ABERDEIN

BBC ENGINEERING HANDBOOK

THE OPERATION AND MAINTENANCE OF KLYSTRONS IN U.H.F. TELEVISION TRANSMITTERS

THE BRITISH BROADCASTING CORPORATION

ENGINEERING DIVISION

TRANSMITTER CAPITAL PROJECTS DEPARTMENT

AND

TRANSMITTER GROUP

The Operation and Maintenance of Klystrons in UHF Television Transmitters

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The Operation and Maintenance

of Klystrons in UHF Television Transmitters

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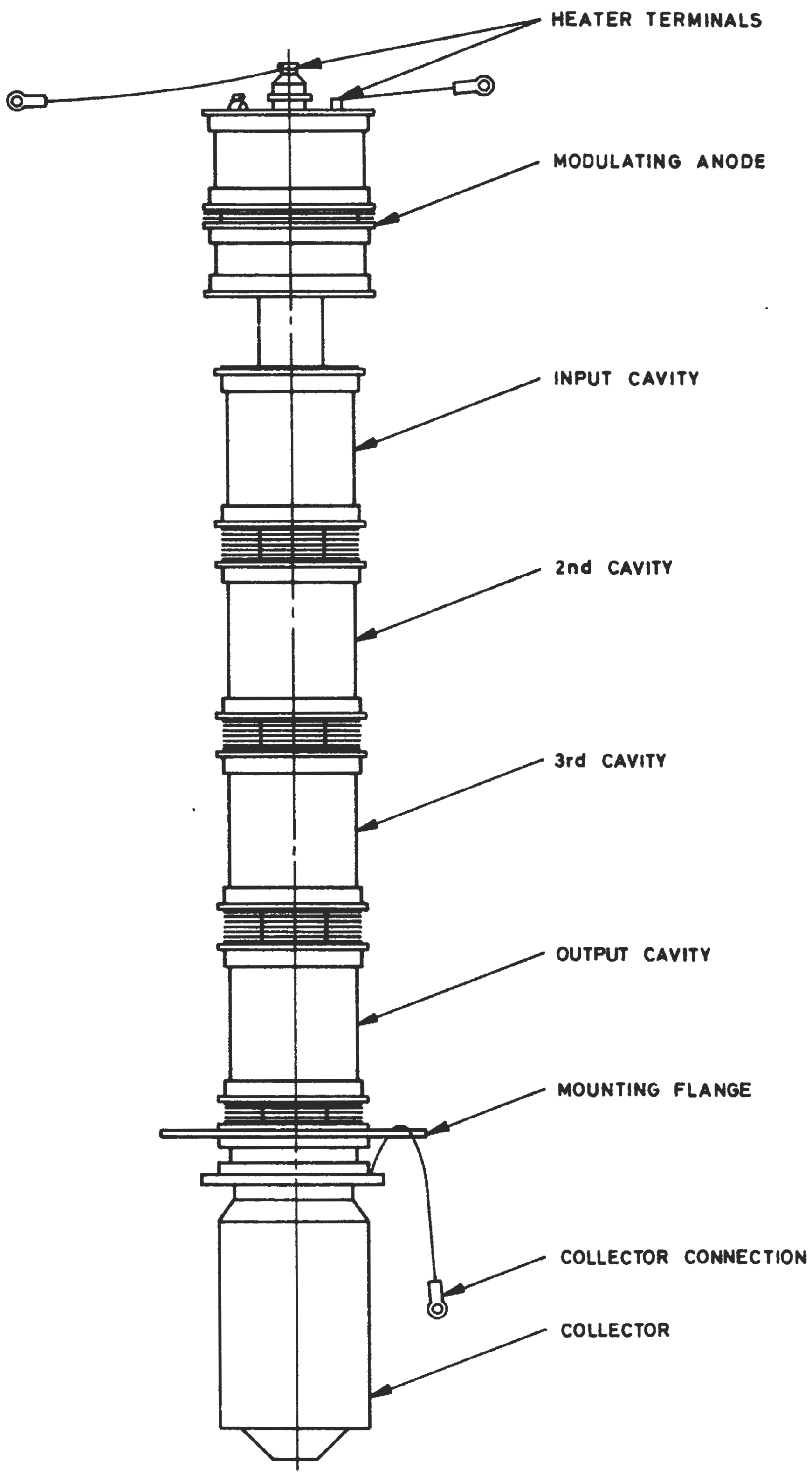

10 KW BAND IV TELEVISION
KLYSTRON LESS EXTERNAL CAVITIES

THE OPERATION AND MAINTENANCE
OF KLYSTRONS IN UHF TELEVISION TRANSMITTERS

1. INTRODUCTION

The word 'Klystron' is derived from a Greek verb which describes the action of waves breaking on the sea shore and one of the objects of this publication is to reveal how fast they have been breaking on our shores since 1966 when major expansion of the UHF services commenced.

A total of over 10 million burning hours has been accumulated by the 276 BBC klystron sockets now operating at 71 transmitter stations resulting in projected average lives of 16,000hrs or greater. The cost per burning hour is about 27p based on 1978 prices but it must be remembered that the individual capital replacement cost is high. For example the average purchase price of a klystron is now £4,420. Altogether there have been 415 or so failures and although in the great majority of cases these have been satisfactorily accounted for, it is recognised that staff have not had as much practical information as the BBC would have liked.

The primary purpose of this publication therefore is to aid staff to more easily identify the causes of failure so that circumstances where recurrent failures occur might be prevented.

In addition some background information of general interest has been included concerning failure statistics.

2. GENERAL

2.1 Klystron Types

All high power klystrons in BBC operation are of the four cavity variety and have typical gains of between 36 and 47dB. Their saturated output power capabilities vary between 6 and 45kW. In general two manufacturers have supplied all requirements. There are in excess of 30 different types stocked, their lengths varying from 1034mm to 1619mm; the corresponding net weights varying from 25kg and 95kg. The major portion of the weight is accounted for by the copper collector.

The klystron is a precision device containing 44 or more vacuum seals and therefore careful handling is essential. The deployment of different klystron types is shown in Appendix I.

2.2 Life Expectancy of Klystrons

Before giving the statistical information, it is necessary to explain a few definitions:-

1. **The Average Life of Failures** is the sum of the burning hours of the failures divided by the number of failures.

2. **The Mean Time Between Failures** (M.T.B.F.) is the total of all burning hours divided by the number of failures.

3. **Projected Average Life** The average life of failures and the M.T.B.F. only become meaningful after a significant number of failures have been recorded. When only a few failures have occurred, it is usual to obtain a comparatively low average life for these failures accompanied by a high M.T.B.F. As time passes, these figures converge. In the interim period it is possible to obtain a projected average life figure. This will lie between the two extremes and take into account the relationship between the number of failures and the number of active sockets.

4. **Survivor Curves** From the lives obtained survivor curves may be plotted or histograms may be drawn. The object of these exercises is to provide estimates for forward maintenance replacements, and to guide manufacturers into realistic production planning. The 'lead time' or time which elapses between order and delivery of a klystron at present varies between 4 and 18 months.

   The manufacturer uses the information as a check on the quality of the product and a guide to the warranty afforded. (See Appendix II–'Klystron Warranty').

   The survivor curve for 25kW water cooled klystrons is illustrated in Fig. 1. From this it is shown that at 4,000hrs life there is a 67% chance of survival; at 10,000hrs a 37·6% chance and at 45,000hrs a 1·1% chance.

   It should be noted that this curve is drawn from all failures to date, including early teething troubles, and a batch which had a manufacturing defect.

5. **Rate (Cost per running hour)** This is the unit cost of the klystron divided by the projected average life.

2.3 Statistics

Statistical information is updated by Valve Section at periodic intervals for each type of klystron to determine the current life expectancy of klystrons and the average running costs (sec Appendix III for details). In 1978 for example, the cumulative burning hours for all BBC klystrons was over 10,000.000 hours. The average life of the failures was about 13,300 hours, the mean time between faults nearly 26,000 hours, and the projected average life 16,600 hours.

Klystrons fail for a variety of reasons, but low emission, gun and vacuum faults account for nearly 80% of the failures. A detailed breakdown is included in Appendix III.

3. TYPES OF FAILURE

Klystron failures can be placed in the following four categories:

1. Natural failure
2. Transmitter faults
3. Klystron manufacturing defects
4. Accidental damage

Category 1 is normal end of life failure. Category 2 refers to a klystron failure which occurs because of a fault in the transmitter. Category 3 is because of a manufacturing defect in the klystron itself. Category 4 is self-evident. Even experienced staff faced with a klystron failure will sometimes find it difficult to recognise the correct category and take the appropriate action.

In the majority of cases natural failure will be the cause, although category 3 still occurs from time to time. Accidental damage is infrequent and most incidences of this type have been the responsibility of contractors installation staff. Category 2 can sometimes be very difficult to recognise but to avoid recurrent failure it is essential for this possibility to be eliminated before a replacement klystron is fitted.

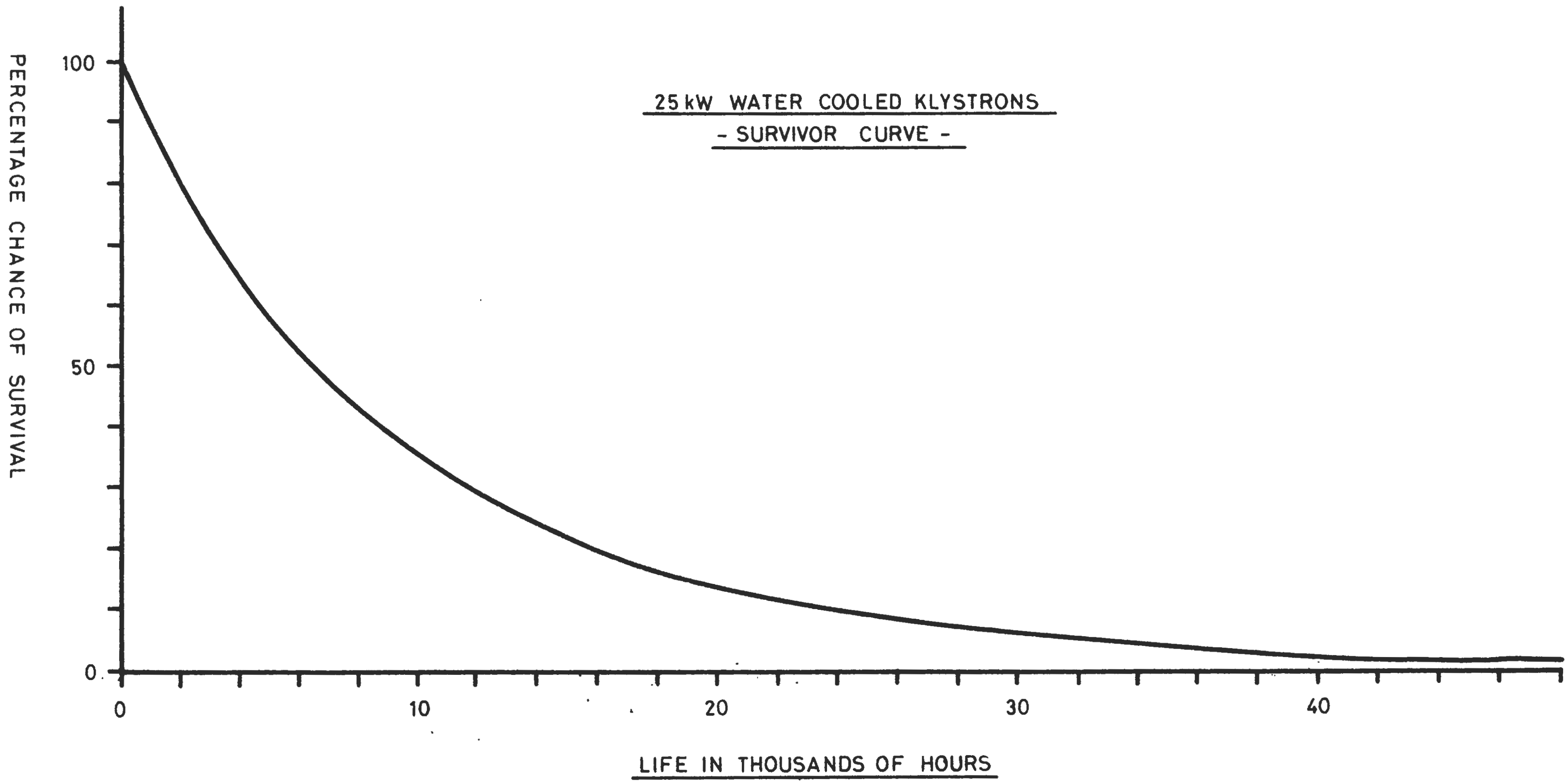
25 kW WATER COOLED KLYSTRONS
- SURVIVOR CURVE -
PERCENTAGE CHANCE OF SURVIVAL
100
50
0
0
10
20
30
40
LIFE IN THOUSANDS OF HOURS

FIG. 1.

3.1 Natural Failure

Natural or end of life failure should normally occur after the klystron has exceeded 10,000 heater burning hours although in some 20% of cases over 25,000 hours have been obtained. In a few instances lives in excess of 45,000 hours are being recorded.

Natural failure is often preceded by a slow deterioration in gain and linearity. There will also be a noticeable decline in collector current and a steady increase in body current. The latter occurs because the electron dynamics deteriorate as the cathode emission declines.

Finally the klystron has to be taken out of service owing to unsatisfactory transmission performance, or because of body current trips when the e.h.t. is applied during 'start up'. The latter is a function of 'slow warm up' whereby the cathode must reach a higher temperature for a given emission as the klystron ages.

Until an adequate level of emission has been attained the klystron will not focus correctly. As a consequence body current trips tend to occur when the e.h.t. is first applied. At some locations the possibility exists for such a klystron to be fitted into a 'Sound only' socket where the operating conditions are less demanding.

3.2 Transmitter Faults

These faults may be sub-divided into the following two areas:

a) Faults within the transmitter or klystron truck
b) Faults due to the heat exchanger or water cooling system

a. Faults within the transmitter or klystron truck

In general, faults covered by this category are normally found in the klystron truck itself although the possibility of faulty metering of the transmitter causing incorrect focus or body current conditions cannot be discounted. As far as the klystron truck is concerned the following four main areas should be considered:

1. The gun assembly
2. The cavity assembly
3. The focus assembly
4. The collector assembly

Faults caused in the gun assembly, see fig. 2, are frequently the result of excess heat. This can arise because of inadequate cooling of the modulating anode or because of resistive power loss at the heater terminals. The former is usually due to the air stream being incorrectly directed and resistive power loss will result if the heater terminals are inadequately tightened. It is important to ensure that the heater current is maintained at the correct value and that the associated metering circuits are operating properly.

External cavity faults are usually caused by the spring fingers making poor contact. This can cause r.f. arcing between the cavity and the klystron flange, or between the walls and tuning doors of the cavity. Arcing between the output coupling loop and the output cavity ceramic flares can cause loss of vacuum. See fig. 3.

At a few sites integral cavity klystrons are installed. These are somewhat special and further details are contained in section 4.6a.

An abnormal focusing condition can produce a concentrated electron beam which does not diverge at the collector. Normally divergence is such that maximum dissipation occurs about half way down the collector.

In the absence of divergence, maximum dissipation will occur at the collector base and burn out will result. This phenomenon is uncommon and the more usual varieties of focus assembly faults such as short circuit turns or short circuit to chassis are unlikely to cause klystron destruction providing the metering and trip circuits are operating correctly.

Faults in the region of the collector can arise because of incorrect boiler positioning or low resistance leakage paths to earth effectively shunting the body current metering circuit. The latter can be particularly difficult to diagnose correctly unless careful records have been maintained of the focus current/body current relationship. More complete details of this type of fault condition are given in section 4.10.

In the case of 6¼ and 10kW klystrons, boiler positioning (height and centering) can be checked with a special jig supplied by the manufacturers. Valve Section hold such a jig which can be sent to site on request. For high power klystrons the boiler position is fixed.

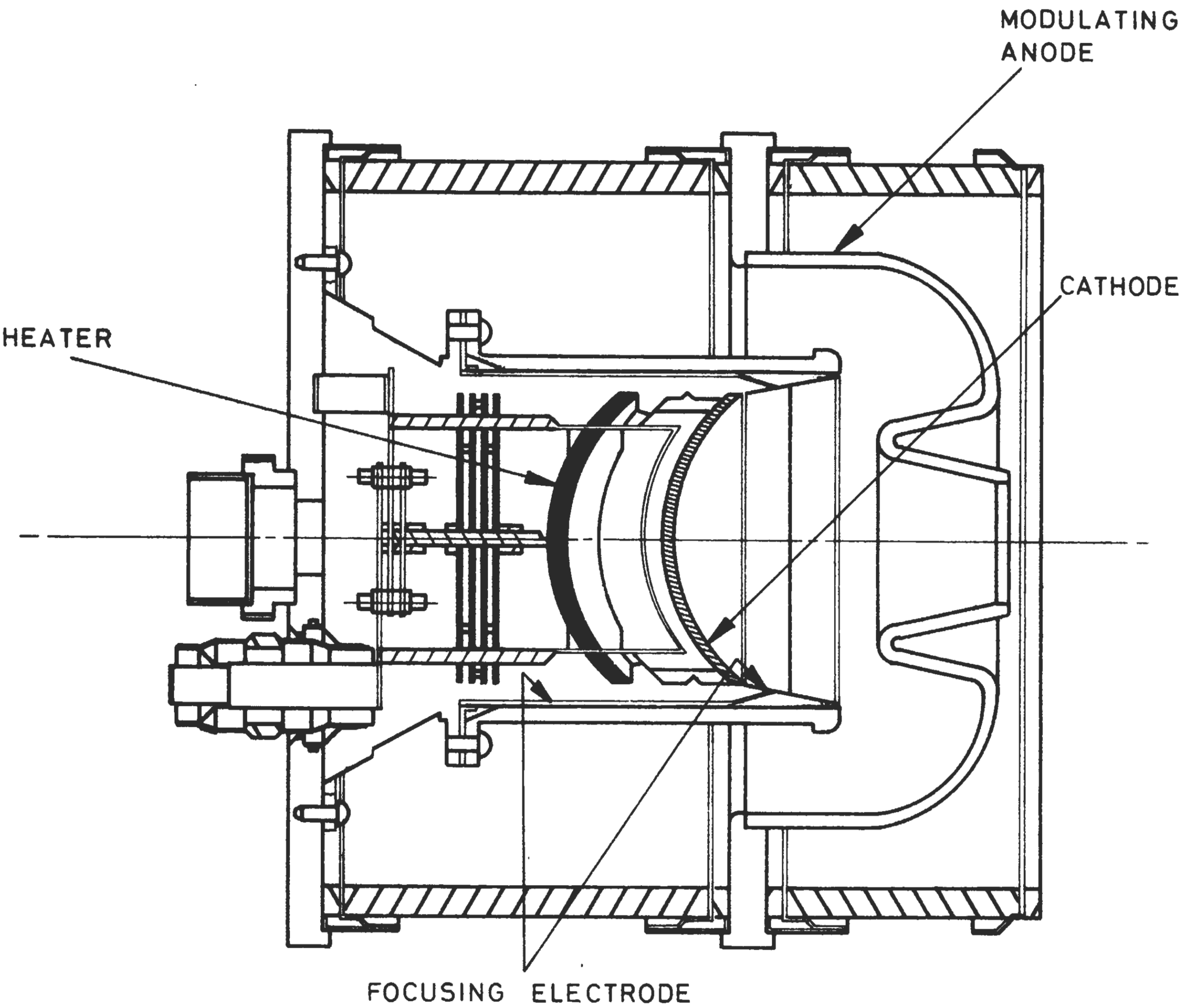

FIG. 2. A TYPICAL ELECTRON GUN CONSTRUCTION

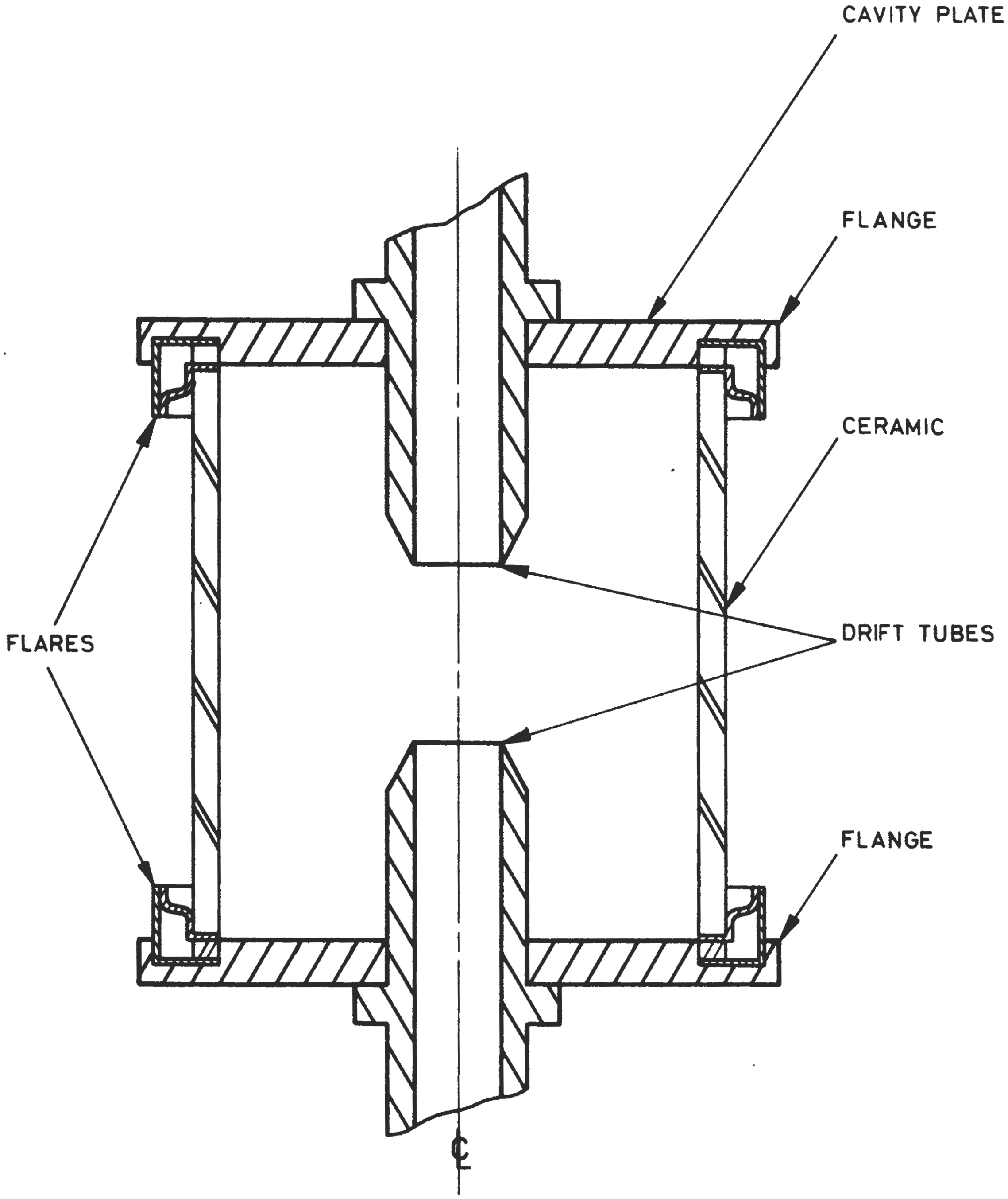

FIG. 3. KLYSTRON CERAMIC TO FLANGE SEAL — DETAIL

b. Failure due to the heat exchanger or water cooling system

Failure due to this category almost always results in severe overheating of the collector but is easy to detect when the klystron is removed from its truck assembly.

It is obvious that whichever type of cooling is employed, whether it be water cooling or vapour phase cooling, it is essential for the correct water level and rate of flow to be maintained. These requirements are detailed in the manufacturers handbooks for particular equipments and should be carefully observed. It is of particular importance to ensure that the low water level trip mechanism is maintained in correct working order.

Contamination of the water supplies can provide a more subtle form of failure which can be extremely difficult to diagnose. Such failures are rare but unless the fault is correctly diagnosed and remedial action taken, recurrent failures are likely. The English Electric Valve Company has published a paper dealing with this topic in considerable detail and copies have been issued to all transmitter managers. The more salient details are given in section 4.9.

3.3 Klystron Manufacturing Defects

A number of failures have occurred over the years due to klystron manufacturing faults usually in the gun assembly. One form of fault involves a partial heater short circuit and this can be readily detected by observing the abnormal behaviour of the heater voltage and current metering.

Other faults involve barium oxide migration from the cathode to the focus electrode. Emission from the focus electrode has resulted in over dissipation of the mod-anode and high body current. This type of fault is less frequent nowadays but it serves to illustrate the type of situation which can arise when the klystron itself has an inherent fault.

3.4 Accidental Damage

Klystrons are fragile devices and must be handled carefully, particularly when being installed or withdrawn from the truck assembly. The manufacturers assembly manual must be followed when either operation is being carried out.

It is of utmost importance to ensure that all connections between the klystron and its truck assembly are released before lifting commences. In the case of 25 and 40kW klystrons it may not be realised that it is necessary to remove the flux plates and the mod-anode clip to permit the gun assembly to pass freely through the mounting frame.

Special care must be exercised when a power operated hoist is being used and where ‘quick fit’ cavities are provided as the klystron is liable to tilt to one side as it is being withdrawn. This is because the guide wheels in the vertical rails restrict lateral movement and tilting generally results in the collector becoming jammed in the boiler aperture.

If a klystron should be accidentally damaged it may be possible for the manufacturer to effect a repair. In fact several klystrons have been successfully repaired at relatively small expense to the BBC. A common form of accident results in the klystron becoming bent and manufacturers have had a good success rate in treating this particular form of damage.

It is emphasised that no attempt to effect repair should be made by maintenance staff nor should attempts be made to fit a damaged klystron into a transmitter.

Staff are asked to report details of any accidents to Valve Section who will arrange for the klystron to be transported to the appropriate manufacturers’ premises for inspection and if possible subsequent repair.

4. OPERATION AND MAINTENANCE

This section is included to provide background information and general guidance only. Inevitably, specific maintenance requirements for particular installations will depend on the individual design and application, and will be subject to local instructions from transmitter managers or Head Office. Further information is also contained in the current issue of ‘The Valve Section Handbook’.

4.1 Acceptance

The klystron container should be opened on receipt and the contents inspected carefully to ensure that no obvious damage has occurred in transit. A gas check should then be carried out. If the ion current measurement is below the figure specified in the manufacturers Data Sheet, the klystron can be regarded as having a satisfactory vacuum, and may be left stored in its transit container to await a power test.

4.2 Gas Checks

A klystron can be used as an ion gauge to check relative gas pressure and thus indicate the condition of its own vacuum. The manufacturers initially stipulated that these tests (see Manufacturers Assembly Manual) should be carried out on acceptance, and then at monthly intervals, whilst in storage. Experience has shown that after the vacuum is proven to be consistently hard over three consecutive months, the interval between tests may be extended to three months. This is with the agreement of the manufacturers.

Because the leakage resistance across the klystron elements involved must be high, very small current measurements are obtained. Attention is drawn to the fact that an external leakage path could be presented by the protective papers or by packing support material, and this may give rise to erroneous measurements.

4.3 Conditioning of Klystrons

If a gas measurement exceeds the maximum value specified in the Klystron Assembly Manual, supplied by the manufacturer with every klystron, it will be necessary to condition the klystron. This may conveniently be carried out by leaving the gas test set in operation, connected to the klystron, whilst exposed in its transit case.

It is recommended that the conditioning be carried out in this way for periods of 5 minutes each hour at approximately hourly intervals, until a satisfactory gas test measurement is obtained. By employing this method it is not necessary for the gun to be forced air cooled, as the external parts of the klystron will not reach the maximum specified temperature of 175°C. When gas testing or conditioning a klystron assembled in its frame, it is necessary to insulate the frame from earth, e.g. move it onto a cork or linoleum floor. If a klystron requires regular conditioning, it is preferable to install it in a working socket at the earliest opportunity.

4.4 Spare Klystrons

Before any spare klystron is placed in a working socket a gas check must be carried out. Upon receipt of a new klystron and after the gas check, it is preferable that it be given a power test and left in service for a proving period. This will identify 'manufacturing defect' types at an early stage and result in full guarantee replacement being obtained.

4.5 Klystron Cleaning

a. Alumina Ceramics

Alumina ceramics are distinguished by their white or pinkish-white colour and are best cleaned with an abrasive household cleaning material (such as Gumption) which does not contain bleaches or dyes. The cleaning pad should always be kept damp and the cleanser should be completely removed by rinsing with clean water before the klystron is returned to service or put in storage.

b. Beryllium Oxide Ceramics

(See also BBC Safety Regulations 2.3.26, 2.7.10 and 3.8.6).

Beryllia ceramics are distinguished by their blue or mauve-blue colour, but there are also some which are off-white and these have a black line around their circumference. They are normally only used on the output cavities of 10kW klystrons and on the penultimate and output cavities of 25kW and 40kW klystrons.

Beryllium oxide dust and fumes are highly toxic if inhaled, or if particles enter a cut or abrasion. Personnel should avoid handling these ceramics; if they are touched, the hands must be washed before smoking or eating.

It is important to avoid doing anything to the beryllium oxide ceramics which may produce dust or fumes. On no account may they be filed or cleaned with abrasive cleaners. If minor cleaning is required, this may be done with a damp cloth. If this is ineffective, no further action may be taken except to report the matter to Valve Section.

If a beryllium oxide ceramic is broken, proceed as follows:-

> Wearing impervious rubber gloves, use water and wet cloths to settle any beryllium dust. Collect any particles. Wrap several layers of adhesive tape (masking or insulating tape is suitable) around the break line of the ceramic. This will prevent any further escape of dust and chips due to abrasion of the broken parts. Return the klystron to its transit case and include the wet contaminated cloths and gloves with the beryllium oxide debris in a suitably sealed container. Valve Section should then be notified so that arrangements can be made for collection.

c. Cleaning of Klystron Flanges

Ceramic-to-metal seals are used on the outer edges of the ceramics and drift tube-to-metal rim seals are provided on the outer edges of the drift tubes. The outer edges of these thin metal rims are folded and welded together, and this section is termed the flare. It is situated underneath and near to the flange upon which the cavity contact fingers engage. For good contact purposes the flange is gold plated, see Fig 3.

On no account may any abrasive be used on the outer edge of the flare. If absolutely necessary, a flange may be cleaned by rubbing very lightly with a woven plastic cleaning pad, such as 'Scotchbrite' soaked in water. It is preferable to clean the flange before cleaning the ceramic, and to protect the ceramic whilst this cleaning is taking place.

4.6 Klystron Cavities

In general, klystron cavities are not interchangeable. The input cavity should always therefore be used as an input cavity, the second cavity as a second cavity, the third cavity as a third cavity and the output cavity as an output cavity. If there are no identifying signs on these cavities, station staff should provide some permanent identification.

a. Integral (Internal) Cavity Klystrons

At Pontop Pike and Winter Hill, 25kW integral cavity type klystrons are installed. These devices are significantly different from the external cavity types more commonly used by the BBC in that the cavity assemblies and tuning elements are contained within the klystron body. A major complication with this design is the need to evacuate the cavities.

In common with 25kW external cavity type klystrons, as these tubes have water cooled bodies and collectors, leaks sometimes occur.

As a precaution certain checks need to be carried out prior to installing a replacement klystron of this type to reduce the likelihood of water seepage. These are performed with the standard glycol/water cooling mixture and a hand-operated 'Tangye' pump. The recommended pump pressure for this test (50lb per square inch) is less than that developed by the pump in the transmitter, to avoid excessive pressure being applied inadvertently, which experience has shown will tend to distort the tuning vanes in the cavities and increase the possibility of klystron malfunction. A further precaution is to avoid operating the tuning vanes to the limits of their travel to prevent them becoming welded to the klystron body if mechanical distortions of the type previously referred to occur in practice.

It is important to ensure that the 5W loads provided to terminate the second cavities are always fitted to avoid the risk of r.f. flashovers across the inner and outer conductors of the 'type N' connectors.

b. External Cavity Klystrons

1) Tuning Control Mechanisms

The original cavity design incorporated ball bearings in the tuning mechanisms but in the course of time these tended to become stiff or even to seize thus hindering tuning adjustments. Evaporation of the original lubricant has also contributed to sheared Allen screws and to wear on the slide pins of the spring loaded cross coupling shafts.

To overcome stiffness, a light application of a cleaning oil is recommended. For seized bearings, complete cleaning and relubrication should be carried out and sometimes it may be necessary to fit a replacement. In the latest cavity design these bearings have been replaced with nylon-nut inserts which are much more satisfactory and the BBC is considering the possibility of applying this modification to all cavities.

2) Cavities and Coupling Loops
When a klystron is replaced the opportunity should be taken to check all the external accessories. In particular the condition of the coupling loops and the internal cavity components should be examined. Dust deposits which tend to be trapped are best removed with an air blower. When normal cleaning is insufficient a clean dry or damp cloth may be used and if absolutely necessary a woven plastic material pad (Scotchbrite etc) damped with water may be employed.

The inside of the cavity is silver plated and harsh abrasive materials must not be used. If significant contact or surface burning has occurred it may be necessary to have them re-plated by the manufacturer.

Coupling loops should be examined and cleaned as necessary. If any arcing has occurred with accompanying burning, high spots must be removed to avoid further corona discharge.

3) Cavity Gauze Filters
Sometimes the gauze filters fitted inside cavities become dust-clogged. In many cases these cannot be removed externally and it becomes necessary to dismantle the cavity for servicing purposes.

These filters are not provided with cavities currently supplied and **it is now recommended that they be removed from all equipments.** This will eliminate a maintenance requirement and may assist in the relief of other problems because micro-dust will be presented with less obstruction and will no longer be blown through the bearings or the spring finger gaps.

The above should not be confused with the r.f. filters fitted in the air cooling pipes of certain cavities.

4.7 Types of Cooling

a. Air Cooling
All klystrons used in BBC transmitters have air cooled gun assemblies but the collectors are usually water or vapour cooled. Some of the larger klystrons also use water cooling for the drift tubes.

At Reigate and Tunbridge Wells, however, the transposers are fitted with an early design of klystron with air cooled collectors and although these klystrons have given good average lives the equipment is noisy and runs rather hot. Modifications have been carried out to improve the focusing and transmitter cooling with a view to improving overall reliability.

b. Water Cooling
Klystrons employing the water cooling principle are used at the following 25kW transmitter stations:

Divis	Sutton Coldfield	Winter Hill
Durris	Wenvoe	
Emley Moor	Pontop Pike	

At these stations the water is cooled by means of forced air heat exchangers situated outdoors, and to avoid the risk of freezing a specially inhibited ethylene-glycol/water mixture is used, one part antifreeze to two parts water. Specially inhibited glycol for this purpose is purchased centrally by Sutton Coldfield and distributed to the other stations as required.

Great care must be exercised to avoid leakage or spillage as glycol is corrosive. Klystron focus assemblies are particularly vulnerable in this respect and instances have occurred where insulation breakdowns have resulted from glycol corrosion. In the event of leaks occurring it is essential for the klystron truck concerned to be taken out of service, the klystron removed and the truck assembly hosed down with water until all traces of glycol have been dispersed. The klystron truck must then be dried out before being used again in a transmitter.

c. Vapour Phase Cooling

Vapour phase cooling is now used in the majority of BBC UHF transmitters. This technique makes use of the high latent heat of vapourisation of water (539 calories/gram) whereby considerable energy is dissipated in converting water to steam. Compared with water cooling this method is preferable because much less water flow is needed for a given rate of heat transfer.

An important feature of vapour cooling relates to the distillation principle which prevents any contaminant present in the cooling system leaving the klystron boiler. As a result all impurities present in the water header tank in relatively low concentration will ultimately be transferred to the boiler where the concentration will be much higher. This potentially dangerous situation requires diligent monitoring of water quality if klystron damage is to be avoided.

4.8 Water Conductivity

Water used to fill and subsequently to top up a cooling system should be pure and have a conductivity in the range 5-10μS*/cm. In order to avoid the possibility of klystron collector corrosion due to chloride ion attack, the water in the boiler should not be allowed to exceed 70μS/cm.

Several relatively inexpensive measuring instruments are currently available for this purpose and each maintenance base should have one.

4.9 Water contamination

4.9.1 General

Water contamination is particularly serious in vapour phase cooling systems because its effects may not be noticed until the concentration in the boiler has increased to such an extent that the collector actually melts internally.

Typical contaminants might be flux residues, sealing compounds, oil or even sulphuric acid. Oil and silicone grease compounds present a special hazard as minute concentrations are sufficient to cause overheating of the collector by thermal runaway. This happens if the oil forms a film over the collector cooling area and insulates it from the water in the boiler, thus severely impairing the heat transfer mechanism.

On at least one occasion sulphuric acid has been inadvertently introduced to a cooling system as a result of contaminated carboys. Fortunately the presence of sulphuric acid can be fairly readily detected because a copper deposit appears on the inside face of the water level sight glass. The other contaminants previously referred to are less easy to detect and the 'shake test' and the 'oil test' are probably the best checks for contamination.

4.9.2 Shake Test

In order to carry out this test a sample is taken in a clean, preferably new 300cc glass bottle. With an air space of 50mm at the top of the bottle, the bottle is shaken vigorously by hand for 10 seconds. Any bubbles produced should be greater than 1mm in diameter, small in number and disperse completely within 30 seconds. If there is a large quantity of very small bubbles, much less than 1mm in diameter, which persist for greater than 2 mins, then foam inducing contaminants are present. Checking for foaming in this way is assisted by comparison with a sample of water which is known to be of good quality.

Foaming of the type described usually results from deposits of flux or sealing compound residues within the cooling system components or pipe work.

*The unit of conductance is the Siemens, abbreviation S. See Appendix V.

4.9.3 Oil Test

The presence of oil is less easy to detect and the following procedure should be followed in those circumstances when it is essential to positively test for this form of contamination. It is necessary for the test bottles described in the following narrative to be absolutely clean and unless this requirement is met the results obtained cannot be relied upon. The use of a solvent such as Ultraclene will sometimes be found suitable for cleaning bottles which the first part of this test rejects as dirty.

a) Obtain two identical clean test bottles and three-quarter fill them with fresh distilled water. Taking each bottle in turn, gently tilt from side to side so that the internal glass surface is completely wetted. Allow to settle and closely observe the manner in which the film of water adhering to the glass surface drains back under gravity. This should take place uniformly without a break appearing in the moving edge of the water film. If a break does occur, this will be accompanied by a streaking effect which indicates the presence of oil or grease. Alternatively, globules of water may appear above the water line which also indicates oil contamination.

b) If the test previously described shows either bottle to be contaminated, the procedure must be repeated with new clean bottles until the test confirms the absence of contamination.

c) Pour the contents of one bottle away and refill to the same level as before from the sample of water to be checked. Repeat the oil test previously described, comparing the behaviour of the sample of water being checked with that of the distilled water in the second test bottle. If no signs of contamination are observed, the bottles should be allowed to stand for twenty-four hours after which the oil test should be repeated. Only after a sample of water has successfully passed the second test can the possibility of oil contamination be disregarded.

Silicone compounds present a special hazard and great care must be exercised to ensure that silicone grease, for example, cannot enter the cooling system. In this context it is important to note that lubrication of sealing rings, gaskets etc., with any compound is now prohibited.

When accessories such as rubber piping, sealing rings etc. require replacement, it is necessary to use components specifically recommended for the purpose. Unapproved components may contain additives which will dissolve into the cooling system causing contamination problems of the type previously described. Transmitter Managers should therefore ensure that sufficient stocks of approved accessories are always maintained.

4.9.4 Collector Appearance

The appearance of a klystron collector after several hundred hours of normal operation should be charcoal-grey due to a harmless deposit being formed when cooling water, which contains dissolved oxygen, is allowed to flow over the hot collector surface. Any other kind of layer on the collector is evidence of cooling water contamination and an investigation must be carried out.

4.10 Focusing

4.10.1 Focusing Adjustments

This is achieved by means of the adjustable flux plates which are situated towards the gun assembly end of the focus coils, together with the focus current setting to achieve minimum body current. As the klystron ages this value will tend to increase. The lowest value of body current which is achieveable with a new klystron, is about 5mA but a somewhat higher figure would be more typical. If a figure of less than 5mA is obtained this should be viewed with suspicion as it will probably be due to a fault condition. Similarly if the body current tends to decrease from a previously known figure as the klystron ages, an investigation should be carried out.

4.10.2 Body Current Behaviour

Figure 4 shows in general terms klystron focusing characteristics. At low focus currents the body current is very high as the magnetic field produced is insufficient to focus the electron beam. As the focus current is increased at constant beam voltage the body current falls to a minimum M1 followed by a first relatively high maximum. Subsequently there are a number of minima and maxima, the maxima having lower values than the first peak. Finally a focus current is reached when the body current again starts to rise to high values.

As the diagram is schematic only, no particular importance should be attached to the number of maxima or minima depicted nor to the exact values of body current indicated. The value of the body current at M1 may be less than or greater than that at the subsequent minima M2, M3 etc.

In the region of M1 the body current may indeed be low, even perhaps lower than at any other focus current, but nevertheless it is a sensitive function of the focus current and any significant change in the latter could result in the body current rising to an undesirably high level. For this reason it is essential that klystrons be operated at focus currents within the specified ranges given in the manufacturers data sheets even though a lower body current may sometimes be obtainable outside the particular range specified.

4.10.3 Focusing Faults

Apart from a fault in the focus current meter or wiring, the most likely cause of low body current will be a short circuit path from collector to earth by-passing the metering circuits.

This can arise if the insulation resistance from boiler to chassis is impaired. The presence of swarf has been known to cause this type of fault and it is useful to keep a record of the boiler to earth resistance with the metering circuit disconnected. The value obtainable will vary depending on local effects over a very wide range e.g. 20K ohms to 1·5M ohms. Local effects relate to water quality and condition of water hoses as this leakage path in the absence of a fault condition is through the water cooling circuit.

For shunting of the metering to take place the resistance from boiler to earth would need to fall to 1K ohm or less depending upon the component values employed in particular metering circuits.

It is recommended therefore that careful long term records of body current be maintained and the relationship between focus current and body current noted. Any significant departure from values previously regarded as normal should be investigated.

4.11 Routine Maintenance

The following routine checks should be carried out on all klystron equipment at the intervals specified.

a. Monthly/Quarterly

All spare klystrons must be gas tested and conditioning procedures carried out if necessary. (See Section 4.2 for exceptions).

b. Quarterly

Samples should be taken from the boilers for 'shake tests' and examined for signs of oil. The water conductivity should also be measured and an investigation carried out if this exceeds 70μS/cm.

The remaining water should then be drained from the boiler, the latter thoroughly flushed out and the sight glasses cleaned if necessary. When the klystrons are replaced, new boiler sealing rings should be fitted.

c. Occasional

For various reasons klystrons sometimes require to be lifted from their trucks thus providing a convenient opportunity for a general inspection to be carried out. This should include a careful examination of water and steam joints for signs of leakage, particular attention being paid to the condition of hoses, washers and sealing rings. See also section 5.3c. Klystron collectors should also be inspected for signs of corrosion and overheating.

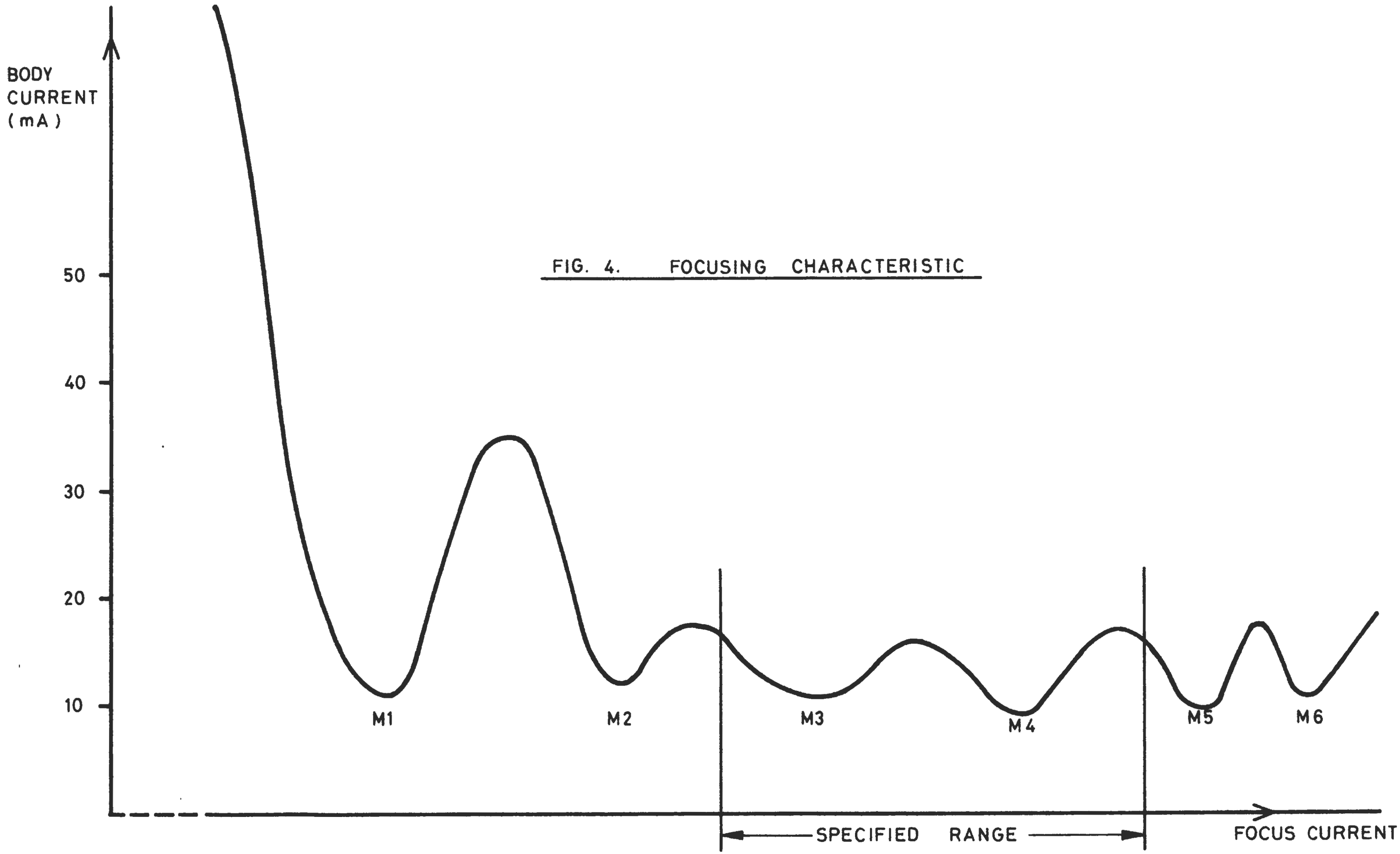

FIG. 4. FOCUSING CHARACTERISTIC

14

Experience has shown that long term problems are likely to be reduced if periodic attention of the type previously described is carried out. The frequency of inspection is subject to the discretion of Transmitter Managers but as a guideline it is thought that whereas for some equipments an annual inspection may be advantageous in general it is considered that somewhat longer intervals will be found adequate. However in the case of a transmitter with a history of klystron problems more frequent attention may be necessary until the possibility of an obscure transmitter fault has been discounted.

If any of the routine tests referred to above indicate a fault condition, an investigation must be carried out to determine the cause and remedial action taken. On occasions it may become necessary to clean out the water piping associated with a transmitter to remove any residue that may have collected. The use of a solvent such as Ultraclene, available from Central Stores, is useful for removing oil or grease. After such a cleaning operation has been undertaken time must be allowed for the pipework to dry out. When re-assembly is complete, the cooling system should be filled with fresh distilled water.

Transmitter Group Headquarters should always be notified of difficulties that give cause for concern such as klystron failure due to water contamination or failures of a recurrent nature.

4.12 Safety

a. High Voltages

BBC transmitter equipment is designed such that operational staff cannot come into contact with high voltage circuits and a system of red and green warning lamps indicates whether mains supplies are connected to a transmitter from its power supply distribution board.

Access to a klystron transmitter can only be achieved by operating the key box interlocked switches which earth the high-tension components. As an additional precaution, however, staff should use the earthing wands provided with each transmitter as a 'back-up' safety measure to ensure that components have been properly discharged before working inside a transmitter cubicle. A feature of this design allows part of the klystron cubicle to be opened during normal operation so enabling tuning adjustments to be carried out whilst preserving the safety measures previously referred to.

b. R.F. Radiation

Personnel must not be exposed to excessive r.f. radiation. All r.f. connectors and cavities must be correctly fitted before a transmitter is operated, so that there is no leakage of r.f. energy. Klystrons must not be operated without a suitable r.f. load at the output and intermediate cavities.

c. X-Ray Radiation

All high voltage thermionic devices operating above 10KV produce X-rays as a by-product of their normal operation but the radiation emanating from klystrons is low and well within the safety limits specified in Publication 15 (1969) of the International Commission for Radiological Protection.

The most significant areas of emission are the cavities and collectors but an inherent safeguard is provided by the shielding effect of the tuning cavity assemblies and by the walls of the collectors. Additional screening is afforded by the klystron boiler and finally any radiation is further reduced by the transmitter cubicle itself.

X-rays are not emitted however when a klystron is connected to a 'gas test set' as the voltages applied are too low for this phenomenon to take place.

5. FAULT DIAGNOSIS

5.1 When to Suspect a Klystron Failure

In the event of a transmitter breakdown, the symptoms which suggest the need to fit a replacement klystron as opposed to some alternative component are generally the registration of body and/or collector current trips when the e.h.t. is switched on.

Before concluding however that a klystron failure has occurred, it is advisable to observe the behaviour of the transmitter metering facilities. The focus current behaviour is of particular importance as de-focusing will also result in body current trips and the filament metering may draw attention to a gun assembly fault.

5.2 When to Fit a Replacement Klystron

Unless one can be sure that failure is either natural or because of klystron manufacturing defects, replacement of the klystron should be delayed until the cause has been established.

5.3 Diagnosis

a. Obtaining the Evidence

Check 1

When the faulty klystron has been lifted from its truck, careful examination should be carried out for signs of overheating. A charcoal-grey deposit should have formed on the surface of the collector if it had previously been run correctly for several hundred hours or more. In other respects the klystron should appear in perfect condition and there should be no evidence of burning in the region of the cavity flares or of the mod-anode ring.

Check 2

The latest set of recorded meter readings should be examined. Body current, focus current and heater metering are of particular importance. Any significant departure from what were previously regarded as normal readings may provide a vital clue as to the cause of failure.

Check 3

A sample of water should be drained from the boiler into a clean receptacle and tests for water contamination carried out. The water conductivity should also be measured and this should not exceed 70μS/cm.

b. Assessing the Evidence

Having obtained the evidence as described in Checks 1, 2 and 3 above, it should be possible to place the klystron failure into one of the previously defined categories.

The following process of elimination may be found helpful.

1) Natural Failure

For this category to apply the klystron should appear normal as defined in Check 1. In addition no tendency to suspect water quality should result from Check 3. Check 2, on the other hand, should reveal a steady deterioration in performance, together with higher than normal body current.

Alternatively, the heater metering may indicate an open circuit or partial short circuit heater.

2) Klystron Defects

Loss of vacuum or gun assembly faults should be considered. A gas test will confirm the former.

3) Transmitter Defects

Focusing defects, inadequate cooling of the mod-anode, overheating of the heater terminals, overheating of the collector and water cooling deficiencies are all possibilities.

In the event of category (1) or (2) positive identification should be possible and the correct procedure would be to fit a replacement klystron.

If identification of category (1) or (2) proves impossible, category (3) should be considered, and a replacement klystron should not be fitted until this possibility has been disproved.

If positive identification of category (3) should occur, the underlying fault must be remedied and the circumstances reported to Transmitter Group Headquarters

c. Klystron Replacement

Before fitting a replacement klystron, the following preliminary work should be carried out.

(i) Wash out the boiler with distilled water and clean the sight glass to the float switch tank if this has become dirty. This should be re-assembled with a new sealing ring.

(ii) Ensure that the float switch operates correctly.

(iii) Fit a new collector flange sealing ring.

(iv) Perform a gas test if it is more than one month since one was last carried out.

(v) Remove the protective papers surrounding the klystron ceramics.

At the time of klystron replacement an additional check should be made to see that all tuning controls are functioning correctly and that the cavities and water seals are in good working order.

6. REFERENCES

G.W.A. Dummer & N.B. Griffin — Electronics, Reliability–Calculation & Design (Pergamon Press)

C.J. Edgcombe & C.N. O'Loughlin — The Television Performance of the Klystron Amplifier (The Radio and Electronic Engineer, Sept 71)

R. Heppinstall & G.T. Clayworth — The Importance of Water Purity in the Successful Operation of Vapour-cooled Television Klystrons (The Radio and Electronic Engineer, Aug 75)

ACKNOWLEDGEMENTS

The authors wish to thank the engineers in Transmitter Group for the reports and life returns from which the statistics in this publication have been compiled, and they greatly appreciate the ideas and guidance provided by their colleagues in Transmitter Group and TCPD. They are also indebted to the engineers of English Electric Valve Co Ltd and ITT for discussions about the problems encountered with high power klystrons in Television Transmitters.

APPENDIX I

EQUIPMENT LOCATION

*Location	Output Power (kW)	EEV Company Type	I.T.T. Type	Tuning Range	Cooling Mode	Operational Sockets
1	5	K384	–	B	1	2
2		K385	–	C	1	2
3	6¼	K3004	Z150/35Z	A	1.3	16
4		K3005	Z160/35Z	B	1.3	27
5		K3006	Z170/35Z	C	1.3	23
6	10	K370	Z151/50Z	A	1.3	34
7		K371	Z161/50Z	B	1.3	26
8		K372	Z171/50Z	C	1.3	40
9		–	Z173/50Z	C	1.3	2**
10	25	K376	4KM100LA	A	1.2	16
11		K377	4KM100LF	B	1.2	20
12		–	4KM100LH	C	1.2	12**
13	25	K3014	Z154/100Z	A	1.2.3.	12
14		K3015	Z165/100Z	B	1.2.3.	4
15		K3016	–	C	1.2.3.	10
16	40	K3017	Z155/150Z	A	1.2.3.	24
17		K3018	Z166/150Z	B	1.2.3.	6
18	Dual 25/40	K3082	Z155/150ZA	A	1.2.3.	–
19		K3083	Z166/150ZA	B	1.2.3.	–
20		K3282	–	A	1.2.3.	–
21		K3283	–	B	1.2.3.	–
22		K3284	–	C	1.2.3.	–

*See page 2 of Appendix I for key to locations
**Integral cavity types. All others external cavity

			Channels
Tuning Range –	(A)	470 – 610 MHz	21–38
	(B)	590 – 720 MHz	36–51
	(C)	700 – 860 MHz	50–69

8 x Channel No + 303·25 = Vision Carrier Frequency in MHz
8 x Channel No + 309·25 = Sound Carrier Frequency in MHz

Cooling Mode
(1) Forced Air
(2) Water
(3) Vapour

APPENDIX I (continued)

Location Use

(1) Tunbridge Wells

(2) Reigate

(3) Aldeburgh, Bressay, Fenton, Haslingden, Kilvey Hill, Lancaster, Larkstoke, Sheffield

(4) Arfon, Bluebell Hill, Cambret Hill, Fremont Point, Guildford, Hemel Hempstead, Keelylang Hill, Londonderry, Skipton, Sudbury

(5) Brierley Hill, Brighton, Dover, Keighley, Londonderry, Rosneath, Salisbury, Sudbury, Waltham

(6) Blaenplwyf, Craigkelly, Darvel, Eitshal, Knockmore, Ridge Hill, Rumster Forest, Wrekin, Sandale, Torosay

(7) Chatton, Dover, Heathfield, Moel-y-Parc, Presely, Redruth, Rosemarkie

(8) Angus, Beacon Hill, Carmel, Huntshaw Cross, Limavady, Llanddona, Midhurst, Oxford, Selkirk, Waltham

(9) Oxford

(10) Divis, Durris

(11) Emley Moor, Sutton Coldfield, Wenvoe

(12) Pontop Pike, Winter Hill

(13) Belmont, Rowridge, Stockland Hill

(14) Hannington

(15) Mendip, Tacolneston, Winter Hill

(16) Bilsdale, Caldbeck, Caradon Hill, Crystal Palace, Sandy Heath

(17) Black Hill, Wenvoe

(18) See 13 and 16

(19) See 14 and 17

(20) See 13 and 16

(21) See 14 and 17

(22) See 15

APPENDIX II

KLYSTRON WARRANTY

EEV Co Types

Power Level	Type	Mode of Operation	Warranty
5kW	(K384)	Cathode current less than 1.25 amp a	100/10,000/36
	(K385)	Cathode current more than 1.25 amp	100/4,000/36
	(K3004)	Transposer Service	100/4,000/36
6¼kW	(K3005)	Vision Amplifier	100/7,500/36
	(K3006)	Sound Amplifier	100/12,000/36
	(K370)	Transposer Service	100/4,000/36
10kW	(K371)	Vision Amplifier	100/7,500/36
	(K372)	Sound Amplifier	100/12,000/36
		Cathode current up to 1 amp	100/10,000/24
25kW	(K376)	Cathode current up to 3.5 amp	100/6,000/24
	(K377)	Cathode current more than 3.5 amp but not exceeding max. rating	100/3,000/24
	(K3014)		
25kW	(K3015)		
	(K3016)		
	(K3017)		
40kW	(K3018)	Vision or Sound Amplifier	100/10,000/36
		Multiplex Operation	100/8,000/36
	(K3082)		
	(K3083)		
Dual 25/40kW	(K3282)		
	(K3283)		
	(K3284)		

ITT Types

Power Level	Type	Mode of Operation	Warranty
	(Z150/35Z)	Transposer Service	100/4,000/36
7kW	(Z160/35Z)	Vision Amplifier	100/7,500/36
	(Z170/35Z)	Sound Amplifier	100/10,000/36
	(Z151/50Z)	Transposer Service	100/4,000/36
11kW	(Z161/50Z)	Vision Amplifier	100/7,500/36
	(Z171/50Z)	Sound Amplifier	100/10,000/36
	(4KM100LA)	Cathode current up to 1 amp	100/10,000/36
25kW	(4KM100LF)	Cathode current up to 3.5 amp	100/6,000/36
	(4KM100LH)	Cathode current more than 3.5 amp but not exceeding max. rating	100/3,000/36
25kW	(Z154/100Z)	All applications	100/10,000/36
40kW	(Z155/150Z) (Z166/150Z)	All applications	100/10,000/36

1. If a klystron is used in more than one mode of operation during its life, the warranty applicable is the lower one.

2. Scrap credit is given on all klystrons which fail in excess of warranty. All failures must be returned to Valve Section.

APPENDIX II (Continued)

Explanation of Warranty Code

The first figure given is the heater life in hours within which the klystron may, at the option of the manufacturers, be replaced free of charge or credited in full, provided that the period indicated by the last figure in months has not expired.

The second figure gives the total warranty period in hours of heater life. For klystrons failing with a heater life in excess of the first figure but less than the second, replacements or credit will be given on a pro rata basis determined by the ratio of the unrealised portion of the warranty life to the total warranty period, providing that the period indicated by the last figure in months has not expired.

The last figure gives the period in months from the date of purchase over which the warranty applies.

Conditions of Warranty (Main Point Summary)

1. The klystron is operated within the published minimum and maximum ratings.
2. It is not subjected to any negligence in use, storage, transportation or handling.
3. Right of access to equipment for the purposes of checking operating conditions is granted to any manufacturer's representative when required and is organised through Valve Section.
4. The klystron is withdrawn from service after alleged failure and returned as soon as possible to the manufacturers.

APPENDIX III

STATISTICAL INFORMATION (JANUARY 1978)

1. Life

a) General Overall Summary

Cumulative hours since introduction	=	10,730,144 hours
Burning hours of all failures	=	5,534,830 hours
Number of failures	=	415
Average life of failures	=	13,337 hours
M.T.B.F.	=	25,856 hours
Projected Average Life	=	16,632 hours
(1978) Current Average Price	=	£4,420
Current Average Rate	=	26.6 p/hour

$$\text{where Current Average Rate} = \frac{\text{Current Average Price}}{\text{Projected Average Life}}$$

b) Power Level Breakdown

Power Level kW	No. of Failures	Projected Average Life	Rate (pence per hour)
5	7	19,960	22.2
6¼	64	17,467	18.5
10	45	20,332	16.3
25 (water cooled)	170	13,472	47.0
25	54	13,160	47.0
40	80	11,745	52.7

c) Life Analysis

(i) Surviving in Circuit

Power Level (kW)	Life (Kh) 0+	13+	15+	20+	25+	30+	35+	40+
5	4	3	3	2	1	1	0	0
6¼	66	34	32	21	19	18	14	8
10	102	76	69	47	32	19	11	2
25 (water cooled)	48	25	20	18	14	11	5	3
25/40 (vapour)	56	22	16	10	5	3	2	1
Totals	276	160	140	98	71	52	32	14
As % sockets	100%	58.0	50.7	35.5	25.7	18.8	11.6	5.1

(ii) Failures

5	7	4	2	1	0	0	0	0
6¼	64	35	28	25	17	12	6	4
10	45	26	23	17	11	7	4	3
25 (water cooled)	170	62	50	33	22	13	7	6
25/40 (vapour)	134	60	45	19	9	4	1	0
Totals	420	187	148	95	59	36	18	13
As % total failures	100%	44.5	35.2	22.6	14.0	8.6	4.3	3.1

APPENDIX III
(continued)

2. Failures

The following breakdown gives, as far as possible, the fundamental reasons for the failures. For example, a Klystron might have been returned reporting that the heater was open circuit, when in fact it had total loss of vacuum which resulted in the failure of the heater. Again, some Klystrons were reported to have total loss of vacuum when in fact this was the result of over-heating of the collectors, due to contamination of the cooling system.

	Reason for Failure	Expressed as % total of Failures (355 Samples)
1)	Low Emission Includes Low Power Output, Slow warm up, Low emission accompanied by High Body current etc.	28
2)	Gun Faults Includes Heater Open Circuit, Intermittent Heater, Cathode to Modulating Anode Short Circuit*, Partial Heater short circuit and focus electrode emission.	27
3)	Vacuum Faults Includes total or partial loss of vacuum etc.	23
4)	Focusing Problems Includes High Body Current and accompanies some other faults.	17
5)	Accidental Damage Includes handling damage (in some instances by external contractors whilst on loan for installation) and external circuit faults which have caused Klystrons to be damaged.	3
6)	R.F. Faults Includes spurious or noisy output.	0.5
7)	Micellaneous Includes internal flash-overs, cracked ceramics, etc.	1.5

* The function of the modulating anode is explained towards the end of Appendix IV.

APPENDIX IV

Theory of Operation

1. Introduction

Conventional vacuum tubes have upper usable frequency amplification limits imposed by electron transit time effects. Useful extention of the range can be obtained by minimum electrode spacing, but this technique only gives a further upper frequency limit with accompanying power limitations.

The klystron was developed in order to overcome these problems. The technique employed is to velocity modulate a constant velocity electron beam between cathode and collector. The signal to be amplified is applied to the drift tube gap within the input cavity. This causes progressive beam electron bunching which induces current into a near resonant suitably spaced second cavity. The voltages generated by this can be many times the original modulating voltage, and the process may be repeated by adding further cavities as required.

2. Conventional Valves

Conventional valves operate on the basis of space-charge control whereby the application of an alternating voltage to a control grid causes a corresponding change in anode current.

When the frequency of the signal applied to the grid is low, the time taken for electrons to travel from cathode to grid can be neglected and the valve operates on the principle of space-charge variation.

At UHF the transit time of electrons becomes significant in relation to the wave length of the signals being amplified and as a consequence gain and efficiency are reduced. With modern UHF triodes and tetrodes the transit time is minimised by employing planar or coaxial electrode configurations, but the small inter-electrode spacings which result limit the extent to which high power outputs can be achieved. Considerable development work is still in progress to further improve the conventional valve and output powers of up to 10kW are now obtainable for UHF television transmitter applications. The stage gain however is generally low and high levels of drive are needed.

The factors which affect the performance of conventional valves can be summarized as follows:-

(a) Inter-electrode capacity
(b) Lead effects. These refer to resistive losses due to skin effect and cathode lead inductance.
(c) Transit time effects.

Inter-electrode capacity becomes highly significant as the electrode spacing is reduced and this sets an upper limit on the resonant frequency of tuned circuits. It also results in feed-back effects. The latter can be partly compensated for by neutralising techniques but neutralising is difficult to achieve with equipment which needs to be tuned over a wide range of operating frequencies and instability is often a problem.

Cathode lead inductance reduces the gain of the valve (when used in the common cathode configuration) due to negative feed-back and an apparent shunt resistance between grid and cathode.

A similar problem arises due to electron transit time whereby the valve input resistance is reduced by the introduction of an apparent shunting resistance between grid and cathode. This effect is referred to as transit time conductance and causes the stage gain to be severely reduced.

3. The Klystron Amplifier

In order to avoid the disadvantages previously referred to a range of high frequency devices have been developed which utilise the fact that electrons take an appreciable time to travel from cathode to anode.

Of these developments the klystron is the most commonly used device for obtaining high power output consistent with high stage gain. Travelling wave tubes, backward wave oscillators, and reflex klystrons are used for other specific purposes.

These devices employ the principle of velocity modulation whereby a density modulated electron beam is obtained by varying the velocity of the electrons. This is achieved by passing an electron beam of constant velocity through a space where a periodic change of velocity is applied to it by means of a varying longitudinal electric field.

A simple klystron amplifier circuit is shown in Fig 1. Electrons leaving the cathode are accelerated to G1 which has a high positive potential applied to it. G1 together with G2 are connected to the first cavity (tuned circuit) into which the input signal is applied. G3 and G4 are connected to the output cavity which is at the same positive potential as the input cavity and therefore electrons traverse the intervening drift space at constant velocity. The electrons are finally absorbed by the collector electrode where their kinetic energy is given up in the form of heat. The electron beam is focused by an external axial magnetic field which is normally provided by a series of coils fed from a stabilised d.c. supply.

The input and output tuned circuits are cavity resonators whereby a wave set up at the front travels across to the rear where it is reflected back again. The cavity dimensions are adjusted to provide resonance at the desired operating frequency. The coaxial input or output connections are obtained by coupling loops which can be rotated to match the cavities to their coaxial input or output feeders.

When an input signal is applied to the first cavity an alternating voltage is set up between the first and second grids which affects the motion of the electrons which pass between them. Electrons which pass when the first grid is positive to the second are slowed down whereas those which pass when the second grid is positive to the first are accelerated.

Therefore on entering the drift space some electrons have velocities which are either higher or lower than the average velocity and as a result bunches of electrons form as they progress towards the output cavity. The bunching effect can be considered as follows. The fast electrons will catch up with the slower ones which started earlier; the slower electrons lag behind and are joined by fast electrons which started later. At some distance from the output cavity bunching is quite pronounced and the value of the H.T. voltage is set to provide maximum bunching as the electrons pass the third grid. These electron bunches in passing between the third and fourth grids cause a pulsating current which results in an alternating field being set up between them. As a result the cavity resonates and power is extracted via the coupling loop.

The mechanism whereby energy is transferred from the electron beam to the output cavity can be considered as follows. Let it be assumed that the output cavity is at resonance such that G3 and G4 are alternatively positive and negative. If G4 is negative with respect to G3 when a bunch of electrons passes between them this longitudinal field will retard the electron bunch causing energy to be released into the output cavity. The electron bunches are separated by intervals of low electron density so that during the next half cycle when G4 is positive to G3 the electrons passing through the gap will be accelerated causing energy to be released from the cavity. Whenever this occurs however, the electrons passing between the grids will be few in number. To summarize, a large amount of energy will be transferred to the output cavity whenever G4 is negative relative to G3 as under these circumstances a bunch of electrons will be retarded. Only a small amount of energy however will be released from the cavity to accelerate electrons when G4 is positive to G3 as under these circumstances only a few electrons will pass between them. The net effect therefore is for a large amount of energy to be transferred from the electron beam into the output cavity and hence the klystron acts as an amplifying device.

Accurate mathematical analysis shows that the procedure previously described does not result in electron bunching at a single point in space and time. In practice further complications arise because the mutual repulsion which occurs between electrons tends to act in opposition to the bunching process. The mathematical analysis which follows contains certain approximations but illustrates the fundamental factors which determine electron bunching.

APPENDIX III

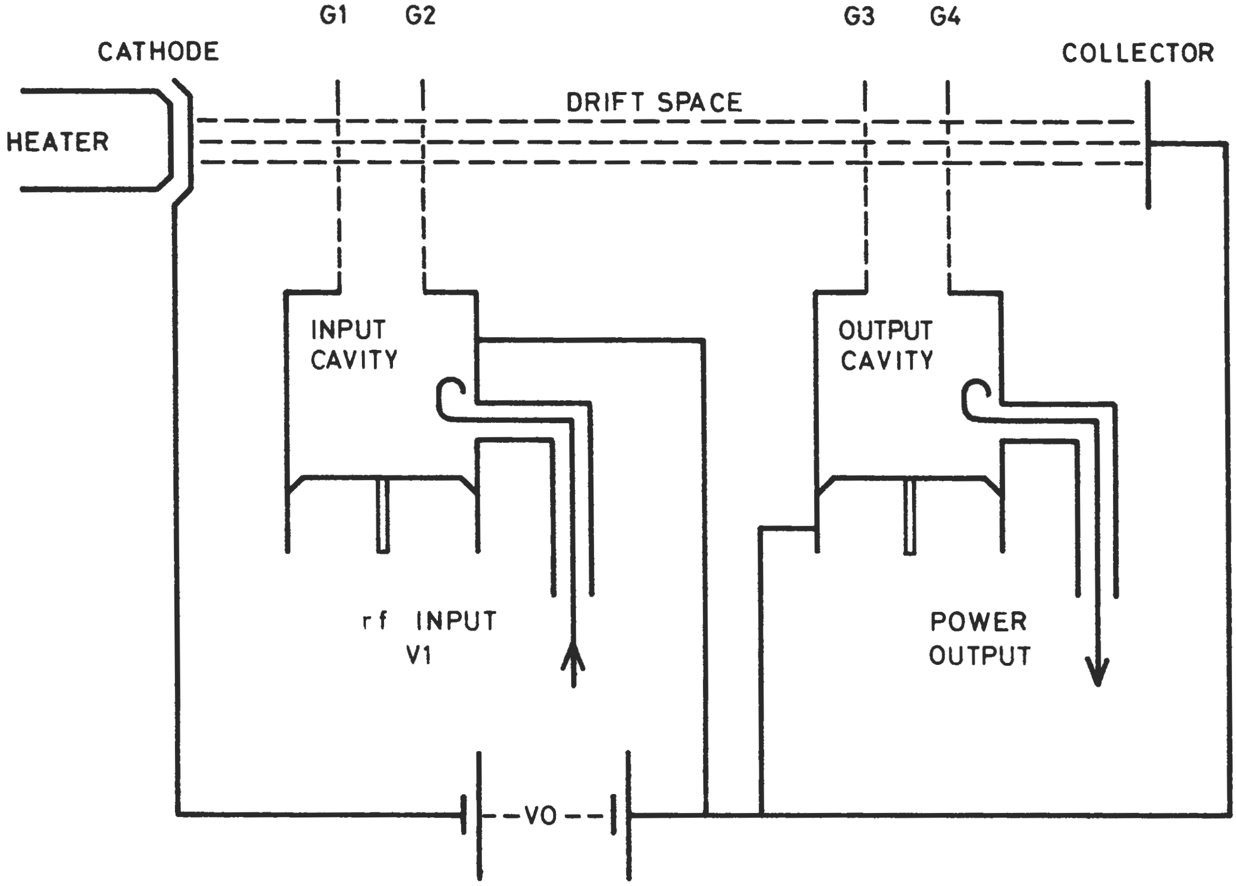

FIG. 1. SIMPLIFIED CIRCUIT OF A TWO CAVITY KLYSTRON AMPLIFIER

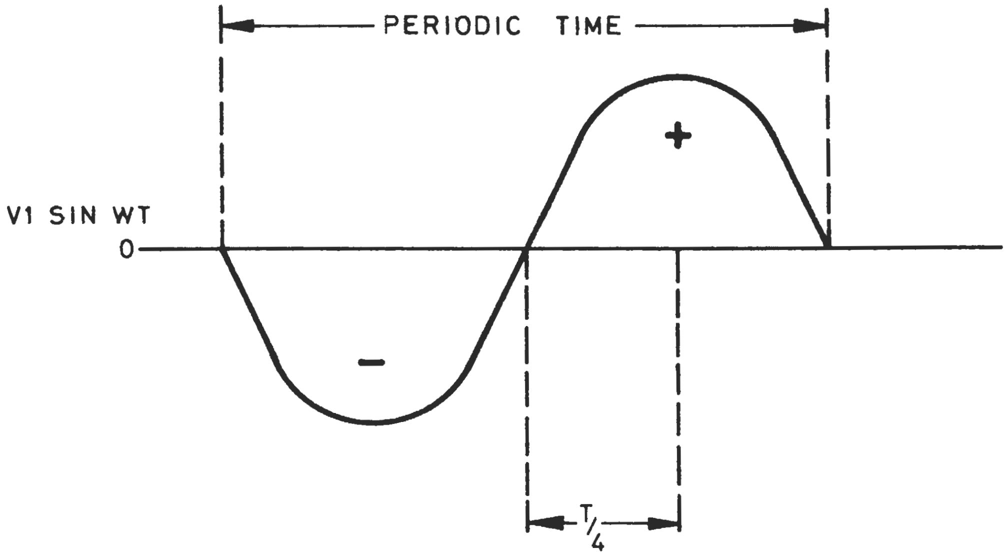

FIG. 2. ONE COMPLETE CYCLE OF INPUT SIGNAL

4. Mathematical Analysis of simple 2-Cavity Klystron

The electron dynamics of the klystron circuit illustrated in Fig. 1 may be considered as follows:

With the high tension supply set to Vo, a sinusoidal signal V1 sin wt is applied to the input cavity. (Where V1 denotes the peak value)

Hence the resultant voltage applied is:-

$$V = Vo + V1 \sin wt \ldots\ldots\ldots\ldots\ldots (i)$$

In the absence of the input signal the voltage between cathode and the cavity is Vo and since the kinetic energy of the electron beam is derived from the potential energy of the power supply, we may write:

$$\tfrac{1}{2} m U_O^2 = eVo$$

where Uo is the velocity of the electron on reaching G1, m is the electron mass and e is the electron charge.

$$\text{Hence } Uo = \left(\frac{2.e.Vo}{m}\right)^{\frac{1}{2}} \ldots\ldots\ldots\ldots (ii)$$

Let U comprise the average velocity Uo plus an incremental velocity due to the input signal.

$$\text{Then } \tfrac{1}{2} m U^2 = e(Vo + V1 \sin wt) \ldots\ldots (iii)$$

By substituting expression (ii)

$$U = Uo\,(1 + \frac{V1}{Vo} \sin wt)^{\frac{1}{2}}$$

but since $\frac{V1}{Vo} << 1$ we may simplify this expression using the binomial expansion to:

$$U = Uo\,(1 + \frac{V1}{2Vo} \sin wt)$$

which gives a maximum velocity

$$Ux = Uo\,(1 + \frac{V1}{2Vo}) \ldots\ldots\ldots\ldots\ldots\ldots (iv)$$

and a minimum velocity

$$Uy = Uo\,(1 - \frac{V1}{2Vo}) \ldots\ldots\ldots\ldots\ldots\ldots (v)$$

Let Fig. 2 represent the signal on G2 relative to G1. Consider the condition when G2 is at zero voltage whereby electrons proceed into the drift space at velocity Uo, followed a ¼ cycle later when G2 is + max by electrons proceeding at maximum velocity Ux.

If the distance between bunches is denoted by s and the time taken for electrons travelling at average velocity to cover this distance is t, employing an approximation

then $s = Uo.t$

and for the fast electrons $s = Ux\,(t - \frac{T}{4}) = Ux\,(t - \frac{1}{4f})$

where f is the frequency in Hz

Hence $Uo.t = Ux\left(t - \frac{1}{4f}\right)$

Therefore $t = \dfrac{Ux}{4f\,(Ux - Uo)}$

Substituting from equation (iv)

$$t = \frac{Uo\left(1 + \frac{V1}{2Vo}\right)}{4f\left(Uo + \frac{UoV1}{2Vo} - Uo\right)}$$

$$= \frac{1 + \frac{V1}{2Vo}}{\frac{4fV1}{2Vo}}$$

But $\dfrac{V1}{2Vo} << 1$ and can be neglected

$$\therefore t = \frac{Vo}{2fV1}$$

The bunching distance S = Uo.t

$$= Uo\left(\frac{Vo}{2fV1}\right)$$

Substituting from equation (ii)

$$s = \left(\frac{2e\,Vo}{m}\right)^{1/2} \cdot \frac{Vo}{2fV1}$$

$$= \left(\frac{e}{2m}\right)^{1/2} \cdot \frac{1}{fV1} \cdot Vo^{3/2}$$

and by using the standard numerical values for e and m we may write

$$s = \frac{3}{fV1} \cdot Vo^{3/2} \cdot 10^{5} \quad \text{metres}$$

This derivation gives the first bunching distance but the process is repeated at equal intervals along the drift space, the intensity of the bunches increasing as the electrons proceed towards the collector.

The bunching effect may be enhanced by adding intermediate cavities which results in the following improvements in performance:

Increase in stage gain
Broadbanding may be achieved by staggered tuning
R.F. response shaping may be achieved by loading the intermediate cavities

A further refinement is the provision of an additional electrode, the modulating anode, which is situated in the electron gun near to the cathode. This can be used to alter the magnitude of the electron beam by means of a control voltage, but in television transmitter applications is usually connected to earth via a 10 k ohm resistance. Under normal operating conditions this carries out no function; however, should a fault condition cause an excessive amount of beam current, the resultant voltage generated across this resistance, tends to bias the klystron off and hence damage to the tube is avoided.

The gun assembly is designed such that during normal operation, the electrostatic and magnetic fields in the vicinity of the cathode, direct the electron beam through the mod-anode aperture. This results in the latter drawing negligible current (about 1mA in the case of a 10kW klystron and about 3mA from a 40kW tube) which circulates back to the e.h.t. supply via the body current metering and protection circuits. A fault condition which causes the mod-anode to draw appreciable current will therefore be followed by a body current interruption of the e.h.t. supply, thus providing a further safeguard to the klystron.

On transmitters where the sound and vision amplifiers share a common HT power supply, the mod-anode of the sound klystron is less positively biased to reduce the beam to a value more appropriate to the lower output power of a sound only transmitter, and hence the efficiency is improved.

Biasing the mode-anode in this way reduces the bandwidth of the klystron from the original design specification of 8MHz, but in the case of a sound only transmitter this is irrelevant.

This technique may also be used to optimise the efficiency of a vision klystron provided that the reduction in bandwidth, gain and linearity can be accommodated.

Although a five cavity klystron design is available for UHF transmitter applications the BBC has standardised on the 4 cavity type as a compromise between adequate gain, simplicity of operation and cost.

Further information regarding the theory of klystron amplifiers may be found in the following references.

References

W. Fraser – Telecommunications (Macdonald London)

J. Thompson Electronics, Services Textbook of Radio Volume 3 (HMSO)

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APPENDIX V

THE UNIT OF CONDUCTIVITY

1. Basic Definitions

Conductivity is the reciprocal of resistivity rho (ρ)

Conductance is the reciprocal of resistance (R)

The unit of conductance is the Siemens (S)

2. Dimensional Analysis

$$R = \frac{\rho L}{A}$$

where:- L is the length in metres
A is the area of cross section in square metres

This expression may be expressed dimensionally as:-

$$R = \frac{\rho L}{L^2} = \frac{\rho}{L}$$

$$\therefore \rho = RL$$

This may be written as $\frac{1}{\rho} = \frac{1}{RL}$

Where $\frac{1}{\rho}$ is the conductivity (from 1st definition)

but $\frac{1}{R} = S$ ..... (from 2nd definition)

$\therefore$ Conductivity $= \frac{S}{L}$ i.e. Siemens/metre

For convenience the unit of length is expressed in centimetres to provide a more convenient numerical value and the unit of conductivity commonly used is the micro Siemens/cm (μS/cm).