

# The Evolution of the Hydrogen Thyatron

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## Abstract and Introduction.

The evolution of the hydrogen thyatron from its early beginnings to the present day is presented from the perspective of one manufacturer. Radar requirements drove the development of the hydrogen thyatron as a repetitive, high power line-type modulator switch. Before the invention of the hydrogen thyatron, line-type radar modulators used a variety of switches. It is worthwhile considering one of these in particular, the mercury vapour thyatron, because this device contained many of the necessary design features that were to be incorporated into the hydrogen thyatron.

## The Mercury Vapour Thyatron.

An example of an Hg vapour thyatron is shown in figure 1. This particular device, the CV22, incorporates the "boxed-in" anode geometry similar to that now used extensively in glass thyatrons [1]. The anode is surrounded by a shield at control-grid potential to avoid long-path breakdown. Another geometry, called the "bulb-filling geometry", was also used, where the anode and control grid electrodes were sized to fit closely with the inside diameter of the glass bulb, rather akin to the geometry in a modern ceramic thyatron. Such features are a necessity for all devices that operate on the left-hand side of the Paschen curve. The CV22 had a directly heated oxide cathode operating at 2.5 V and several tens of amperes.

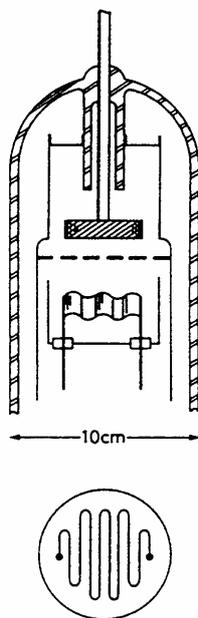


Figure 1. The Hg vapour CV22.

There was a control grid between the cathode and graphite anode. To all intents and purposes, voltage hold-off, triggering, conduction and recovery proceed in the same physical manner

as for the hydrogen thyatron. The CV22, rated to 20 kV and 50 amps, was used extensively in early British radars, as were other Hg vapour thyatrons like the CV12, which was rated to 15kV and 200 amps. These devices suffered from several drawbacks however. Firstly, mercury vapour pressure is a sensitive function of temperature, and thus the entire envelope needed kept at a controlled temperature, generally around 60°C. Secondly, the energy at which Hg ions destroy the oxide cathode is relatively low, and cathode bombardment was often the cause of end of life (if grid emission did not get there first). Thirdly, they had a de-ionisation time by virtue of the ionic mass that limited repetition rates to a few hundred pulses per second. Their ability to withstand inverse voltage was poor and thus if the magnetron should arc, not an infrequent occurrence, the Hg thyatron would arc-back, to its own detriment and to that of the magnetron. Lifetimes were generally inadequate; they lasted up to 200 hours at best, and often less.

## Early Thyatron Development in the USA.

Work started in the USA in 1941 under K. Germeshausen to develop a thyatron with improved characteristics using hydrogen as the gas filling [2]. There were perceived to be two big advantages over mercury that the use of hydrogen would bring. Firstly, the voltage corresponding to the ion velocity at which oxide cathode destruction occurs is about 600 volts for hydrogen, compared to the 30 volts or so for Hg and other gases. Thus, even if the cathode voltage fall for hydrogen was higher than that for Hg (which it is), there should still be scope for improved cathode lifetimes. Secondly, the recovery (de-ionisation) time would be significantly shorter by virtue of the lighter ionic mass, allowing operation at much higher repetition rates. However, one major problem was encountered which simply hadn't been as issue with the Hg vapour thyatron; gas clean-up. Gas clean-up is a result of the vigorous chemical activity of hydrogen, and had to be overcome before a practical device fit for field service could be manufactured. This problem was tackled in two major ways. One was to improve the purity of the materials used to prevent chemical reaction with the hydrogen, and to eliminate as far as was possible all other sources of contamination by improving cleanliness. The high purity materials introduced then, particularly the nickel from which much of the structure was fabricated, are still used today. The geometry also required modification for hydrogen and the structure that emerged is shown in figure 2, where the high voltage gap has been reduced from the 6 or 7 mm used in Hg vapour tubes to around 2 mm. The reasoning behind this is best explained with the help of figure 3, which is taken from data gathered much later [3], and shows how anode dissipation varies with operating pressure. A lower pressure limit for acceptable performance is imposed by a steep increase in anode dissipation, whilst an upper limit for pressure is imposed by Paschen breakdown. The choice of a smaller gap thus allows a reasonably high initial filling pressure, but at the same time provides as large a window of pressure as possible before gas clean-up caused

excessive dissipation. Another significant problem was that of grid emission, where cathode material provides an emission site on the control grid, causing the tube to go into continuous conduction when the grid temperature climbs after a short period of operation; hence the carefully positioned cathode baffle in figure 2. These guiding principles laid down the foundations for the hydrogen thyatron, and by 1948, a range of three service types had been introduced in the USA. These were the 3C45, the 4C35 and the 5C22, with ratings as indicated in Table 1. Figure 4 shows an early representation of a thyatron, in this case an experimental 5C22 manufactured at the Evans Signal Laboratory, Belmar, N.J., in 1945.

Max Ratings	3C45	4C35	5C22	5949	5948
Anode Voltage kV	3	8	16	25	25
Peak Current Amps	35	90	325	500	1000
Average Current (A)	.045	.10	.200	.500	1.00
Heater Power Watts	15	40	65	140	210

Table 1. Thyatron ratings.

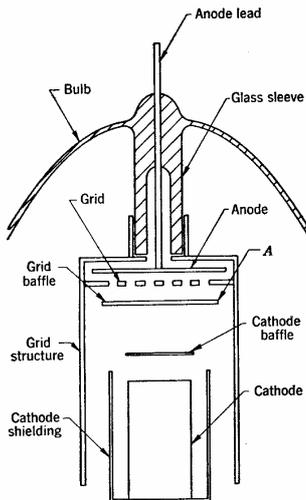


Figure 2. The structure of the hydrogen thyatron.

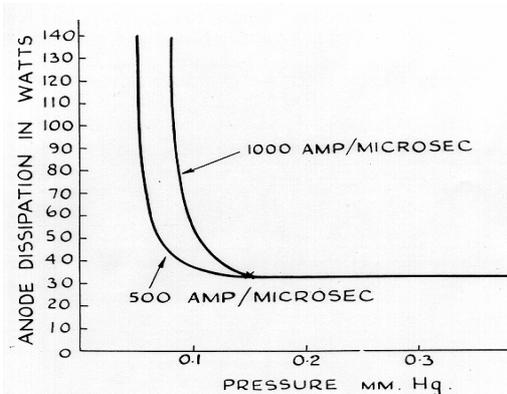


Figure 3. Anode dissipation vs. hydrogen pressure.

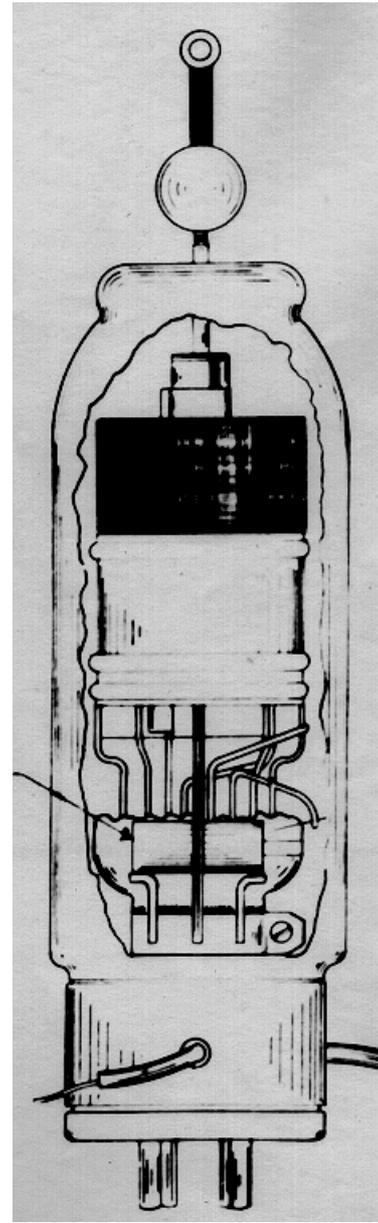
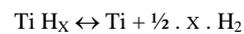


Figure 4. An early representation of a 5C22 (circa 1945).

### The Introduction of the Hydrogen Reservoir.

The very chemical activity that causes the problem of hydrogen clean-up was also to provide a solution. There are various metal-hydride systems that could lend themselves for use as a reservoir material in the hydrogen thyatron, and several of these have subsequently been investigated [4]. However, the one in common use today, namely titanium hydride, was also the first to be reported in detail [5]. The reservoir is a capsule containing titanium hydride that incorporates a heater. The reservoir relies on the reversible chemical reaction that occurs between hydrogen and titanium as a function of temperature:



where  $x$  is a number that depends on the loading of the host metal. As gas clean-up processes remove hydrogen from the right hand side of the above equation, hydrogen is exuded from the metal to maintain pressure equilibrium. However, since the equilibrium pressure is also a function of loading, pressure will still come down although at a slower rate. The reaction above is completely reversible, so the incorporation of a reservoir with a separate heater allows the gas pressure to be increased or decreased by adjusting heater power. Thyatron test specifications include ranging the reservoir voltage, usually between at least 95% and 105% of the set-point, to ensure that the operating window is adequate for service purposes. The reservoir was incorporated into three further service tubes introduced in the USA. These were the 5949, 5948 and 1257 with ratings also shown in Table 1. There are still many radar systems in service today that use the 5C22, 5949A and 5948A.

### Early UK Thyatron Activity [6].

Apart from an early attempt in 1942 [1], soon abandoned because of gas clean-up, it was after the war before thyatron development commenced in the UK. By 1949, and under contract from the government authority CVD, GEC Co. Ltd. at Hirst Research Laboratories had developed the VX3031, which was a non-reservoir tube similar to the 5C22. However, the problem of gas clean-up was very difficult to control, even on a pre-production basis. This led to the introduction of a nickel hydride replenisher mounted on the upper surface of the anode and the resulting device attained approval as the CV456. The concept of the anode replenisher, which did not require a separately heated capsule, was simple enough. As gas clean-up reduced the pressure, anode dissipation would increase and liberate hydrogen to compensate. Unfortunately, this gave the CV456 a rather narrow operating range, particularly in terms of anode voltage and p.r.f. Development of the thyatron at the then English Electric Valve Company (EEV Ltd.) commenced in 1948 under the sponsorship of the Marconi Wireless Telegraph (MWT) Company. MWT had by now manufactured a significant number of radar systems that used the CV12 Hg vapour thyatron, and saw a need to replace these as part of a larger upgrade program. MWT were encouraged by the Ministry of Supply to assist E.E.V. as much as they could, and the first thyatron developed was the FX215, which received ministry approval as the CV2203 in April 1951. The CV2203 was a form, fit and function replacement for the mercury CV12, and of the same overall size as the 5C22.

### Significant Developments: From 1950 to the early 1960s.

Substantial thyatron R&D activity on both sides of the Atlantic occurred during the next decade, much of it funded by the respective government authorities. In the USA, work was undertaken by EG&G, General Electric, Kuthe and others, often in conjunction with and under contract to the team at the Evans Signal Laboratories. In the U.K., the government funded much of the thyatron R&D activity at GEC Hirst Research Laboratories, BTH Co. Ltd. and EEV Co. Ltd, either directly through CVD or indirectly via other companies like MWT. The most significant advances that resulted from this research are presented below.

### Triodes/Tetrodes and Positive/Negative Grid Thyatrons.

All hydrogen thyatrons developed up to 1950 were triodes with a grid structure sufficiently baffled to provide a positive grid characteristic. This meant that the anode field had little penetration through the grid, and thus no negative bias was needed for the tube to hold off the full rated voltage. As part of the FX219 development at EEV to provide an upgraded version of the CV2203 for a new radar transmitter, it was discovered that isolating the cathode baffle and pre-pulsing it as a "grid 1" would provide improved performance, see figure 5 [7]. Anode delay times were more stable, anode delay time drift during warm-up was lower, and jitter was reduced. Further improvements to these characteristics were made by incorporating a more open grid structure. The disadvantage of requiring to hold the control grid 2 at a negative potential of around  $-100V$  was perceived to be outweighed by the improved performance that resulted. Most subsequent development work in the UK incorporated these features.

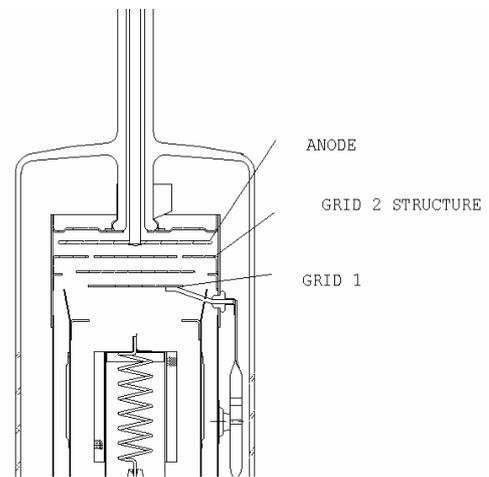


Figure 5. The introduction of grid 1.

### Non-Reservoir Tubes and Gas Clean-up.

Despite the advent of the reservoir, development efforts continued to understand the basic processes that cause gas clean-up and to provide process improvements that would mitigate it. In the UK, it was discovered, quite accidentally, that the non-reservoir CV2203 would absorb a considerable amount of hydrogen into its internal structure when subjected to an intense r.f. field at 200 MHz. This was introduced into the manufacturing process, where CV2203 thyatrons were over-filled and then irradiated with r.f. to bring the pressure back down to operational levels. The resulting tubes had lifetimes which were a factor of two or three greater than those previously obtained, the implication being that hydrogen driven into the structure, perhaps to form nickel hydride, was subsequently liberated at the correct rate. Improvements in processing yielded further benefits, and lifetimes in excess of 2000 hours for the non-reservoir CX1119 operating at close to double the ratings of the similarly-sized 5949 were obtained [7]. As to the root causes of gas clean-up [8]; it requires the formation of atomic hydrogen; it varies as the square root of the power dissipation in the gas; and permanent occlusion occurs predominantly in rifts and voids within the nickel structures.

### Ceramic Envelope Thyratrons.

A major research study, reported in three volumes [9] and spanning the period from 1951 to 1957, was undertaken by EG&G under contract with the Evans Signal Laboratories. This extensive study examined almost every conceivable aspect of the hydrogen thyatron, using the established glass-envelope 4C35 as the research vehicle. The development of the ceramic thyatron was one of the major steps forward that resulted from these efforts. The main operating limitation of glass envelope thyratrons is that the thermal path to the outside world is restricted for the anode and even more so for the control grid. Both of these electrodes experience power dissipation during operation, and this limits tube performance to what, by today's standards, are relatively modest average powers. The earliest proposed ceramic design was soon refined to the more familiar geometry of figure 6. The potential advantages are immediately obvious. This particular development matured into the EG&G 1802, which has the same ratings as the 5948/1754 glass thyatron, but only 1/7 of the volume and 40% of the weight. At around the same time, General Electric had also started the development of ceramic thyratrons. A study of the power losses in thyratrons in the UK lead to an alternative geometry for the ceramic tube as shown in figure 7 [10]. This metal-bodied design has the control grid structure as part of the envelope and allows even better grid cooling.

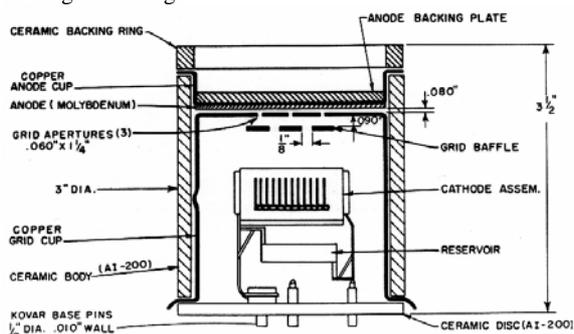


Figure 6. The single-gap ceramic thyatron.

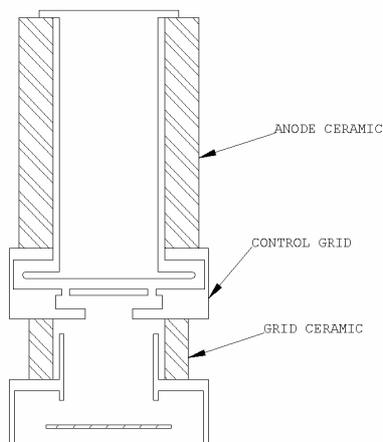


Figure 7. The metal-bodied thyatron.

### Hydrogen and Deuterium.

The use of deuterium was first investigated because the conduction drop across the thyatron was found to be lower [11], and thus tube dissipation would be reduced. Perhaps even more important, it was observed that the Paschen curve for deuterium is shifted to slightly higher p.d values than that of hydrogen, see figure 8. Therefore, at a given operating pressure, deuterium will provide a higher hold-off voltage. Alternatively, for a given operating voltage, deuterium pressures can be higher than those for hydrogen, and thus the thyatron can tolerate faster rates of rise of current before anode dissipation becomes a problem. The only drawback, unimportant for most applications, is that the recovery time is approximately 40% longer than is the case for hydrogen, as indeed theory predicts it should be. The present-day Marconi thyratrons type CX1140 and CX1159 have anode voltage ratings of 25 kV and 33 kV respectively; they are mechanically identical but the CX1159 is deuterium-filled. This discovery allowed a significant increase in peak power.

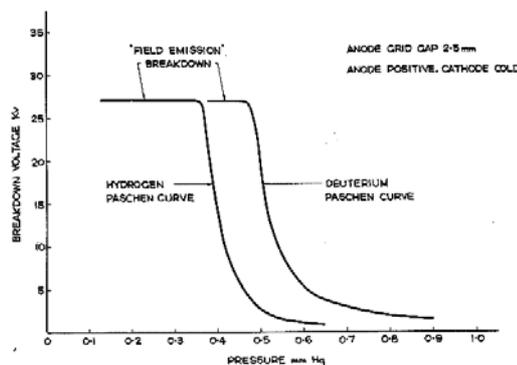


Figure 8. Paschen curves for hydrogen and deuterium.

### Larger Diameters and Multigap Thyratrons.

By 1958, a larger diameter ceramic thyatron, the General Electric Z-5069, had been developed. Under contract with the Signal Laboratory, this was the starting point for further development to attain higher peak and average power handling capabilities. An important step was taken by incorporating an extra electrode between the control grid and the anode, called the "voltage gradient grid" [12]. Figure 9 shows a schematic of this concept, which was similar to the structure of a high-voltage gridded mercury tube. This electrode sits at half the anode potential and this early structure enabled operation at voltages up to 50% higher than those attainable in the single gap version. Subsequent refinements to the geometry such as improved baffling lead to peak and thus average power handling capabilities being nearly doubled. An alternative double-gap geometry was developed [10], based on the metal-bodied thyatron, see figure 10. A third type of high voltage geometry that lends itself easily to the manufacture of multigap structures [13] is shown in figure 11. This repeated structure has been successfully applied to produce thyratrons with eight high voltage gaps.

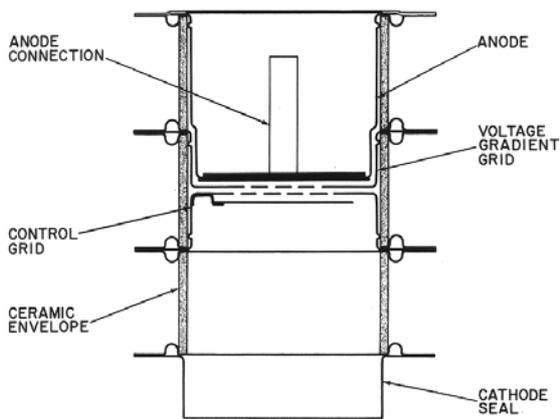


Figure 9. Early voltage gradient grid schematic.

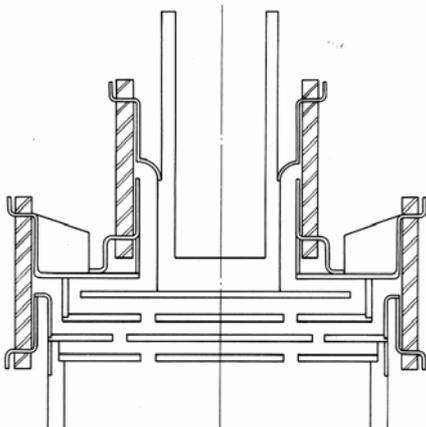


Figure 10. Double gap version of metal-bodied thyatron.

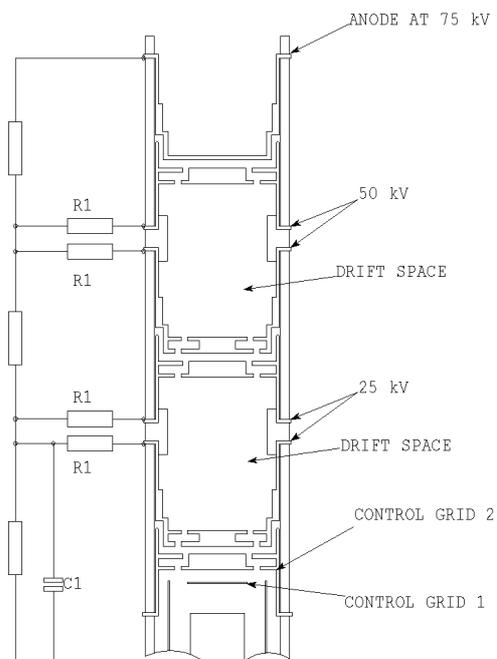


Figure 11. Multi-gap structure with "drift spaces".

### Thyratron Cathode Development.

The original oxide cylindrical cathode geometry as depicted in figure 2 is still used in many thyratrons of modern manufacture. However, effort has been devoted to examining different geometries for the oxide cathode and the introduction of the dispenser cathode for use in thyratrons. The vane-type cathode was introduced as part of the research work described in [9], and incorporated into various types of thyatron. Larger and larger versions of oxide cathode were required as power levels were increased. Factors influencing cathode lifetime were the subject of detailed investigation [14]. It was found that depletion was essentially temperature dependent only, and that every 25°C rise in temperature will approximately half lifetime. It is perhaps surprising that heater voltage programming has not been more extensively adopted as a result of this. The first successful use of an impregnated tungsten matrix, or dispenser cathode was reported in 1958 [15]. By 1960, a dispenser cathode had been incorporated into the metal-bodied VX3336 thyatron, and operated successfully for many hundreds of hours at average powers of about 180kW [16]. Thyratrons with dispenser cathodes have been in regular production in the UK since then.

### Reservoir Improvements.

The reservoir operates with a total gas content that is dictated by the need for it to have an equilibrium pressure that does not vary wildly with temperature fluctuations that might occur due to, for example, small changes in reservoir power. There is an important negative feedback mechanism that helps achieve this [9], where increases in temperature increase the pressure and thus improve the heat loss. A significant improvement to the simple reservoir was to operate a barretter in series with it [17]. The barretter regulates current very effectively, and thus stabilises reservoir temperature against input power fluctuations. As reservoir-filling temperature is decreased, the total gas capacity increases, but so does the sensitivity to temperature. By operating with a barretter in series with the reservoir, significantly higher gas loading can be achieved without suffering large pressure changes as the input power fluctuates. A refined version of this technique has been incorporated into many modern Marconi thyratrons. The effects of gas clean-up are completely annulled and the practice of ranging the reservoir voltage rendered unnecessary for thyratrons that incorporate this high capacity reservoir system.

### Further Developments: Early 1960s Onwards.

Whilst most development work until the early 1960s was for radar and defence requirements, other applications were emerging that were to provide a significant part of the impetus for future hydrogen thyatron development. Indeed, it could be said that defence research had resulted in device development that exceeded the needs of military equipment. These emerging applications were to provide a challenging proving-ground for the devices that had been created. Below, some of the applications and how they helped the evolution of the hydrogen thyatron are considered.

## Radiotherapy.

Just as for radar, the function of the thyatron modulator in a medical linear accelerator is to provide the required pulse for the magnetron or klystron. Anode voltages are generally up to 25 kV, pulse currents are around 1000 amps and pulse widths are a few microseconds. Average electrical powers range from 10 kW to 30 kW. Unlike radar at these power levels, however, there is no soft-start or settling period possible; the thyatron must come on at full power, and operate with minimum delay drift, because the treatment period is only generally a minute or two. Service is intermittent; one or two minutes at full power are followed by ten or so minutes with heaters only, and all of the high power components including the thyatron have to survive the several thousand thermal cycles that occur every year. Whilst radiotherapy doesn't necessarily call for any extension to thyatron operating parameters over that of radar, it imposes stringent requirements in terms of reliability and quality.

## High Energy Physics Research.

In 1957, plans for a two-mile accelerator to be constructed at Stanford in California were unveiled. The project called for 245 klystron modulators operating at ambitious peak and average powers. On the basis of cost and some initially encouraging results, efforts were at first directed towards the evaluation and development of the ignitron as the modulator switch [18]. No thyatron existed at the time that had sufficient ratings to meet the requirement, which by 1963 was as follows; anode voltage 46 kV, peak current 4000 amps, pulse width 4  $\mu$ secs and repetition rate up to 360 pps, representing peak and average powers of about 90 MW and 130 kW. Thyatrons with ratings progressively closer to this requirement were being developed, and the hydrogen thyatron was eventually adopted as the modulator switch. Tubes from most manufacturers were evaluated, and two were selected for linac operation; the Tung-sol CH1191 and the IIT KU275A. These were both 6" diameter tubes with oxide cathodes and a gradient grid. The need for low anode delay time drift required that tetrode thyatrons were used; both of these incorporated what has become known as a "keep-alive" grid 1, which is continuously ionised with a priming current of 200 mA or so. The SLAC modulators were upgraded in the 1980s to higher peak powers [19]. Other physics research establishments have smaller linacs that use similar modulators, for example those at KEK and CERN. Particle physics research generated further applications for thyatrons in the form of pulsed kicker magnets and crowbars. One of these lead to the creation of the double-ended thyatron [20], which has a thermionic cathode, reservoir and grid structure in place of the anode, see figure 12. The double-ended thyatron is a bi-directional switch. The grid 1 at the anode end is kept continuously ionised, and when the voltage reverses across the thyatron, reverse conduction proceeds smoothly with no observable delay. Single and multi-gap thyatrons have been used extensively for pulsed magnet excitation, and are in operation in many facilities throughout the world. To cite just one of the many examples of these, a set of kickers at CERN uses the three-gap CX1171 at 80 kV, producing a 2.7 kA pulse of 0.6  $\mu$ sec duration at up to a few pps. Multigap double-ended thyatrons have also been developed as crowbars for the protection of c.w. super-power klystrons [21], which operate at up to around 100 kV d.c. An

eight-gap thyatron crowbar system has been successfully operated at up to 180 kV dc [22].

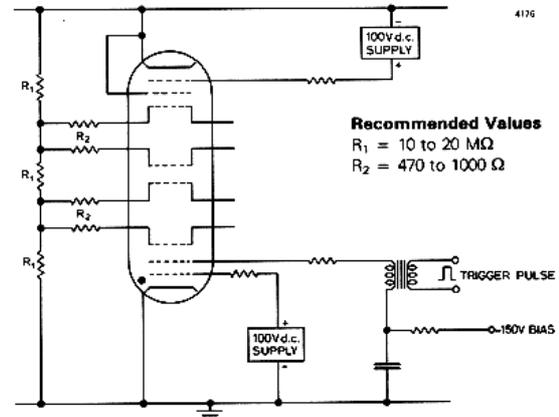


Figure 12. Schematic of a double-ended three-gap structure.

## Induction Linacs.

There have been several induction linear accelerators constructed over the years where thyatrons have been used for pulse charging applications. The first large one was the Astron, which used around 500 hydrogen thyatrons [23]. A more demanding set of operating parameters was required for the larger ATA, which resulted in the development of glass tubes for service at very high peak currents. A combination of three CX1538 thyatrons was used to meet the original requirement of 30 kA peak forward current for 15  $\mu$ secs, followed by 15 kA of reverse current for 12  $\mu$ secs, from a voltage of 27.5 kV [24]. It was the combination of peak current, pulse length and economics that was difficult to meet. Ceramic tubes were tried but, apart from being costly, they suffered quenching and failed due to arc-damage. The CX1538 is the same size as the 5949A or CX1140, and changes were needed to both the geometry and the materials used to meet the requirement. Over 2000 thyatrons were supplied for the ATA. Other induction linear accelerators have been constructed more recently; they use thyatrons that embody the advances made to meet the needs of gas lasers.

## Gas Lasers.

The most demanding gas lasers are of the excimer type. Laser head impedances are always sub-ohm, and fast rates of rise of current (100 kA/ $\mu$ sec) and high peak currents (10 kA) are often required. There is usually reverse current, and it can be as high as 50% of the forward current. These needs, and those of  $N_2$  lasers before them, lead to two new types of thyatron; the grounded grid thyatron and the hollow anode thyatron. The grounded grid thyatron [25] operates with what would conventionally be the control grid connected to ground potential. Triggering is achieved by pulsing the cathode negative with respect to the grounded grid, and conduction proceeds from the surface of the grid in a metal vapour arc. The metal arc can supply high peak current at a high rate of rise of current, and when the current reverses, the arc simply

transfers to the anode. Lifetimes of several tens of millions of shots under excimer laser conditions are achieved, limited by electrode erosion. The hollow anode thyatron [26], see figure 13, has a cavity located behind the anode into which plasma diffuses during forward conduction. When the voltage reverses across the thyatron, the stored plasma initiates a cold-cathode glow discharge from the cavity that can supply the necessary reverse current. Since the reverse conduction is in the glow- rather than the arc-mode, the voltage drop is considerably higher, but the uniformity of the discharge prevents damaging electrode erosion. High power hollow-anode thyatrons have been operated at 35 kV, 10 kA forward, 5 kA reverse at up to 500 pps and provide lifetimes well in excess of 1 billion pulses [27].

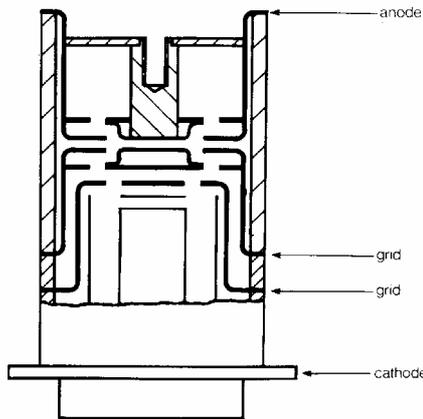


Figure 13. Schematic of a hollow-anode thyatron.

Copper vapour lasers are characterised by modest peak powers but operate at high repetition rate. A typical 10W laser may require the thyatron to operate at around 15 kV anode voltage, with a 500 amp pulse of 250 nsecs duration at up to 15 kHz. A fast recovery, triple grid thyatron has often been used to meet these needs. The control grid is shielded by the other two grids from any significant discharge volume and this speeds up recovery time considerably. Triple-grid thyatrons of this type have been operated at up to and beyond 100 kHz [28].

#### Operation of Thyatrons at Megawatt Average Power.

There have been several R&D programmes to develop and evaluate thyatrons at megawatt average power levels. These programmes have created some of the largest thyatrons ever manufactured. The MAPS 70 programme evaluated experimental 4-gap, 8" diameter thyatrons at up to 70 kV; the MAPS 250 programme evaluated an 8-gap, 4" thyatron at up to 200 kV. The MAPS 40 programme evaluated a 2-gap, 8" diameter thyatron at 40 kV [29]. In all three cases, operation was in adiabatic mode for periods of up to several tens of seconds, and encouraging results were obtained. Other burst mode tests have since been conducted on large diameter thyatrons for ETA II at LLNL [30] and as part of the SDI programme. Continuous operation at 1 megawatt in an inverter application was achieved using two dispenser cathode thyatrons of the metal-bodied type, cooled by oil immersion. The peak current was only 120 A, but the average current was very high at 60 A [31].

#### High Average Power Industrial Linacs.

Various facilities now exist that use accelerators for industrial applications like the sterilisation of medical and food products. These machines are characterised by high average powers (100 – 200 kW), but differ from, say, the SLAC type modulator in that the anode voltage is generally lower and thus the average current is generally higher on a continuous basis (up to 15 amps). Two large diameter tubes resulted from these requirements; the Marconi CX2412A and CX1720 with 6" and 8" diameters respectively. Large area, high power dispenser cathodes were designed for them. The CX2412A has a heater power of 1 kW and the CX1720 has a heater power of 1.5 kW.

#### Cold Cathode Devices and the Metal Arc Thyatron.

There has always been interest in cold cathode discharge switches because they have no standby heater power requirements. Instant start thyatrons, pseudo-spark switches, crossatrons, back-lit thyatrons and other devices have all emerged and been evaluated under many different conditions of operation. Discussion here is limited to the metal-arc thyatron, for no other reason than it is the most recent to emerge [32]. A schematic of this device is shown in figure 14. Facing the anode there is a cold cathode electrode, with a thermionic cathode and apertured grids positioned below it. The cathode and reservoir systems are only present to impart the benefits of thyatron triggering characteristics.

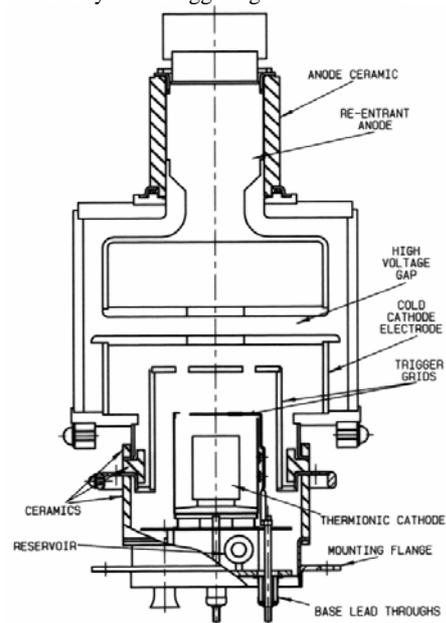


Figure 14. Structure of the metal-arc thyatron.

A positive trigger pulse applied to the control grid creates plasma, which diffuses through apertures into the anode field, where there is rapid ionisation growth, culminating in the formation of a metal vapour arc on the anode-facing surface of the cold cathode electrode. Gap dimensions and hydrogen pressures differ significantly from those in a conventional thyatron. A range of three sizes has been introduced, with peak current ratings from 7.5 kA to 100 kA, and coulomb transfer capabilities up to 40 C. They are intended for discharging high-energy capacitor banks. The largest device, HX3010, incorporates a structure that generates an axial

magnetic field as circuit current passes through the tube, a concept used in vacuum interrupters. This technique prevents arc-constriction and anode spot formation which would otherwise occur, and increases the peak current capabilities by a factor of between five and ten.

### Concluding Remarks.

The evolution of the thyatron from the modest power ratings of the glass envelope 5C22 to the much higher powers of the multigap, large diameter ceramic tubes available today has been described. It is a tribute to the ingenuity and persistence of the many scientists and engineers who have contributed to this process over the years that such impressive progress has been made. Thyratrons remain the switch of first choice for many applications in medicine, science and industry.

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