

QTH FILAMENT COLLAPSE:

An Investigation into the Collapse of Filaments of FEL QTH Lamps used as Irradiance Standards

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Neil Harrison and Emma Woolliams

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Optical Radiation Business Leader, Quality of Life Division

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An Investigation into the Collapse of Filaments of FEL QTH Lamps used as Irradiance Standards

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1 Abstract

Business and science communities rely on spectral irradiance standards to underpin a vast range of measurements. For example, for Earth Observation (climate change, solar UV, ozone) [Hunt & Harrison (1999) and references therein]; for testing Infrared and UV lamps used in photomedicine and photobiology; UV lamps used for sun tanning to ensure safe levels of radiation are being used [Hawk (1999); Moseley (1988) and references therein] and also scientific studies requiring defined irradiance levels in specific spectral regions for growing biological samples and cultures – and so on.

Quartz Tungsten Halogen (QTH) FEL (1000W/120V) lamps are currently the irradiance transfer standard of choice of the international community, following the introduction of a modified version by the USA National Institute of Standards and Technology (NIST) [Ohno (1997); Ohno & Jackson (1996)].

Whilst these lamps are relatively cheap and portable there are now recognized problems with a) transportation b) filament collapse [Hunt & Harrison (1999) p24-27 & references therein].

In addition, manufacturers claim that any burning orientation is acceptable*, see Appendix 10.1 for an example specification. However, whilst researchers have indicated that in order for an FEL to be used in the horizontal position, it should also be calibrated in that position [Early & Thompson (1996)] they did not refer to filament sag; a problem that has been confirmed by our own experience. Refer to figure 1.1 which is of a lamp used in the horizontal position (as shown).

Figure 1.1 modified FEL which has been used in the horizontal position, * this use is not proscribed by the manufacturer.



In this report, there will be a full description of the measurements made at NPL and the changes in spectral irradiance or total flux from new lamps and lamps pre and post collapse.

Work has also been undertaken to develop a simple model to explain the relationship between changes in FEL lamp coil configurations and changes in irradiance.

This model is based on the manufacturer's calculations of projected output. We are indebted to Dr Milan Vukceovich for providing us with a copy of his book on incandescence, which is not generally available; we have used his work extensively to develop our model. This work will highlight the fact that it is difficult to keep up with work in other fields that might materially affect your own. Filament design, manufacture, and associated problems/failures are not new to lamp manufacturers. [*Langmuir (1912); Moon (1936); Baker (1975) Covington (1975) Coaton (1971 & 1978) and others.*] However, their emphasis has been on the consequences of filament failure with respect to lamp life and therefore saleability of the product. Our concerns as metrologists/radiometrists are with the changes in **output** (in our case, this is irradiance) of lamps we use as a metrological tool.

This work will show that FEL filaments collapse, even when they are used in the vertical position; especially the unsupported, modified, FELs currently used as transfer standards. This collapse or sag, even in the very early stages, results in large changes in lamp output (irradiance).

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2 Introduction

The NPL and other NMIs perform measurements on lamps that various communities use as transfer standards. Although it has been known for some years that there are a number of problems associated with their use; (nb this is not restricted to the modified FEL, it applies to lamps in general); transportation, ageing, current change, alignment, repeatability and burn time. These will be discussed in detail in section 5.

In this work we will give a brief overview of the use of lamps as standards, followed by a description of a particular lamp, the Quartz Tungsten Halogen (QTH) FEL 120V/1000W lamp that is most widely used as a transfer standard.

Next, we will describe how lamps are measured at NPL and the changes we observe during these measurements. This will be followed by a brief overview of how lamp manufacturers determine the output and other parameters for lamp design.

We will then use the manufacturers' equations provided in that specialized literature, to show that changes we observe during measurements of these lamps can be predicted by lamp theory. We will rely heavily on an unpublished work by Dr. Milan Vukceovich (this is an in-house text used at GE and cited by their staff in published literature).

3 Lamps as Transfer Standards

According to Frank Clarke, co-designer of the Clarke-Berry standard lamp commonly known these days as a 'polaron' lamp after the specialist manufacturer of the lamp:

"..all calibrated light sources for use in photometric ...{applies equally to radiometric}... measurements should have the following properties: unlimited shelf life, adequate short and long term stability when running under controlled conditions, light emission which varies continuously with a controllable parameter such as current, adequate reproducibility when set up on different occasions under stated conditions and in most cases, a smooth, continuous and predictable spectral power distribution In general....filament lamps can meet the criteria and the problem is to procure suitable types." [Clarke (1978)]

For an excellent historical overview see Carlson and Clark 1965

3.1 Brief History of the QTH Lamp as Spectral Irradiance Transfer Standard

Table 1: A brief history of the Quartz Tungsten Halogen (QTH) Lamp as Spectral Irradiance Transfer Standard

Date	Notes	Reference
1963	Scientists at the USA National Bureau of Standards (NBS) now NIST (National Institute for Standards and Technology) develop a 200W GE quartz iodine (halogen) coiled coil lamp with a tungsten filament for use in spectral irradiance measurements in the wavelength range 250 nm (uncertainty 8%) to 2600 nm (uncertainty 3%)	Stair, et al (1963) <i>A New Standard of Spectral Irradiance</i> Applied Optics Vol 2 p1151
1965	Three sizes set up 100W, 500W and 1kW	Stair et al (1965) <i>The New Tungsten-Filament Standards of Total Irradiance</i> Applied Optics Vol 55 p101

Date	Notes	Reference
1980	The {unmodified ?} FEL is recommended by NBS "The National Bureau of Standards [NBS] (now NIST) presently issues two types of spectral irradiance standards. Type FEL (ANSI designation) lamps, modified to a medium bipost base.... In 1963, the NBS established a scale of spectral irradiance using a group of 200W, quartz-halogen, tungsten coiled-coil filament lamps. Although these lamps were compact and relatively easy to use, the spectral irradiance below 400 nm was insufficient for many applicants. For this reasons, the scale was transferred to a group of 1000W, quartz-halogen lamps which increased the spectral irradiance by a factor of five." [Walker et al (1987)] It is likely this is the first 'modified' FEL	Walker, J.H et al (1987A) <i>NBS Measurement Services Spectral Irradiance Calibrations</i> , NBS Special Publication 250-20 LCC:87-619862
Date? ~1995?	"The FEL type quartz halogen lamps, which were used as spectral irradiance transfer standards at NIST [1], also have not been available as standard quality lamps for the past several years. The characteristics of these lamps at ~3200 K have previously been reported [1,2]..... Although there are several design factors to be noted, there is no way to assure the lamp stability other than by actually testing the lamps. Recently, a new type of FEL, 1000 W quartz halogen lamp [5] has become commercially available in the U.S. These lamps have filament mounts specifically constructed for standard lamps and have a T-6 clear bulb, 18 mm in diameter.." [Ohno & Jackson (1996)] (their reference 1 is Walker 1987a reference 5 is '1000 W T6 Modified FEL type lamp, Osram Sylvania Inc., Danvers, Massachusetts,USA.' See also Ohno 1997 and "Based on extensive investigations of almost 100 high-power quartz-halogen lamps covering thirteen different types, seven different manufacturers and different batches with a total operating time of about 27 000 h, a new type of lamp (1000 W T6 modified FEL-type lamp, Osram Sylvania Inc.) has been selected and its operating conditions have been optimized." [Metzdorf (1998)]	Ohno & Jackson 1996; Ohno 1997; Metzdorf 1998

It is appears there have been two types of modified FEL, because Walker et al (1987 & 1991) use the term as do Ohno and Metzdorf after 1996.

Quartz Tungsten Halogen (QTH) FEL (1000W/120V) lamps are currently the spectral irradiance transfer standard of choice of the international community, following the introduction of a modified version by the USA National Institute of Standards and Technology (NIST) [Ohno (1997); Ohno & Jackson (1996)].

3.2 The Quartz Tungsten Halogen (QTH) FEL

The letters, 'FEL' are a code by which the lamp type is identified. The American National Standards Institute (ANSI) allocates a three-letter code to a lamp type put forward by a manufacturer:

"The purpose of the designation system... ..is to provide a nationally applicable and convenient lamp identification that may be used for both manufacturing and ordering purposes. The designation will ensure, for the user, the interchangeability of lamps that bear that same designation. The lamp characteristics data given by the manufacturer on a Lamp Designation Request Form... ..forms the basis of the assignment of a designation. They have not been approved by ...ANSI and do not constitute an American National Standard.....A lamp designation...shall be assigned only to a lamp whose characteristics are unique...A lamp for which a Request form is filed shall be considered to have the same electrical, physical and performance characteristics as one previously assigned if the characteristics are within the following tolerances

Voltage $\pm 5\%$; Wattage $\pm 5\%$; Mean spherical candela $\pm 20\%$; Screens Lumens in same projection system $\pm 20\%$; Corner/Center Ratio in same projection system ± 15 points; Correlated Color Temperature ± 100 Kelvin; Rated Life $\pm 50\%$; Working distance $\pm 5\%$." [ANSI (1997)]

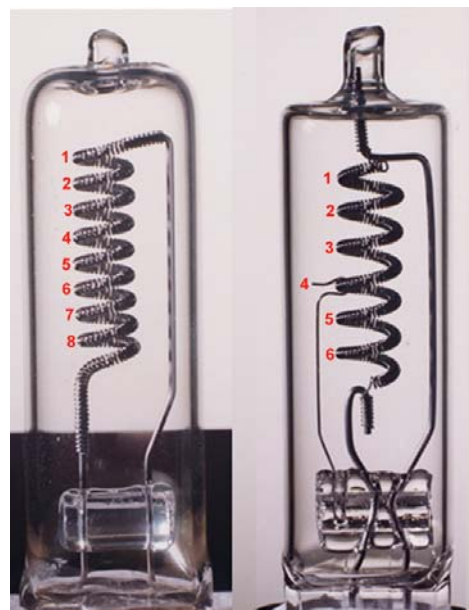
What does this code ‘guarantee’? The ‘normal’ FEL lamp falls within the category “Photographic, Stage and Studio” lamps. Table 2 gives the lamp characteristics required on the ANSI request form for that category. Clarification will only be given where it is relevant to this paper.

Table 2: Lamp characteristics required by ANSI

1	a) Service b) Projection Lens c) Condensing Lens		12	Rated Life
2	Base		13	Sphere Lumens
3	a) Bulb b) Finish c) Material d) Top		14	a) Drawing Reference from Appendix A b) A max c) B max d) C max e) D Basis LCL f) E max g) F Basic Working Distance h) G min i) J MOL (<i>Max Overall Length</i>) j) K k) R
4	Reflector a) Location b) Functional Description c) Coating/finish d) Reference Position		15	a) Layout Reference from Appendix C b) L nominal c) M nominal d) N nominal diameter e) Screen Lumens f) Corner/Center Ratio
5	Lens/Shield		16	Correlated Colour Temperature
6	Operating Position		17	Base Temperature
7	Ventilation		18	Seal Temperature
8	a) Filament b) W max c) H max d) T max	a) Only the filament support code information is requested as specified in section 8 and Appendix B, which has some crude drawings of filament types with the associated number next to them. Note that “Filaments are designated by a letter combination in which C is a coiled wire filament, CC is a coiled wire that is itself wound into a larger coil, and SR is a straight ribbon filament. Numbers represent the type of filament-support arrangement.” <i>[GE (2003)]</i> It is not at all clear how the support arrangement number relates to the supports b) c) d) “..shall be dimensioned in millimeters to show the ‘box’ location limits centered on the intersection of the light center and lamp axis” <i>[ANSI (1997)]</i>.	19	Bulb Temperature
9	Fuse		20	Candlepower
10	Wattage		21	Beam Spread
11	Voltage		22	Special Data

In terms of the filament then, the material, wire dimensions and full coiling design are not required to define the lamp for ANSI code purposes – though manufacturers do state the general ‘shape’; ie coil, coiled-coil, straight and so on. See figure 3.1.

Figure 3.1 Osram/Sylvania ‘modified’ FEL and USHIO ‘unmodified’ FEL. This Figure shows the substantial differences that can exist in a lamp -type with the same ANSI code.



Osram-Sylvania produced a ‘modified FEL’, which is now used as a standard.

As far as can be ascertained, the modified FEL lamp generally used as an irradiance standard has a vertical coiled helical filament with the filament supported only at the top and bottom, a middle filament support which exists in the original projector type lamp has been removed to improve uniformity

Quartz Tungsten Halogen (QTH) FEL (1000W/120V) lamps are currently the irradiance transfer standard of choice of international community. They were first used as standards by NIST as described above.

3.3 NMIs and FELs

3.3.1 Why do NMIs use FELs?

The ‘FEL lamp as standard’ became ubiquitous across the world following the 1986 proposal of the CCPR that there be intercomparisons of the world’s spectral irradiance scales:

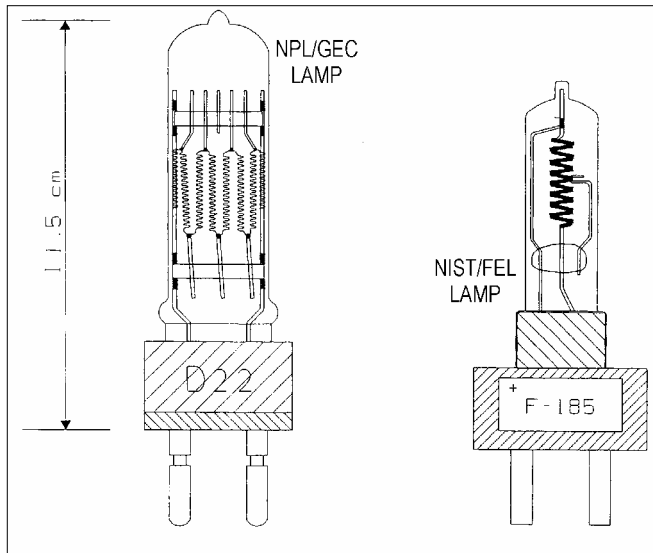
“At the September 1986 Session of the Comité Consultatif de Photométrie et Radiométrie (CCPR) of the International des Poids et Mesures..the delegates of NIST proposed an intercomparison of the spectral-irradiance scales maintained and disseminated by national standards laboratories throughout the world....It was agreed that the inter comparison would cover the spectral region 250 to 2400 nm and that the following schedule would be adhered to:

1987/88 – Invitation to participants, procurement of intercomparison lamps, lamp mounts, and alignment jigs

1989/90 – Initial calibration of a set of three lamps by each participant, calibration of all lamps by NIST, and repeat calibration of each set of lamps by the participants [Walker (1991) p647]

The original NPL/GEC 770W lamp [Goodman & Moore (1987)] intended for this comparison had to be abandoned (see figure 3.2) and

“...replacements could no longer be obtained from GEC. In order to remedy this difficulty, NIST supplied several of its routinely issued spectral irradiance standard lamps (General Electric Company (USA) FEL lamps) ... a detailed description of the NIST/FEL lamp may be found.. {in Walker 1987} [ibid p648-9]”

**Figure 3.2**

Lamps used in the first intercomparison, from Walker 1991, note that at that time, the NIST/GEC{USA}/FEL still had filament support

3.3.2 Current Practice

Pre-selected and pre-aged FELs are chosen (according to a method developed by NIST/PTB) as the most suitable irradiance standards as they have a high colour temperature and a relatively inexpensive cost. At NPL they are calibrated over the spectral range 250 to 2500 nm. One of the main disadvantages of using the FELs is that they require minimum stabilisation time of 30 minutes with maximum stability not reached until after 40 minutes.

A review of the suitability of the FEL lamp as a spectral irradiance standard was investigated by looking at the performance and sensitivity to alignment repeatability, repeatability after transportation, signal variation for a small variation in current and the ageing rates of the lamps (see section 6)

4 Lamp Metrology and Associated Assumptions

This discussion will be confined to QTH FELs.

4.1 How FEL Lamps are Measured at NPL: SRIPS Facility

The NPL Spectral Radiance and Irradiance Primary Scales (SRIPS) facility is used to calibrate both radiance and irradiance sources such as integrating spheres, strip lamps, and FEL and Polaron irradiance lamps.

The facility can calibrate up to four lamps that are held at constant current under PID computer control by the SRIPS control software, or up to six lamps with their own power supplies. Lamps are usually calibrated directly against the Ultra High Temperature Black Body (UHTBB) but can be calibrated against another standard lamp or source if required. Figure 4.1 is a schematic of the SRIPS facility layout.

The measurement instrumentation is mounted on a stage such that it can be positioned in front of each source in turn. Light enters the double grating monochromator at the heart of the facility through an integrating sphere for irradiance measurements. After the monochromator there is a set of detectors mounted on a further stage, which is also fully

automated. See www.npl.co.uk/optical_radiation/primary_standards/srips.html. For a detailed discussion, refer to Woolliams (2003) and Woolliams et al (2004).

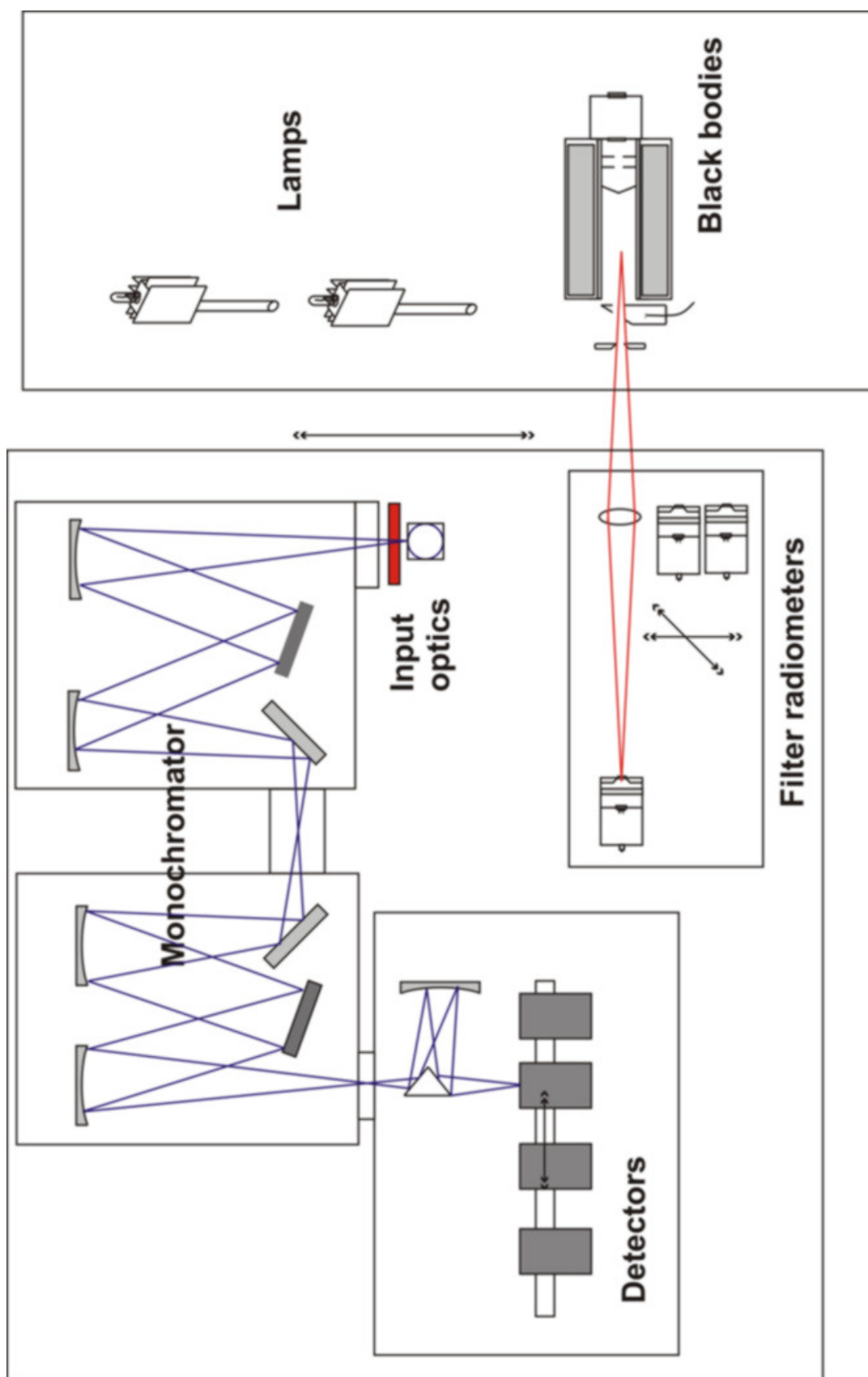


Figure 4.1 The NPL SRIPS (Spectral Radiance & Irradiance Primary Scales) facility

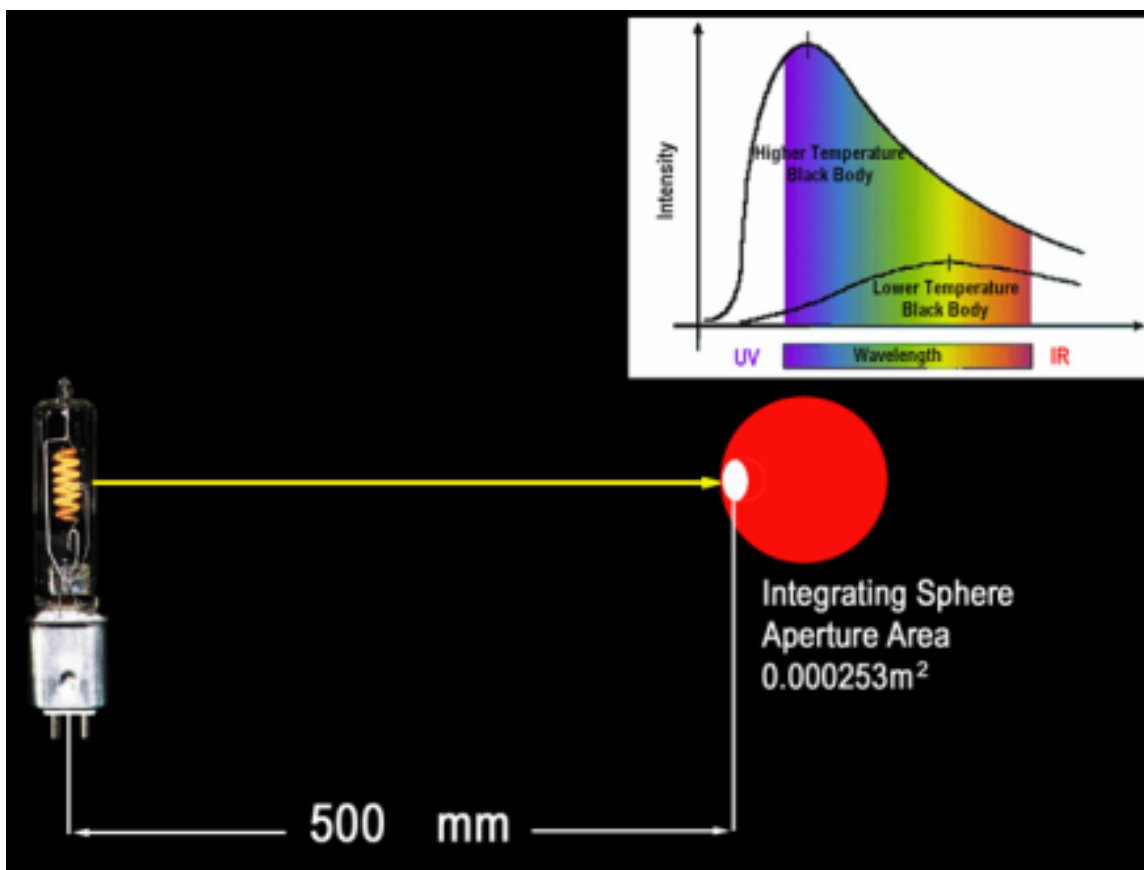


Figure 4.2 Schematic showing the basics of the measurement undertaken on the SRIPS the lamp in the schematic is an FEL with supported filament.

Generally we assume the lamp is a point source and when the aperture is at different distances we should then be able extrapolate the irradiance at various distances from the lamp. However, in reality whether the FEL can be assumed to be a point source and therefore obey the $1/r^2$ rule is usually irrelevant for our purposes, although it can lead to some flexibility for practical user applications. Lamps are usually calibrated at a defined distance of 500 mm, chosen to give good signal levels from 250 nm to 2500 nm.

The FEL is characterised against an Ultra High Temperature Black Body (UHTBB). The irradiance of the BB and the FEL lamp are ratioed. The temperature of the BB is then measured using three different filter radiometers (FRs), generally two with a peak responsivity at 800 nm (FWHM 20 nm) and one at 647nm (FWHM 50 nm). These FRs are calibrated and are temperature controlled using water jackets held at 20.0 ± 0.1 °C as the filters are thermally sensitive. The UHTBB is our closest approximation to a Planckian BB radiator.

The monochromator selects only one specific wavelength at a time and at that wavelength an irradiance value is determined in terms of the radiation flux falling on the integrating sphere aperture. The integrating sphere is included to give a uniform input into the monochromator thereby reducing directional effects.

The lamp's irradiance at specific monochromator selected wavelengths is then ratioed against the BB profile and so the lamp is calibrated.

4.2 Theory for Lamp Measurement

Table of symbols used in this section.

r_1	is FR aperture in metres
r_2	Lens aperture in metres
d	Distance between them in metres
V	is the signal you measure on the voltmeter of the FR in Volts
g	Configuration factor, which takes the geometry of the measurement into account and is given by

$$g = \frac{2\pi(r_1^2)(r_2^2)}{r_1^2 + r_2^2 + d^2 + \sqrt{(r_1^2 + r_2^2 + d^2)^2 + 4r_1^2 r_2^2}}$$

λ	Wavelength in metres
c	Speed of light in a vacuum
n	Refractive index of the air
T	Temperature in Kelvin
k	Boltzmann constant
h	Planck constant
L_{BB}	Radiance of the black body radiance in air, in $\text{W.m}^{-2}.\text{sr}^{-1}$

Planck's Radiation Law (equation 4.1 below) is used to model the output of the UHTBB

$$L_{BB} = \frac{2h(c/n)^2}{\lambda^5 (e^{hc/n\lambda kT} - 1)} \dots\dots\dots 4.1$$

The following are extracts from Woolliams (2003) and describe the lamp measurement process.

"When SRIPS is used to measure the lamp, the signal measured is:

$$V_{lamp} = AE_{lamp} R_{SRIPS} \dots\dots\dots 4.2$$

Where V_{lamp} is the difference between the dark and light signals, A is the area of the integrating sphere aperture and R_{SRIPS} is the responsivity of the SRIPS facility (monochromator throughput, detector responsivity etc). The signal measured with the blackbody is:

$$V_{BB} = \pi \cdot g \cdot L_{BB} R_{SRIPS} \dots\dots\dots 4.3$$

The calculation for lamp irradiance is:

$$E_{lamp} = \frac{\pi g}{A} \cdot L_{BB} \cdot \frac{V_{lamp}}{V_{BB}} \cdot \frac{R_{SRIPS}^{BB}}{R_{SRIPS}^{lamp}} \dots\dots\dots 4.4$$

The final term should be unity, if the SRIPS facility has not drifted, and for the irradiance calculation it is taken to be unity. It is left in at this stage for the purposes of uncertainty calculations.

In practice two measurements of the blackbody have been made at potentially different temperatures. The average of the two ratios: is used, where L_{BB} is calculated for the average of the blackbody temperature measured before and after the relevant monochromator scan.

[*ibid* Chapter 7 p148-9]

The result is an irradiance curve in the familiar blackbody shape (figure 4.3). Although we do measure lamp total output at NPL, it is not part of the spectral irradiance measurement process. We make this comment, because later we will be using lamp manufacturer models to make our case for filament collapse; these use total flux. See later.

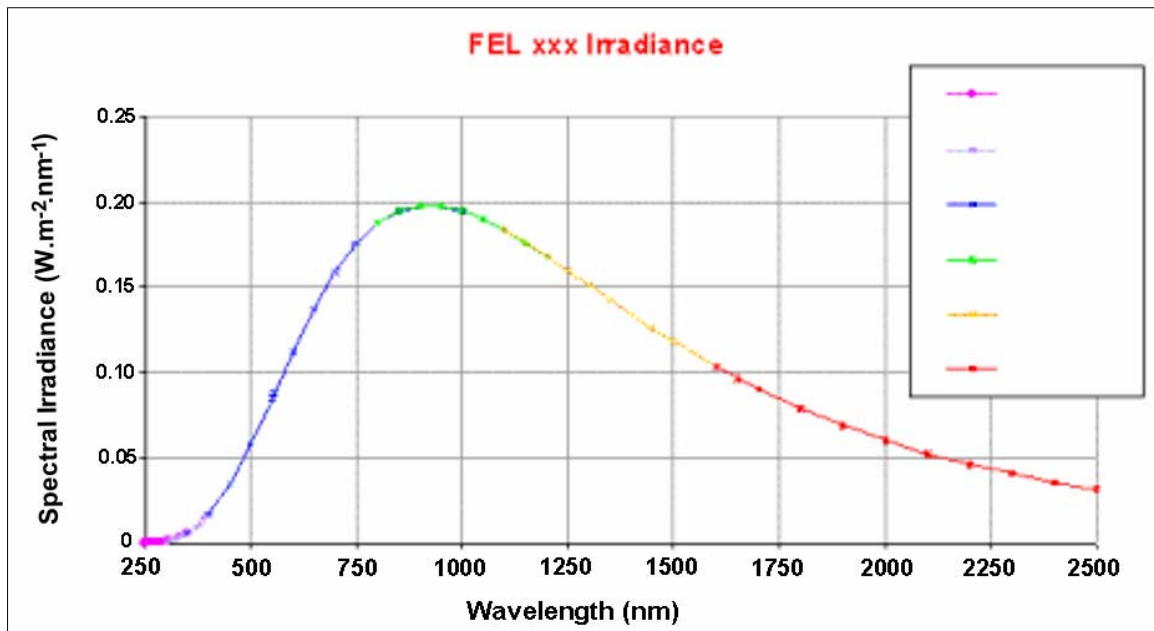


Figure 4.3 Irradiance of an FEL lamp over the range of spectral regions UV to IR

5 Changes in Irradiance Observed During the Intercomparison

The performance of FEL spectral irradiance transfer standard lamps has long been a concern in the radiometry and photometry communities with many anecdotal tales of significant and unpredictable shifts in irradiance. The performance of the modified FEL lamp in carefully controlled laboratory conditions has been reported as excellent when operated under a continuous burn regime [Metzdorf *et al* (1998)]. However, the majority of the physical stress on a lamp occurs when the lamp is switched on or off. Performance of the FEL lamp, when operated under normal use conditions, is affected by the many on/off cycles over the course of the lamp lifetime. Additionally, vibration induced changes in the spectral output of such lamps can occur when lamps are transported by road, rail, air or even when hand carried. These changes with FEL lamp operation or transport are generally caused by bulk movement of the filament, or by collapse of the internal filament windings, and may not always be apparent in changes to the voltage and current supplied to the lamp, but rather as changes to the spectral profile of the lamp. In preparation for the CCPR K1-a irradiance key comparison between National Measurement Institutes 'real-life' testing of over thirty FEL lamps both pre-selected, according to published procedures, and direct from the manufacturer were performed at NPL.

The simulated use-cycle ageing rate of a pre-selected, pre-aged FEL lamp typically resulted in a filament coil collapse after 140 to 250 hours burn time. Ageing rates between different lamps varied significantly with the lamps showing early coil collapse generally giving higher ageing rates. A rate of change of up to 4% per 100 hours burn time for a pre-aged, pre-selected lamp which suffered coil collapse at a 140 hours accumulated burn time was the highest ageing rate recorded. This compares with reported ageing rates of between 0.2% and 1% for lamps with operating lifetimes of 500 hours or more tested under continuous burn conditions [Metzdorf *et al* (1998)]. No difference in behaviour was found between the pre-selected and off the shelf lamps in terms of their ageing rates and coil collapse after an initial ageing period for previously unseasoned lamps. A wide variety of operational parameters were changed such as lamp current, the ramp up/ramp down time, burn time and lamp off time. The conclusion of the tests was always the same, coil collapse at between 140 hours and 250 hours burn time and a much higher ageing rate on a simulated use cycle than observed and reported elsewhere. In terms of lamp on/off cycles coil collapse starts to occur from as few as 100 cycles. Full details of the testing procedure and results are given in [Harrison *et al* (2000)].

Of equal importance to the key comparison results was the reproducibility of the FEL lamps after transportation. Road and rail transportation tests were performed and it was found that, typically, transportation changed the output of over 1 in 3 lamps tested. However, it is important to note that in most cases the lamp voltage and current characteristics did not change and there was not always an obvious change in filament conformation. The results from the transportation tests were similar to actual results seen in the intercomparison. Figure 5.1 shows typical intercomparison results for three lamps, each lamp had been pre-aged and pre-selected by a commercial supplier. It can be clearly seen that one lamp shows a significant absolute shift in output.

The effects of transportation may also explain some of the results reported in [Kiedron *et al* (1999)]. Differences of over 10% between calibrated lamps from several sources are

reported. Even the lamps calibrated and supplied by NIST show differences higher than the quoted uncertainties of the calibration.

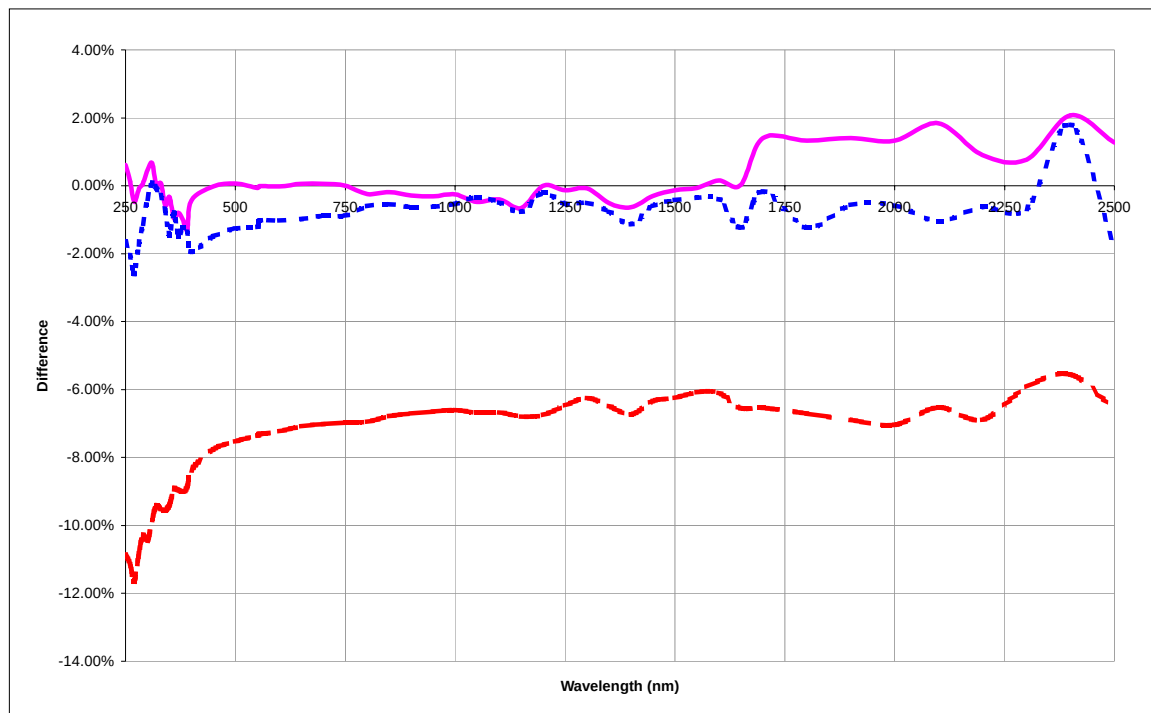


Figure 5.1 Graph showing typical changes in FEL lamp irradiance after transportation for a set of three CCPR k1-a comparison lamps.

This is not new news. “Another drawback, which is seldom observed but cannot be excluded, is an unforeseeable sudden step in the spectral irradiance in the 1 % range, which was observed with very few of the new FEL-type lamps of the first batch but was no longer observed with lamps of a new batch The step in spectral irradiance was a result of a weak but noticeable widening of the coiled filament” [Mezdorf *et al* (1998)]

However, they didn’t justify this finding; they just stated it.

6 Properties & Sensitivities of Lamps; in Particular the Current Modified FEL

In order to separate out the changes described in section 5, the properties and sensitivities of the modified FEL currently in use as a secondary transfer standard will be discussed.

6.1 Uniformity

Lamp output uniformity is an important property of the FEL, therefore, an x-y translation stage (supporting a filter radiometer with an integrating sphere on the front to remove any angle of incidence effects on the interference filters) was used to monitor the lamp output in a plane normal to the optical axis of the lamp.

For a typical FEL lamp measured at a distance of 500 mm from the measurement plane, irradiance uniformity of $\pm 0.2\%$ is achieved over an area of 30 x 60 mm (figure 6.1).

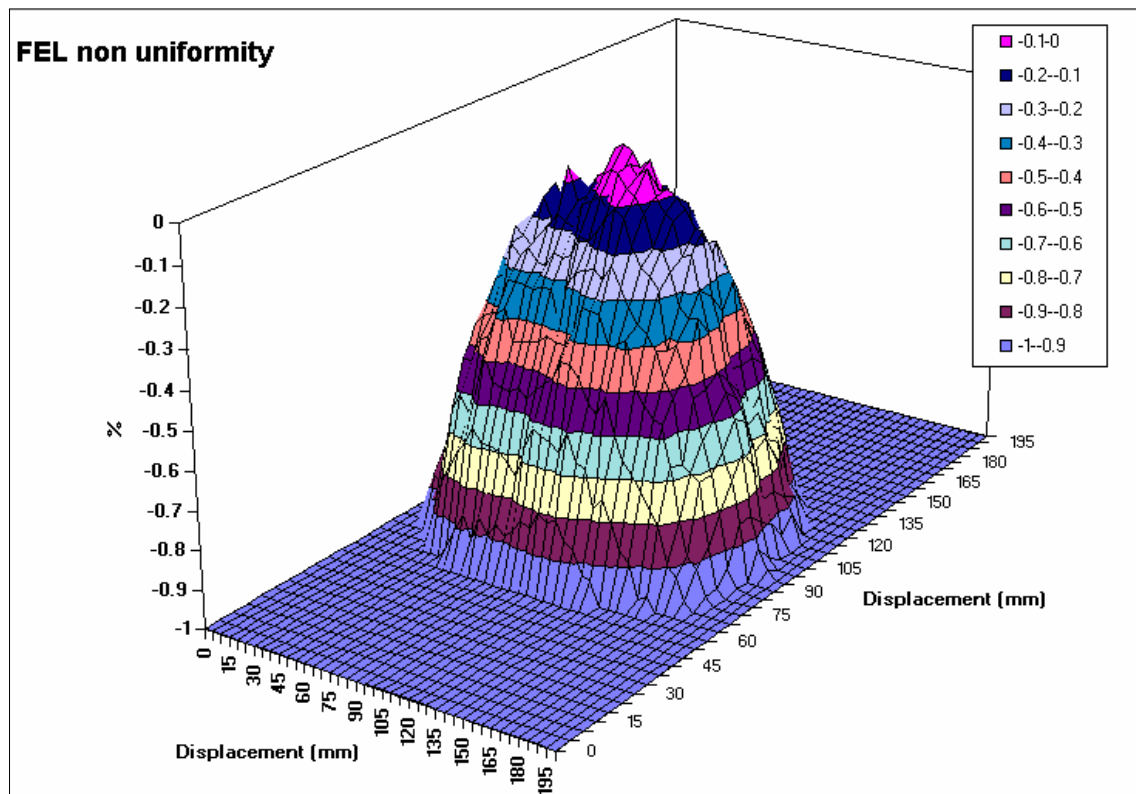


Figure 6.1 Typical, normalized irradiance uniformity plot of an FEL at 500 mm from the measurement plane.

6.2 Repeatability after transportation

The FELs were taken on a number of journeys to and from work, and were subjected to road, rail transport.

The results of transportation of the FEL were not correlated with the mode of transport. Some of the lamps appeared to have changed their colour temperature while others appeared to have remained ‘colour temperature neutral’ – the shift was constant with wavelength; this shift may be due to a shift in the filament position. In total, about 1 in 3 lamps showed a significant change after transportation.

Most of the lamps will have considerable airfreight time when they could experience shocks of up to 70g. A more rigorous transportation experiment should be performed using standard rail and road shock tests.

Further, just because a lamp did not exhibit a significant change (after one road or rail journey), this does not mean it would not exhibit a change after a second or further transportation. During tests, it was found that walking up stairs could be sufficient to cause a change therefore even one case of “mishandling” can cause problems.

6.3 Alignment repeatability

The alignment repeatability for the FEL was about 0.06% when using a measuring stick; however although this may be improved upon if we used an interferometer. To date this has not been tried and since it is not a dominant source of uncertainty is not felt necessary.

6.4 Small changes in current

FEL current increases of 0.06% and 0.12% of the base current result in signal increases of 0.4% and 0.9% at 400nm as would be expected.

6.5 Ageing of the FEL lamps

The majority of physical stress occurs when the lamp is switched on or off. General bulk movement of the filament causes changes in the spectral output of the lamp; this may not always be obvious from looking at the voltage or the current.

When the lamps have been tested and studied in the past, they have not been tested in the manner in which they are used. In general they were burnt for long periods of time with only a few turns on/off. Typically, standard lamps are generally run for up to an hour at a time and then turned off again. It is during the warming up and cooling down times when the fastest ageing process occurs due to thermal and mechanical stress.

During tests on the lamps prior to the intercomparisons, lamps were aged on a typical life cycle of 30 minutes on, 30 minutes off; plus 5 minutes ramp up/down time. Despite the lamps having been pre-aged and pre-selected it was found that they still changed their output by around 1% during the first 40 hours of testing, which corresponds to 22 hours burn time. This is within the possible burn time of the intercomparison. After 160 hours accumulated burn time, filament sag is clearly visible.

The highest ageing rate recorded was a change of 4% per 100 hours burn time for a pre-aged, pre-selected lamp that suffered coil collapse after 140 hours accumulated burn time. This compares to ageing rates of between 0.2% and 1% for lamps with operating lifetimes of 500 hours or more tested under continuous burn conditions. When operated vertically all of the lamps tested suffered terminal coil collapse after between 140 and 250 hours burn time coil collapse was noted after only 100 on/off cycles in some cases.

6.6 Measurements on Intercomparison Lamps

As part of the SRIPS (Spectral Radiance and Irradiance Primary Scales) facility and the new scales development the subject of lamp filament change over time has been investigated. The lamps used for the intercomparison of spectral irradiance scales are being monitored over their burning time. There are 13 national laboratories in all taking part in the spectral irradiance scales intercomparison for which NPL is the pilot. Each of the lamps were initially calibrated by NPL and then by the participants, they were then calibrated a second time by NPL and finally by the participants again. The majority of the lamps have completed their final calibrations.

Each participating country was given three pre-aged and pre-selected standard lamps, which were each measured at least twice. The lamps were measured in the region 200-2500 nm. As a quality/acceptance test for NPL measurements the following criteria were chosen: In the UV an agreement between two calibrations of 1.5% was required and in the visible to IR regions, a repeatability of 0.5%. If the results did not agree then a third, fourth and sometimes fifth calibration was performed until three calibrations in agreement are achieved.

Following calibration by participants a comparison is then made between the first and second phase of calibrations at NPL to see if there are significant variations in the two sets of results (i.e to identify any transportation induced drift). To carefully monitor the internal and external factors affecting the lamp, a lamp history was kept.

6.6.1 Factors Affecting Lamp Performance.

As already discussed above, factors affecting the assessment of lamp performance (not in order of importance) are: Transportation, ageing/contamination, current change, alignment, repeatability, burn time, and switch-on/off cycles.

One of the major contributing factors is the lamp burn time. Due to the difference in the number of lamp measurements carried out varying from lamp to lamp and from laboratory to laboratory a strict diary of lamp burn time was kept.

Even the length of the coiled filament or the length of the filament wire when extended straight may not be the same. This appears surprising, as the equations that follow, strongly suggest that these dimensions are critical to the optical radiation emitted by the lamp. (However, one would hope that in practise in an automated process there is unlikely to be significant variation, at least from batch to batch).

6.6.2 Photography as a Method of Determining Changes in Filament Geometry

This approach did not work, but is discussed here for completeness.

The lamps were studied as independent entities and the change in the filament was monitored for each. The lamps were photographed at the end of the first calibration at NPL. They were then re-photographed at the end of the second calibration using a 2.5 Mega pixel digital camera.

The filaments were photographed against a background of millimetre graph paper with the FEL number clearly showing either on the lamp base or written next to the lamp. See figure 6.2. These have been removed from the figures in this document to maintain the anonymity of participants. First and second photographs were then printed side by side (figure 6.3) and the filament coiled coil lengths measured. From this, the percentage increase or decrease was calculated. The results of the intercomparison were then studied to determine the change in the averaged irradiance value of the lamp at 550nm between the two different phases of calibrations measured.

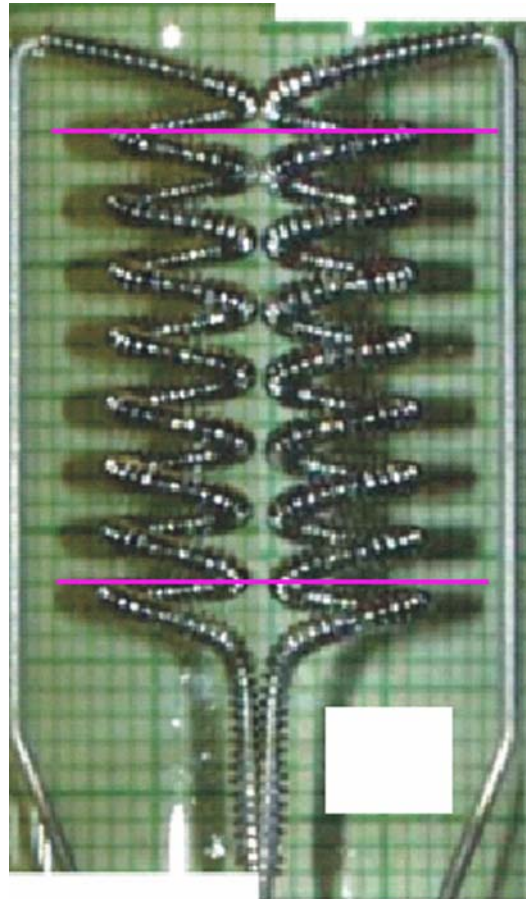


Figure 6.2

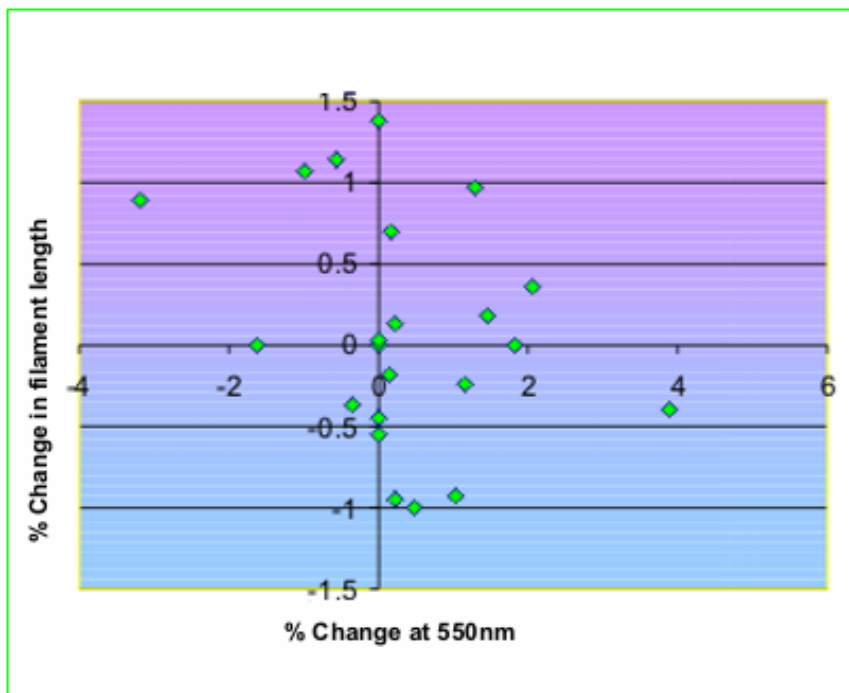
This picture was taken using a digital camera (2.5 mega pixel)

Figure 6.3

This picture is of an FEL measured during the intercomparison. On the left is a photograph of the filament during the first phase of measurements and on the right the filament during the second phase of measurements. The photographs are aligned for easy comparison of the changed filaments. Note the right hand filament has lengthened slightly.



A graph of the variation of percentage change in the filament length against the percentage change in the irradiance at 550 nm was then plotted (figure 6.3). At the start of the measurements it was expected that large changes in the filament would correspond to large changes in the irradiance of the lamp, ideally in a linear relationship.

**Figure 6.4**

Variation of percentage change in filament length against percentage change in irradiance at 550 nm.

The percentage increase or decrease in the overall coiled coil filament length varied between -1% to +1.5%. The percentage change in the irradiance varied between -3% to +4%.

Examination of the graph in figure 6.4 clearly demonstrates that there appears to be no clear, simple relationship between a change in coil length and a change in irradiance. As there was no clear pattern emerging it was obvious that a more thorough investigation of the changes in the lamp coil was required.

7 How Manufacturers Design Incandescent Lamps

Most lamps made are designed for architectural and industrial lighting and for the motor trade. There are relatively few lamps produced specifically for science because setting-up costs are enormous. A request to a manufacturer for a specific lamp-type will result in the answer ‘how many thousands’ when generally ~10 only would be useful for proving.

Lamps have been designed at NPL in the past, most notably the Clarke-Berry or Polaron lamp which is still used as a standard. However, this is no longer possible due to the spiralling costs. In common with other scientists who need lamps for their work, we select ‘off the shelf’ lamps which most closely match our needs. Occasionally the manufacturers will make lamps within their R&D sections, but this is rare. Although lamp technology has improved greatly, there are fundamental limiting factors in the make-up of a lamp, such that, as time goes by, the needs of radiometry are outgrowing this technology. However, we still rely heavily on the use of lamps and must, therefore, be able to characterise their performance in order to ensure they are adequate for whatever purpose they are required.

In this section we investigate how lamp manufacturers predict the initial performance of incandescent lamps as part of the design process; and discuss some of the assumption they make. The starting point is usually well-known heat transfer equations.

“The design of a filament can be calculated from well known physical processes. The underlying theory of such calculations appear in Langmuir’s early work (1916) and by more recent authors.... {he then cites Moon’s key work *The Scientific Basis of Illuminating Engineering* (revised 1961); originally published in 1936}.. The radiated power can be obtained by specifying the power input and calculating the total power losses.....solutions to... {the} equations yields the ‘active’ surface area for a given filament temperature, hence life; a knowledge of the supply voltage then enables a discrete wire length and diameter to be defined.” [Coaton (1978)]

However, until ~1980s lamp filament design was progressed using primarily empirical methods:

“The design of filaments for incandescent lamps using traditional methods is often a lengthy process involving a series of lamp trials.” [Howe (1985)]

Thanks to Coaton, Howe, Vukceovich and others, there are now several equations we can use to see what is going on – although where people give different equations and make different assumptions, (leading to different results) it is sometimes hard for the layperson (in that field) to make a judgement regarding the ‘correct’ equation, as will be seen in the discussions that follow.

7.1 Power Balance Equations

When predicting the output of a new lamp, manufacturers start with power balance equations. What is the power input required for the desired output wattage? What are the losses? See for example Vukceovich (~1992), Page et al (1989), Howe (1985), Covington (1978). Most of this work was done on miniature lamps and no similar discussion has been found specifically for higher power lamps such as the FELs that we wish to investigate; however, it is likely that much remains the same; and where we have concerns, we will highlight these. They generally start as follows:

“In a gas filled lamp, the input power W_{IN} is balanced by the sum of the radiated power W_{RAD} , the conducted power to the gas W_{GAS} and the conducted power to the lead and support wires W_C then $W_{IN} = W_{RAD} + W_{GAS} + W_C$.” [Howe (1985) p581]

Using the conventional symbol for flux, Φ , we can rewrite this equation as:

$$\Phi_{IN} = \Phi_{RADIATED.manuf} + \Phi_{GAS.losses} + \Phi_{SUPPORT.losses} \dots\dots\dots 7.1$$

What we want to determine, is the power radiated by a particular lamp, the modified FEL, and whether by changing any of the fundamental parameters used in the design, we can predict the changes in ‘irradiance’ observed during measurements, made at NPL.

It would be nice to be able to calculate Φ_{OUT} but that is not trivial due to losses and viewing geometry. Hence we will only work with the first term on the right-hand side of equation 7.1 to show that the changes we observe during measurement can be predicted by the equations supplied by the manufacturers. However, for completeness, we will provide a brief discussion of some of the other terms.

A detailed analysis will be given in section 8. Some sub-terms and issues are mentioned here to give an indication of the complexity of the subject. These will be prefaced with the words ‘complexity issue’.

7.1.1 Φ_{IN} Electrical Power Input (Watts)

In dealing with the electrical power required to give the desired output, the following assumptions are made:

- 1) There are no resistive losses in lead wires
- 2) There is negligible deformation of filament wire in coiling process
- 3) It is valid to use the mean filament temperature to simplify the calculations; i.e. ignoring the steep axial gradients at the extremities of the filament and near the supports See figures 7.1 and 7.2.

Whilst figure 7.1 is for the single coil of a miniature lamp, it illustrates the general points.

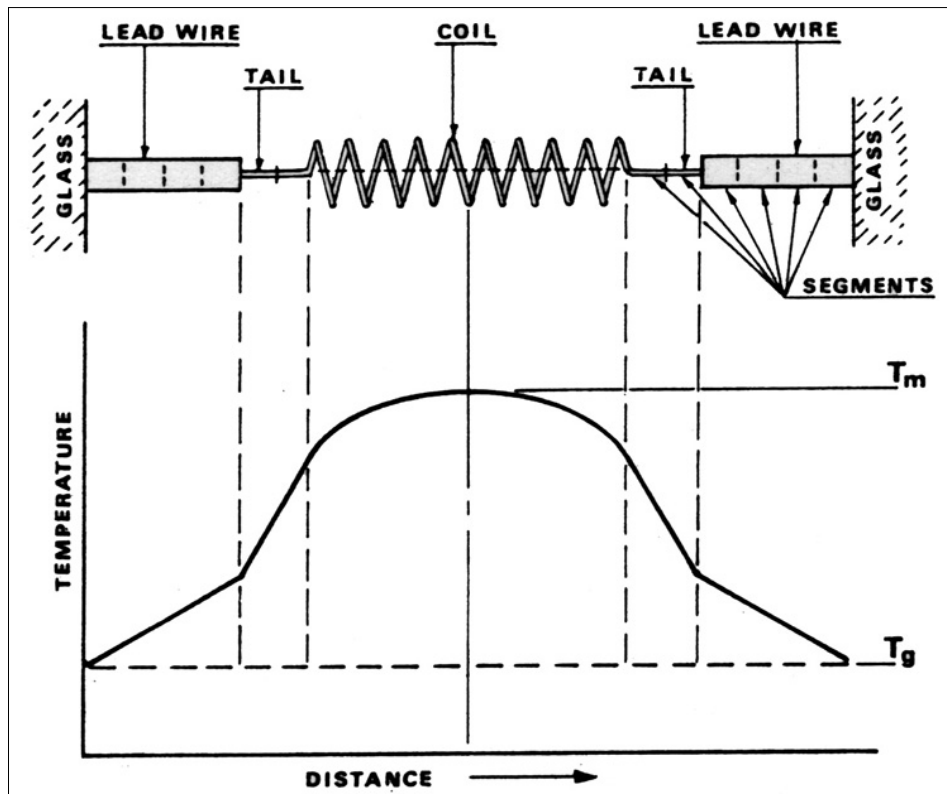
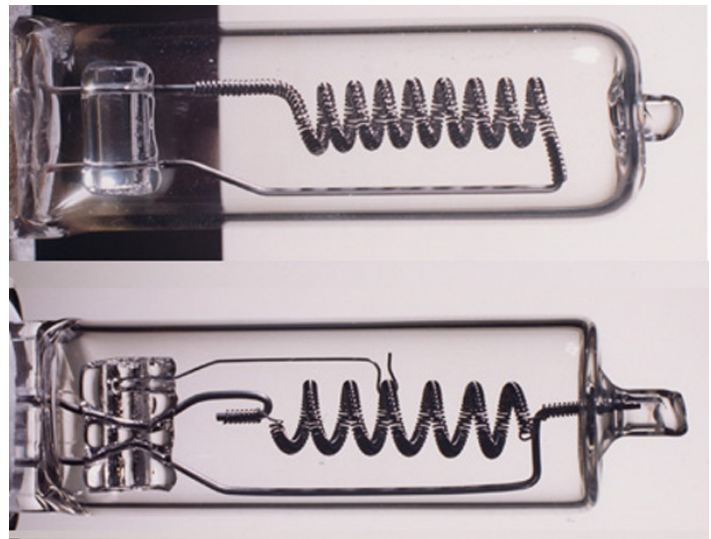


Figure 7.1 “Temperature profile in a miniature incandescent lamp” [Howe 1983 p128]
 T_m is taken to be the temperature at the centre of the filament, and T_g of the leadwire-glass interface.

Figure 7.2 Photographs of Osram/Sylvania (top) & Ushio FELs.



Note regarding the FELs in figure 7.2:

- a) they have different number of coiled coils and configuration (geometry, support) of those coils
- b) composition of tail/lead wires is unknown

There is more symmetry in the coiled coil (cc) endings in the USHIO type and the temperature profile is more likely to be ‘similar’ to figure 7.1. **NB:** Lamps shown in this orientation for comparison with Figure 7.1 only. They should not be burnt in this position.

There are several sub-terms required with complex inter-dependencies. These will now be discussed, briefly.

7.1.1.1 Lamp filaments can be treated as resistors

“Electrical resistance is a separable function of resistor geometry and temperature dependent material properties. For a wire, the geometrical dependence is proportional to the length of the wire over which the electrical potential is applied, and inversely proportional to the cross-sectional area.” [Page (1989) p109]

Thus
$$R_F = \frac{l\tilde{\rho}(\bar{T}_F)}{\pi r^2} \quad \text{Ohms} \quad \dots\dots\dots 7.2$$

Or according to Vukceovich (his p10, equation 1.2) it is given by

$$R_F = \frac{4l\tilde{\rho}(\bar{T}_F)}{\pi D^2} \quad \text{Ohms} \quad \dots\dots\dots 7.2A$$

Where $D=2r$ (see later and Appendix 10.2 for definitions of lamp parameters)

Then according to Page

$$\Phi_{IN} = \frac{V^2}{R_F} = \frac{\pi r^2}{l\tilde{\rho}(\bar{T}_F)} V^2 \quad \dots\dots\dots 7.3A$$

Where:

V	is voltage (V)
R_F	is filament resistance (Ω)
r	is wire radius (cm)
l	(total) length of wire in filament coil
$\bar{T}_F$	is mean temperature of the filament

$\tilde{\rho}(\bar{T}_F)$ is the resistivity of the filament material at the mean temperature of the filament.
NB: we have modified this as the same Greek symbol is used for the *reflectivity* (see later).

Complexity issue 1: Whilst it is possible to get information on resistivity for *tungsten*; lamp filaments are not pure tungsten. Also care must be taken with units, they come as (Ohm.cm) and (microOhm.cm).

The Vukceovich version of equation 7.3A is (his page 14 equation 1.9) though he says it is for wires (ie not coils)

$$\Phi_{IN} = \frac{V^2}{R_F} = \frac{\pi D^2}{4l\tilde{\rho}(\bar{T}_F)} V^2 \quad \dots\dots\dots 7.3B$$

7.1.1.2 Mean filament temperature for an FEL.

Note that the melting point of Tungsten, symbol **W**, is ~3695K.

Complexity issue 2: There is no simple way to get at the mean filament temperature. According to Howe, it can be obtained from the correlated colour temperature CCT. However, there is often confusion regarding CCT and colour temperature. This issue was discussed elsewhere by the first author, and key issues are quoted here:

"For ideal black bodies...the colour temperature is the same as the true temperature, however, incandescent lamps only approximate this theoretical model. As the science of *colour* has progressed, the concept of a colour temperature has become more complex and the CIE introduced a variation called *correlated colour temperature*. According to McCluney (1994):

"Colour temperature as applied to an illuminant is the temperature of a blackbody whose colour is the same as that of the illuminant. If the colour of the illuminant does not quite match that of any blackbody, then a modification.....called the correlated colour temperature, is available. That temperature which produces light from a blackbody having a colour closest to the colour of the source of interest having the same brightness under the same viewing conditions.." [McCluney (1994) p364]

McCluney cites CIE (1986) at the end of this quote, however, there is no **definition** of colour temperature in the CIE document, although this term is used in the introduction, then at page 7, a reference is made to correlated colour temperature, again without defining it. From page 7 through page 39, only correlated colour temperature is referred to, for which, confusingly the symbol **T_c** is used. Finally, on page 38, a definition of sorts appears:

"The correlated colour temperature of a given stimulus is the temperature of the Planckian radiator whose perceived colour most closely resembles that of the stimulus at the same brightness and under the same viewing conditions"[CIE (1986) p38]

Brightness is not defined. The document then goes on to make a distinction between 'illuminant' and 'source' but does not relate those back to the definition for colour temperature of a 'stimulus' quoted above. The distinction between illuminant and source is given as follows:

"The term 'source' refers to a physical emitter of light, such as a lamp or the sun and sky. The term 'illuminant' refers to a specific spectral power distribution, not necessarily provided directly by a source" [CIE (1986) p 39] The term *colour temperature* makes its last appearance on page 39 in the sentence: *"The modification... {of radiation constant C₂}... affects the colour temperature or correlated colour temperature of the CIE illuminants and sources..."[CIE (1986) p39]*

Next, there is a definition of the correlated colour temperature of an **illuminant**

"...is defined by the temperature corresponding to the point on the Planckian locus which is nearest to the point representing the chromaticity of the illuminant in a plot of 2v N/3 against u N, when based on the data of the CIE 1931 standard colorimetric observer.." [CIE (1986) p40]

The authoritative textbook on lamps and lighting, edited by Coaton and Marsden, distinguishes the two colour temperatures as follows:

"Colour temperature: Temperature of a full radiator which emits radiation of the same chromaticity as the radiation considered (often used incorrectly as CCT). CCT: The colour temperature corresponding to the point on the full radiator locus which is nearest the point representing the chromaticity of the illuminant considered on a (u,v) uniform-chromaticity scale diagram" [Coaton & Marsden (1997) p93]

...it is no surprise that there is general confusion as a websearch on either **colour temperature** or **correlated colour temperature** will reveal; CCT and colour temperature are indeed being used interchangeably. It appears that there is no 'official' CCT for lamps - incandescent or otherwise - (since they are by CIE definition, 'sources'). On the other hand, they are not Planckian emitters either Lamp manufacturers generally quote colour temperature for incandescent lamps and CCT for fluorescent and discharge lamps, which seems reasonable. However, a recent email exchange with the co-author of chapter 8 of Coaton and Marsden; Stephen Howe of General Electric, UK., suggests that matters are not so simple? ...

"There is a strict relationship between CCT and T for tungsten surfaces which can be calculated from emissivity data. It can be approximated over a wide range about 3000K by $CCT=2E-5T^2+0.9593T+33.3$. I have run the model to create a colour temperature vs voltage plot. For a 60W 240V GLS (General Lighting Service {incandescent}) lamp, the CCT follows $\log_{10}(\text{Correlated Colour Temperature})=2.46579+0.400 * \log_{10}(\text{Voltage})$; i.e. $CCT = 292 * V^{0.400}$. 240V, CCT = 2618K; at 264V, CCT = 2720K; at 216V, CCT = 2510K" [Howe (2000)]

Extended quote from Hunt (2001).

The equation supplied by Stephen Howe is re-written for clarity:

“There is a strict relationship between CCT and T for tungsten surfaces which can be calculated from emissivity data. It can be approximated over a wide range about 3000K by {equation 7.4A}” [Howe (2000)]

$$CCT = 2 \times 10^{-5} T_F^2 + 0.9593 T_F + 33.3 \quad \dots\dots\dots 7.4A$$

We have performed the calculation for the modified FEL using 3200K, the ‘colour temperature’ supplied by Osram/Sylvania (refer to the manufacturer’s specification sheet in Appendix 10.1). This leads to a ‘filament temperature’ of **3100.6K**; and the parenthesis is there to indicate that there is a question mark regarding the CCT vs colour temperature issue here.

However, according to Vukcevic, for a SINGLE or PRIMARY COIL (his p139 equation 9.30) the filament temperature can be calculated using the following equation:

$$T_F = 4902.2 * \left(\frac{V}{l} \right)^{0.342} * \left(\frac{D}{\delta \zeta} \right)^{0.171} \quad \dots\dots\dots 7.4B$$

Where $D=2r$ and

$$\zeta = \frac{1}{2} \left[1 + \sqrt{1 - \frac{\pi^4 (K_m + 1)^2}{[\pi^2 (K_m + 1)^2 + K_p^2]^2}} \right] \quad \dots\dots\dots 7.5$$

(ibid p138 equation 9.26) which is:

“...the Van Horn (1972)... correction factor by which the wire resistance has to be adjusted {read ‘multiplied’, it is in fact a constant of proportionality TH} in order to obtain the coil resistance (p138).....strictly applicable to single or primary coils. However, second coiling has orders of magnitude smaller effect on resistance than first coiling and can be safely neglected.” (ibid p139)

δ , the shadow factor, given in equation 7.4B would also be that for a primary coil. However, as Vukcevic has not helped us by producing a equation for filament temperature for coiled coils; all we can do is plug the shadow factor he gives for coiled coils (see later) into equation 7.4B and hope this is valid.

NB: All terms will be clarified and discussed in more detail in section 8. According to Howe:

“For tungsten, tabulated values of the bulk electrical resistivity vs temperature have been reduced to a polynomial...” [Howe (1985) p581 equation 3]

$$\bar{\rho}(T_F) = a T_F^2 + b T_F + c \quad \text{in } (\Omega.m) \quad \dots\dots\dots 7.6$$

“..giving errors not greater than $\pm 0.05\%$ over the range 2200-3200K when compared to the tabulated values” [ibid]

But Howe does not give us the values of the coefficients *a*, *b* and *c* for equation 7.6. In order to determine these, the following was taken from the literature

Table 7.1a: Electrical Resistivity

T(°C)	(micrOhm.cm)	T(K)	(x10 ⁻⁷) Ohm.m
20	5.5	293.15	0.55
227	10.5	500.15	1.05
727	25.3	1000.15	2.43
1727	55.7	2000.15	5.57
2727	90.4	3000.15	9.04
3227	108.5	3500.15	9.73

With the following notes:

“Values are affected by impurities Values given in different sources vary considerably. Those given here are an average if there is no great consensus. Resistivity is temperature dependent.....In some cases, resistivity depends upon in which direction along a single crystal the measurement is made.....Values are often quoted in micro ohm cm and to convert to these units, multiply by 100 000 000.”

[Dean (ed) (1992); James & Lord (1992); Kaye & Laby (1993); Lide (ed.) (1998)]

The temperatures were converted to the absolute scale, using T=273.15 Kelvin at 0 °C, and the resistivity was converted to Ohm.m and values of the coefficients *a*, *b* and *c* for equation 7.6 were determined by plotting the data in table 7.1a in an excel spreadsheet, putting in trendline for a 2nd order polynomial and displaying the equation. The resulting coefficients may or may not be the same as those used by Howe:

<i>a</i>	<i>b</i>	<i>c</i>
-6.00E-15	3.00E-10	-5.00E-08

At the filament temperature 3100.6 calculated using equation 7.4A; equation 7.6 gave a value for $\bar{\rho}(T_F)_{\text{HOWE}} \sim 8.22 \times 10^{-7} \Omega.m$. Table 7.1b is presented to give an indication of the validity of using Howe’s polynomial.

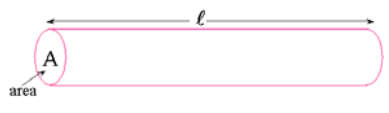
Table 7.1b

From the literature		Check Howe Equation validity		
T(K)	Ohm.m	T(K)	Ohm.m	difference
293.15	5.5E-08	293	3.74E-08	32.03%
500.15	1.05E-07	500	9.85E-08	6.19%
1000.15	2.43E-07	1000	2.44E-07	-0.41%
2000.15	5.57E-07	2000	5.26E-07	5.57%
3000.15	9.04E-07	3000	7.96E-07	11.95%
3500.15	9.73E-07	3500	9.27E-07	4.78%

The mean filament temperature using the Vukceovich equation (7.4B) is ~3150K (and depends on careful evaluation of the wire length – see later- compared to Howe’s value of ~3101K); on his p138, he warns us that:

"When calculating the energy balance of a lamp, the effect of coiling on electrical resistance is important.....This problem was recognized by Van Horn (1972), who defined the correction factor by which the wire resistance has to be adjusted to obtain the coil resistance {Vukceovich equation 9.25}"

$$R_{coil} = \zeta * R_{wire} \quad \dots\dots\dots 7.7A$$



The wire resistance is given by $R_{wire} = \frac{\rho(T) * l}{A} \quad \dots 7.7B$

Figure 7.3a

As has already been seen in equations 7.2. This leads to an equation for the resistance of a coil (note, not a coiled coil) as follows:

$$R_{coil} = \zeta * \frac{\rho(\bar{T}_F) * l}{A} \quad \dots\dots\dots 7.7C$$

However, according to Vukceovich:

"The formula ..{ie for ζ }.. is strictly applicable to single, or primary coils. However, second coiling has orders of magnitude smaller effect on resistance than first coiling, and can be safely neglected." [ibid p138]

this correction was not used by Howe (though it may not make much difference; given the difference in filament temperature obtained using their respective equations 7.4).

Plugging equation 7.7C into equation 7.3B gives

$$\Phi_{IN} = \frac{V^2}{R_F} = \frac{\pi D^2}{\zeta 4l \bar{\rho}(\bar{T}_F)} V^2 \quad \dots\dots\dots 7.7A$$

(Vukceovich page 139 equation 9.28)

However, according to Vukceovich:

"For temperatures above 1000K, the resistivity ... {of a straight metal wire, not a coil}.. can be rather accurately represented by the simple formula..." [ibid p11]

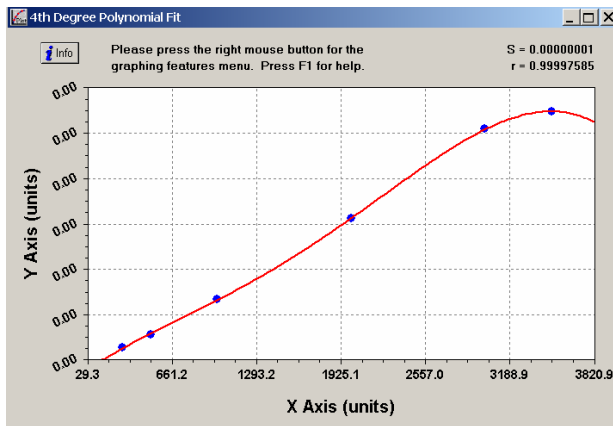
$$\bar{\rho}(T_F) = 2.42 \times 10^{-5} * \left[\frac{T_F}{1000} \right]^{1.203} \quad \dots\dots\dots 7.8$$

For the filament temperature 3150K calculated using equation 7.4B; this gives a value for the resistivity of $\bar{\rho}(\bar{T}_F)_{VUKCEVITCH} \sim 9.62 \times 10^{-7} \Omega.m$.

Table 7.1c

From the literature		Check Vukceovich Equation validity		
T(K)	Ohm.m	T(K)	Ohm.m	difference
293.15	5.5E-08	293	5.46E-08	0.75%
500.15	1.05E-07	500	1.05E-07	-0.11%
1000.15	2.43E-07	1000	2.42E-07	0.41%
2000.15	5.57E-07	2000	5.57E-07	-0.02%
3000.15	9.04E-07	3000	9.07E-07	-0.37%
3500.15	9.73E-07	3500	1.09E-06	-12.26%

To get a grip on this, we used Daniel Hyams' CurveFit programme with the data from the literature, which gave the following results:

**Figure 7.3**

Plot of resistivity data from the literature using Hyams' Curvefit 1.3.

4th Degree Polynomial Fit, where $y = a + bx + cx^2 + dx^3 + ex^4$

and Coefficient Data:

a =	-4.14E-09
b =	2.29E-10
c =	-3.21E-14
d =	5.13E-17
e =	-1.09E-20

Table 7.1d

Interpolating using this data gave the results shown in table 7.1d

From the literature as check.		
T(K)	Ohm.m	Curvefit Value
293.15	5.5E-08	5.25E-08
500.15	1.05E-07	1.10E-07
1000.15	2.43E-07	2.40E-07
2000.15	5.57E-07	5.58E-07
3000.15	9.04E-07	9.03E-07
3500.15	9.73E-07	9.73E-07
At Howe T _F	3100.6	9.27E-07
At Vukceovich T _F	3150.3	9.37E-07

Noting the following further assumptions/cautions apply (in addition to those already discussed):

- The rated voltage is not an absolute.
- Filaments are NOT made of pure tungsten hence resistivity will vary.

Possible values for Φ_{IN} given in Table 7.2 below are presented to show how input values may/not affect the final result.

Table 7.2: possible values of Φ_{IN} for an FEL (which has a Φ_{OUT} specified by manufacturers and ANSI as having and output of $\sim 1000\text{W} \pm 50\text{W}$)

Equation used	Filament Temperature (Kelvin)	Resistivity ($\Omega\cdot\text{m}$) at that filament temperature	Φ_{IN}	~Watts
Equation 7.3A	3100.6	8.22E-7	Filament temperature based on <i>Howe</i> method and manufacturer quoted 'colour temperature'; Resistivity on <i>Howe</i> and literature	1326
Equation 7.3A	3100.6	9.27E-07	Filament temperature based on <i>Howe</i> method and manufacturer quoted 'colour temperature'; Resistivity on literature using Curvefit	1177
Equation 7.3A WITH van Horn correction	3100.6	9.27E-07	Filament temperature based on <i>Howe</i> method and manufacturer quoted 'colour temperature'; Resistivity on literature using Curvefit	1200
Equation 7.7A	3150.3	9.62E-07	Resistivity and Filament temperature based on <i>Vukceвич</i> (ie includes van Horn correction)	1156
Equation 7.7A	3150.3	9.37E-07	Resistivity literature using Curvefit; Temperature <i>Vukceвич</i>	1187

7.1.2 $\Phi_{GAS,losses}$ Losses to the Gas inside the Bulb

In order to get a handle on the losses to the gas surrounding the filament and inside the bulb, we need to discuss the Langmuir sheath. Refer to figure 7.4 below.

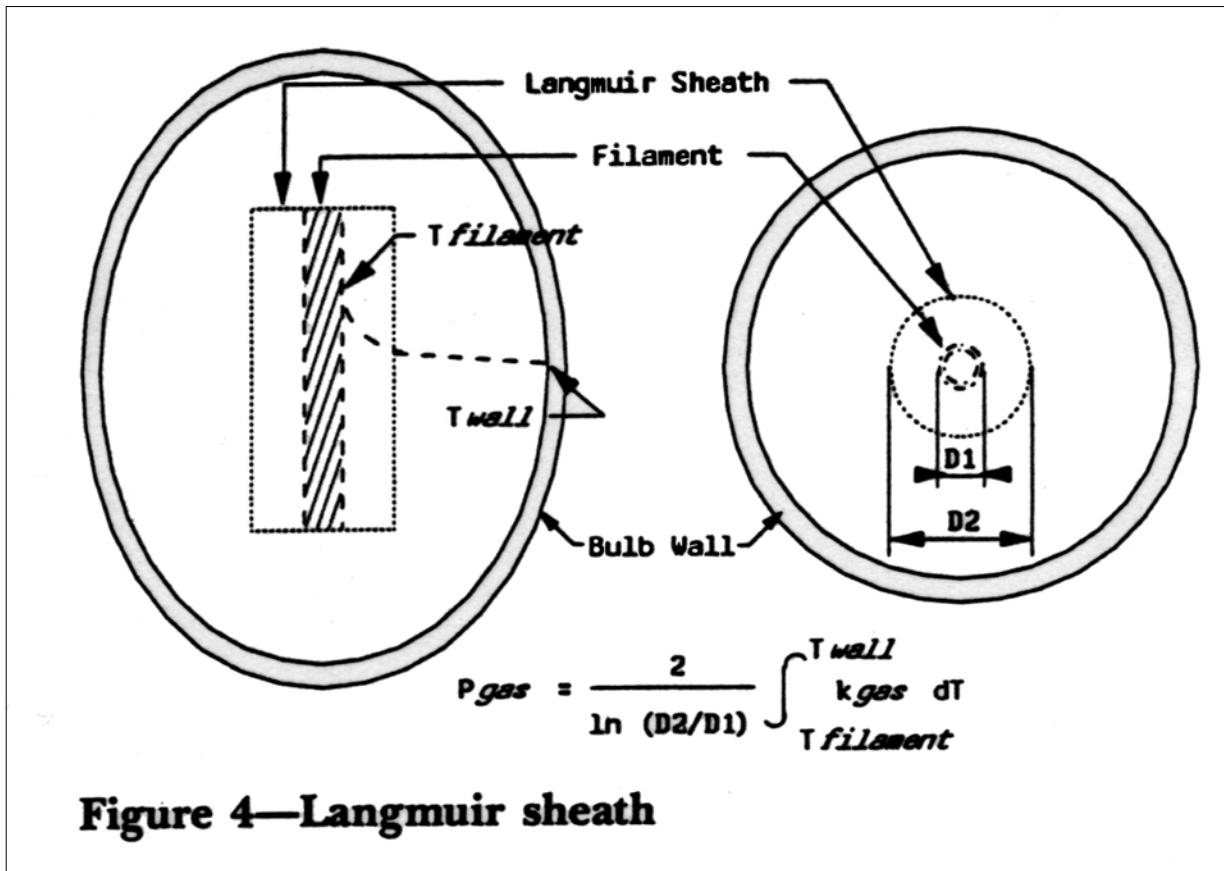


Figure 7.4 Langmuir sheath - From Page (1989)

“.....The thermal conductivity of gasses also increases with temperature. Therefore, the conductive heat transfer near the filament will also be large. From these observations Langmuir proposed that there exists a region near the filament in which the gas may be considered stagnant. In this region the heat transfer takes the form of conduction. Outside the region fluid velocities are large, and therefore convective heat transfer to the wall is rapid. The imaginary boundary separating these two regions is called the Langmuir sheath... to simplify the calculations, Langmuir suggests that the region outside the sheath be treated as isothermal at the temperature of the wall.” [Page (1989) p111]

Although Page is discussing coiled filaments, he does not deal with the coiling with respect to losses to gas.

Whilst Howe (1985) acknowledges that this approach is oversimplified. He produces a prediction for *one* typical, design (ie it is NOT supposed to apply generally, each case has to be calculated separately. He simply states that:

“since the Langmuir sheaths of adjacent coils of the planar filament overlap...(see figure 7.5)... the power loss to the gas is reduced.” [Howe (1995) p584]

This does not deal with the real 3D situation (figure 7.6) and it certainly does not address the *coiled* coil case. It is a section through a single coil, treating the wires as plane parallel, which they are not - see figure 7.7.

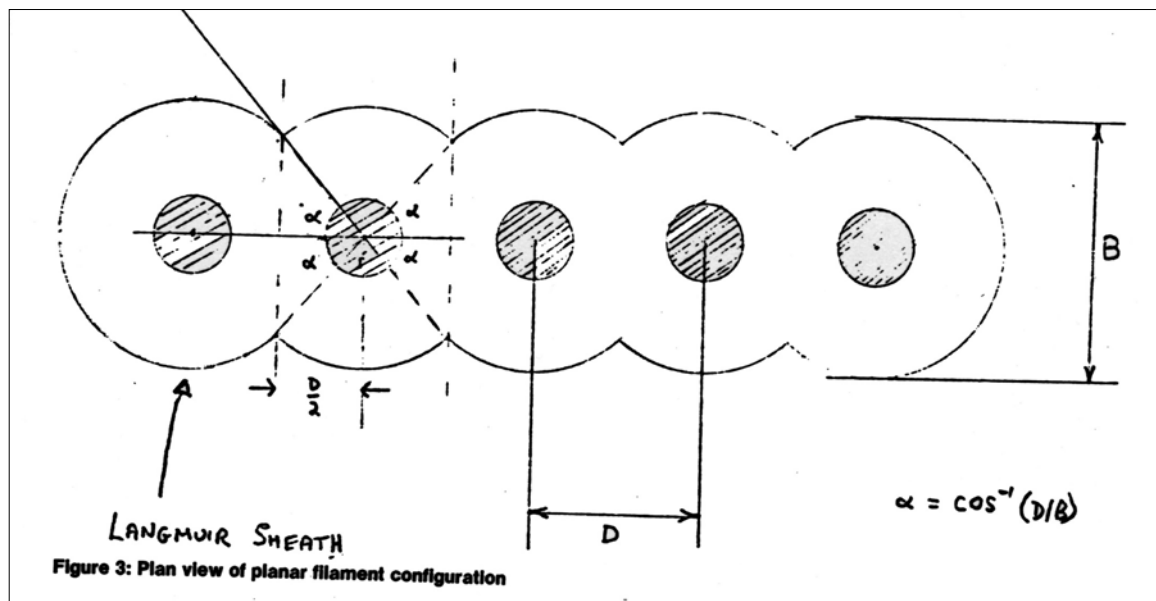


Figure 7.5 Howe's sketch of a coiled filament for single coil [Howe (1985)]

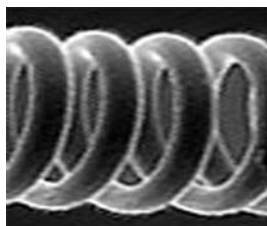


Figure 7.6 Photograph, single coil filament.

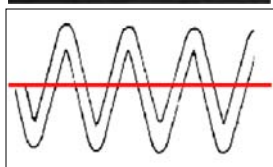


Figure 7.7 Schematic of a single coil, with red line showing the section supposedly represented in figure 7.5

It is no surprise that the coiled coil case has not been dealt with explicitly; this report will be no exception to that rule!

Figures 7.8 and 7.9 will give some indication of the problem/s.

Figure 7.8 Coiled Coil, with red line showing the location of the section suggested in figure 79

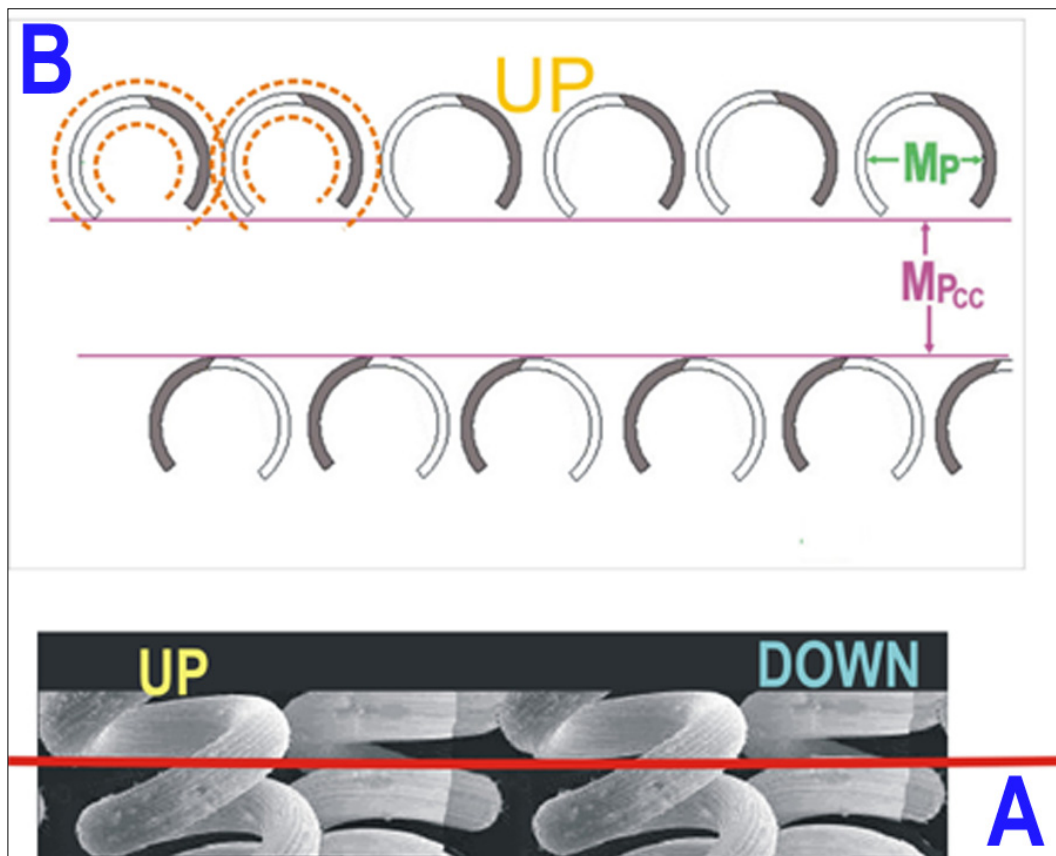
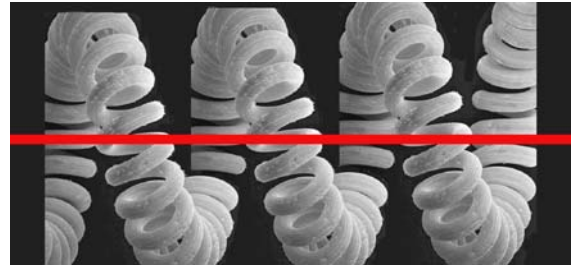


Figure 7.9 A) Enlargement of coiled coil, looking down on filament, red line indicates a section through and showing individual ‘rings’ up and down B) schematic of a section through this coiled coil filament. The dark grey line indicates it is offset and further back. The orange dotted line indicates the possible tubular shape of the Langmuir sheath.

It is tempting to think of the Langmuir sheath for both the single coil and coiled coil filaments as tubular ‘socks’ over the filament wire. However, though there may be pockets of ‘non sheath’ inside individual rings, there is likely a great deal of overlap, as Howe has attempted to indicate for the single coil case (figure 7.5). These figures are presented to show just how complicated matters are in reality; and as we do not need to delve into these matters to make our case, we refer the reader to the relevant texts and references therein for more information [Langmuir (1912); Coaton (1971); Howe (1985); Correa (1987); Page (1989)].

7.1.3 $\Phi_{\text{SUPPORT.losses}}$ Losses to Filament Support & Lead Wires

According to Coaton,

“The number of filament supports is usually dictated by the mechanical requirements of the lamp filament: too few result in excessive filament sag under the influence of gravity which drops the luminous efficacy of the lamp, and may lead to winding pitch distortion, which reduces life. However, the supports do conduct heat from the filament, and this source of loss was again recognised and reported by Langmuir, in vacuum lamp designs {1930}.” [Coaton (1978)]

He then goes on to produce an expression for this loss of power, in Watts, as follows:

$$\Phi_{\text{SUPPORT.losses}} = T_m^{1.3} I \left[1.29 - 2.49 \left\{ \frac{T_L}{T_m} \right\}^{2.6} + 1.2 \left\{ \frac{T_L}{T_m} \right\}^{5.4} \right]^{0.5} * 10^{-5} \dots\dots\dots 7.9$$

Where: T_m is filament temperature between supports or leadwires
 T_L is filament temperature at the junction of the leadwire and filament
 I is the filament current

This equation is given for completeness. A citation search on this key paper to date, yielded only Howe’s 1983 and 1985 papers.

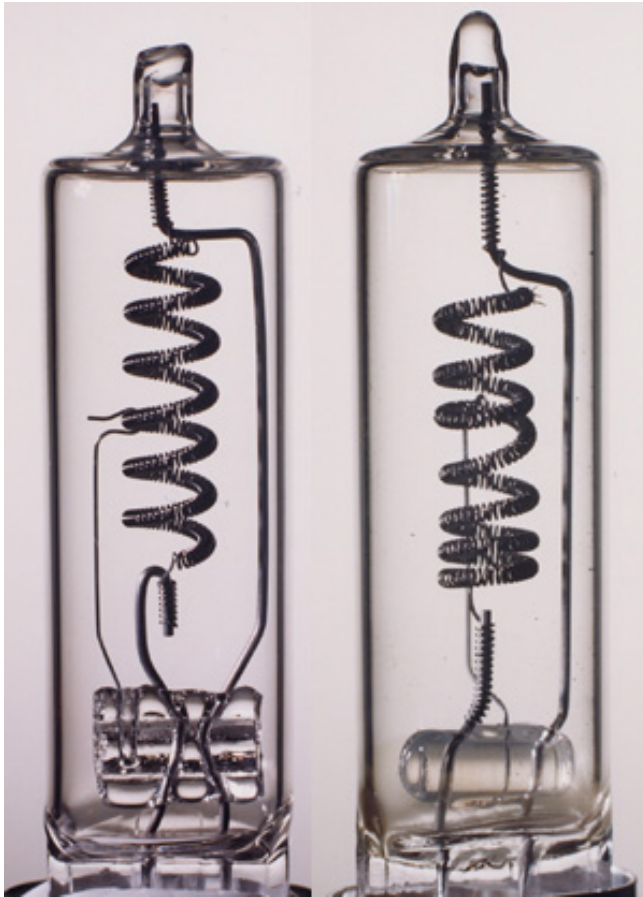
8 Putting the Manufacturer’s Equations to Work

During our work on international lamp intercomparisons, we measure many modified Osram/Sylvania FEL lamps, we have observed general filament sag caused by the collapse of some of the bottom coils, as shown in the central and right-hand pictures of Figure 8.1; which is an extreme case. NB: These two views are of the same lamp to show that the lamps do not simply collapse vertically. The single coil from which the coiled coil is fashioned is supported top and bottom, because of this whilst there can be some small movement at the bottom of the filament, the collapse (under gravity) tends to make the filament sag/bulge as shown. Whilst we have used an intermediate case (extreme cases make it to the bulb wall); in the early stages of collapse, the bulge due to the sag may be imperceptible to the naked eye.

Figure 8.1a

Osram/Sylvania Modified FEL lamps used as irradiance transfer standards. The first photograph is of a lamp with a ‘good’ (uncollapsed – to naked eye) filament.





It should be pointed out at this time, that whilst other FELs have an extra support, (removed from the modified FEL to reduce asymmetry in output for metrological purposes) this does not prevent collapse as shown in figure 8.1b.

Figure 8.1b

Ushio unmodified FEL with support; a new lamp is shown on the left and collapsed lamp on the right. Careful inspection of the top coil of the collapsed lamp reveals protrusions which are *dendritic crystal growth deposited on the colder parts of the filament which are normally seen at the end of lamp {operating} life. These are due to filament material, which has not been ‘reabsorbed’ into the filament during the halogen cycle. *[Goodman & Moore 1987]

It should be noted with respect to the new or ‘good’ lamps shown in figures 8.1a and 8.1b; the apparent (visible to the naked eye) symmetry does not mean the coils are evenly spaced (either the single coils or the resulting coiled coils).

Regarding the {coiled} coil pitch, (symbol P_{cc} – refer to section 8.1) those involved with the manufacture and design of lamps and filaments have said:

“In modern coiling practice, the pitch is affected by the surface friction between wire and the machine [Vukceovich (1992) p141]

The assumption that coil pitch does not change over the whole of a ‘new’ filament is unrealistic.

“Coil pitch carries across the whole filament, rather than being uniform except at one well-defined defect.” [Baker (1975) p9]

The coiled coil pitch will turn out to be very important for our calculations and conclusions.

Coiling parameters will now be defined.

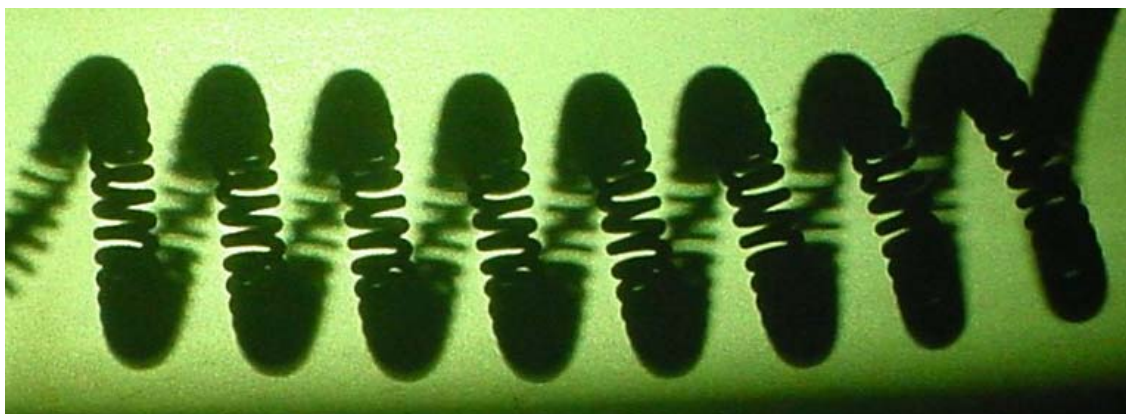
8.1 Defining Terms: Lamp and Filament Parameters

Detailed measurements were made on several modified FEL lamps using a shadowgraph. There is some subjectivity associated with alignment and the decisions regarding where to define a boundary during such measurements. These rely on operator vision, and care must be taken to avoid parallax; an experiment was done at different magnifications and using different operators, to get a handle on the problem and the example results are given in table 8.1.

Table 8.1 Measurements of single coil diameter, made on the NPL shadowgraph.

Dimension measured	<i>Same operator</i>		<i>Different operator</i>	
	Measurement made ~centre filament; Mag x50 (mm)	Measurement made ~centre filament; Mag x10 (mm)	Measurement made at base end of filament; Mag x50 (mm)	Measurement made at base end of filament; Mag x50 (mm)
FEL 208	1.320	1.304	1.284	1.320
Difference from mean	0.013	-0.003	-0.023	0.013

This revealed that a change of operator led to the greatest changes. The same operator was used for all the subsequent measurements. Figure 8.1c is a photograph taken by the shadowgraph facility.

**Figure 8.1c** Photograph of an FEL coil taken with the NPL shadowgraph.

Not all parameters measured were used in the final calculations, but they are listed here for completeness.

8.1.1 SINGLE COILS

Figure 8.2
Single coil parameters defined.

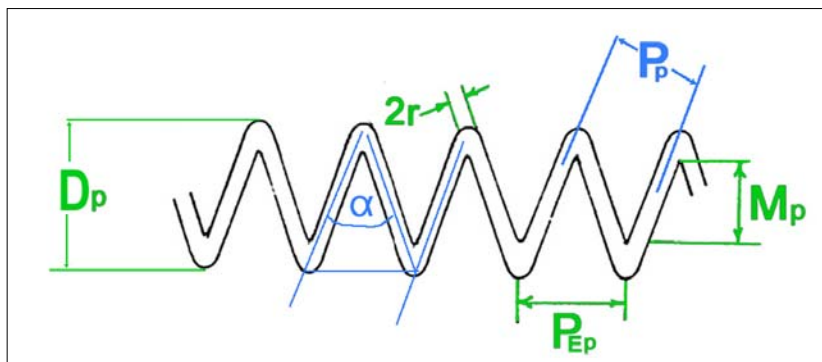


Table 8.2 Symbols and descriptions of single coil parameters, and results of Measurements made on a number of modified FELs using the NPL shadowgraph

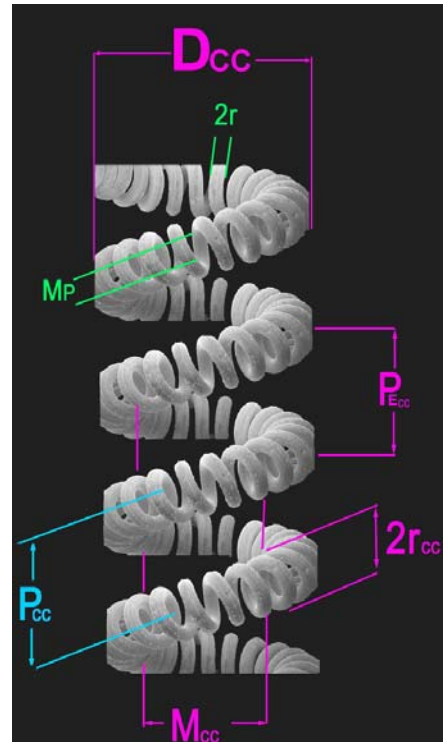
Parameter	DESCRIPTION	FEL 220	FEL 252	FEL 207	FEL 209	FEL 206	FEL 247	AVERAGE (cm)
l	Length of the wire from which filament is coiled.	CALCULATED. SEE LATER						
n_p	Number of turns (coils) in the primary coil. (sometimes the symbol n_l is used in the literature)	CALCULATED. SEE LATER						
L_c	Coil Length (single coil)	$L_c = n_l h' = n_p P_{Ep}$ AND $L_c = l \frac{K_p}{\pi(K_m + 1)}$						
D_p	COIL Diameter (primary coil) [should = $2r_{cc}$]	0.132	0.127	0.132	0.128	0.133	0.132	0.131
M_p	Mandrel Diameter (primary coil) (sometimes the symbol m is used in the literature)	0.077	0.072	0.074	0.069	0.074	0.075	0.074
$2r$	Wire Diameter (primary coil) (sometimes the symbol D is used in the literature)	0.028	0.027	0.029	0.029	0.029	0.029	0.029
P_p	Coil Pitch (primary coil) (sometimes the symbol h is used in the literature)	0.046	0.054	0.054	0.056	0.055	0.049	0.052
P_{Ep}	ENGINEERING Coil Pitch (primary coil) (sometimes the symbol h' is used in the literature)	0.047	0.047	0.045	0.049	0.048	0.049	0.048
α	Primary Pitch ANGLE (degrees & minutes)	23:50	24:40	27:30	29:30	28:40	25:40	26:38
$K_p = \frac{h}{D} = \frac{P_p}{2r}$	Primary Pitch RATIO	1.652	1.956	1.842	1.912	1.871	1.708	1.824
$K_m = \frac{m}{D} = \frac{M_p}{2r}$	Primary Mandrel RATIO	2.797	2.642	2.521	2.347	2.531	2.597	2.572

8.1.2 COILED COILS

Only single coil parameters are defined in detail in the literature, and there is no drawing similar to the one shown in figure 8.2, which is amalgamated from several sources. We have simply ‘scaled up’ the single coil parameters in figures 8.3a and 8.3b

Figure 8.3a:

Coiled coil parameters defined. Single coil parameters are shown in green.



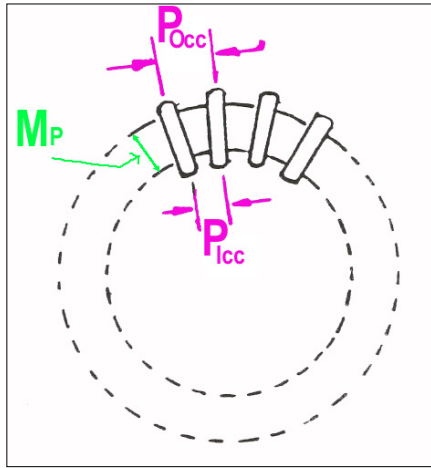


Figure 8.3b Coiled Coil Parameters, single turn

Table 8.3 Symbols and descriptions of coiled coil (cc) parameters, and results of Measurements made on a number of modified FELs using the NPL shadowgraph

Parameter	DESCRIPTION	FEL 220	FEL 252	FEL 207	FEL 209	FEL 206	FEL 247	AVERAGE (cm)
n_{cc}	Number of turns (coils) in the coiled coil.	8	8	8	8	8	8	8
L_{cc}	Coil Length (coiled coil)	$L_{cc} = n_{cc} P_{Ecc}$ AND $L_{cc} = l \frac{K_p K_{p,2}}{\pi^2 (K_m + 1)(K_{m,2} + 1)}$						
CC_{Ltot}	CC gross length (refer to figure 6.4)	3.033	3.147	3.023	3.088	3.049	3.125	3.077
CC_{Lturns}	CC length turns only (refer to figure 6.4)	1.755	1.911	1.950	1.962	1.942	1.832	1.892
D_{cc}	Coil Diameter (coiled coil)	0.603	0.595	0.604	0.606	0.587	0.617	0.602
M_{cc}	Mandrel Diameter (coiled coil)	0.339	0.341	0.340	0.350	0.320	0.352	0.341
$2r_{cc}$	Coiled FILAMENT External Diameter CC [Should = D_p above]	0.132	0.127	0.132	0.128	0.133	0.132	0.131
P_{cc}	Coil Pitch (coiled coil)	0.271	0.262	0.252	0.240	0.249	0.248	0.254
P_{Ecc}	ENGINEERING Coil Pitch (coiled coil)	0.247	0.256	0.251	0.254	0.238	0.235	0.247
β	CC Pitch ANGLE [same principle as α in figure 6.2]	NOT MEASURED (PROBABLY IMPOSSIBLE TO DEFINE PROPERLY)						
P_{Occ}	CC OUTSIDE Pitch	NOT MEASURED						
P_{Icc}	Coiled Coil INSIDE Pitch	NOT MEASURED						
$K_{p,2} = \frac{P_{cc}}{2r_{cc}}$	Coiled Coil Pitch RATIO	2.044	2.063	1.909	1.879	1.868	1.872	1.939
$K_{m,2} = \frac{M_{cc}}{2r_{cc}}$	Coiled Coil Mandrel RATIO	2.557	2.681	2.579	2.742	2.405	2.660	2.604

8.1.3 Other Lamp Parameters

Table 8.4 gives the remaining parameters for the modified FEL.

Table 8.4 Various other parameters for the modified FEL

Parameter	Description	Information from Manufacturer
W	Rated Watts	$1050 \pm 5\%$
V	Rated Volts	120
L	Rated Life (Hours)	300
C	Coil Type	CC8
-	Coil composition	<i>Not given</i>
-	Bulb composition	T6 Fused Silica
-	Bulb Gas	<i>Not given</i>

Parameter	Description	Information from Manufacturer						
-	Bulb Gas Pressure	<i>Not given</i>						
-	Burning Position	ANY						
Lm	Lumens	27,500						
-	'Colour Temperature' (Kelvin) <i>NB: but is it CT or CCT?</i>	3,200						
-	Support Wire Composition	<i>Not given</i>						
Parameter	DESCRIPTION	FEL 220	FEL 252	FEL 207	FEL 209	FEL 206	FEL 247	AVERAGE (cm)
B_{WT}	Bulb wall thickness	0.141	0.137	0.143	0.132	0.156	0.128	0.139
B_D	Bulb Diameter	Single measurement, new lamp						1.753
SW_D	Support Wire Diameter	Single measurement, new lamp						0.068

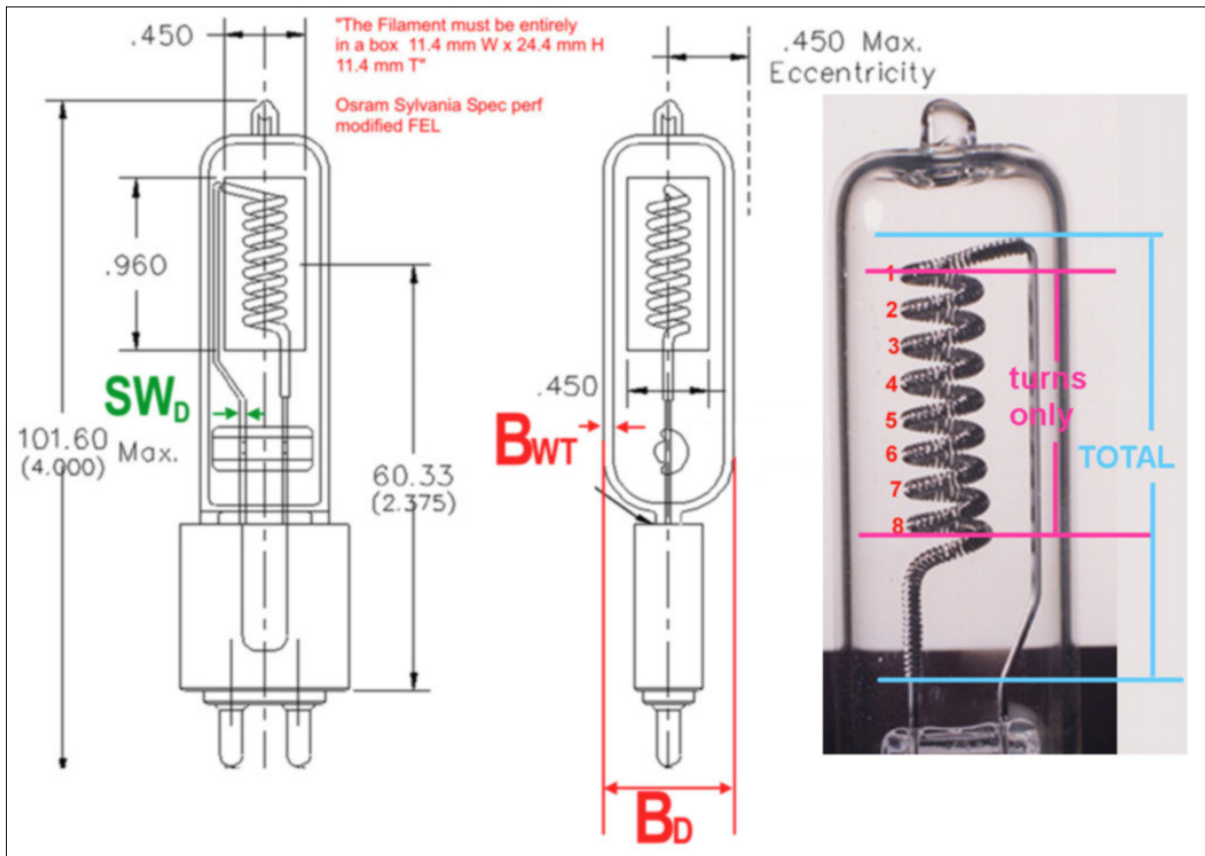


Figure 8.4 Other lamp parameters and issues for the Osram/Sylvania modified FEL

The images in figure 8.4 show:

- the nature of the single coil top and bottom support
- the problem of defining the length of the coiled coil {filament}.

The performance specification from Osram/Sylvania for their modified FEL from which the images on the left and centre of the figure are taken, indicate a distance of 24.4 mm (0.960 inches). The words in red appear at the bottom of the complete specification (see Appendix 12.1).

In particular note, the words 'the filament must be entirely within a box..' ...of that height. However whilst the top of said box, takes in that part of the single coil that is not coiled further, the bottom half stops before the end of the single coil (possibly at the top of the support wire?).

When attempting to measure the filament length of these lamps with the shadowgraph; it was difficult to decide what to use that would be the same *for all lamps*, so that they could be compared. This problem arises because the individual lamps are not identical. They do not have exactly the same number of single coils on the support wires or just above them.

We decided to take two measurements as shown in the right-hand side of figure 8.4, for which we have created the symbols given in table 8.2.

- Coiled coil gross length (ie Total), $CC_{L_{tot}}$ that is, this takes in the whole of the single coil from which the coiled coil is fashioned

- b) Turns only, CC_{Lturns} . The lamps that were measured were either in various stages of collapse; or already had different coil pitch spacing along their length. Whilst we are missing some ‘radiating’ coil surface by this definition, at least we could measure from a clearly defined point at the top and bottom as seen on the shadowgraph. That is, the approximate centre of the first and last coiled coil turn.

Fortunately, we didn’t need this in the end.

8.2 Looking at Manufacturers’ Equations in more Detail

We have measured a % difference in irradiance in lamps as described in section 5, which we believe is due to coil collapse.

It is already well known and understood that shadowing (radiation ‘trapped’ inside the coiling, or masked by the coiling in the direction in which the lamp is measured) modifies that filament output (actual and measured). However, there does not appear to be consensus on the (very complicated) equations that model this effect; this becomes ‘more true’ the more complex the coiling becomes.

What can be said, and is not disputed, is that changes in *coiling geometry* will have a marked effect on the measured output of a lamp. This does not appear to have been properly quantified to date. In addition to those papers and comments from the lamp manufacturer community already mentioned, this from the measurement community:

“Another drawback, which is seldom observed but cannot be excluded, is an unforeseeable sudden step in the spectral irradiance in the 1 % range, which was observed with very few of the new FEL-type lamps of the first batch but was no longer observed with lamps of a new batch The step in spectral irradiance was a result of a weak but noticeable widening of the coiled filament” [Mezdorf *et al* (1998)]

However, this statement that the change in irradiance was due to the ‘widening of the coiled filament’ was not justified (explained and quantified). Can it be shown using the equations the lamp manufacturers provide?

According to Vukceovich, [Vukceovich (1992) p129 equation 9.2] the power (in Watts) put into a lamp with a coiled coil filament is given by

$$\Phi_{IN} = \pi 2rl\delta_{cc} J[T] + \Delta\Phi \quad \dots\dots\dots 8.1a$$

(This has already been discussed in section 7.1). Where $\Delta\Phi$ is that portion of the *input* power that is lost to in heating the lamp gas, bulb, leads etc – all losses. If we neglect this term, we can re-write equation 8.1a in terms of the {potential} power radiated by a filament with those parameters, hence

$$\Phi_{RADmanuf} = \pi 2rl\delta_{cc} J[T] \quad \dots\dots\dots 8.1b$$

The radiation (power) **from** the filament coil, where:

$2r$ is the diameter of the wire from which the filament is coiled, in cm

- l is the total length of the wire from which the filament is coiled, in cm
- δ_{cc} is the radiation coefficient, for a coiled coil (**complex term**) and note that this should really be $\delta_{cc}(\lambda, T)$ see later. (Essentially a configuration factor for radiation exchange within the coil structure)
- J/T is the radiation integrated over all wavelengths in Watts/cm² (we would call this exitance) and defined only for the range 2500-3000K by an equation given later (**complex term**). We would call this Exitance, M .

There are problems/issues associated with this equation. These will be dealt with within the complex terms where they arise. Note: no criticism of Dr Vukceovich (or indeed any of the other scientists working within the industry) is intended. This ‘averaged’ equation is used to familiarize students and employees of GE with the concepts; ie shortcuts etc, it was not designed for public/ external consumption. Though the book itself has been the most cited, non-available work the authors have ever encountered!

Essentially, $\Phi_{RADIATEDmanuf} = M * A * configuration.factor$

Where M is Exitance, A is total radiating area

In fairness, on p223, Vukceovich gives the following equation for “watts transmitted out of a lamp” containing a coiled filament as follows:

$$\Phi_{TransmittedLamp} = \int_0^{\infty} \frac{\delta[\lambda, T] \cdot \epsilon[\lambda, T] \cdot T[\lambda]}{1 - \{1 - g(1 - p[\lambda, T])\} R[\lambda]} d\lambda$$

<u>Where</u>	δ	is the radiation coefficient for the coiled filament – see later
	ϵ	is the emissivity of {Tungsten} the surface of the coiled filament
	T	is the transmittance of the film-coated bulb
	J	is the exitance
	g	is “a design factor to.... ..describe the reflecting efficacy of a lamp design” [ibid p217]
	$(1-p)$	is “the fraction of photons which gets absorbed by the filament, either immediately, or after an unspecified number of bounces from the filament wire” [ibid p219]
	R	is the is the reflectance of the film-coated bulb

However, it is not possible to use this equation without detailed information from the lamp manufacturers (which generally they are reluctant to provide!); so we are left to use the averaged versions, for the coiled coil filament (ie rather than the whole lamp).

8.2.1 Complex Terms (in Equation 8.1b) defined

8.2.1.1 δ Radiation Coefficient for Coils

Vukceovich has derived the expression for a single coil as follows (Vukceovich p129)

$$\delta_{single\ coil} = \delta_l = \left(\frac{\text{Radiation intensity from a coiled wire}}{\text{Radiation intensity from a straight wire}} \right)_{2r, l, T}$$

Where $2r$ is wire diameter in cm
 l is wire length in cm
 T is wire temperature in Kelvin

These parameters are the same for the straight wire and the ‘uncoiled coil’

For a coiled (or double) coil, the **overall** radiation coefficient is given by

$$\delta_{cc} = (\delta_1 \delta_2)_{2r, l, T} \dots\dots\dots 8.2a$$

Where $2r$ is wire diameter in cm
 l is wire length in cm
 T is wire temperature in Kelvin

And are the same for the ‘uncoiled’ single and double coils

AND

$$\delta_1 = \frac{1}{2} \left[\left(1 + \frac{1}{\pi(K_m + 1)} \right) + \left(1 - \frac{1}{\pi(K_m + 1)} \right) \frac{K_p - 1}{K_p - \rho(\lambda, T)} \right] \dots\dots\dots 8.2b$$

$$\delta_2 = \frac{1}{2} \left[\left(1 + \frac{1}{\pi(K_{m.2} + 1)} \right) \delta_1 + \left(1 - \frac{1}{\pi(K_{m.2} + 1)} \right) \frac{K_{p.2} - f_1}{K_{p.2} - \rho_1(\lambda, T)} \right] \dots\dots\dots 8.2c$$

for δ_l

$\rho(\lambda, T)$ the **reflectivity** of the primary coil, **surface** given by

$$\rho(\lambda, T) = 1 - \varepsilon(\lambda, T) \dots\dots\dots 8.3a$$

and **$\varepsilon(\lambda, T)$** is the emissivity of the coil surface - actually of tungsten (ie rather than of the tungsten-based material from which the filament is manufactured).

Complexity issue 3: Vukceovich gives this equation on his p21 (equation 2.3). But for his derivation of the radiation coefficient on p131 equation 9.6 he uses $\rho = 1 - \varepsilon$; ie without temperature or wavelength dependence, yet he had already given the correct version of the equation. We have added the wavelength and temperature dependence here; though it is unlikely we shall be able to use this equation ‘properly’.

Values were calculated from 3000-3400K using an equation for total **tungsten** emissivity from Bergman et al (1998) p16;

$$\varepsilon(T) = -2.03926.10^{-2} + 1.88601.10^{-4}T - 2.35764.10^{-8}T^2 \quad \dots\dots\dots 8.3b$$

This resulted in a reflectivity range ρ (3000)~ 0.667 to ρ (3400)~0.652. For this work, we have rounded the value to 0.7 – in order to simplify and because due to all the assumptions, the use of 3 decimal places is unjustified and not necessary to make the case.

for δ_2

$\rho_1(\lambda, T)$ is the reflectivity of the *primary coil* given by

$$\rho_1(\lambda, T) = 1 - \delta_1(\lambda, T)\varepsilon(\lambda, T) \quad \dots\dots\dots 8.3c$$

For his derivation (his page 137 equation 9.23) Vukceovich once more does not indicate the temperature and wavelength dependence

Using the values obtained for emissivity indicated above and the calculated values of δ_1 resulted in a reflectivity range ρ_1 (3000)~ 0.711 to ρ_1 (3400)~0.699. For this work a value of 0.7 will be used, for the same reasons as given above.

$$f_I \quad \text{is the opacity of the primary coil, given by } f_I = 1 - \left(\frac{K_p - 1}{K_p} \right)^2 \quad \dots\dots\dots 8.4$$

(ibid p137 equation 9.24) This was calculated using measurements from several lamps as ~0.8.

8.2.1.2 $J[T_{fcc}]$ Radiation integrated over all wavelengths (Watts/cm²)

We would call this exitance; with the filament temperature, T , in the range 2500-3000K may be given “very approximately” by

$$J(T) = 0.883 * \left(\frac{T}{1000} \right)^{4.65} \quad \dots\dots\dots 8.5$$

the “total amount of radiation from an incandescent metal surface increases by a power higher than 4” [ibid]

However, (and using Vukceovich notation) the total radiated flux from a black body is given by

$$j(T) = \int_0^\infty j(\lambda, T).d\lambda$$

This is called spectral exitance, otherwise known as radiant flux per unit area.

Table 8.4

T(K)	J[T]
2200	34.06
2300	42.20
2400	51.71
2500	62.71
2600	75.33
2700	89.73
2800	106.04
2900	124.41
3000	145.00
3100	167.96
3200	193.44
3300	221.62
3400	252.65
3500	286.71

But “Tungsten’s surface is not a black body” which leads to the well-known correction using emissivity. Vukceovich gives the correct equation for “the total radiation” (his page 51, equation 4.7) as

$$J(T) = \int_0^{\infty} \varepsilon(\lambda, T) \cdot j(\lambda, T) \cdot d\lambda \quad \text{NB: } J[T] \text{ is in W/cm}^2 \text{ in table 8.4}$$

The emissivity of Tungsten is the critical parameter measured and calculated by de Vos in 1954 (key work) and modified and improved slightly over the years. Vukceovich makes the following very interesting comment

“Calculated properties of tungsten are given in.. (his) ..table 4.2. These numbers are significantly different from old data by Forsythe and Worthing (1925) and by Forsythe and Watson (1933) which were used at GE Lighting until recently. **Discrepancies are due to changes in the temperature scale and photometric standards** and to improved experimental techniques by de Vos” [ibid p54]

Words emboldened by authors of this text.

The values of $J(T)$ vs T as calculated by Vukceovich are given in Table 8.4. As Vukceovich says, “It is not possible to fit the results.... to any simple formula which would be accurate for all temperatures. However, for estimates between 2600 and 3000 K (where most incandescent lamps operate)...” equation 8.5 applies.

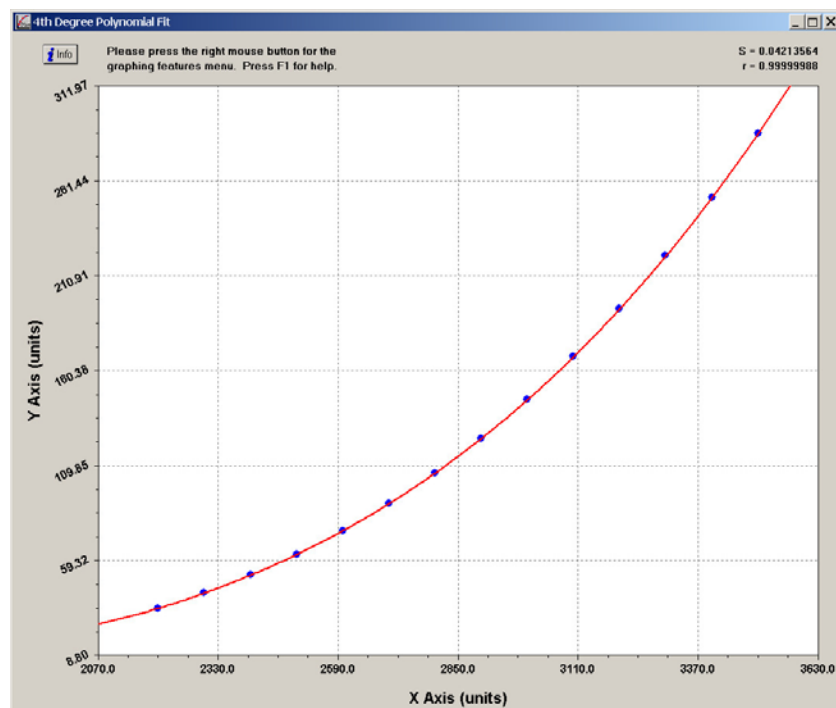
However, we want to use it beyond 3000K.

Checking the data in table 8.4 with Daniel Hyams’ CurveFit 1.3 software, shows that all points fit a 4th Degree Polynomial; where the polynomial is given by $y = a + bx + cx^2 + dx^3 + ex^4$; and where the Coefficient Data are given by

$$\begin{aligned} a &= 93.767731 \\ b &= -0.12280177 \\ c &= 5.77\text{E-}05 \\ d &= -1.41\text{E-}08 \\ e &= 3.46\text{E-}12 \end{aligned}$$

Figure 8.5a:

Plot through points in table 1. Curve fitted by Curvefit 1.3



As a double check, the values in table 8.4 (interpolated using CurveFit 1.3) were plotted against values obtained using equation 8.5, giving the results shown in figure 8.5b

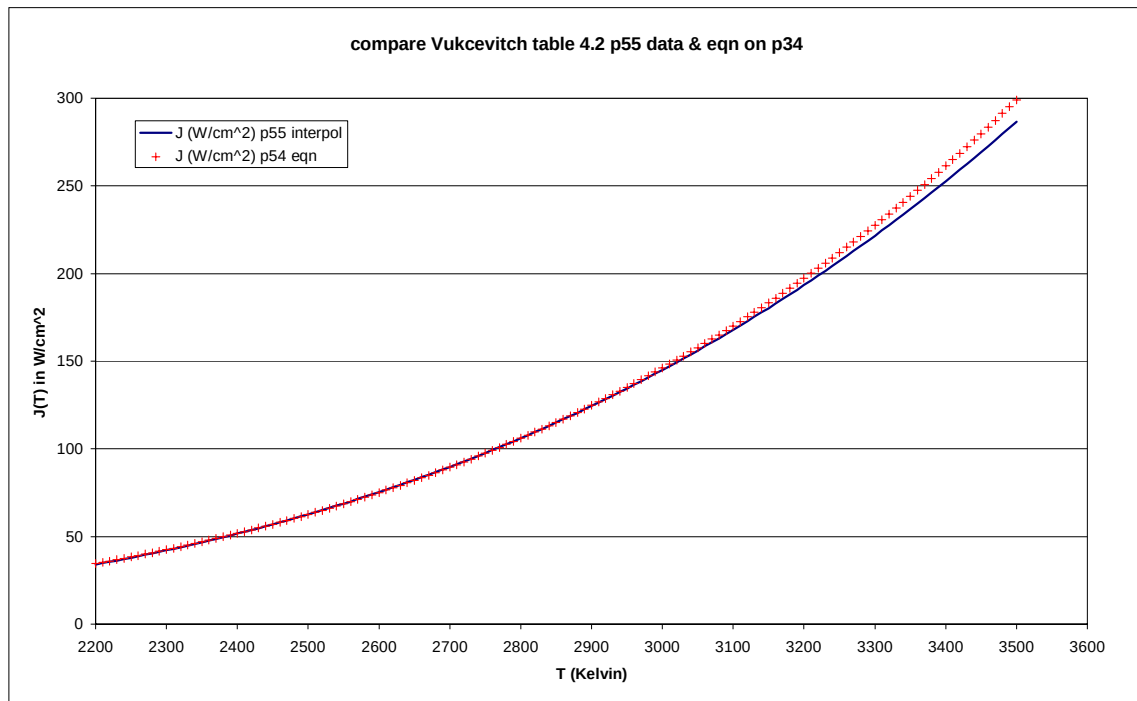


Figure 8.5b:

The plots begin to diverge just before ~3000K. Whilst the data does not fit above 3000K as Vukcevich says, the divergence can be neglected and equation 8.5 is used out to ~3400K for the purposes of this work.

8.2.1.3 What is the Mean Filament Temperature?

Vukcevich gives an equation for the wire/filament temperature, T in equation 8.5 as

$$T_F = 4902.2 * \left(\frac{V}{l}\right)^{0.342} * \left(\frac{2r}{\delta\zeta}\right)^{0.171} \dots\dots\dots 8.6$$

This is derived on his p139, and he calls it T_f , the filament temperature. It is not clear whether he is suggesting this equation is ‘universal’ ie for all coiling geometries. It is in a section called ‘temperature of a coil’. Here we will make the assumption that the temperature of the filament wire is the same as coiled coil filament temperature, so we can use the manufacturer equations.

Ie assuming $T_{wire} = T_{filament \text{ single coil uncoiled}} = T_{fcc \text{ uncoiled}}$; but using coiled coil parameters to perform the calculation, where:

V is voltage used (120V in this case)

l is the length of the uncoiled filament – see following

- $2r$ is the diameter of the filament wire
- δ is the relevant radiation coefficient, in this case, for a coiled coil, $\delta_{cc} = (\delta_1 \delta_2)_{2r,l,T}$
- ζ is "...the Van Horn (1972)... correction factor by which the wire resistance has to be adjusted {it is in fact a constant of proportionality in that case TH} in order to obtain the coil resistance (*ibid* p138).....strictly applicable to single or primary coils. However, second coiling has orders of magnitude smaller effect on resistance than first coiling and can be safely neglected (*ibid* p139)"

and is itself given by

$$\zeta = \frac{1}{2} \left[1 + \sqrt{1 - \frac{\pi^4 (K_m + 1)^2}{[\pi^2 (K_m + 1)^2 + K_p^2]^2}} \right] \dots\dots\dots 8.7$$

Where K_m is the primary mandrel ratio
 K_p is the primary pitch ratio

However, there is a problem with equation 8.6, which we discuss for completeness. Vukceovich derives it by using Ohm's law and substituting for the resistance to as follows:

$$\Phi_{IN} = \frac{V^2}{R_F} = \frac{\pi D^2}{4l \zeta \bar{\rho}(\bar{T}_F)} V^2 \dots\dots\dots 8.8$$

Where V = voltage
 R_F = filament resistance
 D = wire diameter
 l = (total) length of wire in filament coil.
 $\bar{\rho}(\bar{T}_F)$ = resistivity of the filament material at the mean temperature of the filament (Ωm)

Vukceovich then sets 8.8 equal to the first term in equation 8.1a, saying "When the ..two formulae are set equal to each other, and the temperature sensitive terms are separated on one side of the equation, we find:" (his p139 equation 9.29)

$$\bar{\rho}(\bar{T}_F) J(\bar{T}_F) = \frac{D}{4l^2 \delta \zeta} V^2 \dots\dots\dots 8.9$$

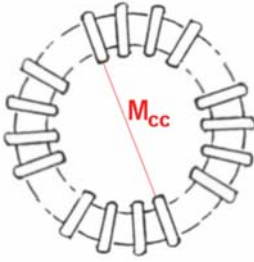
But we have already seen that the radiation coefficient, δ , is both temperature and wavelength dependent, carried by the reflectivity, through its relation to emissivity.

Using the values calculated for the radiation coefficient of a coiled coil, $\delta_{cc} = (\delta_1 \delta_2)_{2r,l,T}$ This resulted in a filament temperature range for a 'typical' uncollapsed FEL filament of $\delta_{cc} (3000) \rightarrow 3147K$ through $\delta_{cc} (3400) \rightarrow 3154K$.

NB: It is not clear what this means – also wavelength dependence is neglected. Note also that melting point of Tungsten, symbol **W**, is $\sim 3695K$.

8.2.1.4 Estimating primary turns, n_p , to obtain wire length, l

Figure 8.6A



The total length of the wire from which the coiled coil is fashioned is required. This is not given and is hard to calculate accurately.

Figure 8.6B



Figure 8.6A is a schematic of a single coiled coil turn, showing the mandrel {internal} diameter, figure 8.6B is a photograph of a modified FEL filament with graph paper behind it, showing that there are ~3 primary turns per mm.

Using the following:

- the equation for the circumference of a circle, 2π times radius
- the Mandrel Diameter divided by 2 for the radius; this was a judgement call {ie rather than the alternatives which would have been a) the external diameter $D_{cc}/2$; or b) $(M_{cc} + D_p)/2$ } also based on what we could just about count from enlarged photographs.
- The value of ~3 primary turns per mm from the enlarged photographs example shown in figure 8.6B

$$n_p = x(\pi M_{cc} n_{cc}) + y \quad \dots\dots\dots 8.10$$

Where : x is the number of primary turns per mm
 y is the number of primary turns at the top and bottom of the coiled coil above and below the first and last turns.

Result: Approximate number of primary turns for modified FEL, $n_p = 290.7$
 In order to obtain the length of the wire from which the primary coil was fashioned, we need to use the equations for the coiled coil length from table 8.1

$$L_c = l \frac{K_p}{\pi(K_m + 1)} = n_p P_{Ep} \quad \dots\dots\dots 8.11A$$

Rearrange and solving, yields a value for the wire length, $l \sim 85$ cm

$$l = n_p P_{Ep} \frac{\pi(K_m + 1)}{K_p} \quad \dots\dots\dots 8.11B$$

8.2.2 Summary of Results for a 'Perfect' FEL

Output wattage for a 'perfect' modified FEL using equation 8.1B and associated equations is:

$$\Phi_{RADmanuf} \approx \pi 2rl \delta_{cc} J[T] \sim 1084 \quad (\text{Watts}) \quad \dots\dots\dots 8.12$$

Obtained using values given in Table 8.5 in addition to those already discussed.

Table 8.5: Summary of Results for sub-terms making up equation 8.1B for $\Phi_{RADmanf}$ and giving the value (Wattage) shown in equation 8.12.

Main Symbol or Equation	Description	Value	Units
$2r$	Diameter of the wire from which the filament is coiled. Average, measured	0.029	cm
$l = n_p P_{Ep} \frac{\pi(K_m + 1)}{K_p}$	Total length of the wire from which the filament is coiled.	84.992	cm
δ_{cc}	Radiation coefficient, for this coiled coil, calculated	0.773	
$J(T) = 0.883 \left(\frac{T}{1000} \right)^{4.65}$	Radiation integrated over all wavelengths in Watts/cm ² (Exitance) for a (calculated) filament temperature of 3150.3K	183.414	W/cm ²
Associated Equations and Results			
$n_p = x(\pi M_{cc} n_{cc}) + y$	Number of turns (coils) in the primary coil.	290.7	
$T_F = 4902.2 * \left(\frac{V}{l} \right)^{0.342} * \left(\frac{2r}{\delta \zeta} \right)^{0.171}$	Mean filament temperature of a coil; strictly, for a single coil	3150.3	Kelvin
Values at T_F=3150.3K for sub terms not already collated			
$\delta_1 = \frac{1}{2} \left[\left(1 + \frac{1}{\pi(K_m + 1)} \right) + \left(1 - \frac{1}{\pi(K_m + 1)} \right) \frac{K_p - 1}{K_p - \rho(T)} \right]$	Primary Radiation Coefficient	0.866	
$\rho(T) = 1 - \varepsilon(T)$	Reflectivity of the primary coil surface	0.706	
$\delta_2 = \frac{1}{2} \left[\left(1 + \frac{1}{\pi(K_{m2} + 1)} \right) \delta_1 + \left(1 - \frac{1}{\pi(K_{m2} + 1)} \right) \frac{K_{p2} - f_1}{K_{p2} - \rho_1(T)} \right]$	Radiation coefficient second coiling	0.893	
$\rho_1(T) = 1 - \delta_1 \varepsilon(T)$	Reflectivity of second coiling	0.706	
$f_1 = 1 - \left(\frac{K_p - 1}{K_p} \right)^2$	Opacity of the primary coil	0.797	
$\zeta = \frac{1}{2} \left[1 + \sqrt{1 - \frac{\pi^4 (K_m + 1)^2}{[\pi^2 (K_m + 1)^2 + K_p^2]}} \right]$	Van Horn correction for single coil resistance	0.981	

9 Modelling FEL Collapse using the Manufacturers' Equations & some Assumptions.

Somehow, we have to link the changes in **lamp irradiance** we observe during our measurements, back to equation 8.12, which gives the **filament total radiant flux**; is this justified? Since irradiance is radiant flux per unit area, they are intimately connected. We are talking about total radiant flux emerging from the filament in a 360° 'spherical' shell (clearly the cylindrical symmetry means that this is only true if we stand back and consider the filament a 'point source').

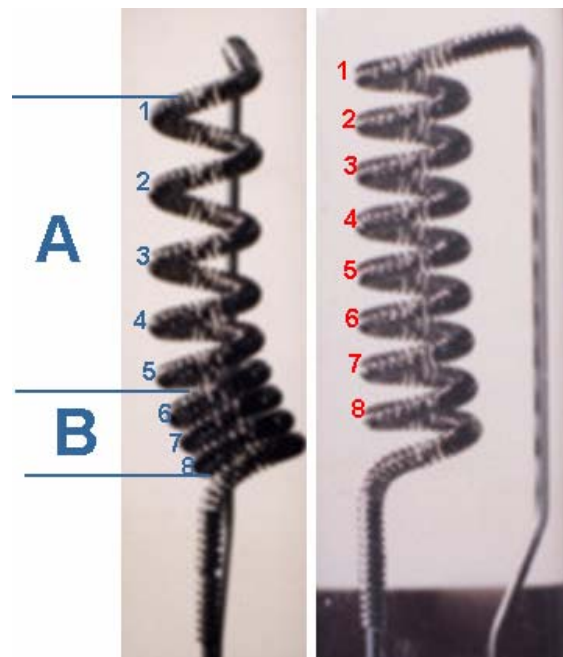
For the traditional irradiance measurements we only sample a portion of this shell with our measuring instruments (which define the surface over which the flux falls and the distance to the source) hence we state the irradiance for that lamp {as a point source} at that distance.

The only real difference is that we are measuring the lamp output, ie which are subject to the losses described earlier.

However, whilst we can measure the secondary coil pitch; there are too many lamps for us to measure the coil pitch for every turn in a single lamp (remembering that they are not the same). We need to find a way of showing how the filament geometry changes, change the output wattage as defined in equation 8.13.

Figure 9.1

We will do this by splitting the coiled coil into two joined coiled coils as shown in figure 9.1 (the number of coils stretched and collapsed will vary from lamp to lamp). Note also that there would be bulge or general sag as shown due to the fixed coiled coil wire support at the bottom; this will be ignored for the purposes of this work.



Where:

- A** STRETCHED portion of the coiled coil, caused by
- B** COLLAPSED portion of the coiled coil

and making the following assumptions:

- 1) the joins between these two parts are seamless; and a filament in two parts like this can be subject to the same equations

- 2) The total number of turns in the modified FEL coiled coil is 8 and is given by

$$n_{cc} = n_{ccA} + n_{ccB} = 8 \quad \dots\dots\dots 9.1$$

- 3) All **primary** coil parameters remain unchanged in the two parts of this coiled coil, and the total length of the wire, from which the two coiled coils are fashioned is given by

$$l_{cc} = l_A + l_B \quad \dots\dots\dots 9.2$$

NB: It is also assumed that there has been no stretching *of the wire* from which the coiled coil is fashioned as a result of the stretch/collapse of the coiled coil geometry itself. The average length for a typical unmodified FEL was calculated at ~85 cm

- 4) The amount of wire per coiled coil turn is constant. Which we will use to make two further sub assumptions

a) Thus, if $(n_{ccA} + n_{ccB}) / n_{cc} = 8/8$, then $(l_A + l_B) / l_{cc} = 8/8$

AND

thus if $n_{ccA}=5$ and $n_{ccA}/n_{cc} = 5/8$, then $l_A/l = 5/8$

b) The voltage drop across each turn can be thought of as

Total drop across whole filament/Number of coiled coil turns ie treating the coils as 8 resistors in series.

- 5) The following **coiled coil** (secondary) parameters remain unchanged in the two parts, **A** and **B** that comprise the total coil – all are clearly untrue in reality – as can be seen by figure 9.1; but it is hoped that making these assumptions will give us an insight into what is going on:

a) D_{cc} (external diameter of single coiled coil, coil, is not distorted by the collapse)

b) $2r_{cc}=D_p$ (external diameter of single coil remains unchanged)

c) M_{cc} (internal mandrel diameter is unchanged – ie bulging due to vertical collapse is neglected), and hence $K_{m,2}$ coiled coil mandrel ratio is unchanged by collapse.

- 6) The **total** length of the coiled filament can be represented by

$$L_{ccTOTAL} = L_{cc} = L_{ccA} + L_{ccB} \quad \dots\dots\dots 9.3$$

Taking $L_{ccTOTAL}$ as turns only, CC_{Lturns} as defined earlier, the average measurement over several lamps for this was ~1.9 cm.

- 7) P_{ccA} , the coiled coil pitch of the STRETCHED part of the total filament is constant throughout the stretched portion

- 8) P_{ccB} , the coiled coil pitch of the COLLAPSED part of the total filament is constant throughout the collapsed portion. Refer to figure 8.3a: Since the coiled coil pitch is taken from the centre of the ‘elbow’ of the coil, as shown, as collapse tends to catastrophic (coils touching) then P_{cc} tends to the external diameter of the single coil

from which the coiled coil is fashioned. Ie $P_{cc} \rightarrow D_p = 2r_{cc}$. Average value over several lamps was ~ 0.131 cm.

- 9) δ_{ccB} is the radiation coefficient of the collapsed part of the total filament. Average values were calculated using assumption 8 above and will be used, as ‘typical’; value ~ 0.68 .

Can this be justified? Hidden inside the coiled coil shadow factor are several other dependencies which will now be discussed.

- a) In the primary coiling shadow factor (equation 3) the only dependence we need to check is the reflectivity, $\rho(\lambda, T) = 1 - \varepsilon(\lambda, T)$ - since we have already agreed that all other single coiling parameters will be assumed unchanged by the distortion in the coiled coil. Using equation 8.3b at the lower limit of $T=2400K$ given by Bergman, still gave a value for $\rho \sim 0.7$.

- b) As a consequence, in the secondary coiling shadow factor (equation 8.2c), the relevant reflectivity given by $\rho_1(T) = 1 - \delta_1 \varepsilon(T)$

is similarly unchanged significantly enough to concern us.

- 10) The **total** flux from the coiled filament can be represented by

$$\Phi_{ccTOTAL} = \Phi_{cc} = \Phi_{ccA} + \Phi_{ccB} \dots\dots\dots 9.4$$

9.1 THE PLAN

To plug in all the assumptions and end up with a form of equation 8.1b (and 8.13) that depends only on the unknown coil pitches of the stretched portion P_{ccA} and the number of turns in the collapsed and stretched portions respectively.

Potential problem – the temperature of **A** and **B** will NOT be the same.

Plugging the relevant assumptions into equation 9.4, using the form of equation 8.1b, gives:

$$\Phi_{ccSAG} \approx \pi 2r (l_A \delta_{ccA} [\lambda, T_A] J_A [\lambda, T_A] + l_B \delta_{ccB} [\lambda, T_B] J_B [\lambda, T_B]) \dots\dots\dots 9.5$$

We need to eliminate as many unknowns as possible; starting with assumptions 1-4, ie Eliminate l_A and leaving out the dependencies to make it easier to see what is going on gives:

$$\Phi_{ccSAG} \approx \pi 2r (\{l - l_B\} \delta_{ccA} J_A + l_B \delta_{ccB} J_B) \dots\dots\dots 9.6a$$

leading to

$$\Phi_{ccSAG} \approx 0.09(l\delta_{ccA}J_A - l_B\delta_{ccA}J_A + l_B\delta_{ccB}J_B) \quad \dots\dots\dots 9.6b$$

Using assumption 9, average values for δ_{ccB} were calculated and will be used, as ‘typical’; value ~ 0.68

$$\Phi_{ccSAG} \approx 0.09l\delta_{ccA}J_A - 0.09l_B\delta_{ccA}J_A + 0.06l_BJ_B \quad \dots\dots\dots 9.7$$

In order to simplify further, we need to deconstruct δ_{ccA} . For the stretched portion of the filament, the coiled coil shadow factor becomes

$$\delta_{ccA} = (\delta_1\delta_{2A})_{2r,T} \quad \dots\dots\dots 9.8a$$

Notice, we have removed the condition that wire length, l is unchanged, as it plays no role in the calculation of the component parts of the equation. Leaving the temperature dependence as unchanged between the two parts is clearly untrue as this smaller, stretched coil ‘A’ will have a different temperature to ‘B’, the collapsed portion.

Continuing, since we have assumed all single coil parameters are unchanged, we can say $\delta_I = \delta_{IA} = \delta_{IB}$ which works out as ~ 0.866 . Assumption 9 is used here to deal with the reflectivities, so that in this case, the only unknown is the coil pitch of the stretched portion. Hence we can write

$$\delta_{2A} = \frac{1}{2} \left[\left(1 + \frac{1}{\pi(K_{m,2} + 1)} \right) \delta_1 + \left(1 - \frac{1}{\pi(K_{m,2} + 1)} \right) \frac{K_{p,2} - f_1}{K_{p,2} - \rho_1(\lambda, T)} \right] \quad \dots\dots\dots 9.8b$$

leading to

$$\delta_{2A} = \left[0.47 + 0.46 \frac{K_{p,2} - f_1}{K_{p,2} - \rho_1(\lambda, T)} \right] \quad \dots\dots\dots 9.8c$$

and finally

$$\delta_{2A} = 0.47 + 0.46 \left[\frac{P_{ccA} - 0.104}{P_{ccA} - 0.09} \right] \quad \dots\dots\dots 9.8d$$

Plugging equation 9.8d into 9.8a, gives

$$\delta_{ccA} = 0.41 + 0.39 \left[\frac{P_{ccA} - 0.104}{P_{ccA} - 0.09} \right] \quad \dots\dots\dots 9.9$$

Then, plugging equation 9.9 into equation 9.7 gives

$$\Phi_{ccSAG} \approx 0.09lJ_A \left[0.41 + 0.39 \left(\frac{P_{ccA} - 0.104}{P_{ccA} - 0.09} \right) \right] - 0.09l_BJ_A \left[0.41 + 0.39 \left(\frac{P_{ccA} - 0.104}{P_{ccA} - 0.09} \right) \right] + 0.06l_BJ_B \quad \dots\dots\dots 9.10a$$

which leads to

$$\Phi_{ccSAG} \approx J_A \langle l - l_B \rangle \left[0.037 + 0.035 \left(\frac{P_{ccA} - 0.104}{P_{ccA} - 0.09} \right) \right] + 0.06 l_B J_B \quad \dots 9.10b$$

We next have to deal with the exitance contributions J_A and J_B , which we have seen can be approximated by equation 8.5, which was $J(T) = 0.883 * \left(\frac{T_F}{1000} \right)^{4.65}$ and which depends only on the filament temperature. This in turn was given by equation 8.6, which was $T_F = 4902.2 * \left(\frac{V}{l} \right)^{0.342} * \left(\frac{2r}{\delta \zeta} \right)^{0.171}$

We can no longer avoid the temperature issue. But in order to use equation 8.6 to estimate the temperature of the separate portions of the collapsed filament, we will now use assumption 4b that the voltage across each turn of the modified FEL is 120/8 volts.

Plugging equation 8.6 into equation 8.5 for each case, **A** and **B** yields

$$J_A = 0.883 * \left(4.9 * \left\{ \frac{120n_A/8}{l_A} \right\}^{0.342} * \left\{ \frac{0.029}{0.98 * \delta_{ccA}} \right\}^{0.171} \right)^{4.65} \quad \dots 9.11a$$

Using equation 9.2 and equation 9.9 in equation 9.11a; leads to

$$J_A = 0.883 * \left(4.9 * \left\{ \frac{15n_A}{l - l_B} \right\}^{0.342} * \left\{ \frac{0.03}{0.4 + 0.39 \frac{P_{ccA} - 0.104}{P_{ccA} - 0.09}} \right\}^{0.171} \right)^{4.65} \quad \dots 9.11b$$

AND

$$J_B = 0.883 * \left(4.9 * \left\{ \frac{15n_B}{l_B} \right\}^{0.342} * \left\{ \frac{0.029}{0.98 * \delta_{ccB}} \right\}^{0.171} \right)^{4.65} \quad \dots 9.12a$$

giving

$$J_B = 0.883 * \left(2.86 * \left\{ \frac{15n_B}{l_B} \right\}^{0.342} \right)^{4.65} \quad \dots 8.12b$$

We cannot simplify further. So now we need to use 8.10b, 8.11b and 8.12b using estimates for number of coils that have collapsed.

10 Results

Calculations were made using all the arguments and equations described above. Spreadsheets were set up for J_A , J_B and Φ_{ccSAG} and different values for the number of collapsed coils, n_{ccB} were tested.

Finally, we determined how each possible collapse as represented by the number of collapsed coils; varied with the subsequent change in the coil pitch P_{ccA} for the stretched portion. That is, as the coils collapse what might be the resulting stretch and then, how would that affect the output as compared to the output of an ideal FEL?

In a ‘typical’ modified FEL, according to our measurements, $P_{cc} \sim 0.254$ cm; and the stretched coil pitch would grow from that value. The key results are presented in the tables that follow:

10.1 % Difference In Filament Output for changes in n_{ccB}

	for $n_{ccB}=1$		for $n_{ccB}=2$		for $n_{ccB}=3$	
For P_{ccA} (cm)	Φ_{ccSAG}	% difference from 1084 Watts	Φ_{ccSAG}	% difference from 1084 Watts	Φ_{ccSAG}	% difference from 1084 Watts
0.255	1104.69	1.923%	1094.35	0.969%	1084.02	0.016%
0.256	1104.74	1.927%	1094.40	0.973%	1084.05	0.019%
0.257	1104.79	1.932%	1094.44	0.977%	1084.09	0.022%
0.258	1104.83	1.936%	1094.48	0.980%	1084.12	0.025%
0.259	1104.88	1.940%	1094.52	0.984%	1084.16	0.028%
0.260	1104.93	1.944%	1094.56	0.988%	1084.19	0.031%
0.270	1105.36	1.985%	1094.93	1.022%	1084.50	0.060%
0.280	1105.75	2.020%	1095.26	1.053%	1084.78	0.085%
0.290	1106.10	2.052%	1095.56	1.080%	1085.02	0.108%
0.300	1106.41	2.081%	1095.83	1.105%	1085.25	0.129%

	for $n_{ccB}=4$		for $n_{ccB}=5$		for $n_{ccB}=6$		for $n_{ccB}=7$	
For P_{ccA} (cm)	Φ_{ccSAG}	% difference from 1084 Watts	Φ_{ccSAG}	% difference from 1084 Watts	Φ_{ccSAG}	% difference from 1084 Watts	Φ_{ccSAG}	% difference from 1084 Watts
0.255	1073.68	-0.938%	1063.35	-1.892%	1053.01	-2.845%	1042.68	-3.799%
0.256	1073.71	-0.935%	1063.37	-1.890%	1053.03	-2.844%	1042.69	-3.798%
0.257	1073.74	-0.933%	1063.39	-1.888%	1053.04	-2.843%	1042.69	-3.797%
0.258	1073.77	-0.930%	1063.41	-1.886%	1053.06	-2.841%	1042.70	-3.797%
0.259	1073.79	-0.928%	1063.43	-1.884%	1053.07	-2.840%	1042.71	-3.796%
0.260	1073.82	-0.925%	1063.45	-1.882%	1053.08	-2.839%	1042.71	-3.795%
0.270	1074.07	-0.903%	1063.64	-1.865%	1053.21	-2.827%	1042.78	-3.790%
0.280	1074.29	-0.882%	1063.80	-1.850%	1053.32	-2.817%	1042.83	-3.785%
0.290	1074.49	-0.864%	1063.95	-1.836%	1053.42	-2.808%	1042.88	-3.780%
0.300	1074.67	-0.847%	1064.09	-1.823%	1053.51	-2.800%	1042.93	-3.776%

11 Conclusions

We have described changes seen in spectral irradiance during the normal lifetime of an FEL lamp (section 5). These were changes seen during international intercomparison measurements.

We have used lamp manufacturer models and equations to show that a change in geometry of the filament caused by collapse, leads to a change in total output of the lamp.

When we measure a lamp, although we treat it as a point source, in reality we are 'looking' at an extended source (the coiled coil) and only in one direction; perpendicular to the central axis through the 'cylinder'.

It has been shown experimentally that the output of a 'perfect' FEL filament which is rotationally symmetric is constant from all viewing points perpendicular to the central axis [*Ohno & Jackson (1996)*].

However, if the gross shape of the filament changes due to collapse the filament is no longer symmetrical and

1. the effective cavity of the 'black body' (inside the coils) changes
2. different parts of the coiled coils are obscured/visible
3. effectively, the total radiation surface of the construction has changed

Subsequently,

4. the irradiance is now directionally dependent
5. the overall output of the cavity appears to have been spectrally altered

In optical radiation metrology, we need stable, transportable standards to disseminate spectral emission scales to end users. For many years the FEL has been used as an inexpensive alternative to lamps with more robust coil/filament structures.

The current solution (by international agreement within the metrology community) has been to use a minimum of 3 lamps for any one set of measurements or calibrations; this is because if they all change in a different way then you are aware of 'a problem'.

However, due to the unpredictable nature of the collapse process it is impossible to quantify the uncertainty in the irradiance of your measurement.

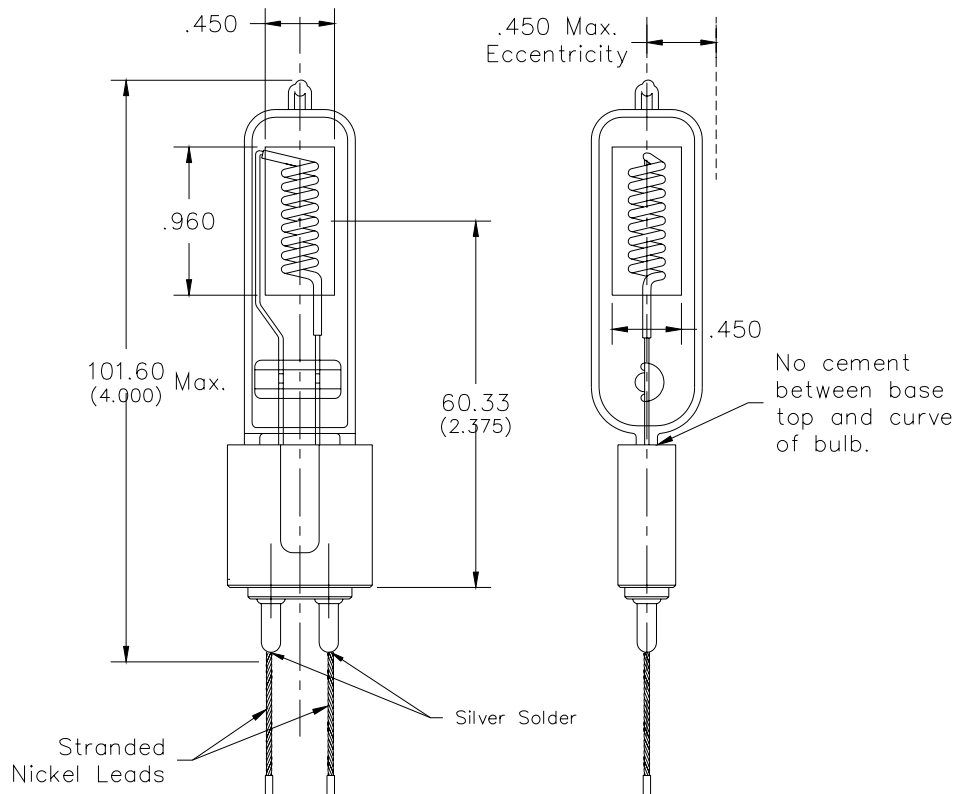
There is currently no better standard with a similarly high colour temperature and irradiance available, and the search is on for a replacement standard.

12 Appendices

APPENDICES

12.1 APPENDIX 1:**Modified FEL specification****OSRAM
SYLVANIA****SPECIFICATION DEPARTMENT
JUAREZ, MEXICO.**

SPEC #:	PHOTO FEL
DATE:	02/11/02
SUPERCEDES:	
SHEET:	1/1

SUBJECT: SPECIFICATION PERFORMANCE SE 1000W MODIFIED FEL

RATED WATTS: 1050 $\pm$ 5%
 RATED VOLTS: 120
 RATED LIFE: 300 Hr.
 COIL: CC8
 BULB: T6 Fused Silica
 BASE: G9.5 with Stranded Nickel Leads
 BURNING POSITION: ANY
 LUMENS: 27,500
 OPERATING LIMITS:
 MAX. BULB TEMP: 900°C
 MIN. BULB TEMP: 250°C
 MAX. SEAL TEMP: 350°C
 COLOR TEMP.: 3200 K

NOTE: FILAMENT MUST BE ENTIRELY WITHIN A BOX 11.4mmW X 24.4mmH X 11.4mmT LOCATED ON THE CENTER LINE OF THE LAMP AT THE LIGHT-CENTER SHOWN.

ECN TRAIL:

ENGINEERING:

SPECIFICATIONS:

ENG 029.DOC

7/8/99

NOTE: DOCUMENT VALID BY 24 HOURS IF LACKING OF STAMP

Sent to the first author by email 11/2/02 as a word document attachment by R. Daubach
 Research Manager Applications & Measurements Laboratory OSRAM SYLVANIA

12.2 APPENDIX 2: Rationalizing Lamp Parameters

12.2.1 SINGLE COILS

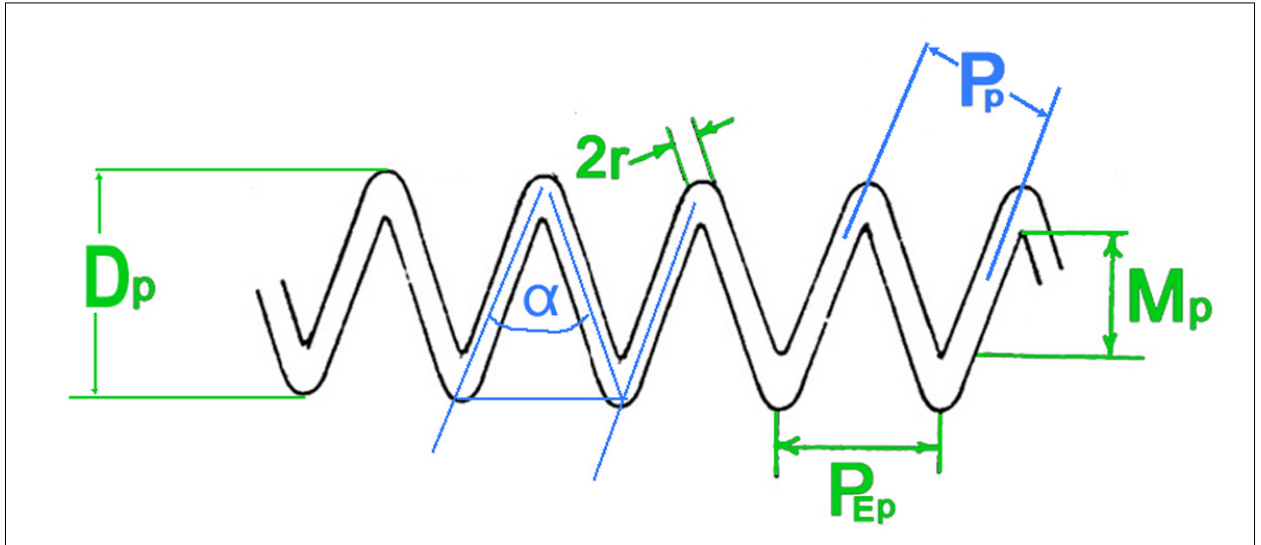


Figure Apx2.1: Single Coil Parameters

PRIMARY PITCH RATIO IS

$$K_p = \frac{h}{D} = \frac{P_p}{2r}$$

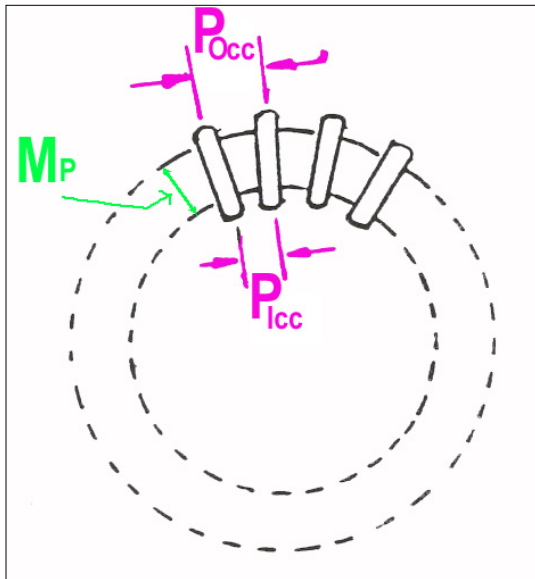
PRIMARY MANDREL RATIO IS

$$K_m = \frac{m}{D} = \frac{M_p}{2r}$$

12.2.2 COILED COILS

Figure Apx2.2A

Coiled Coil Parameters - whole



COILED COIL PITCH RATIO IS

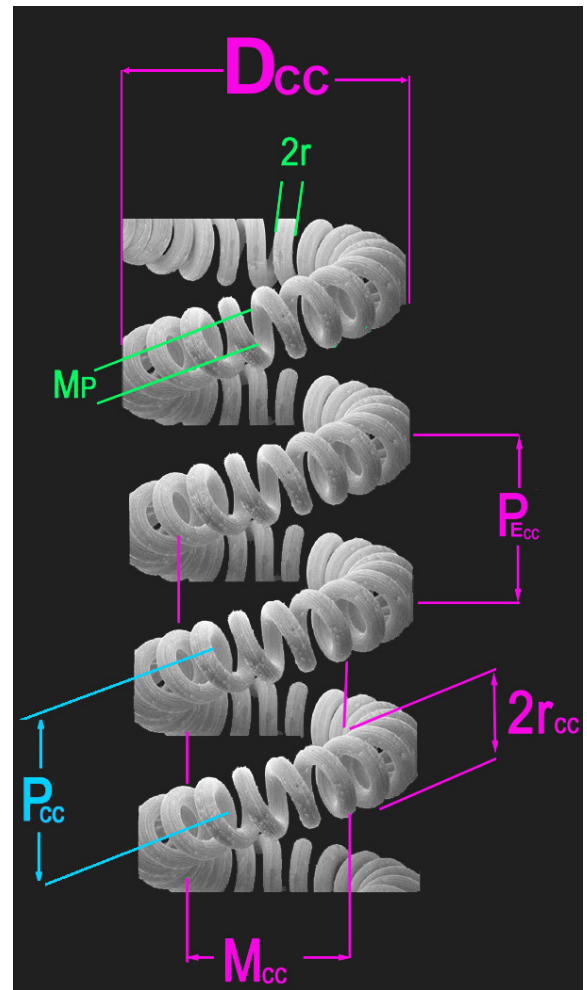


Figure Apx2.2B:

Coiled Coil Parameters - single turn

$$K_{p.2} = \frac{P_{cc}}{2r_{cc}}$$

COILED COIL MANDREL RATIO IS

$$K_{m.2} = \frac{M_{cc}}{2r_{cc}}$$

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