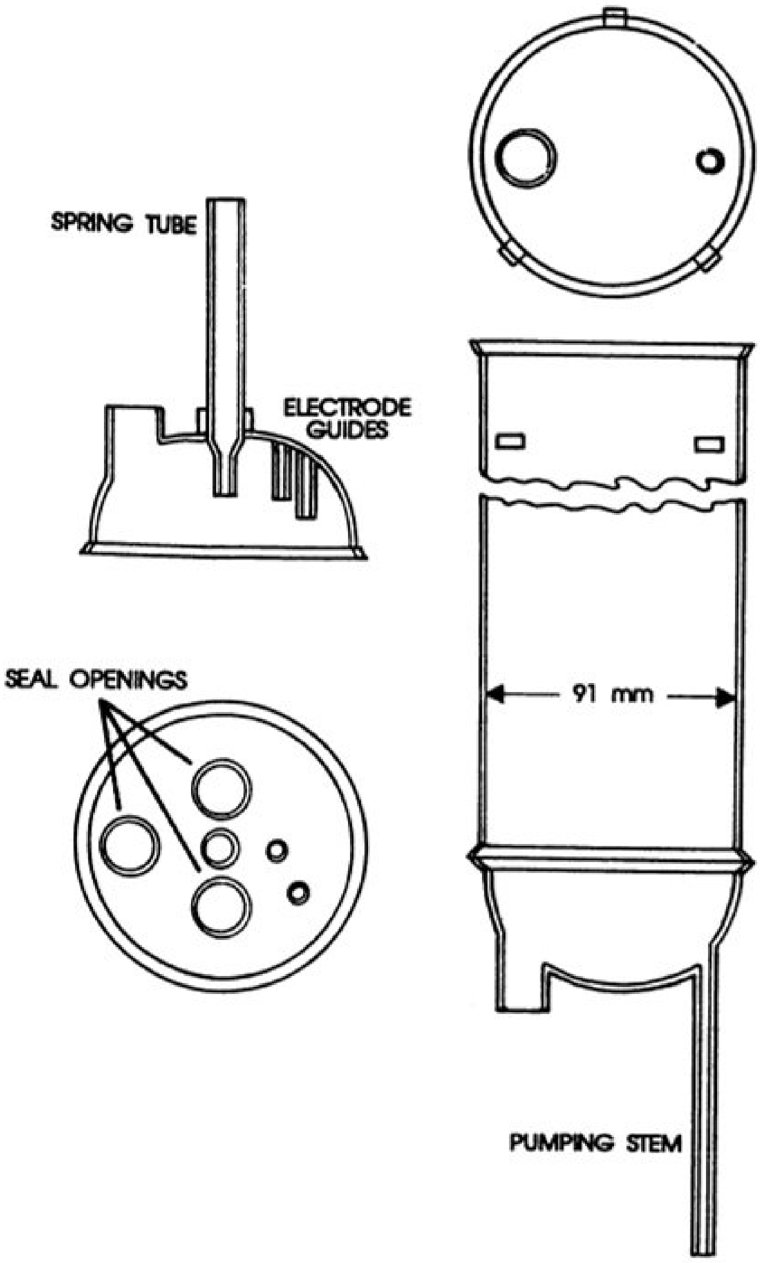
The Silica Parts

Each valve type used an individually specified set of silica parts, comprising a cylindrical body, two approximately hemispherical end-caps with sleeved openings to take the lead-out seals and, in some cases, brackets or spacers to locate the electrodes. On one end-cap there was also a central tube to take the filament tensioning spring, and a tube for connection to the vacuum pumping system. Both body and end-caps were flanged to simplify sealing them together.

There were three standard body diameters, 90-mm, 100-mm and a corrugated cylinder 150-mm diameter. Body length was chosen to fit the specified electrode lengths (Figure 3.1). In practice, a new valve was designed to use as far as possible existing body and cap parts, possibly with modification to the seal opening positions. Figure 3.2 shows a typical bulb with end-cap fitted.



3.1 Corrugated envelope for NT22B (© Defence Research Agency)



3.2 Typical bulb with end-cap fitted (© Defence Research Agency)

It has been noted above that the Thermal Syndicate Co was the sole parts manufacturer. Details of their manufacturing processes were never disclosed, but it is understood that a moulding process using graphite moulds was employed.

The Lead-out Seals

The formation of a vacuum-tight seal with a metal was the major problem in silica technology. The coefficient of thermal expansion of silica is several orders less than for metals, and also it is chemically very inert, with the result that there is no chemical bonding at the interface. Three schemes to overcome the difficulty have been used, as follows:

The Metallic Lead Seal

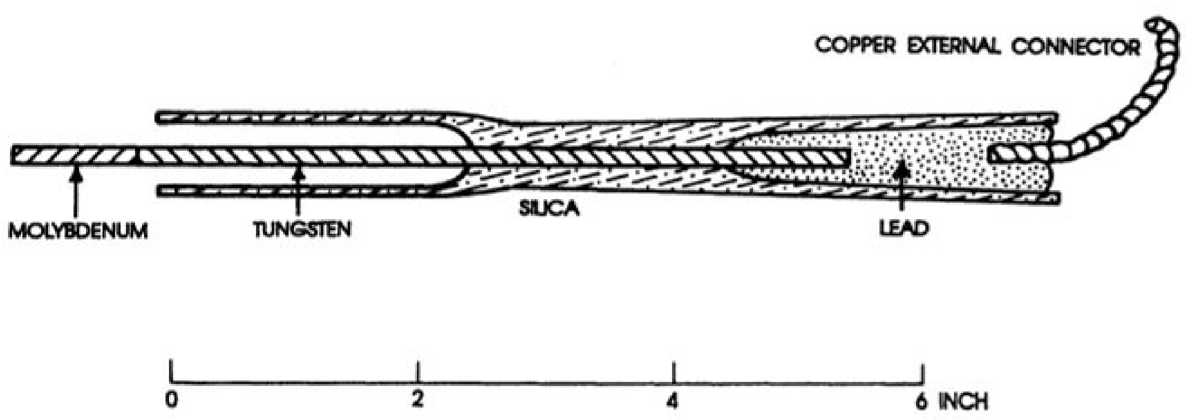
Historically this was the first solution, having been patented by Sand and Reynolds of the Silica Syndicate (later a part of Thermal Syndicate) in 1913 for use in quartz arc lamps. However the Signal School scientists appear to have been unaware of it till after the war.

In this scheme (Figure 3.3) a silica tube 6-in long and 0.5-in bore was shrunk on to a 3-mm tungsten rod over a length of about 2-in near its mid-point. Held in the vertical position, molten lead was poured into the annular space around the tungsten rod, and a flexible copper lead was set in the open end of lead to make an external connection. At the inner end, a molybdenum rod was butt-welded to the tungsten for connection to an electrode. The system was vacuum-tight because the metallic lead was sufficiently plastic to take up thermal expansion changes in the tungsten.

There were two disadvantages – the seals required strong air cooling in use to prevent the lead melting, and they were necessarily long, which limited a valve's use to frequencies below about 40 MHz. Their maximum current-carrying capacity was 25 amps.

The Strip Seal

In this scheme a thick-walled silica tube was fused and squeezed on to a feather-edged strip of molybdenum 5-mm wide, 0.2-mm thick and about 2-in long, with connecting wires welded to the ends. The very thin molybdenum had such a small overall thickness change on heating that the seal remained vacuum-tight. Its maximum current-carrying capacity was only a few amperes so it did not have many applications in transmitting valves. It seems to have been used only in one small split-anode magnetron.



3.3 Lead seal (© Defence Research Agency)

The Graded-Glass Seal

In this design a thin sleeve of a hard glass was fused on to a 3-mm tungsten rod over a length of about 1.5-in (Figure 3.4). To this sleeve was sealed a short length of glass tube, of 20-mm bore, the glass having a slightly lower expansion-coefficient than the sleeve. Two further annular rings were sealed to this tube, each with a successively lower expansion coefficient. Finally a length of silica tube was sealed to the last ring, which could be sealed directly into the bulb openings. As with the lead seal a molybdenum rod was butt-welded at one end, and a copper connector brazed to the other end. The current-carrying capacity was 30 amps. It was only about 2-in long, less than one-third the length of the lead seal, making possible much higher frequency operation.

This design was invented by Philips in Eindhoven in 1939, and independently by GEC a little later.

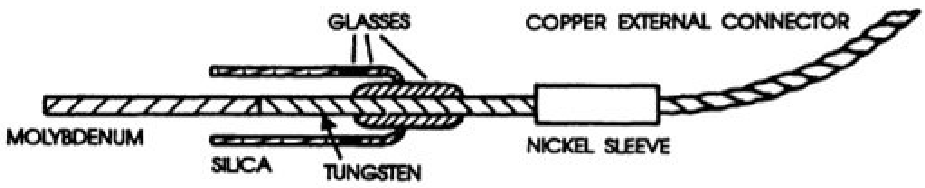


Figure 3.4 Graded-glass seal (© Defence Research Agency)

Valve Assembly

First the electrodes (formed as described above) were cleaned, by dipping into hot sodium nitrite, and then washed thoroughly. Each electrode was then bound or riveted to a seal rod, and the set of electrodes fitted in the valve body, and the end caps sealed to the body. Finally the seals were fused to the sleeves in the caps. Unlike glass, silica does not readily flow together, and the sealing operations involved pushing the heated surfaces together with a small, spade-shaped molybdenum tool. When the sealing was complete the surface around the fused area was found to be covered with a hard white deposit, a lower oxide of silicon, and this had to be 'burned off' by playing an oxidising flame over the surface.

Processing

There were three main processing stages:

- The valve was baked for four hours at 1050°C with hydrogen streaming through the valve to remove oxides from electrodes and seals.

- The valve was sealed to the pumping system – a single-stage mercury diffusion pump backed by a rotary pump, and with a liquid nitrogen trap – and was vacuum-baked at 1000°C till the pressure was less than 10^{-5}-mm mercury.
- The anode and grid were heated by electron bombardment to a temperature well above that at which they would operate and held till the pressure reached a 'sticky' vacuum on the Macleod gauge. The valve was then sealed off.

In valves with a thoriated-tungsten filament the process was modified. After the hydrogen-bake the filament carbonisation was carried out, and the electrode bombardment was replaced by eddy current heating of anode and grid.

In general, radar valves operated at very high voltages, which often resulted in flash-arcs between grid and anode. To avoid this, immediately after seal-off a controlled arcing, or 'spot-knocking', was done by applying a high voltage with a high resistance in series to prevent the arc current reaching a damaging level.

Valve Repair

A frequent cause of valve failure, particularly with pure tungsten-filament types, was filament burn-out. The electrode assembly was designed in such a way that a valve could be cut open with a narrow carborundum wheel through one of the body/end-cap flanges, thus allowing removal of the electrodes. It was a simple matter to replace the filament or a damaged electrode, reseal and pump the valve. This represented a big cost saving over that of a new valve.

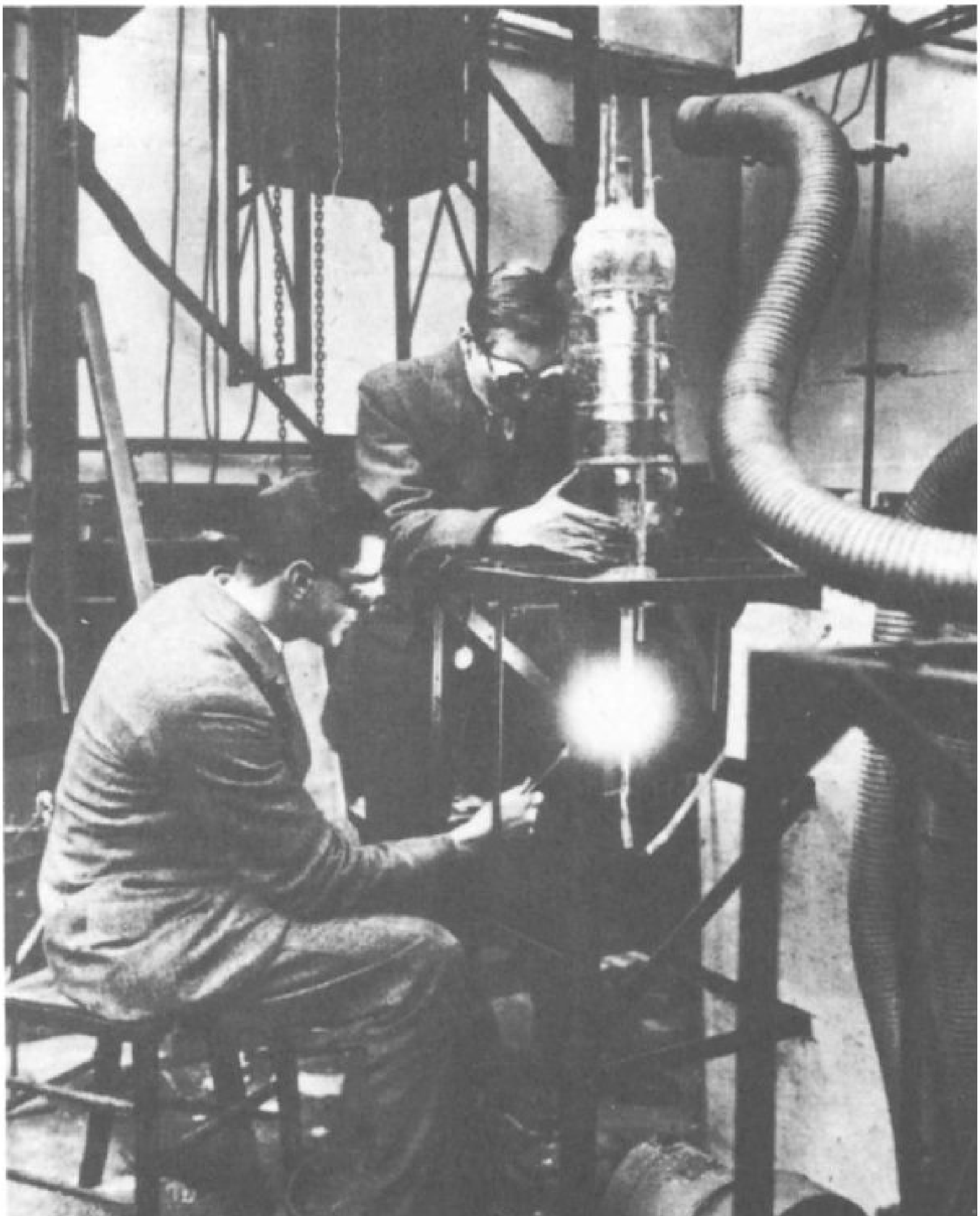
SILICA VALVES FOR RADIO TRANSMITTERS

The first silica valve for the Navy, the T22 output power valve, was designed by the Signal School early in 1920. Clearly there were as yet no valve technicians in Signal School, for the first sample was assembled by Thermal Syndicate using electrodes made by the new Mullard Co. The valve was about 6-in in diameter and 3-ft long, with an anode dissipation of 10 kW. It was sent to Signal School for pumping, but unfortunately collapsed on the pumps.

Presumably, Thermal Syndicate had been training Signal School staff in silica-working techniques because the next sample was made in Portsmouth using a strengthened envelope – probably the corrugated design used later for all the largest types. On this sample the flanges cracked during sealing. A third sample was completed successfully in September 1920.

There is no record of the T22 actually operating in a transmitter, but a slightly modified design, the T23, was used in the long-wave (4000-m) transmitter at Pembroke W/T Station. It produced about 8 kW in the antenna from a pair of valves, which was three times the power achieved with glass valves. The set also used a pair of U21 silica rectifiers.

Figure 3.5 shows one of these very-high-power valves being sealed off the pumps in Signal School in 1922.



3.5 H. G. Hughes and T. E. Goldup sealing-off a silica valve, 1922 (© Defence Research Agency)

Valves for short-wave use were made by Mullard in early 1922 using the standard large envelope, but with very short electrodes; oscillation was obtained down to 6-m. The Naval short-wave set 7H, using silica valves, operated at 10-m and was fitted in *Hood* and *Repulse*. A similar set, the 7K, was fitted in some aircraft.

Silica valves were used in all Naval transmitters during the next 15 years. A number of types, most of them in smaller envelopes (about 4-in diameter) than the early 6-in corrugated design, were introduced for ship and shore transmitters. Ship sets in the early days (1922) seem to have been largely experimental, for the study of propagation at different wavelengths between 1000-m and 5000-m. Much shorter electrode structures were designed for experiments at 15-m (1938) but the lead seals (the only design available) were inherently long, and set a lower limit to the achievable wavelength. In all, 21 silica types were standardised for communication sets; of these 19 were triodes, and two were pentodes. Ten rectifiers were also standardised.

It is worth noting here that, in 1932, after discussions with E. C. S. Megaw at GEC Research Laboratories, a split-anode magnetron, with four anodes in a small silica envelope (NT52) was developed for a homing-beacon transmitter for aircraft carriers. Opposite anodes were internally connected and brought out to a Lecher-wire system, and oscillation was obtained down to about 1-m.

SILICA VALVES FOR RADAR

The Start

It was perhaps, in a way, fortuitous that silica valves played such a vital role in the earliest days of radar. When the first experiments on aircraft detection were set up at Orfordness in 1935, silica-valve technology was indeed one of the most advanced available, although this was not the decisive reason for its choice.

Suggestions that aircraft might be detected by radio waves had come from various sources, starting with Alder's patent application in 1928 (see Monograph 1). No experiments were done in the UK, however, till those by Watson-Watt's team from the Radio Research Station in 1935. The same team had been studying reflections from the ionosphere using a short-pulse transmitter on 50-m. The output valves in that set were silica types, designed and made by Signal School. This transmitter was adopted for the aircraft-detection experiments, which were successful and expanded, and Signal School was charged with making a number of additional valves. By this time the chance of war with Germany seemed likely, and aircraft-detection research was initiated, and made highly secret. The fact that the transmitting valves came from a secure Service Laboratory was a vital factor in continuing to use silica valves. As late as May 1938 A.P. Rowe, of the Air Ministry Research Station, Bawdsey (AMRE) wrote to DSR, Admiralty, noting that 'we are completely dependent on HM Signal School for sealed-off valve research.' Aircraft- and later ship- detection experiments were started in Signal School in 1936, using the same valve types as AMRE, Bawdsey.

The first type used at Bawdsey was the triode NT41. It had been designed for a CW radio transmitter and was certainly not optimised for a short-pulse mode. Initially, processing changes were made to allow higher-voltage working, and in use the filament was over-run to increase the peak emission and hence the output power.

Special Developments

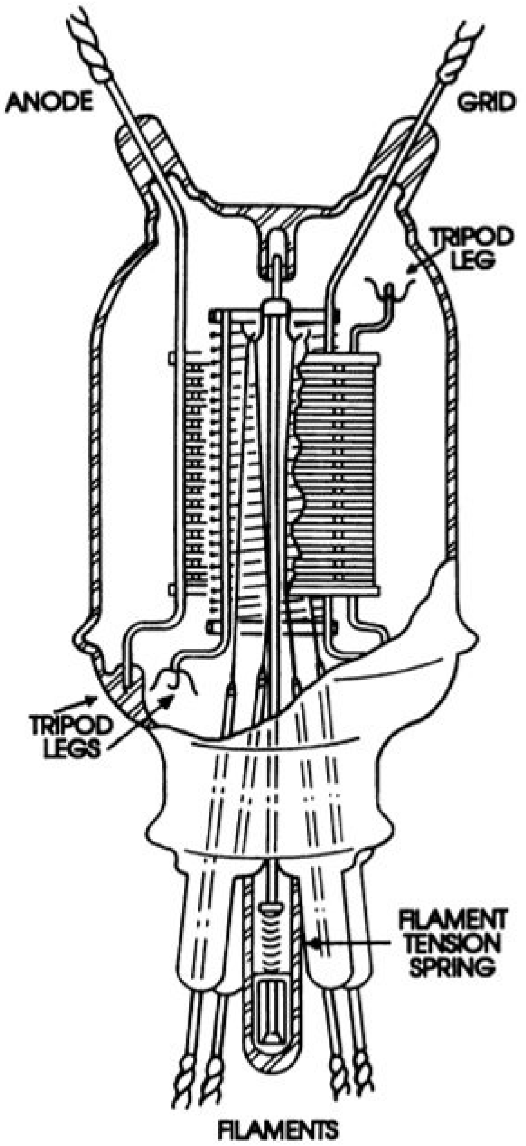
Full radar development was started at AMRE, Bawdsey, following a visit by the Tizard Committee in June 1935. In July Signal School were asked to undertake the development of special valves. The record reads:

'Signal School to produce six experimental silica valves, on the lines of the NT41 modified as required for the voltage conditions (5kV but worked up to 12 kV). Of these 2 to be ready by September 1, and 4 by October 1. Also 2 NT41A experimental valves to be supplied immediately. These were for 4-metre to 8-metre trials; for 25-metre to 50-metre trials, 2 NT41 valves to be supplied. Also consideration to be given in Signal School to possible modification to NT34 as regards peak emission. Three experimental valves to be made up for test by November 1935'.

Completely new designs for radar were in development by early 1937. Obviously there was still a shortage of valve-development engineers because, in January 1937, Signal School advised Bawdsey that they did not have staff to work on the higher-powered valves they had requested (This was surely due to bureaucracy, no doubt coupled with a lack of appreciation of the importance of radar). The first type designed specifically for pulse radar, NT57, was used by both Bawdsey and Signal School in experimental work, and in early operational sets.

Early in 1939 NT57 was modified by the introduction of Jones's thoriated-tungsten filament, and also of the new, short, graded-glass seals. There was an immediate increase in power output, by a factor of four, to 70 kW from a pair, and the possibility of operation at twice the frequency. Bawdsey used this type NT57T (Figure 3.6) to drive another silica valve, the tetrode NT77A, in a mobile radar, and it was the output valve in the Naval sets Types 79Z and 279 (see Monograph 4).

In the summer of 1939 a series modulator triode and an output triode were designed specially for the new Naval 3-m set, Type 281. The



3.6 The NT57T silica valve (© E. B. Callick and Peter Peregrinus Ltd)

modulator, NT78, had serious development problems due to overheating of the grid by back-radiation from the anode, the resulting high grid emission causing flash-over during hold-off. Replacement of the basket-anode by one of carbonised nickel, a high-efficiency radiator, was tried, but was difficult to process and tended to poison the filament. Finally the whole electrode structure was increased in diameter, holding the spacing the same, and using a basket anode. The larger anode-radiating area and the loss of more filament radiation from the structure ends lowered the anode temperature sufficiently to ensure a low grid temperature, and negligible grid emission.

The output valve (NT86) was a short-structure triode. A pair of NT86s driven by four NT78As in parallel gave a peak output in the short-pulse mode of 1 MW. A number of these sets were in operational use, very reliably, till well after the war.

In 1939 the RAF, using a huge number of mobile radars, needed large-scale production of NT77As. This requirement was difficult to satisfy using only the manual production technology of silica valves. GEC, by this time privy to the radar secrets, were asked to develop a metal-to-glass equivalent, and the silica valve was phased out. The Navy continued to use them.

In 1941 an attempt was made to develop a much smaller silica triode to work at 240 MHz in a small-ship radar. This was the NT88. The electrode structure and envelope were made as short as the very-high-temperature silica sealing allowed, and samples were produced. On test in the radar the output was very variable from valve to valve. It was found that valves were operating on the steep part of the efficiency/frequency curve, and that minor parameter variations were causing wide output variation. Such variability was clearly unacceptable, and the design was abandoned. This attempt showed the design limitation of silica technology for high-frequency operation, and undoubtedly spelled its demise.

The End of the Era

One further type, a very-high-power series modulator, the CV313, was developed successfully. It was a modulator tetrode with a very low amplification factor (4.5), and could therefore pass very high current without driving the grid positive. Further, by careful alignment of the grids and by taking precautions to obtain a smooth grid surface, it was able to hold off very high voltages without arcing. Three of these in parallel were used to switch the 2 MW magnetron in the Naval Type 992 TI set, which went into service about 1950. They continued to operate reliably till the much smaller hydrogen-thyratron replaced them during an equipment modification in the 1960s.

This was the last silica valve used operationally for either radio or radar by the Navy. For some time after that the Mullard Co continued to market several types for industrial RF heating applications, but the silica valve is now a lost technology.