A UNIVERSAL MULTI-MODE FILAMENT REGULATOR FOR HARD TUBES

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ABSTRACT

High power RF triodes used to power the injector linac cavities on the ISIS spallation neutron source at RAL tended to fail prematurely through low emission. The implication of this was a tube temperature problem. The tube manufacturer was consulted and in parallel a review instigated of the heater control system.
A direct relationship between applied power and filament temperature exists and the Richardson-Dushman equation shows that for a small increase in filament temperature, a significant increase in the availability of electron emission occurs. The resulting increased depletion of filament carburization shortens the lifetime of the tube. Development and installation of a universal filament management system to replace obsolete equipment and simultaneously improve the operational stability has resulted in significantly extended tube service life. Reductions in capital costs and the ability to predict RF tube life has become possible, promoting the establishment of an effective tube replacement strategy. Actual filament lifetime data, accumulated over several years, is presented.

1. INTRODUCTION

In the late 1980's tube lifetime was a concern and after consultation with Thomson, modifications were introduced to assist in the transfer of heat from inside the tube to the external cooling arrangements. The need to improve equipment performance and tube lifetime provided the impetus behind the development of a universal filament regulator allowing all high power RF tubes at ISIS to be driven from one standard unit. Information gained from various sources[3,4,5] suggested that a tight filament voltage control system could increase heater lifetimes by 100%. Elsewhere[1] the idea of stabilising thoriated tungsten filament power rather than voltage seemed sensible. A Filament Regulator was designed and built to allow closed loop control of filament voltage, current or power. One unit was capable of stabilising, to better than 1%, any of the 4 different high power RF tubes used at ISIS. The Filament Regulator has been in use for ~ 6000 hours per year since ~ 1990, but, because of the resultant increase in tube lifetimes, it is only recently that the relevant statistics have become meaningful. This paper concentrates on the Thomson TH116 tubes used as the final drives for the ISIS linac cavities.

2. FILAMENTS

Factors affecting the TH116 triode lifetimes were high internal temperatures and the use of step-change filament supplies.

Statistics produced by Thomson[4] based on French TV station transmitter tubes, showed that a small percentage increase in filament voltage reduced a tube's expected life from a minimum of 8,657 hours down to 3,500 hours. Ziegler[3] made reference to the possibilities of extended tube life by controlling filament temperature.

Thoriated tungsten filaments are made by adding 1 or 2 per cent thorium oxide ThO_2 to the tungsten before it is sintered and drawn into shape. After drawing, the filament is heated in a hydrocarbon vapour atmosphere converting the surface layer to tungsten carbide.
Langmuir[2] discovered that, through evaporation, the end of useful filament life occurred when this layer became depleted. Work done elsewhere[1] suggested that a carburized filament would, at 2000°K, provide a possible tube lifetime of 35,000 hours. Because tungsten carbide has a higher resistance than thoriated tungsten, a filament with a 25% carburized cross-section has an increased hot filament resistance of approximately 15% (cold resistance by 30%).
By monitoring filament voltage and current, the characteristic resistance curve may be plotted over a tubes lifetime. From the initial resistance value observed, the tube is considered near or at the end of its life when the hot filament resistance is down 15%.

Depletion of the carburised layer, results in a fall in filament resistance and, with a constant voltage across it, current increases. Increased power demand results in a rise in filament temperature. It is argued, therefore, that a power management system be employed.

The Richardson-Dushman[5] equation

$$I_s = AT^2 e^{-\varphi_0/kT}$$

where I_s = filament emission current density,
A = 60.2 a constant for pure metal
T is absolute temperature,
ϕ_0 filament work function, for thoriated tungsten 2.55
k is Boltzmann's constant (0.863 x 10^{-4} V/°K)
(1 amp = 0.624 x 10^{19} electrons/sec)

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permits evaluation of electron emission for various filament temperatures.
So for an increase in filament temperature say from 2000°K to 2100°K due to RF heating, or over driving the filament, then the following figures are obtained: -

At 2000°K, I_s = 92.3 amps/cm^2
Or 5.76 x 10^{20} electrons/sec

At 2020°K, I_s = 109.6 amps/cm^2
Or 6.84 x 10^{20} electrons/sec

i.e. ~ 20% increase in electron emission and a significant reduction in filament life due to the higher temperatures.

3. FILAMENT REGULATOR

3.1 Specification

The requirement was for a regulator, of simple design, capable of voltage, current or power control. To rationalise spares, the unit should be able to be configured to drive any one of 4 different types of high power RF tube at ISIS. Soft start, hard off, overcurrent interlocks and the ability to monitor all relevant voltages, currents and powers for each tube were incorporated.

3.2 The System

The Filament Regulator System comprises a Filament Regulator module, SCR Trigger module and an SCR module. Fig. 1 shows a schematic of the system.

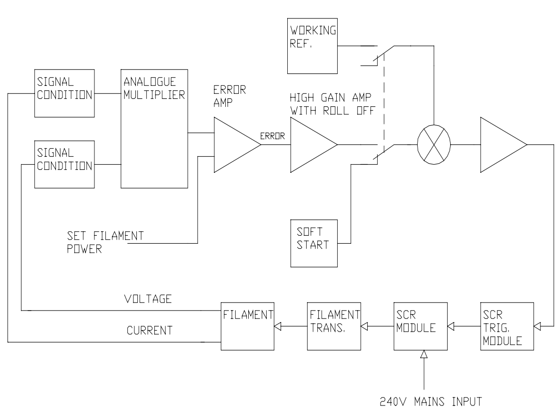

Figure 1. Schematic diagram of Filament Regulator

3.3 Filament Regulator

Samples of filament voltage and current waveforms are filtered and scaled, converted to dc, multiplied together and compared to a reference. The resulting error voltage is passed to a high gain amplifier with roll-off and summed with a switchable arrangement of a 'working level' reference and a ramp generator. The latter provides a soft start for filament run-up. When power in the filament reaches that set by the reference level, the ramp input is switched out and replaced by a dc level and the error signal voltage.

3.4 SCR Trigger Module & SRC Module

A zero to 5V dc output level is compared to a stable ac derived reference ramp to produce a variable width pulse. This is used to gate an asynchronous pulse train and drives a pair of FET switched pulse transformers. Proprietary SCR trigger modules available at the time provided an unreliable zero crossing start and therefore an 'in-house' design was used.
Mains power is switched by a solid state relay, via isolator and applied to an inverse parallel pair of phase angle controlled thyristors. The trigger pulse train drives the appropriate phase controlled thyristor, a typical waveform is shown in Fig. 2. At stabilization, the filament voltage is shown in Fig. 3.

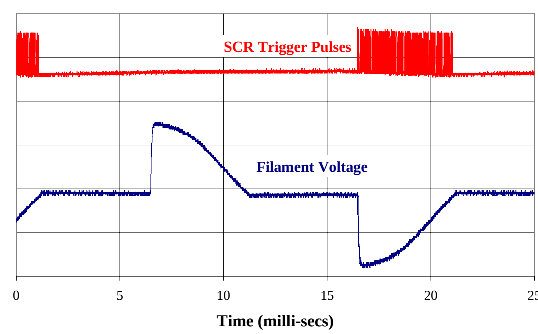

Fig. 2 SCR Trigger pulses Filament Voltage
(shown during run up)

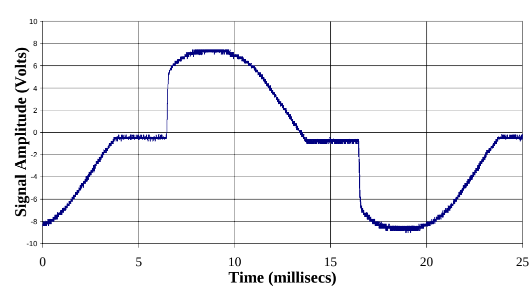

Figure 3. Filament Voltage (shown stabilized)

4. DATA

The data contained in Table 1 was recorded over the period October 1986 to the present day. Bracketed numbers in the tube serial no. column indicate various incarnations of the TH116 in a bid to overcome lifetime problems. Type (3) became the standard.

Figure 4 gives complete lifetime curves of hot filament voltage and resistance for TH116 tube serial no. AR1 with measurements taken on a monthly basis. Upward variations in filament voltage were due to operator adjustments. The resistance curve shows a high rate of carbon loss over the first 1000 hours with some degree of linearity thereafter.

Tube S/N	Hours	Failure Mode
RF System 1 (10MeV)		
W3 (1)	3,331	Low emission
Z2 (1)	2,828	Low emission
AB2 (2)	5,755	Low emission
AH2 (2)	5,020	Low emission
AJ6 (3)	5,140	Low emission
AL1 (3)	23,456	Low emission (Filament Regulator installed 6.10.90)
AR1 (3)	25,927	Low emission
AR2 (3)	7,968	In Service at Present
RF System 2 (20MeV)		
AF4 (2)	4,227	Low Emission
AF3 (2)	678	Undocumented Failure
AJ4 (3)	5,499	Low Emission
AK1 (4)	730	Glass cracked (Filament Regulator installed 26.4.89)
AK4 (3)	8,575	Spark Damage
AM1 (3)	12,549	Low Emission
AR4 (3)	27,836	Low Emission
AP3 (3)	11,272	In Service at Present
RF System 3 (20MeV)		
AF1 (5)	5,348	Low Emission
AJ5 (3)	4,166	Not failed. Returned to Thomson for Inspection
AF5 (2)	3,794	Low Emission
AF3 (2)	4,842	Low Emission
AK2 (3)	8,486	Low Emission (Filament Regulator installed 22.5.90)
AM3 (3)	10,775	Low Emission
AN5 (3)	19,467	Low Emission
AK5 (3)	14,691	Low Emission
AW1 (3)	5,879	In Service at Present
RF System 4 (20MeV)		
AA4 (2)	3,567	Low Emission
AE3 (2)	2,831	Filament o/c
AF1 (5)	5,348	Low Emission
AJ3 (4)	11,130	Low Emission (Filament Regulator installed 24.8.90)
AL2 (3)	12,517	Low Emission
AM5 (3)	9,132	Suspect tube
AQ3 (3)	19,437	Low Emission
AQ1 (3)	14,170	In Service at Present

Table 1. ISIS Linac - TH116 History

It should be noted that even though RF system 1 is a low dissipation system, tube life prior to incorporation of tube modifications and power stabilisation was similar to that of high dissipation systems.

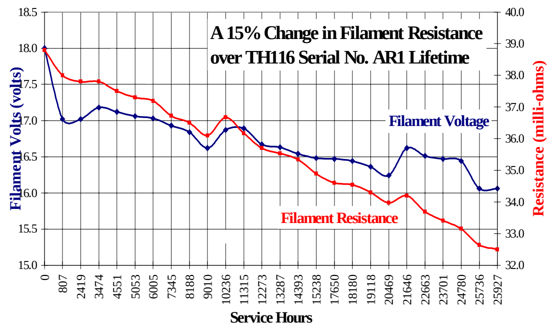

Figure 4. TH116 Serial No. AR1 Filament Voltage & Resistance Curves over its Entire Lifetime

5. CONCLUSIONS

The 15% change in hot filament resistance has proved to be the yardstick for 'end of life' predictions and allows for tube changes within maintenance schedules. It is essential, therefore, that filament data is recorded at the time of new tube installation and throughout its life to enable the characteristic resistance to be plotted.

From the historical data shown, it is clear that, for ISIS, the change from a 'window' operated voltage regulator system to that of power control of the TH116 filament has had a marked beneficial effect on tube lifetimes. An estimated saving of the order £60k per annum, based on average lifetimes prior to installation, compared with the most recent whole-life filament data, are made.

6. REFERENCES

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