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Practical section for growers

1 Commercial Benefits

The project has produced a wide range of commercial benefits which will have an impact on growers who are either using or planning to use supplementary lighting. The key findings provide growers with a better understanding of the factors affecting the performance of a lighting installation including planning a new installation, equipment selection and maintenance and replacement policy. This will ensure that a lighting installation will perform as required over the whole of its lifetime and as a consequence that the anticipated increase in productivity is achieved.

2 Background & Objectives

The use of supplementary lighting in the U.K. is less widespread than in some other parts of Europe where intensive protected cropping has developed. However market forces are reversing this trend. A need to become increasingly more efficient against a background of rising energy costs and competition mean that growers need the production advantages that can be had through the use of supplementary lighting.

The objectives of this project were to help growers correctly specify and operate a supplementary lighting installation by providing information on the following:

- Assess the difference in performance between commercially available ‘standard’ and ‘enhanced’ lamps
- Identify the factors affecting lamp performance and deterioration over their lifetime
- Identify and evaluate appropriate technical criteria to assist the selection of luminaires and improve the overall efficiency of lighting installations
- Investigate the potential of improved reflective materials to increase the efficiency and longevity of luminaire reflectors
- Provide recommendations on best practice electrical installation methods with regard to uniformity of lighting and minimisation of electrical harmonics and their effects.

3 Key Findings and Action Points

3.1 What light measurement should be used ?

There has been great debate about the 'best' measurement to use when specifying the lighting intensity in a glasshouse. Alternative measurement systems are:

- **The Lumen** – this is widely used because lamp performance data is easily obtained in this form. However, the lumen is based on the response of the human eye and not the photosynthetic response of a plant
- **Photosynthetically active radiation (PAR) watts** – plants only use light from within the wavelength band 400 – 700nm. PAR watts is a measure of the total amount of light energy produced in this wavelength band
- **Adjusted PAR output** such as the one measured by McCree which are adjusted according to plant response curves
- **Micro-mole** – this is a measure of the building blocks of light known as photons. 1 micro-mole = 1 x 10^{17} photons

Analysis of the spectral output of the most commonly used lamps i.e. high pressure sodium SONT+ has shown that PAR watts represents the 'best compromise' measurement. Where PAR output information is not readily available standard conversion factors (lumens to PAR watts) have been proven to be quite accurate irrespective of the specific make and model of SONT+ lamp used. Table 1 below gives some useful conversion factors determined using data from tests carried out as part of this project on the most commonly used high pressure sodium SONT+ lamps.

Table 1 – Useful light measurement conversion factors for SONT+ lamps

From	**To**	**Multiply by**
1000 lumens or 1000 lux	PAR watts or PAR watts/m^2	2.4
1000 lumens or 1000 lux	Micro-moles/s or micro-moles/s/m^2	11.8
PAR watts or PAR watts/m^2	Micro-moles/sec or micro-moles/s/m^2	5.0

3.2 How do I ensure that I get the light level I require when specifying an installation ?

The project results have shown that the total light output of even a new lamp and luminaire can be significantly below manufacturers quoted output. In fact:

- The output of all the lamps tested was 5 – 10% below the quoted value
- Variations between lamps of the same make and model were up to 10%
- Variations between different manufacturers lamps of the same nominal electrical power (watts) were up to 10%
- After 10,000 hours, lamp output will be up to 4 - 10% below it's 'as new' output
- Electricity supply voltage has a major impact on light output. For every 1% (approx. 2.4V) below the voltage specified on the ballast, light output drops by 3%
- The percentage of light directed down towards the crop by a well maintained and cleaned reflector can fall by as much as 13% in 1 year.

The combined effect can be a total light output as much as 20% below the design lighting intensity even for a new installation. A further 20% can be expected after 4 years if the lamps are not replaced.

The choice of initial light intensity depends on the degree to which the effect of reduced light levels on crop quality can be tolerated. System maintenance policy (lamp and reflector replacement and cleaning) will also have a big effect on how light output will change over time. Clearly a compromise has to be made between lighting performance at 'day one' of an installation, and what is required at later stages. Normally this will mean a higher light intensity than required at the start which gradually reduces to slightly below it when the lamps are replaced.

3.3 What type of lamp should I use ?

High pressure sodium SONT+ lamps are most commonly used as they represent the best compromise between cost, efficiency and light quality. However there are also different types of SONT+ lamp including some that have been modified (enhanced) to improve their light output for horticultural applications. Tests comparing the 'enhanced' lamps with more standard SONT+ lamps showed that there was little difference in performance when comparing both their efficiency and spectral output (light quality). The following points should be borne in mind when selecting lamps:

- Some manufacturers produce long life, lower output lamps and high output lamps. The latter are generally preferable
- Total lumen output - expect 50,000 to 60,000 lumens for a 400W lamp and 85,000 to 95,000 lumens for a 600W lamp.

3.4 Should I use 400W or 600W lamps ?

Increasingly, 600W lamps are being used in new installations. The specification of higher light intensities means that they invariably provide the most cost-effective solution through a reduction in the number of luminaires in an installation. Additional factors which should be considered are:

- Watt for Watt, 600W lamps are more efficient than 400W lamps. A 600W luminaire can be expected to be 10% more efficient than an equivalent 400W unit
- To ensure acceptable lighting uniformity 600W luminaires need a greater mounting height and / or different reflectors. This can be a problem in older glasshouses.

3.5 How often should I replace the lamps ?

- It is clear that in many cases lamp operating hours are not accurately recorded. Similarly lamps that have failed prematurely and been replaced are not recorded. Without an appropriate recording system any lamp replacement policy cannot be implemented accurately
- To avoid production losses and higher energy costs (where lamps are operated for longer to compensate for reduced output), lamps should be replaced at least every 10,000 – 12,000 hours. Some crops are very sensitive to day length and increasing the operating hours to compensate for reduced light intensity is not possible, so lamps may have to be replaced earlier if a significant drop in

productivity is to be avoided. Lamps will also fail more frequently as they get older. The inconvenience caused by an increased rate of failure and difficulties in replacement whilst there is a growing crop in place may mean that more frequent replacement is cost effective. For a typical system operating for 2000 hours per annum replacing lamps at the end of a season once they have exceed 8,000 hours may be the best compromise

- Variation between the output of individual lamps increases as they get older leading to increased non-uniformity of light intensity across the growing crop.

The method of disposal of old lamps should be carefully considered especially when re-lamping a whole installation. The Health and Safety Executive has a useful publication 'Disposal of Discharge Lamps' (HSE 253/3) and there is a government backed help line – Envirowise 0800 585794 that can advise on lamp disposal.

3.6 What features should I look for in a luminaire ?

3.6.1 Basic features

- Current limiting device – the current standard is iron core reactor ballasts but be aware of new developments especially electronic ballasts that give improved performance
- Power factor – should be higher than 0.80, preferably 0.90
- Small 'foot print' – reduced shading effect excluding natural day light
- Easily removed reflector to aid cleaning
- As lightweight as possible is best from a mounting point of view. But note this may be at the expense of a cheaper ballast which can mean lower efficiency, light output and reliability.

3.6.2 Efficiency

Many people concentrate solely on the efficiency of the lamp. However the luminaire has an equally important effect on how efficiently the lighting installation operates and how much of the light from the lamp reaches the target.

By way of example:

- A 400W lamp on its own may produce 135 lumens / watt
- Electrical gear losses and reflector efficiency can reduce this to 102 lumens / watt (26% lower)
- Wide-angle reflectors help to achieve good uniformity but can reduce the efficiency of a lighting installation by 10% compared to focussed reflectors

3.6.3 Uniformity of light intensity

Poor uniformity can give:

- Variability in crop quality requiring additional grading and sorting and reduced average sale price
- Variation in crop maturity requiring repeated harvesting and continued lighting for reducing numbers of plants.

There are two basic ways of improving the uniformity of light intensity:

1. A greater number of smaller luminaires rather than fewer larger ones
2. Wide-angle reflectors rather than narrow focussed ones.

The first method will increase the capital cost of the installation and the maintenance cost due to the greater number of luminaires. It will also reduce the amount of natural daylight reaching the crop due to increased shading. Both options will reduce the overall efficiency of the installation due to either increased losses in the electrical gear (option 1) or reduced reflector efficiency (option 2)

The benefits of improved uniformity are difficult to assess. However practical experience has shown that a ratio of minimum to average light intensity of 0.80 represents a reasonable target.

3.7 What about the control system ?

Most existing glasshouse climate control systems have the facility to control a supplementary lighting system or they can be upgraded to incorporate this facility. In practice three different levels of control can be applied:

- Manual control – not advisable as it is labour intensive and prone to mismanagement
- Timer based control – this is commonly used especially for crops where day length is important. Times can be set to coincide with cheap electricity price periods. This can be implemented through a simple time switch or the existing climate control system
- Day light intensity – this normally integrates with the climate control system where a light sensor measures the natural day light and turns the lights on or off at predetermined levels. Frequent switching of lamps can reduce their life by up to 40% and they take up to 2 minutes to reach full output after switching on. Lamps should operate for at least 30 minutes whenever turned on.

3.8 Lamp and reflector cleaning and maintenance

The project revealed significant reductions in the performance of reflectors after a number of years use:

- Tests on a 4 year-old well maintained reflector showed a drop in efficiency of 12% compared to a new reflector even after it was cleaned
- A 1 year-old reflector before cleaning was 6% below the performance of a new reflector. This fell to 2% after it was cleaned.

There is no doubt that the operating conditions have a significant effect on the reduction in reflector and lamp performance making it difficult to give ‘across the board’ recommendations with a reasonable degree of accuracy. There are no specific guidelines regarding lamp and reflector cleaning. However some basic recommendations are applicable:

- Do not use a cleaning system that could scratch the lamp or reflector surface
- A weak solution of acetic acid (vinegar) or other acid will help to remove limescale resulting from misting and fogging but care needs to be taken with any acid
- Commercial or domestic window cleaning products can be suitable

- If chemical residues are a particular problem great care should be taken when using any cleaning product as resulting chemical reactions can generate toxic substances. If in any doubt check the chemical product data sheets or consult the manufacturer
- Check any new cleaning product on a small area of a lamp and reflector before widespread use.

3.9 Luminaire installation and mounting

The actual physical means by which luminaires are suspended above the crop are varied. However factors to bear in mind when choosing a mounting system remain the same:

- Accuracy of positioning – to ensure the best light uniformity possible
- Ease of removal and replacement of the luminaire and reflector for maintenance
- Position of luminaires relative to walkways to make access easier for maintenance when a crop is being grown
- Position of luminaires relative to heating or irrigation pipes to reduce the interception of light (shading)
- Check the load bearing capability of the supporting structure and install additional supports if necessary.

3.10 Electrical installation issues for supplementary lighting

The use of supplementary lighting in horticulture presents a particularly unusual electrical installation environment. The high harmonic content of the electrical load currents for discharge lighting are a major departure from most conventional electrical systems, and special provisions have to be made to deal with possible problems.

In dealing with Electrical contractors it should not be assumed that they will be aware of the special nature of this type of installation. Their attention should be drawn to the following points:

- The Institution of Electrical Engineers Wiring regulations (BS 7671) specifically mention the installation of discharge lighting circuits. Refer to Regulations 524-02-03, and sizing of components
- Multicore 3 phase cables will have to be de-rated by as much as 14% to cope with high neutral currents
- Transformers (or generators) used for the supply of large installations have either to be specially constructed for high harmonic use or de-rated by about 10%. The

local electricity distribution company should be alerted to the possibility of harmonic currents of up to 25% of the fundamental
- True RMS meters should always be used when measuring voltage and currents in lighting circuits. Averaging meters may produce massive underestimates of current.

In very large systems, especially where generators are used harmonic filters are an effective method of controlling harmonic currents. Filtration as near to the source of disturbance is preferable. Good electrical design in the first place will produce a cheaper solution to harmonic problems than retrofit solutions.

4 Practical & Financial Benefits

The practical benefits resulting from this project relate to the provision of information to growers so that they can select and operate efficient supplementary lighting systems. Simple guidelines have been produced that will enable growers to:

- Specify the requirements of a new installation more accurately
- Operate existing installations efficiently

The project has identified that inadequately specified and badly maintained supplementary lighting installations may produce light levels up to 40% below the initial design output.

However application of the simple guidelines can ensure that:

- A new installation performs as specified
- The inevitable reduction in performance that occurs over time is minimised

Financial benefits are difficult to quantify, as specific crops require differing lighting treatments. In addition their response to light can vary significantly. However, the commonly applied rule of thumb '1% more light produces 1% more crop' illustrates that optimising light output will ensure crop response is maximised.

For example, if an installation used to light chrysanthemums grown on a site in southern England operates at 40% below specification, the crop will typically receive 8% less light (total of solar PAR plus supplementary PAR) than intended over the 6 month 'winter period' from October to March inclusive. This will therefore reduce crop performance by a similar amount and the reduction in income could easily be considerably more than this. The effect on crops grown at a more northerly location or with higher dependence on supplementary lighting will be far greater.

In addition to the effect on crop output, growers should bear in mind that a well specified and operated lighting installation has the ability to enhance the potential for further improvements including:

- Reduced cropping times
- Consistent and uniform quality which in turn will aid harvesting performance
- The reduction of equipment failure.

This project has concentrated on the selection and operation of equipment with regard to efficient operation i.e. reducing running costs and maintaining light output. However capital costs make up a significant part of the total cost of ownership of a lighting installation. Figures extrapolated from Supplementary Lighting of pot chrysanthemums[8] show that capital costs can represent around 25% of the total cost of ownership. Therefore growers should be wary of reducing operating hours as a cost saving measure as the effect on total operating costs will be small compared to the potential reduction in crop production.

Science Section

1 Introduction & Background

Despite considerable research in the UK, supplementary lighting has still not been fully embraced by UK horticulture as an essential production technique. This is in contrast to other countries with similar light conditions (e.g. Netherlands, Denmark, Germany etc) where supplementary lighting is commonplace on the majority of nurseries. This situation is changing quickly however because of:

- Increasing demands from customers for consistent quality and continuity of supply
- The need to increase output and efficiency through better utilisation of the existing cropping area
- The need to improve margins and retain markets through improved product quality.

Even when a grower has decided to investigate the costs of a lighting installation there are still a lot of vagaries relating to installation design and specification. This means that it is difficult for growers to accurately specify and compare installation quotes on a like for like basis. Simply asking for a specific lighting level does not adequately define the true requirements and this leaves the installer with a lot of leeway and the potential for unforeseen problems.

Difficulties in being able to accurately specify a lighting installation design arise from the following areas.

- Lamp types currently in use are a product of the commercial lighting market (factory, office and street lighting). Some manufacturers have produced 'enhanced' lamps targeted specifically at the horticultural market but uncertainty exists over their actual benefits
- The choice of luminaire for a given installation is governed by a number of factors that affect the final light intensity and uniformity of distribution. Lighting system designers quote data on the uniformity of light distribution but its effect on crop variability has not been established
- Additional issues relating to luminaire performance such as the efficiency and longevity of the reflector are unknown and make it difficult to estimate ongoing replacement and maintenance costs. There are also some new reflective materials that may offer better reflectivity, longevity and easier cleaning
- The specification of the electrical installation can have a significant effect on the uniformity of light distribution and lamp life. High intensity discharge

lamps generate electrical harmonics that can adversely affect other electrical equipment installed on site (electronic equipment in particular) and even the electricity supply network. The sizing of electrical components cannot be carried out using the same 'rules' used for more conventional loads but recommendations on suitable control and installation techniques in horticulture are not well documented. A lack of appreciation of this problem in particular has resulted in some 'problem' installations incurring additional capital cost following completion of the installation.

1.1 What unit of light measurement should be used ?

For conventional uses, the output of a lamp is normally quoted in lumens which is the unit of light as seen by the human eye. Illuminance (light intensity) is measured in lux, where:

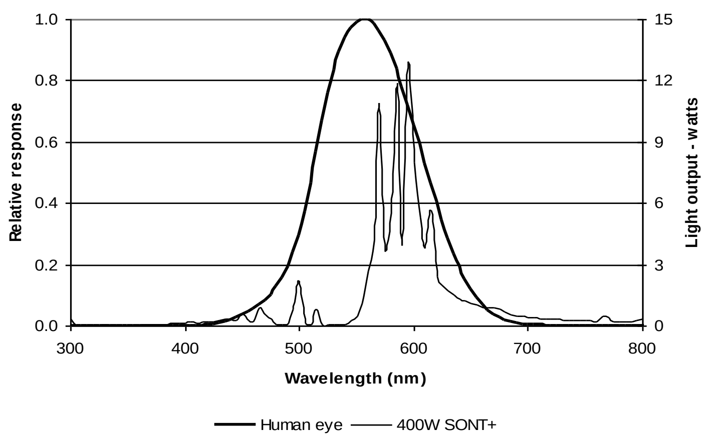
1 lux = 1 lumen / square meter

In imperial measurement this is the foot-candle, where:

1 foot-candle = 1 lumen / square foot = 10.8 lux

The sensitivity of the human eye varies depending on the wavelength (colour) of the light as well as the amount of light. Figure 1 below shows the relative response of the human eye to light energy of differing wavelength. This is known as the CIE photopic curve or human eye response curve.

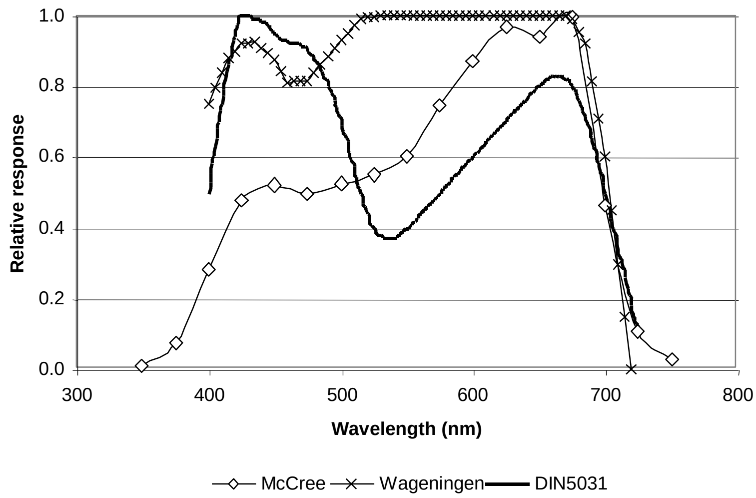
Figure 1 - Human eye response curve and typical lamp output



The human eye has a peak response to light at a wavelength of around 555nm. The result is that 1 watt of light at a wavelength of 555nm appears twice as bright as 1 watt of light at 510nm. As the majority of equipment supplied by manufacturers is for commercial, industrial and domestic lighting i.e. for people, the performance of lamps and luminaires is widely quoted in lumens and lux. However plants do not 'see' light in the same way as humans.

It is widely accepted that plants only respond to light between 400 to 700 nm in wavelength. Light produced in this wavelength band is known as photosynthetically active radiation or PAR. Hence PAR watts / m^2 can be used to specify light intensity for plants. However as with the human eye the photosynthetic response of plants to light varies depending on the wavelength. This is not as well defined as the human eye response and several such response curves exist as shown in Figure 2.

Figure 2 – Photosynthetic response curves



The 'McCree curve' is probably the original and most widely applied response curve[1]. There is also the response curve defined in DIN 5031-10[2]. The third curve is the result of work carried out in the Netherlands by the Institute for Horticultural Research at Wageningen University[3]. Clearly, there are considerable differences between the three curves. It was beyond the scope of this project to investigate the validity of these response curves.

Light can also be measured as photons, which are discrete packets of light energy. As photons contain a very small amount of energy the number of photons is measured in micro-moles where:

1 micro-mole = 6 x 10^{17} photons

Plant physiologists and researchers tend to use micro-moles as a more definitive measure of light from ‘a plants eye view’.

There is no direct relationship between PAR watts and micro-moles because the energy content of a photon varies depending on the wavelength as follows:

Micro-moles = (wavelength x light energy) / 119.708

Where the wavelength is measured in nano-meters and light energy in watts.

Two lamps could have the same PAR watt output but different micro-mole output because their spectral output (wavelength distribution) is different. However the difference between lamps of the same generic type i.e. different manufacturers SONT+ lamps, is minimal and standard conversion factors can be used with a reasonable level of confidence. Figure 3 below shows the output of two different types of lamp.

Figure 3 - Typical spectral output for metal halide and high pressure sodium SONT+ lamps

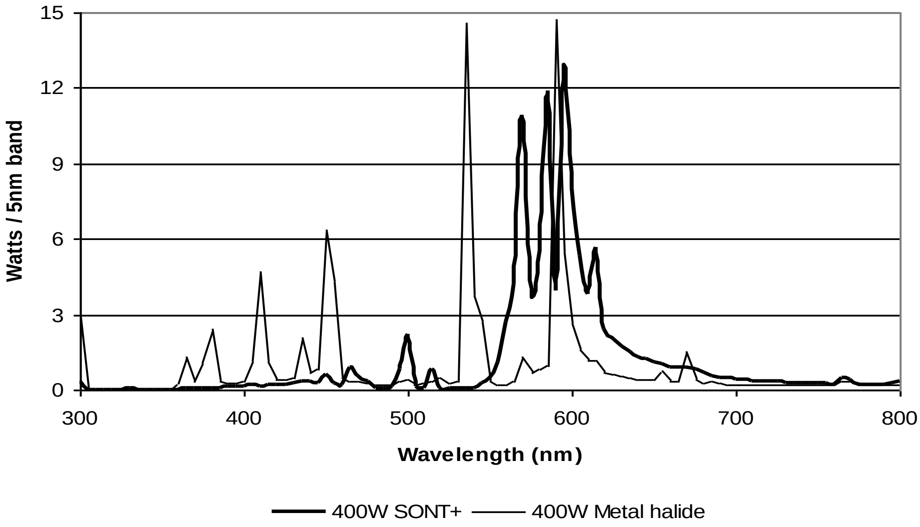


Table 2 below shows some common conversion factors used in commercial horticulture.

Table 2 - Standard light conversion factors[4]

Light source	W PAR per 1000 lumens	Micro-moles/sec per 1 W PAR
Daylight, sun & cloud	4.0	4.6
Daylight, blue sky	4.6	4.2
High pressure sodium SONT+	2.5	5.0
Low pressure sodium	1.9	4.9
Metal Halide	3.1	4.6
Warm white fluorescent	2.8	4.7
Cool White fluorescent	2.9	4.6
Incandescent	4.0	5.0

Independent testing carried out as part of this project gave figures ranging between 2.13 and 2.41 W PAR per 1000 lumens for high pressure sodium SONT+ lamps and 2.77 to 3.46 W PAR per 1000 lumens for metal halide lamps.

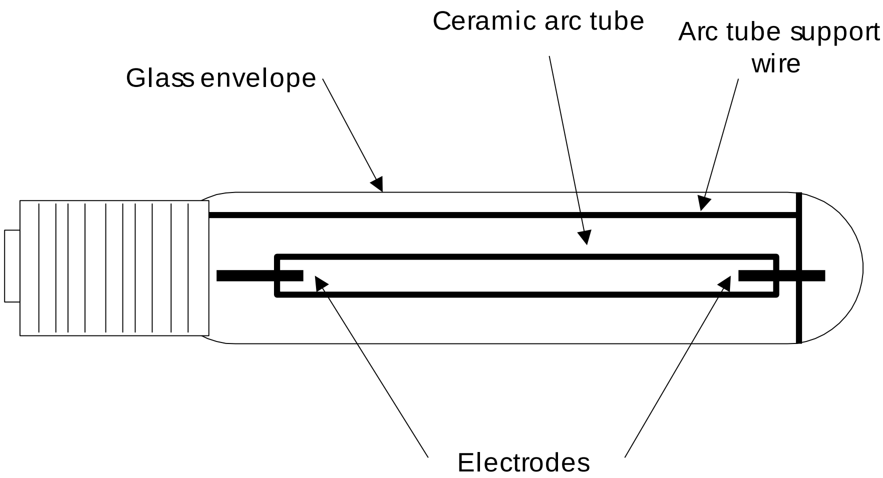
1.2 How do lamps work?

A wide range of generic lamp types are available:

- Incandescent
- Fluorescent
- High intensity discharge – including high pressure sodium, low pressure sodium and metal halide.

As far as supplementary lighting is concerned high intensity discharge (HID) lamps, or more specifically high pressure sodium, are the lamps of greatest interest.

Figure 4 - Basic construction of a high-pressure sodium lamp



The heart of a HID lamp is the ceramic arc tube and its contents. In the case of high pressure sodium lamps it includes a mixture of inert gasses and metals such as argon, neon, xenon, sodium and mercury. Both the ratio of each of these components and the absolute quantity of each one within the arc tube affect the total light output and the spectral composition of the light.

Voltage is applied across the electrodes to stimulate an electrical arc, this ‘excites’ the contents of the arc tube which produce the light. The glass envelope protects the arc tube from the atmosphere by excluding oxygen and insulating it from ambient conditions. Once stabilised the temperature of the arc tube can be around 1250^{o}C and the outer glass envelope up to 400^{o}C.

When the lamp is cold i.e. has been turned off for more than 2 - 3 minutes, all the metal within the arc tube is in the solid phase. The electrical resistance between the electrodes is dependent on the gas in the arc tube alone and is relatively high. Once the lamp is running the metal within the arc tube is vaporised and the electrical resistance between the electrodes is relatively low. The characteristics of this type of lamp are that the hotter it gets the lower its resistance. Hence, if it were connected directly to the mains electricity supply is would draw increasing amounts of power as it gets progressively hotter. If the power drawn by the lamp were not limited it would simply overheat and fail. Hence the electrical control gear built into a luminaire has to be able to provide a high voltage pulse to ‘start’ the lamp and then restrict the power drawn to avoid premature lamp failure.

1.3 What are the requirements for luminaires ?

The luminaire (light fitting) can be defined as the body which contains the lamp. It generally comprises the reflector, the electrical components and an appropriate protective case.

The basic functions of a luminaire are as follows:

- Provide the necessary voltage and current conditions to ensure correct operation of the lamp within the manufacturers specifications
- Reflect as much of the light produced as possible onto the target area in a uniform pattern
- Prevent damage to the lamp
- Reduce the effect of the lamp on the electricity supply system

There are a wide range of technologies and materials available for the construction and assembly of luminaires. The final choice will have a significant impact on the lighting installation as a whole.

1.4 What are the requirements for an electrical installation ?

The electrical installation comprises the necessary transformers, fuses, switch gear and cables to transmit the electrical power from the mains (or generator) to the lamp.

The electrical installation has to deliver power to the lamps whilst maintaining good 'quality' of power and minimising energy losses.

Quality of power pertains to the delivery of the correct voltage level and waveform to the lamp. Although this would appear to be a simple fundamental issue, the characteristics of high pressure discharge lighting introduce special problems to the designer which, if not dealt with properly, can lead to substandard lamp output, system component failure and disturbance of other electrical loads.

2 Research and Testing

2.1 Objectives

The objectives of this project were to:

- Assess the difference in performance between commercially available ‘standard’ and ‘enhanced’ lamps to allow growers to make better informed purchasing decisions
- Identify the factors affecting lamp performance and deterioration over their lifetime to reduce the total cost of ownership
- Identify and evaluate appropriate technical criteria to assist the selection of luminaires and improve the overall efficiency of lighting installations
- Investigate the potential of improved reflective materials to increase the efficiency and longevity of luminaire reflectors
- Provide recommendations on best practice electrical installation methods with regard to uniformity of lighting and minimisation of electrical disturbance.

2.2 Materials & methods

At the outset, the bulk of the information required to complete the project was expected to be available from manufacturers. As such, the work initially focused on obtaining this information. This was to be followed by a limited amount of testing to verify the data supplied and fill in any gaps in the information.

In practice obtaining the information from manufacturers proved to be much more difficult than anticipated particularly with regard to spectral output data for lamps and light distribution data for luminaires. Even contacts found within specific companies could not locate original source data used to calculate more broadly based performance data. This meant that the test program had to be modified to ensure that the gaps in knowledge were filled. Although replication of work has not been ideal, the breadth of the testing carried out has been much greater than initially anticipated. It is therefore accepted that the statistical significance of some of the results have been compromised in favour of a wider overview of the subject matter.

The objectives of this project fell into three distinct areas:

- Lamp characteristics
- Luminaire characteristics
- Electrical installation specification and electrical harmonic disturbance.

2.2.1 Test procedures

2.2.1.1 Lamps

2.2.1.1.1. Test program

Irrespective of the lower than anticipated availability of detailed information the specific objectives of the lamp testing remained the same.

- Comparison of different manufacturers lamps and verification of data provided. Focusing on spectral output and energy consumption to allow assessment of their PAR and micro-mole energy efficiency in particular
- Comparison of 400W and 600W lamps of the same type
- Assessment of special lamp types including enhanced SONT+ and metal halide lamps.

Table 3 below lists the most common lamps in use in UK horticulture. It includes two metal halide lamps that can be used in luminaires with high pressure sodium ballast and electrical gear and one relatively new 'enhanced' lamp the Sylvania Grolux. Although not in widespread use the metal halide lamps in particular have significantly different light output characteristics worth closer investigation using the measurements discussed earlier in this report.

Table 3 - Common lamp types currently in use

Manufacturer	Lamp model	Watts
Philips	SONT plus	400 & 600
Philips	SONT Agro (enhanced SONT+)	400 only
Philips	HPI-T (metal halide)	400 only
Osram	NAV-T Super (SONT+)	400 & 600
Osram	Planta (enhanced SONT+)	400 & 600
Osram	HQI-BT (metal halide)	400 only
GE	Lucalox HO (SONT+)	400 & 600
Sylvania	Grolux (enhanced SONT+)	400 & 600

The test program was developed in three parts. The first part was designed to allow:

- A comparison of 400W and 600W lamps of the same make and model
- A comparison of different manufacturers lamps of the same generic type and nominal power
- A comparison of ‘standard’ vs. ‘enhanced’ lamps
- An assessment of the output of metal halide lamps compared to high pressure sodium SONT+.

At this stage the number of replicates was kept small to allow greater flexibility in the latter stages of testing if required.

Table 4 – Lamp test program, part 1

Manufacturer	Lamp model	Watts	Replications
Philips	SONT+	400	2
Philips	SONT+	600	2
Philips	HPI-T (metal halide)	400	1
Osram	NAV-T Super (SONT+)	400	2
Osram	HQI-BT (metal halide)	400	1
GE	Lucalox HO (SONT+)	600	2
Sylvania	Grolux (enhanced SONT+)	400	2

Analysis of the results from this first set of tests showed that although the voltage at the lamp terminals of the 400W lamps was correct the output was below that quoted by the manufacturers. However in the case of the 600W lamps the output compared to the manufacturer data was even lower (%) than the 400W lamps and the voltage at the lamp terminals was also low. This suggested that there could be an effect due to the electrical gear used.

The second part of the test program was designed to investigate the effect of electrical gear on lamp output and increase the number of repetitions of each individual test to improve the reliability of the final results. The second part of the test program included:

- A repeat of the part 1 tests using lamps from different production batches, but excluding the metal halide lamps
- Test all 600W GE lamps with a second set of electrical gear.

The third and final stage of lamp testing was used to investigate the performance of new lighting technologies that have yet to be established in the market. The most promising development that had just reached the market was 'over power' operation of lamps. This is where 400W and 600W lamps are operated at typically 550W and 750W respectively with various claimed effects on their spectral output as well as their total output.

The complete range of lamps tests carried out is summarised in Table 5 below.

Table 5 – Lamp tests carried out

Manufacturer	Model	Nominal power – Watts	Configuration	No. repetitions
Philips	SONT+	400	400W electrical gear (1)	4
Philips	SONT+	600	600W electrical gear (1)	4
Philips	HPI-T (metal halide)	400	400W electrical gear (1)	1
Osram	HQI-BT (metal halide)	400	400W electrical gear (1)	1
GE	Lucalox HO SONT+	600	600W electrical gear (1)	4
GE	Lucalox HO SONT+	600	600W electrical gear (2)	4
Sylvania	Grolux SONT+	425	400W electrical gear (1)	4
Philips	SONT+	400	Over power gear, 400W setting	4
Philips	SONT+	400	Over power gear, 550W setting	4
Philips	SONT+	600	Over power gear, 600W setting	4
Philips	SONT+	600	Over power gear, 750W setting	4
Sylvania	Grolux SONT+	425	Over power gear, 400W setting	4
Sylvania	Grolux SONT+	425	Over power gear, 550W setting	4

Total number of lamp tests 46.

2.2.1.1.1. Test protocol

Where possible, lamps from different production batches were used. Each lamp was operated for 100 hours prior to testing to allow the lamp characteristics to stabilise. This matches the condition used by manufacturers when quoting lamp output. All the lamp testing was carried out by Scientifics Ltd of Derby, who are accredited by UKAS Testing and to ISO 9001.

All measurements were taken after the lamps had been running for 30 minutes to ensure that their output had stabilised.

Figure 5 – Picture of the integrating sphere used for lamp testing

Measurements of total luminous flux
This was carried out using an integrating sphere of 1.0 m in diameter, incorporating a precision photopic correction silicon photodiode and picoammeter. Both were calibrated using a tungsten halogen source giving an accuracy of +/- 2% of the actual reading.

Electrical power consumption
The electrical power consumption of the lamps was calculated from direct measurements of voltage and current between the ballast and lamp using calibrated multi-meters.

Spectral power output
The same integrating sphere as used for the total luminous flux was coupled via a fibre-optic wave guide to a scanning monochromator system. This system was also calibrated using a tungsten halogen source. The spectral output over the wavelength range 300 – 800 nm was measured in 5 nm bands and recorded in electronic format to allow further analysis (for results and discussion see page 26 onwards).

2.2.1.2 Luminaires

2.2.1.2.1. Test program

Preliminary investigation into luminaire design and performance showed that there was no such thing as the ‘best’ luminaire. As with many things, individual site factors and to a minor extent personal preferences dictate the final choice.

The most energy efficient luminaires are those with 600W lamps and narrow beam reflectors. However, unless they can be mounted at particularly great heights and good lighting uniformity is not too important they are not suitable for some installations. At the other extreme 400W lamps with wide angle reflectors will give very good uniformity even at low mounting heights but their energy efficiency will be quite poor. As with many things the choice of luminaire is a compromise. The section covering luminaire design and selection discusses the points that should be considered to enable a grower to make a well informed decision.

It became apparent that the effect of age and operating conditions on the performance of reflectors was potentially very significant from both an energy efficiency and final lighting intensity point of view. However there was no information available on the magnitude of these effects. Luminaire performance testing therefore concentrated on quantifying the impact of reflector age and operating conditions on lighting installation performance. To determine these effects reflectors in three different conditions were tested:

1. New
2. Several years old but well maintained
3. The reflector as in 2 but following cleaning

Availability and ease of testing determined the choice of reflector types to be tested. Gavita and Hortilux luminaires collectively represent a significant share of the market, they also have easily removed and replaced reflectors. The reflectors are made from deep drawn anodised aluminium, which coincidentally are supplied to both companies by the same manufacturer. Therefore an assessment of the effect of ageing and cleaning on one manufacturer’s reflector was deemed to be representative of both company’s products.

An additional area of work investigated the potential benefits of higher reflectivity materials on luminaire efficiency compared to the current standard reflector material of anodised aluminium. This was carried out in conjunction with 3M who have developed a highly reflective adhesive film. Initial testing carried out by 3M showed that simply

lining the reflectors of existing luminaire designs with the film was not practical. This was because the high temperatures associated with 400 and 600W lamps causing the film to melt. However it was possible to run a 150W SONT+ lamp in an industrial low bay luminaire to allow an assessment of the performance of the film compared to the standard stucco aluminium reflector.
The full range of luminaire and reflector types tested is shown in Table 6 below.

Table 6 – Reflector test program

Test no.	Luminaire	Reflector	Condition
1	Hortilux	Medium	New
2	Hortilux	Medium	Used
3	Hortilux	Medium	Test 2 cleaned
4	Hortilux	Wide	New
5	Hortilux	Wide	Used
6	Hortilux	Wide	Test 5 cleaned
7	Thorn	Stucco aluminium	New
8	Thorn	3M reflective film	New

2.2.1.2.1. Test protocol

K.A.G. Luminaire Ltd carried out the tests using measurement methods as defined in British Standard 5225 and Technical Memorandum 5 of the Chartered Institute of Building Services Engineers. Tests 1 to 6 were carried out using the same luminaire body (ballast, ignitor) and 600W Philips 600W SONT+ lamp to ensure that the only differences measured were due to the reflector. Tests 7 and 8 were both carried out using the same 150W Thorn luminaire body and Philips SONT+ lamp.

2.2.1.3 Electrical harmonic measurements

As part of the assessment of the electrical performance of a typical lamp installation an on-site 'case study' was undertaken. The site was the Donaldson nursery near Chichester where AYR spray chrysanthemums are produced. The installation comprised 800kW of high pressure sodium lighting using 600W Hortilux fittings. The electricity supply was from an 'islanded' generator. The site had a switchable Siemens 3rd Harmonic filter, which allowed assessment of the value and effect of such a device.

Measurements of phase voltage and currents, and the harmonics within these parameters were taken at several key points in the electrical installation using a Dranetz power quality analyser.

2.3 Results and discussion

2.3.1 Lamps

2.3.1.1 Output

Detailed results of the lamp tests are given in Appendix 1 (page 77). The following tables, results and discussions refer to the average output of each lamp tested (manufacturer, model) compared to the information available from the manufacturer.

2.3.1.1.1. Total light output – manufacturer & test data (lumens)

Table 7 and Table 8 show the total lumen output and power consumption of 400W and 600W lamps respectively. The 'Test' and 'Man.' columns refer to the actual measured value and manufacturers data respectively, while the % column is the ratio of the test data to the manufacturers data. Where a cell is empty it means that testing on that particular lamp was not carried out or that the data was not available from the manufacturer.

A number of basic points were immediately apparent:

400W lamps

- The total lumen output of all lamps was between 13.1% and 5.6% below that quoted by the manufacturer
- Lamp power was also lower. The result was that lamp efficiency (lumens / Watt) was comparable with the manufacturers data.

600W lamps

- The total lumen output of the lamps when operated with ballast 1 was between 18.8% and 11.9% below that quoted by the manufacturer
- The output of the same GE lamps tested with different ballasts gave differences in total lumen output of over 10%
- The efficiency (lumens / Watt) was consistently below that quoted by the manufacturer irrespective of the ballast used (between 6.4% and 7.9%).

Preliminary results from part 1 of the lamp test program (Table 4, page 21) showed that the output of all lamps was appreciably below that quoted by the manufacturers. In the case of the 400W lamps the voltage at the lamp terminals was within 2% of the manufacturers specification. Therefore the electrical gear was running the lamps at the correct operating point and the reduced lamp output was due to the lamp itself i.e. manufacturing tolerances.

However the total lumen output of the 600W lamps when operated with ballast 1, especially the GE lamps, was very low. In this case the voltage at the lamp terminals was around 10% below that specified by the manufacturer. This prompted the addition of another manufacturers 600W ballast to stage 2 of the lamp test program to investigate the effect. The voltage at the 600W GE lamp terminals using ballast 2 was much closer to the manufacturer's specification (4% below) and the total lumen output was 10% higher than when operated with ballast 1. It should be noted however that the lamp power also increased with the result that the lamp efficiency was essentially unchanged.

Table 7 – 400W lamp total light output (lumens)

Lamp	**Lamp power Watts**			**Light output Lumens (x1000)**			**Lamp efficiency Lumens / Watt**		
	Test	Man.	%	Test	Man.	%	Test	Man.	%
High pressure sodium SONT+ lamps									
Philips SONT+	358	400	89.4	49.1	55.0	89.2	137.2	137.5	99.8
Philips SONT Agro		400			55.0			137.5	
GE Lucalox HO		400			56.5			141.3	
Osram NAVT Super	375	400	93.9	50.7	55.5	91.4	135.2	138.8	97.4
Sylvania Grolux	400	425	94.2	54.8	58.0	94.4	137.0	136.5	100.4
Osram Planta		400			52.0			130.0	
Metal halide lamps									
Philips HPI T	392	445	88.1	33.0	38.0	86.9	84.2	85.4	98.6
Osram HQI BT	393	420	93.6	30.0	32.0	93.7	76.3	76.2	100.2

Table 8 – 600W lamp total light output (lumens)

Lamp	Lamp power Watts			Light output Lumens (x1000)			Lamp efficiency Lumens / Watt		
	Test	Man.	%	Test	Man.	%	Test	Man.	%
Philips SONT+ ballast 1	565	600	94.2	79.3	90.0	88.1	140.4	150.0	93.6
GE Lucalox HO ballast 1	557	600	92.8	77.1	90.0	81.2	138.4	150.0	92.3
GE Lucalox HO ballast 2	622	600	103.7	85.9	90.0	91.9	138.1	150.0	92.1
Osram NAVT Super		600			90.0			150.0	
Sylvania Grolux		615			87.0			141.5	
Osram Planta		600			81.0			135.0	

N.B. all 600W lamps tested were of the high pressure sodium SONT+ type

2.3.1.1.1. PAR Watts, micro-moles etc.

Earlier discussions about the most suitable measurement of light for plants identified four alternatives to lumens.

- PAR watts
- Micro-moles
- Watts adjusted according to the McCree relative response curve
- Watts adjusted according to the DIN5031 relative response curve.

Lumens tend to be the most common way of specifying lamp output in commercial lighting. In many cases lamp output data provided by manufacturers is only available in lumens and it is common for growers to use ‘standard’ conversion factors to convert from lumens to PAR watts, micro-moles etc. This is based on the assumption that the spectral output of all SONT+ lamps is the same. To be totally correct this is not the case, in fact some manufacturers particularly those that produce enhanced lamps such as the Philips Agro and Sylvania Grolux specifically for horticulture promote the fact that their lamp is different and potentially better for horticultural lighting than standard SONT+ lamps.

The testing carried out was sufficiently detailed to allow the lamp output using each of the four different measurements to be accurately calculated for each lamp tested. The results (see Appendix 1, page 77) were used to calculate the conversion factors for each lamp. Table 9 and Table 10 show these conversion factors (Act. Column). To aid comparison, the % column gives the percentage of the actual value compared to the equivalent conversion factor for the Philips SONT+ lamp.

Table 9 – Lumen to PAR, micro-mole, McCree & DIN5031 conversion factors for individual 400W lamps

Lamp	**PAR Watts /1000 lumens**		**Micro-moles /1000 lumens**		**McCree Watts /1000 lumens**		**DIN5031 Watts /1000 lumens**	
	Act.	%	Act.	%	Act.	%	Act.	%
High pressure sodium SONT+ lamps								
Philips SONT+	2.31	100	11.42	100	1.86	100	1.39	100
Philips * SONT Agro	2.44	106	11.84	104	1.95	105	1.49	107
GE * Lucalox HO	2.46	106	12.15	106	1.99	107	1.50	108
Osram NAVT Super	2.40	104	11.94	105	1.95	105	1.46	105
Sylvania Grolux	2.37	103	11.81	103	1.94	104	1.44	104
Osram Planta	No data available							
Metal halide lamps								
Philips HPI T	2.77	120	12.63	111	1.86	100	1.77	127
Osram HQI BT	3.46	150	16.14	141	2.35	126	2.30	165

* - data supplied by the manufacturer

Table 10 – Lumen to PAR, micro-mole, McCree & DIN5031 conversion factors for individual 600W lamps

Lamp	PAR Watts /1000 lumens		Micro-moles /1000 lumens		McCree Watts /1000 lumens		DIN5031 Watts /1000 lumens	
	Act.	%	Act.	%	Act.	%	Act.	%
Philips SONT+	2.41	100	11.91	100	1.95	100	1.44	100
GE Lucalox HO ballast 1	2.36	98	11.66	98	1.90	97	1.40	97
GE Lucalox HO ballast 2	2.39	99	11.88	100	1.94	99	1.43	99
Sylvania * Grolux			12.53	105				
Osram * Planta	2.32	96	11.38	96	1.88	96	1.41	98

* - data supplied by the manufacturer

Due to their significantly different spectral output the conversion factors for metal halide lamps vary widely from those of the SONT+ lamps. There are also significant differences between specific metal halide lamps which makes the use of a 'standard' conversion factor for metal halide lamps somewhat unreliable.

Taking the SONT+ lamps in isolation, the variation in PAR Watts / 1000 lumens conversion factors relative to the Philips SONT+ lamp shows the following:

- Maximum of 6% (Philips SONT+ Agro & GE Lucalox HO) variation. However it should be noted that in both cases the lamps were not actually tested, the data was provided by the manufacturers
- Comparing the 600W Philips SONT+ and 600W GE Lucalox HO the difference was only 2%. In this case both sets of data were from actual test results
- Taking an average of all the actual test data gives a conversion factor of 2.37 PAR watts / 1000 lumens. If this was applied as a standard conversion factor the maximum possible error would be between +1.7% and –3.5% compared to using lamp specific test results.

Several ‘standard’ PAR watts to lumen conversion factors are used. The most common is 2.4. This is only a difference of 1.26% from the average test result which could easily be accounted for by measurement error. In practice the effect is minimal, for example if lumen output data was only available and the target light intensity was 9.6 PAR W/m^2, the variation in lamp spectral output would give an actual illuminance of between 9.24 and 9.64 PAR W/m^2. This compares to 9.36 and 9.76 PAW W/m^2 if a conversion factor of 2.37 was used.

There are similar differences between individual lamp conversion factors for micro-mole, McCree Watts and DIN5031 Watts per 1000 lumens. A significant point however is that when comparing a single lamp to the Philips SONT+, the difference is consistent regardless of the measurement used. For example the Sylvania Grolux consistently gives between 3 and 4% more PAR watts, micro-moles etc. than the Philips SONT+. Although from a scientific point of view micro-moles, McCree adjusted watts etc. are arguably more accurate, in practice the spectral composition of the common SONT+ lamps is such that designing to a specific PAR W/m^2 light intensity as opposed to micro-moles/sec/m^2 etc. will not introduce significant errors.

2.3.1.1.1. Efficiency

Earlier discussions debated the validity of lumens as a measurement of light from a ‘plants eye view’. The conclusion was that although PAR watts or PAR watts / m^2 may be less than ideal they provide a much more accurate means of comparing lamp output and controlling lighting installations than lumens or lux. Therefore comparing the energy efficiency of lamps using PAR watts / electrical watts input is the most accurate energy efficiency measurement.

The lack of manufacturer data relating to PAR output meant that it was difficult to compare it to the test data. Comparing manufacturer vs. test lamp efficiency in terms of lumens / watt showed that although the total lumen output of the 400W lamps was up to 10% below the manufacturer’s quoted figure, the power consumption was also lower. The result was that the 400W lamp lumens / watt efficiency figures measured were within 3% of those quoted by the manufacturers. The same was not the case for the 600W lamps, the measured lumens / watt figure was consistently 7 to 8% below the manufacturer data regardless of lamp or ballast type. In practice this meant that the average lumens / watt figure of 600W lamps was only marginally better than the 400W lamps, 139.0 and 136.5 lumens / watt respectively.

The efficiency figures given in Table 11 below give the PAR watts of light energy produced per watt of electrical energy input to the lamp both with and without losses from the electrical gear. This helps in comparing 400W and 600W lamps as the gear losses are almost the same for both (33W & 35W respectively) and therefore proportionately less significant for the 600W lamps. The % figure is the efficiency of the lamp relative to that of the 400W Philips SONT+.

Table 11 - Lamp efficiencies PAR watts / watt electrical energy

Lamp	**PAR watts / watt (electrical)**		**%**	
	Lamp	Lamp + gear	Lamp	Lamp + gear
400W High pressure sodium SONT+				
Philips SONT+	0.32	0.29	100	100
Osram NAVT Super	0.32	0.30	100	103
Sylvania Grolux	0.33	0.30	103	103
400W Metal Halide				
Philips HPI T	0.23	0.22	72	76
Osram HQI BT	0.26	0.24	81	83
600W High pressure sodium SONT+				
Philips SONT+	0.34	0.32	106	110
GE Lucalox HO ballast 1	0.33	0.31	103	107
GE Lucalox HO ballast 2	0.33	0.31	103	107

Looking at the lamps alone (excluding electrical gear losses) the differences in the energy efficiency of lamps of the same nominal power are minimal (3%). The difference between the efficiency of 400W and 600W lamps is also small (3%). However when electrical gear losses are taken into account the difference between 400W and 600W lamps increases to an average of 6%. It is also worth noting that assuming the electrical gear losses are the same for the different 600W electrical gear sets tested they have no effect on the energy efficiency of the lamp.

2.3.1.1.1. 400W or 600W lamps?

600W lamps are inherently more efficient than 400W lamps because of reduced losses both within the lamp itself and in the electrical gear. Manufacturer's data shows 600W lamps as being 9% more efficient than 400W lamps. The only direct comparison made during testing was for the Philips SONT+ where the 600W lamp was 6% more efficient when considering the lamp in isolation and 10% when including the electrical gear losses. Although minor differences in the spectral output of 400W vs. 600W lamps were measured they were essentially the same.

The main drawback when considering 600W instead of 400W lamps is the uniformity of lighting. The main reason for using 600W lamps is that less luminaires are required and hence the cost of an installation is greatly reduced. Similarly the cost of replacement lamps for a given area of lighting is lower. Using 'wide' reflectors can compensate for the effect on uniformity. However, as explained in the luminaire section, this type of reflector tends to be less efficient. This can cancel out the increased efficiency of the 600W lamp to the extent that there is little difference in the efficiency of the whole installation.

Other benefits resulting from the reduced number of luminaires are that there is less total weight to be suspended from the glasshouse structure, less shading effect, fewer electrical connections and a reduced labour requirement for maintenance (lamp replacement, cleaning etc.)

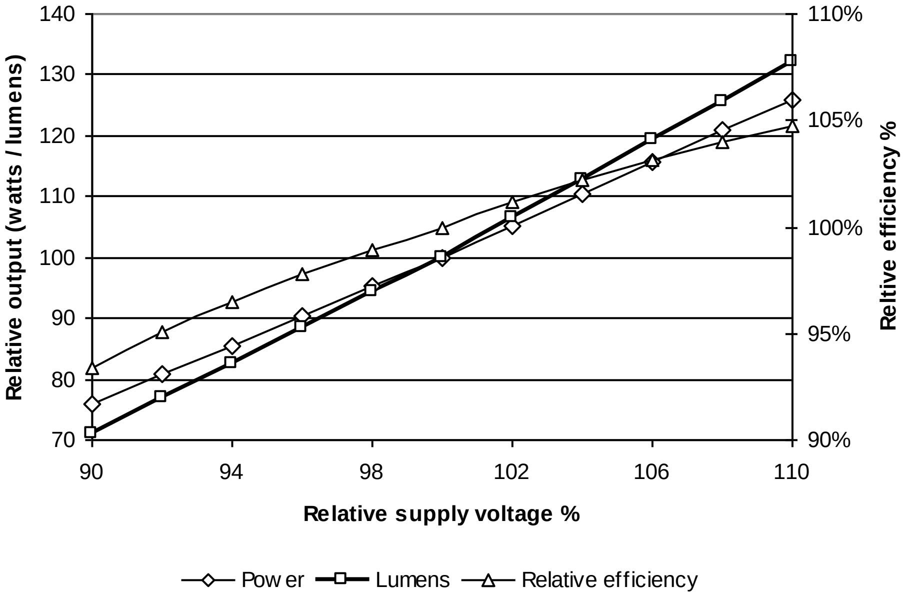
2.3.1.1.1. Supply voltage

The effect of supply voltage on lamp output varies depending on the type of electrical gear used to run the lamp. Although there is a wide range of ballast types and configurations, the compromise between cost and performance means that simple reactor ballasts with laminated iron cores and copper or aluminium wire are used. Ballasts are also specified according to the lamp power (typically 400 or 600W) and the nominal supply voltage (220, 230 or 240 V). The effect of mains supply voltage variations is therefore specific to this type of ballast. Further information about the selection of ballasts is covered in the section on luminaires (page 47).

The effect of mains supply voltage variations on each type of HID lamp i.e. high or low pressure sodium and metal halide are different. As supplementary lighting installations almost exclusively use high pressure sodium lamps the effects described in the remainder of this section relate specifically to these lamps.

The combination of high pressure sodium lamp and simple reactor ballast means that an increase in supply voltage is reflected in an increase in the voltage at the lamp terminals. This in turn means that the power consumed by the lamp increases, the temperature of the arc tube increases and the total light output increases. The opposite applies for a decrease in mains supply voltage. The relationship between the percentage increase and decrease in supply voltage, total light output and lamp power consumption is shown in Figure 6 below.

Figure 6 – The effect of supply voltage on the output of high pressure sodium lamps



A relative supply voltage of 100% means that the supply voltage is the same as that required by the ballast for optimum performance. For example a relative supply voltage of 90% could be represented by 207V connected to a 230V ballast or 216V connected to a 240V ballast.

A supply voltage 10% below the optimum causes a much greater reduction in total lumen output (29%) than power consumption (26%). A supply voltage of 10% above the optimum gives 32% more lumens but only uses 26% more power. From an energy efficiency point of view increasing the supply voltage by 10% increases lamp efficiency by 5%. A 10% drop in supply voltage not only reduces the lighting intensity by 29% but also reduces the energy efficiency of the lighting installation by almost 7%.
As a guide:

- For every 1% below the design supply voltage there is a 3% drop in total lumen output.

The rational reaction to this would be to operate lamps at a higher voltage than specified on the ballast. However any variation in the supply voltage also has an effect on the life of the lamp. As discussed earlier, an increase in supply voltage causes the arc tube to operate at a higher temperature. The end result is a reduction in lamp life, although no data is available to quantify the actual effect on lamp life.

Adjusting the lamp voltage outside normal operating bands also affects the spectral composition of the light produced by a lamp. Increasing the voltage shifts the output towards the red (longer wavelength) end of the spectrum and decreasing voltage shifts spectral output towards the blue end. As with lamp life, little data has been available to quantify this effect. However some information provided by manufacturers gives an indication of what might be expected (Table 12 below).

Table 12 – Effect of high and low mains voltage on high pressure sodium lamps

Lamp characteristic	**Over voltage***	**Under voltage****
Initial spectral output	None	None
Spectral output over lifetime	None	None
Ease of starting	None	None
Lumen output	Increased	Reduced
Lumen maintenance	None	None
Average rated life	Reduced	Increased

* 220V ballast connected to a 230V supply up to 243.8V (+6% worst case)

** 230V ballast connected to a 220V supply down to 198V (-10% worst case)

It is worth noting that the nominal mains electricity supply in the U.K. is 230V with an allowable operating band of 216.2V to 253V. It is quite possible for the voltage at different locations to vary between 220 and 250V i.e. a total variation of 12%. As a result the total light output of the same lamp and luminaire combination at these two locations would vary by 36%.

In addition to the voltage of the electricity supply there is the issue of harmonic voltage. This is a form of voltage disturbance embedded on the main 50Hz AC waveform. There has been some speculation amongst growers about how it affects the output of lamps. As long as the harmonic voltage does not generate a voltage in the neutral conductor (typically 2-3V) thus reducing the voltage effectively applied to the lamp, the lamp output is not affected. As discussed later in the electrical installation section, as long as the neutral conductor is correctly sized the net effect will negligible.

2.3.1.1.1. Ambient temperature

The temperature of the arc tube is of prime importance to the output of HID lamps. However the ambient or background temperature has little ultimate effect. The main reasons for this are:

- The outer glass envelope thermally insulates the arc tube from ambient conditions
- The glass envelope operates at around 400°C. The variation in glasshouse temperature is small in comparison.

2.3.1.1.1. Cleaning

Even if a lamp only has a light film of dirt on it, it will absorb some of the light being emitted by the arc tube and convert it into heat rather than allow it to pass uninterrupted. As with other lamp life factors there is no data available relating to the effect of dirt on lamps and so the benefits associated with regular cleaning cannot be quantified.

There are very few recommendations available for lamp cleaning procedures. The nature of the dirt generally determines the best cleaning method. There are two principal sources of dirt:

- Lime scale resulting from high humidity and fogging or watering systems combined with dust
- Chemical residue from crop protection products.

Naturally, any abrasive cleaners that could scratch the glass should be avoided. A simple acetic acid (vinegar) solution would be a suitable lime scale remover. Other acids could be used but health and safety implications become more onerous. It is always advisable to check the effect of any unproven cleaning agent on a dead bulb. Chemical residues will normally be soluble in water. However great care needs to be taken when cleaning chemicals from a lamp, reactions between the chemical and cleaning substance (vinegar, acid etc.) can generate toxic substances. Alcohol can be particularly useful for removing greasy substances from lamps but again care needs to be taken with its use from a health and safety point of view. However simple domestic window cleaners can be just as effective.

2.3.1.2 Factors affecting lamp life

From a grower’s point of view lamp life does not refer exclusively to the ultimate failure of a lamp but more importantly to it’s ‘economic’ life. As the operating hours of a lamp increase it’s output decreases due to the progressive ageing of components, in particular discolouration of the arc tube. The lamp will therefore reach a point at which the increased running cost due to a drop in efficiency will justify it’s replacement.

As with lamp output, a wide range of factors affect ‘lamp life’ and the diversity of operating conditions means that it is almost impossible for manufacturers to give accurate data specific to any particular application. It is now common practice for manufacturers to only quote the lamp life in terms of the number of operating hours under standard conditions at which 50% of the lamps are expected to have failed.

The standard operating conditions are typically an ambient temperature of 15^{o}C, 10 hours operation per on-off cycle and mains supply voltage as required by the ballast.

2.3.1.2.1. Ambient Temperature

As with lamp output, ambient temperature can affect lamp life. High and low temperatures will decrease and increase lamp life respectively. However the extremes required to have any noticeable effect are not encountered in horticultural situations hence ambient temperature has little effect on the life of a lamp.

2.3.1.2.1. Mains supply voltage

The effect of mains supply voltage on lamp output was discussed in detail earlier, the effects on lamp life apply similarly for the same reasons.

A mains supply voltage higher than the rating of the ballast will reduce the lamp life due to the higher operating temperature. Conversely a lower voltage will increase lamp life but at the expense of reduced light output.

2.3.1.2.1. The number of on - off cycles

Assuming that the mains supply voltage remains within acceptable limits (+10%, -6%) the number of on - off cycles is one of the most significant factors affecting complete failure of lamps.

Two basic processes happen every time a lamp is turned on:

- High voltage pulses are applied to the electrodes to ‘start’ the lamp
- The arc tube heats up from ambient temperature to 1250^{o}C and similarly cools down when it is turned off

When a lamp is running an electric arc is generated between the electrodes which gradually erodes them and so the distance between them gradually increases. As this happens, the voltage required to generate the electrical arc also increases. One of the most common reasons for the failure of HID lamps is that once the initial high voltage starting pulses cease the ‘running’ voltage supplied via the ballast is insufficient to generate an electric arc. In practice this is seen as a lamp that is continuously in the start phase which, if left in the luminaire will lead to premature failure of the starting gear of the luminaire. The high voltage used to start a lamp causes much faster erosion of the electrodes than the normal running voltage and the number of ‘starts’ significantly accelerates the failure of a lamp in this way.

Another common cause of lamp failure is through physical damage to the arc tube in the form of cracks from thermal stress. Every time a lamp is turned on and off thermal stresses are generated which accelerate failure of the arc tube in this way.

The points below give an indication of the effect of number of starts on the life of a lamp. Taking the lamp life at 10 hours operation per start as 100%:

- 5 hours run time per start, reduces the lamp life by 25%
- 2 1/2 hours run time per start, reduces the lamp life by 45%
- 1 1/4 hours run time per start, reduces the lamp life by 60%

As can be seen the effect is quite significant. It is worth noting however that failure of the types described are ‘rapid’ failure and are not preceded by a significant drop in total light output.

2.3.1.2.1. Cleaning

The most obvious effect of dirt on the lamp itself is reduced light output. However the light that is 'lost' is converted into heat which can cause premature failure due to increased thermal stresses as discussed earlier.

There is no data available relating to the effectiveness of cleaning, or the lack of it on total light output and lamp life. As the level of soiling of lamps depends on watering and fogging systems, chemical applications, mounting height etc, and varies significantly between sites, it would be difficult to determine the specific effect on lamp life and output with any level of accuracy.

2.3.1.2.1. Typical lamp life and output data

The light output from a lamp will fall at much the same rate irrespective of its likely failure time. For example:

- A lamp that fails after say 12000 hours may have a lumen output of 96% of its 'as new' output after 4000 hours operation
- A lamp that fails after 4010 hours will, in the majority of cases also have a lumen output of 96% of its 'as new' output after 4000 hours operation

It was originally planned to carry out a number of surveys at commercial glasshouse installations to determine lamp life in typical operating conditions. However it became immediately clear that the majority of growers either did not have the means to measure the hours of operation of lamps or did not record it. Without this any lamp replacement policy would be difficult to apply. Even a blanket approach of say replacement of all lamps every 4 years (8000 hours) is flawed bearing in mind that even under ideal operating conditions 5% of the lamps will have been replaced during this period due to early failure. It is clear that some sort of recording system should be put in place to allow more reliable recording of lamp operating hours.

Figure 7 to Figure 9 overleaf show lamp survival and lumen loss curves from different manufacturers. These are predominantly sourced from older technical literature produced by manufacturers with some more recent data provided by a single manufacturer. The latter more closely matches the trends that would be expected.

Although the lumen loss figures appear to be considerably different for the information sources, closer inspection shows reasonable similarity. Note that Figure 7 only goes as far as 12,000 hours whereas Figure 8 continues to 32,000 hours. At 12,000 hours the average lumen output on both graphs is around 91% of the initial output. Another point of note is the difference between the best case and worst case. As with most things the drop in light output varies around the average. In this case the variation from the average also increases as the lamps get older. At 12,000 hours there is a difference of 7.5% whereas at 24,000 hours it is 14%. Therefore not only does the total light output fall with operating hours but the variation in lamp output increases as well resulting in a progressive reduction in uniformity of light intensity.

Figure 7 – The effect of operating hours on lamp output (old data)

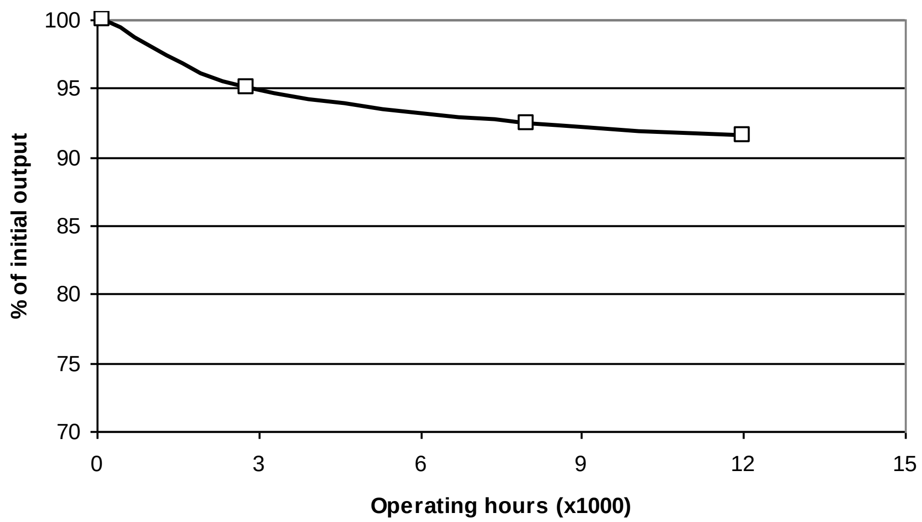


Figure 8 – The effect of operating hours on lamp output (most recent data)

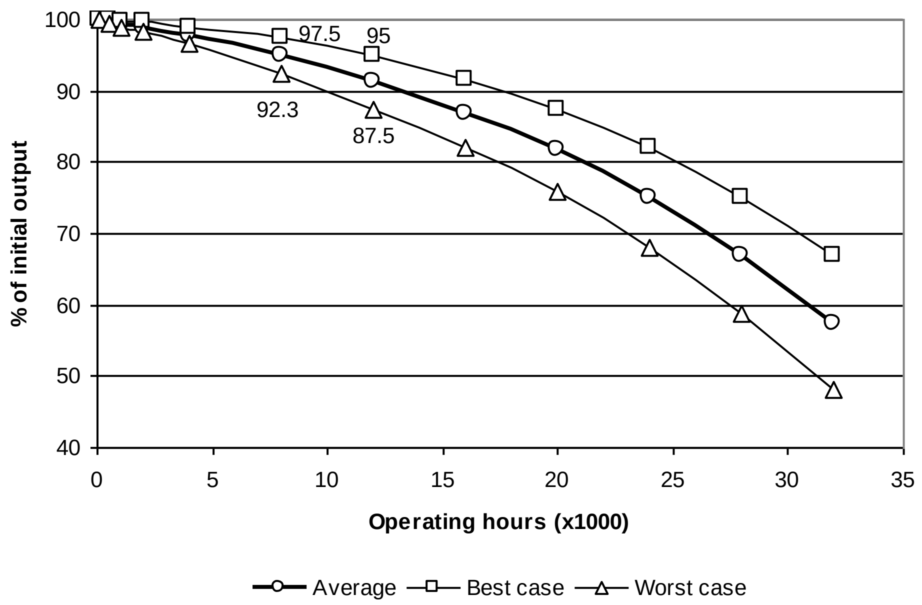
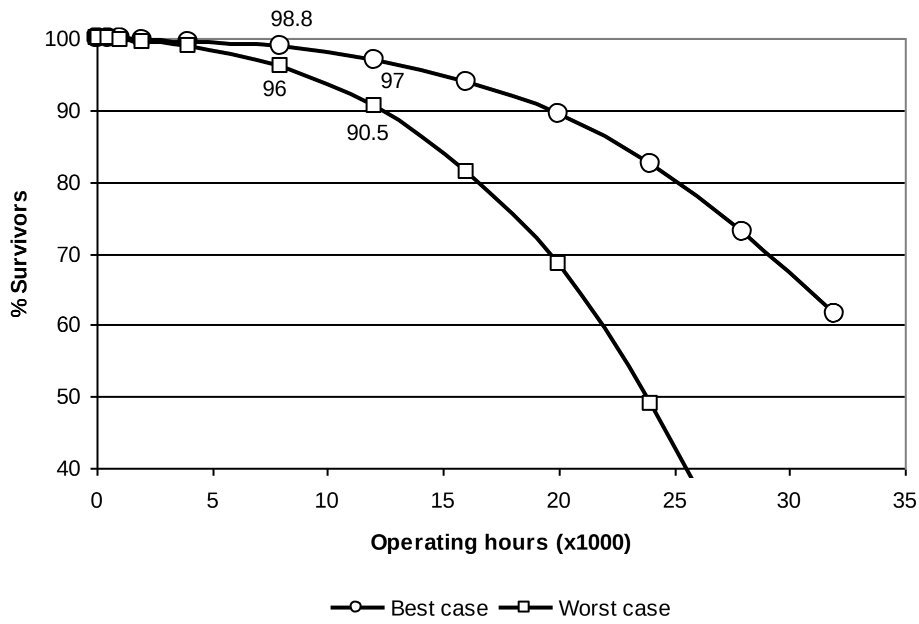


Figure 9 below shows the % of lamps that continue to operate after a given number of operating hours. As with the reduction in light output there is some variation depending on the operating conditions.

Figure 9 - Survival curve for typical 400 and 600W SONT lamps (recent data)



2.3.1.2.1. An economic appraisal of lamp replacement strategy

This relates to the question:

'At what point should I replace the lamps even if they have not failed?'

The main issue when determining a replacement strategy is the gradual reduction in light output. In practical terms, a grower has two options when faced with reducing light output, before he decides to replace the lamps. He can either:

- Compensate for the lower light output of the lamps by leaving them switched on for a longer period each day, thus keeping the total light energy input at the same level.

  Daily light energy input (MJ per day/m^2) =
  Light intensity (PAR Watts/m^2) x operating hours per day x 0.0036

  This is of course conditional on the plant suffering no adverse physiological or metamorphic effects due to the longer lighting period

- Do nothing, and stand the financial loss associated with the sub-optimal performance of the crop.

In either case there is a financial implication. In the first case it is the cost of the extra energy input. In the second it is the reduction in productivity and quality.

In most cases the grower will have to suffer the loss in production as supplementary lighting systems tend to be run for a fixed number of hours per day during the winter months, irrespective of the drop in output. Operating hours are governed by cheap electricity tariff time periods and plant day length requirements.

Although it would be useful to put some financial figures around the loss of production resulting from marginal decreases in light input, it is beyond the scope of this ‘engineering’ project to analyse this type of effect. The value or cost of reduced crop production is specific to individual businesses and their management practices in addition to the type of crop grown. The most obvious effects are longer cropping cycles and reduced crop quality compared to a recently re-lamped installation.

This leaves the simpler ‘engineering’ approach to provide some guidance on lamp replacement policy.

To this end, two models were created to calculate:

- The running cost per MJ of PAR supplied assuming that lamp operating hours are increased to compensate for reduced light output
- The running cost per MJ of PAR supplied assuming that lamp operating hours remain fixed.

The models used the following basic information:

- Single 600W SONT+ lamp with a total power consumption of 635W (including electrical gear losses) and an initial output of 200 PAR watts
- Single 400W SONT+ lamp with a total power consumption of 433W (including electrical gear losses) and an initial output of 133 PAR watts
- Nominal 2000 hours operation per annum taking place over a 180 day ‘winter’, giving a total of 1440 MJ PAR per annum (600W lamp), 960 MJ (400W lamp)
- First 2000 hours occurs during cheap rate tariff periods, any additional hours occur during a higher priced tariff period.

Table 13 and Table 14 below show how the PAR watts output of 400W and 600W lamps falls over their lifetime and the effect on the MJ of PAR produced per 2000 hours of operation. The final column shows how long the lamp would have to operate to maintain a total output equal to their 'as new' performance at different stages in their life. For example between 0 and 2,000 hours the 600W lamp will deliver 1440 MJ if operated for 2000 hours. But between 6,000 and 8,000 hours it will only deliver 1394 MJ if operated for 2,000 hours. If a total of 1440 MJ is required the lamp will have to be operated for 2,066 hours to compensate for the reduced PAR watts output.

Table 13 – Effect of age on 600W lamp PAR watts output

Lamp age Total operating hours	Output PAR watts	MJ per 2000 hours	Operating hours required to maintain 1440 MJ p.a.
0	200	1440	2000
2,000	198	1425	2020
4,000	196	1411	2040
6,000	194	1394	2066
8,000	191	1373	2098
10,000	187	1348	2137
12,000	183	1319	2183
14,000	179	1287	2237
16,000	174	1252	2301

Table 14 – Effect of age on 400W lamp PAR watts output

Lamp age Total operating hours	Output PAR watts	MJ per 2000 hours	Operating hours required to maintain 960 MJ p.a.
0	133	960	2000
2,000	132	950	2020
4,000	131	941	2040
6,000	129	929	2066
8,000	127	915	2098
10,000	125	898	2137
12,000	122	879	2183
14,000	119	858	2237
16,000	116	834	2301

Typical tariff structures mean that 11 hours of supplementary lighting per day can normally be scheduled to take place during cheap rate tariff periods. Over a 180 day 'winter' lighting period this means that the lamps can be operated for 2,000 hours using 'cheap electricity'. Additional operating hours will normally take place during higher priced tariff periods which increases the cost per MJ of light energy delivered over and above the additional cost due to reduced lamp output.

The cost per MJ of light energy delivered by a lamp over its lifetime is made up of two components, the fixed cost of the lamp and the variable cost of the energy. The fixed cost component per MJ reduces as the lamp gets older i.e. its total MJ output increases. The variable cost component per MJ increases over the lifetime of the lamp due to reduced lamp output and operation during higher priced tariff periods. Early in a lamps 'life' the cost per MJ will be dominated by the cost of the lamp and the cost can be expected to fall with increasing operating hours. However at some point the energy cost will become dominant and the cost per MJ will rise, once this point is reached the lamp should be replaced. The economic life of a lamp therefore depends on its purchase price and the cost of energy. Both of these vary from site to site depending on the quantity bought and the prevailing tariff structure.

The cost of replacement lamps at the time of writing this report can vary as follows:

- 400W, £15 - £20
- 600W, £20 - £25.

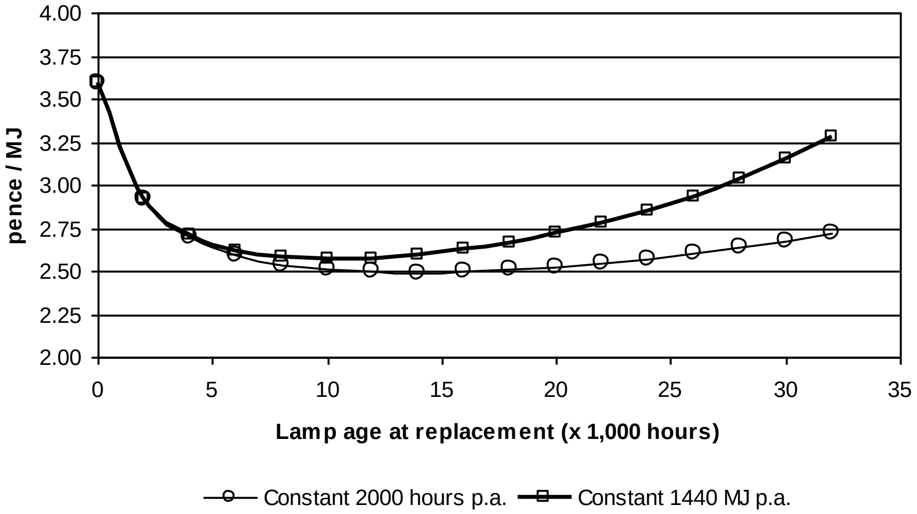
The cost of electricity generally varies depending on the size of the site:

- Smaller growers can expect to be paying an average 3.0 p/kWh (evening / weekend cheap rate) and 6.0 p/kWh (daytime)
- Larger growers can expect to be paying 2.5 & 5.0 p/kWh
- Prior to the introduction of the competitive electricity market prices of around 3.5 and 8.5 p/kWh were common.

Figure 10 overleaf shows how the cost per MJ varies over the life of a 600W lamp under the following conditions:

- Lamp cost £20
- Electricity cost 2.5 & 5.0 p/kWh.

Figure 10 – Lifetime variation in lamp running cost



With this set of operating conditions and the lamp operating time is kept constant (2000 hours per annum) the lamp should be replaced after 12,000 hours. Whereas if a constant 1440 MJ per annum is required and the lamp is operated during more expensive tariff periods it should be replaced after 8,000 hours.

Table 15 below shows the optimum life of 400W and 600W lamps for the range of lamp and electricity costs expected to be encountered.

Table 15 – Lamp life calculations

		Optimum life – hours			
		Fixed 2,000 hours p.a.		**Hours increased to keep constant MJ p.a.**	
Electricity cost - p/kWh	**Lamp cost - £**	**400W**	**600W**	**400W**	**600W**
2.5 / 5.0	10	12,000	10,000	8,000	8,000
2.5 / 5.0	15	14,000	12,000	10,000	10,000
2.5 / 5.0	20	16,000	12,000	12,000	10,000
2.5 / 5.0	25	16,000	14,000	12,000	12,000
2.5 / 5.0	30	18,000	16,000	14,000	14,000
3.0 / 6.0	10	12,000	10,000	8,000	6,000
3.0 / 6.0	15	14,000	12,000	10,000	8,000
3.0 / 6.0	20	14,000	14,000	10,000	10,000
3.0 / 6.0	25	16,000	14,000	12,000	10,000
3.0 / 6.0	30	16,000	16,000	12,000	12,000
3.5 / 7.5	10	10,000	8,000	8,000	6,000
3.5 / 7.5	15	12,000	10,000	10,000	8,000
3.5 / 7.5	20	14,000	12,000	10,000	8,000
3.5 / 7.5	25	16,000	14,000	12,000	10,000
3.5 / 7.5	30	16,000	14,000	12,000	10,000

The lack of detail in the lamp data masks some trends however a number are relatively clear:

- Optimum lamp life increases as the electricity prices fall
- Optimum lamp life increases as the purchase price of the lamp increases.

The 'Fixed 2,000 hours per annum' lamp life figures do not include the cost of reduced productivity from the cropped area. Allowing for the different purchase price of 400W and 600W lamps their optimum life is very similar at 12,000 to 14,000 hours. The information relating lamp age to light output should enable growers who cannot adjust day length to make a reasonable assessment of the cost of reduced light intensity due to lamp ageing if they know the relationship between total daily irradiance and the response of their specific crops.

The ‘Constant MJ per annum’ lamp life figures should give the same level of productivity from the cropped area as long as there is no day length effect. Under this operating regime and allowing for lamp different purchase costs the optimum life for 400W and 600W lamps is also very similar at 10,000 to 12,000 hours.

It should also be noted that lamp failure is increasingly likely as the lamps get older. During the first 8,000 hours of operation an average of 2.6% of the lamps can be expected to have failed. Between 8,000 and 12,000 hours another 3.7% can be expected to fail. The level of inconvenience caused by lamp failure during use may therefore point the grower towards more frequent lamp replacement. Similarly the deviation of individual lamps from the average lumen output curve gets progressively greater as the lamps get older. At 8,000 hours manufacturers data suggests that there will be a difference of 4.8% in the output of lamps, this rises to 7.5% after 12,000 hours. This is in addition to the differences measured in tests on new lamps as part of this project. Therefore the uniformity of light intensity can be expected to get progressively worse as the lamps get older.

2.3.2 Luminaires

2.3.2.1 Construction

There is a wide range of technologies and materials available for the construction and assembly of luminaires. The final choice has a significant impact on the lighting installation as a whole. Issues include:

- Overall efficiency (running cost)
- Ease of installation and maintenance
- Electrical infrastructure – cable size, electricity supply
- Uniformity of light distribution within the glasshouse
- Lamp output and life.

2.3.2.1.1. Electrical gear

As discussed in the section covering the basic construction and operation of HID lamps two basic components are required to ensure the correct operation of the lamp:

- Ingnitor (also known as the starter)
- Power limiting device (ballast).

Additional components are included that have little effect on the performance of the lamp. These reduce the impact of the lamp on the electrical infrastructure and electricity supply:

- Power factor correction capacitor
- Electrical harmonic filters.

- Ingnitor

Basically the ignitor has only one function, that is to provide the correct ignition voltage and waveform to start the discharge in a high intensity discharge (HID) lamp. Once the lamp has 'started' the ignitor is effectively redundant. The voltage, duration and frequency of the pulse required to start a HID lamp varies depending on the type i.e. low pressure sodium, high pressure sodium and metal halide. The choice of ignitor is also dependent on the current limiting device (see below). The choice of ignitor is therefore very important, although some different HID lamp types may start with the same ignitor and current limiting device combination it is likely that the lamp will not run at its most efficient point. The overall life of both the lamp and control gear may also be adversely affected.

As described in the lamp section, a common reason for lamp failure is that they 'fail to start'. In practice this is seen as a lamp that is continually in the starting phase. If the lamp is not quickly replaced the continuous start cycle will significantly reduce the life of the ignitor. Self-stopping ignitors are available which switch off after trying to start a lamp after around 5 to 15 minutes but they tend not to be used because of their cost.

- Current or power limiting device

A current limiting device is required to limit the power drawn by a HID lamp. If there is no such system in place the lamp will overheat and fail prematurely.

A variety of different current limiting devices are available. The types applicable to supplementary lighting are listed below:

- Chokes or reactor ballasts
- Constant –wattage autotransformers

Chokes or reactor ballasts

The function of this type is based on the self-inductance principle. They are made from copper or aluminium wire wound around a laminated steel core. They are cheap and have low losses (typically 35W). However they do require power factor correction, have a high starting current (1.5 x running current) and are relatively sensitive to mains voltage variations. A 10% drop in mains voltage can cause a 30% drop in lamp output (see page 33). As such this type of ballast has to be carefully selected to match the mains supply voltage. Some have the facility to be connected in different ways depending on the mains supply voltage, others are 'factory set' for one voltage only. In spite of these disadvantages they are almost exclusively used in luminaires for supplementary lighting installations and they currently represent the best cost vs. performance compromise.

Constant wattage auto-transformers

These are the most commonly used circuit in the USA, however they are not widely available in the UK. Their construction includes a capacitor that also provides power factor correction. Their main benefits over reactor ballasts are better voltage stability – 10% voltage drop will give no more than 10% light output drop, the starting current is no greater than the running current and voltage dips are less likely to cause a lamp to extinguish. They are still specified according to the mains supply voltage as with reactor ballasts.

- Power factor correction capacitor

Inductance based current limiting devices such as the reactor ballasts generally have a poor power factor. In simple terms, a device with a poor power factor draws more current than it uses. This has a significant effect on the requirements of the electrical installation i.e. bigger cables, greater losses due to heating in cables and higher capacity mains supply. Without power factor correction a SONT+ lamp with reactor ballast will have a power factor of around 0.5. This means that the current drawn by a luminaire will be twice that required by the lamp. The addition of a power factor correction capacitor can improve this to a minimum of 0.80 and preferably 0.90.

- Harmonic filters

The characteristics of HID lamps and their associated electrical gear means that they generate electrical 'noise' in the form of sinusoidal current waveforms superimposed on the main current waveform. This can cause considerable problems within the electrical installation on site and even with the mains electricity supply. One solution to this problem is to add a harmonic filter to the electrical gear of each luminaire. The effect of electrical harmonic distortion and alternative solutions are discussed in greater detail in the section covering electrical installation requirements and recommendations (page 56).

2.3.2.1.1. Reflector

Without a reflector over 50% of the light produced by a lamp will not reach the plant canopy. The primary function of a reflector is to resolve this problem, it also protects the lamp from dirt in the form of solid particles and water droplets.

Reflectors are made almost exclusively from one of two different types of aluminium:

- Stucco aluminium
- Deep drawn aluminium.

Stucco aluminium is a form of polished, dimpled, anodised sheet aluminium. Metal forming and manufacturing processes are limited to rolling and bending. Reflectors made from deep drawn aluminium are normally formed from ductile sheet aluminium with the final process being cleaning and anodising. Complex shape, one piece, self supporting reflectors are more easily made from the latter. Anodising forms a thin layer of aluminium oxide on the surface of the reflector. Aluminium oxide is more resistant to corrosion and hence degradation of its reflective properties than untreated polished aluminium.

There are some new reflective materials already in use in specialist applications that have much better reflective properties than these two types of aluminium. One such product is a polymer manufactured by 3M. It also offers the potential for easier cleaning and better maintenance of its reflective properties throughout its lifetime.

A significant lack of information exists about the effect of degradation of the reflective properties of a reflector whilst in use in a glasshouse. With this information replacement and cleaning policies along the same lines as those developed for lamps could be produced.

2.3.2.2 Performance

Measurements relating to the performance of a luminaire fall into two areas:

- Efficiency – watts per unit of light reaching the target
- Uniformity of light distribution.

2.3.2.2.1. Efficiency

The efficiency of a luminaire (excluding the lamp) is a function of the efficiency of the electrical gear and the reflector.

The electrical gear for a 400W lamp will have standing (fixed) losses of around 33W therefore the gross power consumption is actually 433W per luminaire. Similarly the electrical gear for a 600W lamp will have losses of around 35W. Therefore irrespective of the relative efficiencies of a 400 vs. a 600W lamps in isolation, a 600W lamp 'installed' is more efficient than a 400W lamp because the losses in the electrical gear are less significant. Table 16 below uses manufacturers standard data to show this effect.

Table 16 – The effect of gear losses on lamp efficiency

Lamp power – W	400	600
Gear losses – W	33	35
Total lumen output	55000	90000
Lamp efficiency lumens/W	137.5	150.0
Overall efficiency lumens/W	127.0	141.7
Overall efficiency as % of lamp efficiency	92.4	94.5

The efficiency of the reflector is dependant on the material used and the design (shape). This is measured in two progressing steps:

- Downward light output ratio (DLOR)
- Utilisation factor (UF).

The DLOR is the proportion of light produced by the lamp that is directed downwards towards the crop by the reflector. This typically varies between 0.8 and 0.9.

The UF takes account of the DLOR and the properties of the room within which the luminaire is installed (room index) to determine how much light actually reaches the target. The room index takes account of the geometry of the room and the reflectance of the surfaces (walls, floor, ceiling) to produce a figure that gives the proportion of downward heading light that finally reaches the target. For example, take a reflector that produces a very wide spread pattern in a small room. Some of the light will heads downward at a very shallow angle, this light will be reflected off the walls before it reaches the target. Every time the light is reflected off a surface some of it is absorbed. As a guide, the utilisation factor for a supplementary lighting installation in a glasshouse can be between 0.75 and 0.86. This means that only 75 – 86% of the light produced by the lamp actually reaches the crop.

When all these effects are combined the end result is quite significant. Table 17 below shows the cumulative effect of the losses. A typical 400W lamp starts with an output of 137.5 lumens / Watt. The electrical gear losses reduce this efficiency to 127.0 lumens / Watt. The final efficiency following losses in the reflector and light spillage and absorption can be as low as 101.6 lumens / Watt. This represents only 73.9% of the initial lamp output. The difference between the final efficiency of a 'good' and a 'poor' luminaire design can be over 10%.

Table 17 – Combined effect of luminaire efficiencies

		Efficiency at each stage (Lumens / Watt)	**% of initial lamp efficiency**
Nominal lamp power (Watts)	400		
Lamp output (Lumens)	55000	137.5	100
Electrical gear losses (Watts)	33	127.0	92.4
'Poor' luminaire			
UF	0.80	101.6	73.9
'Good' luminaire			
UF	0.90	114.3	83.1

2.3.2.2.1. Uniformity of light distribution

In the previous section on the overall efficiency of a luminaire the 'best' luminaires had a high downwards light output ratio and utilisation factor. An inherent property of these luminaires is that they have much smaller spread patterns (lighting footprint), whereas the 'worst' luminaires have very wide spread patterns and hence light a greater area. From the point of view of uniformity, luminaires with a wide spread pattern perform better. Similarly a greater number of smaller luminaires will also give better uniformity. However the efficiency and cost of the installation will be higher. Therefore a compromise has to be made especially in older glasshouses that tend to have much lower roofs.

The efficiency of a lamp & luminaire combination and the associated running cost benefits are relatively easily assessed. However the cost of less than perfect light distribution is much less straightforward. Even if the average illuminance in the glasshouse is as specified, non-uniformity can cause a variety of problems. Plants in areas of lower illuminance will not reach the point of sale at the same time as those in brighter areas. This may require repeated harvesting cycles to ensure that plant quality is consistent. The lights will have to remain switched on for a decreasing number of plants hence increasing the running cost per plant. Another effect can be increased time between crops, which may be determined by the slowest growing plants. Crops that are harvested as a block will be of variable quality and size. This will require greater sorting and grading and result in a lower average sale price.

The economic consequences of non-uniform light distribution can be significant. However this is highly dependent on the crop, intended markets and the management and harvesting system. The availability of data quantifying the difference in plant growth resulting from small differences in light intensity is very limited. Thus an economic assessment of uniformity of lighting vs. plant quality and growth was not possible.

How is uniformity of illuminance specified and measured?
A standard lighting industry figure is the ratio of minimum lighting level : maximum lighting level. This figure is not that useful as it is only based on two points within the glasshouse and takes no account of the area being over or under lit. A much better criterion is the ratio of the minimum light intensity to the average.

Lighting uniformity is also affected by changes in mounting height. Generally speaking the greater the mounting height the better the uniformity but this will reduce the utilisation factor and hence the final efficiency of the lighting installation.

Allowance should be made for plants that increase in height significantly over their growing cycle. The effective mounting height of the luminaires relative to the target will change. A compromise will have to be made as to what is the average or optimum mounting height as it is generally impractical to adjust the mounting height of lamps during cropping.

In practice a uniformity of around 80% (min : average) has proven to be a reasonable target.

Growers should take care when they assess the uniformity of lighting designs provided by potential suppliers. It is common practice to quote the uniformity for a small area in the centre of the glasshouse. At this point the area half way between two adjacent rows of luminaires receives 50% of its light from each of the rows of luminaires either side of it. Compare this to the crop around the perimeter of the glasshouse which only receives light from one row of luminaires. The resulting light intensity can be substantially lower than the rest of the glasshouse. This 'under lit' area around the perimeter can easily account for over 10% of the cropped area in some cases. Lighting designs that address this issue or at the very least acknowledge its presence are rare.

2.3.2.3 Mounting

The actual physical means by which luminaires are suspended above the crop vary widely. However factors to bear in mind when choosing a mounting system remain the same for all structures. These are:

- Accuracy of positioning
- Lamp orientation
- Ease of removal and replacement of luminaires and reflectors
- Position of luminaires relative to walkways and heating or irrigation pipes
- Load bearing capability of the supporting structure .

Lighting uniformity and intensity are far from perfect even at the design stage. Every practical effort should be made to ensure the accurate positioning of luminaires according to the layout plan to avoid any additional inaccuracies. Bearers in the form of conduit or pipes running parallel to the line of the glasshouse roof are normally fixed permanently by the installer and therefore any potential error in this dimension will be insignificant. However positioning along the length of the bearer can vary particularly when removing or replacing luminaires. To aid maintenance the position of each luminaire along the bearer should be clearly marked. Another aspect to bear in mind is the angle of the luminaire relative to the target. This is of greatest significance for luminaires with 'focussed' reflectors and lower mounting heights.

Lamp orientation within the luminaire also has an effect on lighting uniformity. This was noticed by chance during tests on reflector performance.

A wire frame supports the arc tube within a lamp (Figure 4, page 17). The wire should ideally be at the '12-o'clock' position. However this should not be at the expense of good electrical contact between the lamp and lamp holder terminals. Most lamp holders only give a maximum of ¼ turn flexibility from this point of view.

Once installed, the luminaires on many installations are never removed unless they need to be repaired or replaced. However it is clear that lamps and reflectors should be cleaned periodically to maintain their performance. The design of the luminaire, the mounting system and electrical connections combine to make this task easier or harder.

The position of the luminaires relative to walkways is a maintenance issue. If they are predominantly over a walkway rather than directly over a bed of plants they are more easily reached using a stepladder. However this may mean that areas of highest light intensity fall over a walkway rather than a cropped area. The position relative to high level heating or irrigation pipes should be borne in mind because of their shading effect and potential impact on light uniformity and intensity.

The weight of a single 600W luminaire is around 11kg so a complete lighting installation can add considerable weight to an existing glasshouse structure. The ability of the structure to carry the extra weight should be confirmed with the manufacturer or installer of the glasshouse. It may even be necessary to add supports to the structure.

2.3.2.4 Cleaning

Lamp cleaning and replacement has already been discussed earlier in this report but it was clear that although reflectors undergo similar ageing processes there was limited information regarding the effect on their reflective properties. Table 18 below shows the results from tests carried out on a limited range of reflectors.

Table 18 – Effect of dirt and age on reflector performance

	Downwards Light Output Ratio		
	As found	**Cleaned**	**New**
4 year old, 15,000 hours lamp operation - ‘focussed’ spread pattern	N.D.	0.75	0.87
1 years old 5,000 hours lamp operation - ‘medium’ spread pattern	0.75	0.79	0.81

N.D. – not done, due to problems with test facility

Although these tests were very limited in number, the reflectors chosen were well maintained and therefore represented the ‘best case scenario’. Visual inspection of both the used luminaires did not show significant levels of dirt but the benefits of cleaning the 1 year-old medium reflector were appreciable at 4%. Calculations relating to lamp replacement strategy gave an optimum lamp life of around 10,000 hours which coincides with a drop in output of 10%. The efficiency of the 4 year-old focussed reflector, even after cleaning was 12% less than a new reflector. This would suggest that a reflector replacement policy similar to that of lamps would be beneficial.

Table 19 – Performance of new reflector material

	Downwards Light Output Ratio
	New
Low bay luminaire with stucco aluminium reflector	0.76
Low bay luminaire (as above) with 3M material	0.86

The 3M high reflectivity material increased the performance of the low bay reflector by 12%. However this would not necessarily translate into a 12% improvement if it was applied to the 'medium' reflector that already has a DLOR of 0.87. It was not possible to test the 3M material with either a 400W or 600W lamp because the temperature of the reflector in this configuration melts the material. There are also problems coating complex reflector shapes with the material, which is currently only available as an adhesive film. The results do however show the potential for improvement over current reflective materials. Although the decrease in performance of this material in service has not been measured it is expected that it will be easier to clean. Following cleaning it's performance should also be closer to 'as new' than similarly aged aluminium reflectors.

It is clear from the limited testing and investigation carried out that the performance of reflectors over their lifetime can reduce the efficiency of a lighting installation and hence the light intensity by over 10%. Cleaning frequency, methods and materials are not well defined and warrant further investigation along with more detailed measurements of the degradation in reflector performance. Current best practice methods should follow the same recommendations as those for lamp cleaning.

2.3.3 Electrical installation

The use of supplementary lighting in horticulture presents a particularly unusual electrical installation environment. The high lighting levels required are unprecedented in almost any other environment and this means that unusually high power densities are experienced. The high harmonic content of the electrical load currents for discharge lighting is a major departure from most conventional systems.

Electrical strains put on system components by high harmonic currents mean that the consequence on electrical installation design is significant. Conventional electrical design information does not adequately cover this. Consequently, installers who are inexperienced with these issues are likely to make errors in design if they stick to the normal 'rules' of electrical design.

Having pointed out the unusual characteristics of this type of load, it is possible, by following simple recommendation, and using simple adjustments in the sizing of components, to avoid practical problems with installations.

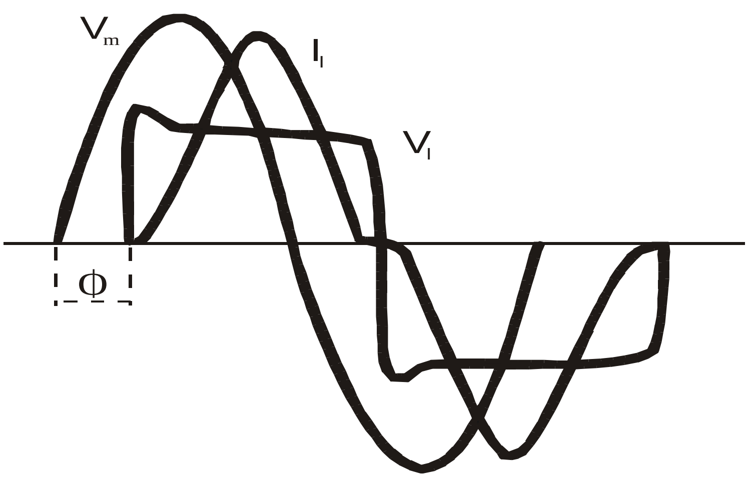
2.3.3.1 The characteristics of high pressure sodium lighting

HP sodium lighting is termed a 'non linear' electrical load. This means that it does not consume power, over an alternating voltage cycle, in the same the smooth sinusoidal pattern of the applied voltage (see Figure 11). This is in contrast to resistive loads like heating or tungsten lighting which absorb power in direct proportion to the applied voltage.

The components of the discharge lamp type used in horticulture are fairly simple. The lamp itself absorbs power as it produces light. A 'ballast' or electrical coil acts as a choke, to limit the electrical current which would tend to naturally overload once the lamp gas starts to conduct. Finally a capacitor is incorporated, which improves the 'power factor' of the lamp circuit – that is it reduces wasteful circulating currents.

The shape of the current absorption of a lamp is shown in Figure 11 below.

Figure 11 - Current & voltage waveforms for a HID lamp



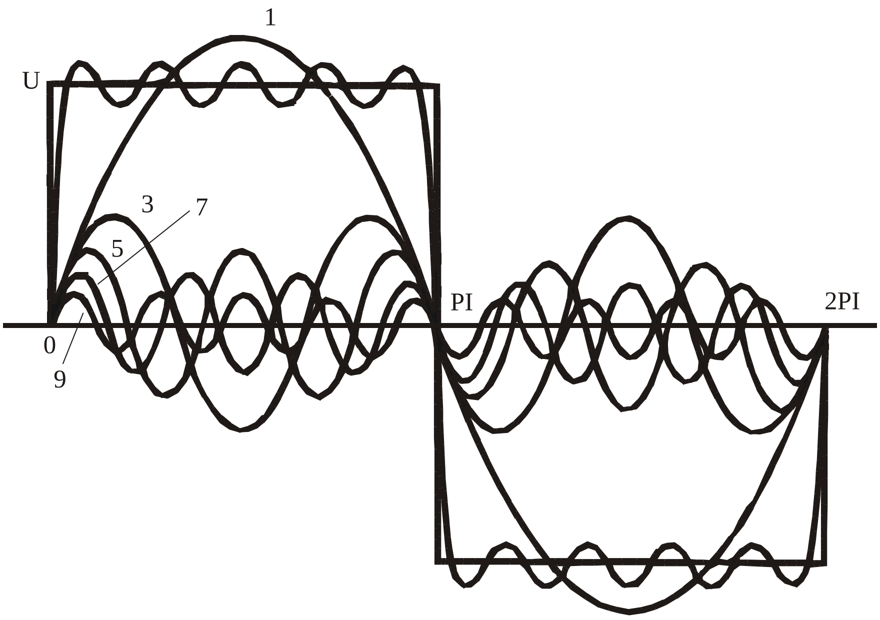
Having recognised that the current curve of a discharge lamp is non-linear, it helps to be able to quantify and differentiate the characteristics. One way of doing this is using a technique called Fourier analysis.

Fourier analysis is a complicated mathematical process but the concepts it employs and the results that it produces are very useful in understanding the problems and solutions surrounding non-linear loads.

In simple terms, Fourier analysis allows a non sinusoidal repeating waveform to be defined as a series of sinusoidal waveforms of higher frequencies. Each sinusoid has a frequency which is an exact multiple of that of the main waveform or fundamental frequency. These waveforms are referred to as the 'harmonics' of the basic sinusoidal waveform. For example the 2nd harmonic has a frequency of twice the fundamental, the 3rd harmonic has a frequency of 3 times the fundamental, and so on.

Figure 12 below shows a typical waveform and how, through Fourier analysis it can be broken down into a series of simple sinusoids.

Figure 12 - Harmonic content of a square wave



Harmonics in a normal power system are small and have little effect on other equipment, but where there are a large number of high pressure sodium lights the degree of harmonic content can start to distort the natural shape of the electricity supply voltage. Taken to the extreme this distortion will have undesirable effects on the performance of other electrical equipment and the components of the electrical distribution equipment.

The harmonic currents of a typical lamp quantified for each harmonic number are shown in Table 20 and Table 21 below. The first table assumes a completely ‘clean’ supply with no external voltage harmonic stimulation.

Table 20 - Harmonic currents for one lamp on a clean supply (manufacturers data)

Total Harmonic Distortion	17%
3rd Harmonic	15.7%
5th Harmonic	6.3%
7th Harmonic	1.6%

It is important to note that small harmonics in the voltage will stimulate larger harmonic currents. So on a site where 3rd and 5th harmonics are larger, the following might be the result

Table 21 - Harmonics currents for one lamp on a glasshouse site

Total Harmonic Distortion	25.4%
3rd Harmonic	24..6%
5th Harmonic	6.2%
7th Harmonic	1.3%

On sites that are connected to transformers which are also used by shops or offices, the effects of 5th and higher order harmonics might be significant.

In practical terms some harmonics cause more practical problems than others. The most significant in electrical circuits is the 3rd Harmonic and its multiples (9th ,15th , etc). The third harmonic component of the current component has a frequency of 3 times the fundamental. In the UK electricity mains system (50Hz) this is the current component with an electrical frequency of 150Hz.

2.3.3.1.1. 'Triple N' harmonic and neutral current.

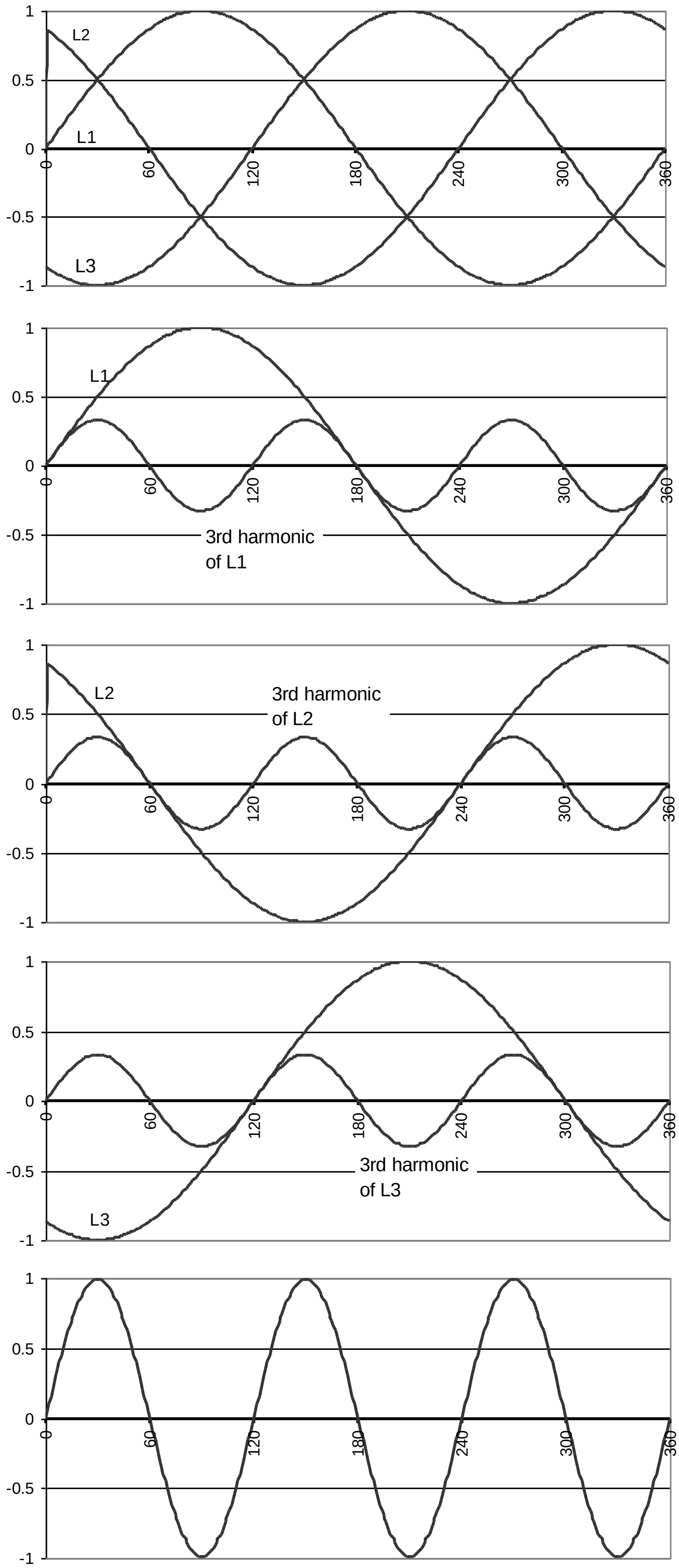
In a normal three phase electricity system each phase reaches it's peak a third of a cycle after the preceding one. The resultant currents which return through the neutral conductor effectively cancel each other out. So, in a balanced three phase system connected to a linear load the neutral current will be in zero. In practice, imbalances and non linear loads lead to some neutral current but these are normally low.

As the 'cancelling' effect of neutral currents is normal, it is common practice, in large electrical circuits, to install neutral conductors which are smaller than the corresponding phase conductors.

Where large Tripling harmonics are present, the harmonics phase currents do not cancel each other out. In fact, they have a cumulative effect in the neutral of a three phase system. This is demonstrated in Figure 13 overleaf.

Where neutral conductors are overloaded with harmonic currents, overheating of the conductors occurs. At worst this can lead to damage and fire risk. At best the harmonics will cause power loss in the cables, and a lowering of voltage through the electrical installation.

Figure 13 - 3rd harmonic build up in the neutral of a 3 phase system



2.3.3.2 Problems caused by high harmonic currents

If provision is not made to cope with or suppress harmonic current a number of problems may become evident. These are as follows:

- Transformer overheating

Electrical transformers convert grid voltages to usable voltages at customer levels. The normal operating voltage of the UK final circuit supplies are 230V (phase to neutral voltage) and 400V (phase voltage). Transformers derive this voltage from the 11,000V distribution system.

Most glasshouses have a dedicated transformer feeding only the glasshouse site. In most situations the transformer is owned by the Electricity Distributor and the growers own electrical installation starts on the low voltage (400V) side of the transformer. In some situations the grower takes his power at high voltage (11,000V) and the transformer used is part of his own electrical installation.

Harmonic currents in the load generate small circulating currents in the core of the transformer and this causes extra heating. These are called eddy current losses.

- Generator and motor overheating

Where a lighting installation is fed from a generator rather than the electrical mains, harmonic currents can lead to overheating in the same way as discussed with transformers. Likewise, the windings of electrical motors can be affected causing overheating, although this is generally less problematical.

- Electronic equipment disturbance

The power supplies of computers and any other electronic equipment can be affected by harmonic currents. In extreme cases this can lead to malfunction of the equipment and damage.

- Power factor equipment and capacitors

Large electrical installations are often fitted with power factor correction capacitors to optimise the use of current in the system. These capacitors conduct high currents if the applied voltage is of higher frequency. Therefore overloading can occur where harmonic distortion is high. Also interactions between the lamp ballasts and capacitors can cause an electrical resonance to occur. These are relatively rare and difficult to predict, but they can lead to high circulating currents in system circuits.

2.3.3.3 Solutions to harmonic problems

The production of harmonic currents in conventional lamp circuits is inevitable. An installer has the option of either reducing them through a number of electrical techniques and components, or designing systems that can tolerate their presence.

In most cases the latter solution is the most cost effective. This is especially the case where a new installation is being planned. It is therefore important that these issues are taken into consideration when specifying the electrical installation.

In practice, the measures, which need to be employed in most installations, are reasonably well documented and understood. However it must be emphasised that for most electrical contractors who are not involved in supplementary lighting installations on a regular basis, the chance of these issues being overlooked is high. In the experience of the writers, it is all too common to find that professional designers have not taken into account the special nature of supplementary lighting installations.

2.3.3.3.1. Cable sizing

Sizing cables requires that an installer takes into account the current which has to be carried and allowable voltage drop through the circuits. In single phase circuits this is simple, as the harmonic currents are simply a part of the RMS (root mean square) current stated by the manufacturer of the lamp. So no special measures have to be taken. However, where single phase circuits come together to meet three phase circuits and a common neutral is employed then, the resultant high currents in the neutral have to be considered.

Neutral conductors are either separate single core cables, or they are built in to a multicore cable that includes the phase conductors. The Institution of Electrical Engineers Wiring Regulations (BS 7671) specifically mention the installation of discharge lighting circuits. Regulations 524-02-03 states

> "In a discharge lighting circuit the neutral conductor shall have a cross sectional area not less than the phase conductor"

This is a good guide where conductor groups are made up of single cables. Where multicore cables are to be used it may be necessary to derate cables, even though the neutral is the same size as the phase conductors.
The "Commentary on BS 7671" gives indications on the necessary derating of multicore cables with high third harmonics:

Table 22 - Rating factors for multicore cables with 3rd harmonic currents

3rd Harmonic content of phase current, %	Neutral current as a % of phase current	Cable selection	Correction factor
0 –15	0 – 45	Phase current	1
15 – 33	45 – 99	Phase current	0.86
33 – 45	99 – 135	Neutral current	0.86
> 45	> 135	Neutral current	1

Notes on table

1. Neutral current for 3rd harmonics is three times the phase 3rd harmonic
2. When the neutral current exceeds the phase current, selection is based on the neutral current
3. Harmonic currents reduce the rating of a cable. Where the neutral current exceeds 135% of the phase current and selection is based on the neutral current, no correction factor is applied.

2.3.3.3.1. Transformer sizing and selection

The problem of harmonics in transformers can be tackled in two ways. The first is to choose a design of transformer which is less affected by harmonic currents. The degree to which transformers are affected is expressed using a measure called the K-factor. It is given by the following formula:

$$K = \frac{P_t}{P_f} = \sum_{h=1}^{h=h_{\max}} I_h^2 h^2$$

Where P_t is the total eddy current loss

P_f is the eddy current loss at fundamental frequency

H is the harmonic number

I_h is the harmonic current

The K factor can be measured directly from many handheld electrical meters. A typical K-factor for discharge lamp load is 4. Using this a correctly specified transformer can be selected.

K-factors are widely used in the USA as a method of transformer classification

An alternative measure is ‘factor K’, which although of similar name is a different measure and method of transformer selection.

Factor K is a method of derating a transformer to cope with a certain level of harmonic current.

The formulae used are more complex and outside the scope of this study. However with harmonic distortion of the following (typical supplementary lighting installation) a k-factor of 0.85 should be used to derate a standard UK distribution transformer.

2.3.3.3.1. Harmonic Filters

It is possible using specially designed filters to suppress harmonic currents at lamp level or for whole installation. This can be explained in terms of the incorporation of circuit components – capacitors and inductors – which block the harmonic currents.

Such systems have been demonstrated as being very effective in controlling harmonics. However they are an added expense and can add between £9 and £15 per lamp into the cost of an installation.

2.3.3.3.1. Alternative lamp connection methods

One novel technique which can control high harmonic currents in neutral conductors is to have special transformers fitted for groups of lamps to allow them to be connected without a neutral conductor. Lamps are connected from phase to phase rather than phase to neutral. This is called a delta connection (as opposed to a star connection which is the standard connection system.

In this way, the ‘tripling’ neutral harmonics cancel themselves out and no 3rd harmonics flow back into the electrical system.

2.3.3.4 Selection of harmonic control method

If is clear that it is not always necessary to make provision to control harmonics if the integrity of the overall electrical system is such that harmonics which are generated can be adequately handled.

In most cases the extra provisions which need to be taken to handle harmonic problems are the most cost effective measure for coping with the problem. Such provisions are likely to add a maximum of 10% to the cost of the electrical component price of installation.

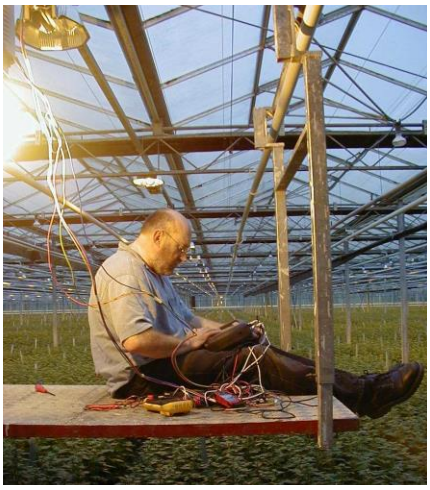
In cases where a marginal reduction in harmonic currents will avoid a step change in the sizing of a large piece of electrical equipment then it is possible that the cost of harmonic suppression measures such as filtering could be cost effective.

Likewise, where an existing installation exhibits harmonic linked problems, choosing harmonic filtration techniques rather than re-equipping a major part of the electrical system can be a cost effective solution.

2.3.3.5 Case Study - Donaldson Flowers Ltd

This nursery grows AYR stem chrysanthemums and uses 820 kW of high pressure sodium lighting over an area of about 4Ha to produce a target illuminance of 4000 lux.

Figure 14 – Measuring electrical harmonics in a glasshouse



The electrical load is supplied by a static generator with a capacity of approximately 1 MW.

In a response to problems of conductor and generator overheating from harmonic disturbance, nursery management installed a filter to reduce the harmonics and high neutral currents.

The general electrical installation on the site was good. However the neutral conductors between the generator and the main switch had originally been down sized, which is not good in this type of system design. It was not possible to determine the exact sizing criteria of the multicore cables between the main distribution board and the sub-distribution boards. However, measurements taken through the system and the temperature of the cables would indicate that they were adequate.

To test the level of harmonic disturbance and the effect of the filter, electrical measurements were taken using a Dranetz power quality analyser. Measurements were taken at a number of points from the farthest lamp from the generator to the main distribution point near the generator.
Results showing the levels of current and voltage harmonic disturbance are included in Appendix 2.

The notable measurements from the site assessment illustrate the following.

1. Without filtration the *current* at the main distribution board contained approximately 26% 3rd harmonic. This would summate in the neutral currents in a perfectly balanced system to represent 78% of the phase currents. This means it would be good practice to size the neutral conductors between the generator and the main switchboard connection at a size at least equivalent to the main phase conductors. The multicore cables between the main distribution point and the local distribution boards would have to be derated by 86% (see Table , page 64)
2. With filtration, the current harmonic distortion drops dramatically with 3rd harmonic distortion less than 3 % at the main distribution board and 4.5% at the farthest lamp. This certainly gets over the neutral conductor sizing problem, and the possibility of conductor over-heating
3. Total *voltage* harmonic distortion shows some interesting characteristics. The voltage harmonics were measured on the load side of the harmonic filter and exhibit a total voltage harmonic of 4.7% without filtration and 4.74 with filtration. One omission was measurement of harmonic distortion on the generator side of the filter
4. Voltage distortion at the farthest lamp showed 11% with filtration and 6% with out filtration.

2.3.3.5.1. Implications

This nursery is somewhat unusual in that the electricity supply system was based on electricity generated locally. In general, where this is the case, the electricity system is technically less robust that with a mains supply and consequently the influence of harmonics is greater. Results measured here are therefore likely to be slightly worse than one would expect for a mains connected unit.

It is clear that, compared with normally recorded levels for harmonic distortion without filtration, as set out in manufacturers' leaflets, the actual levels are somewhat higher. Harmonic current components for an individual lamp are normally stated to be around 20%, but it is more realistic to work on an average of 30% for an installation of this size.

Filtration worked well in controlling harmonic current, reducing 3rd harmonic neutral currents at the main distribution point from 78% of phase current to 7.5%. The problem of overheating of the neutral conductors connected between the main distribution panel and transformer was solved using the filter.

Filtration had no effect on harmonic voltage distortion on the load side of the filter. This means that, where supplies are to be taken to other equipment or to an office, for example, the supply should be taken from the supply side of the filter rather than the load side.

In general the level of voltage harmonic distortion for the farthest lamp circuits might be of concern. Normal recommended maximums for total harmonic voltage distortion on electrical systems is 5% (metering position). The figure at the farthest lamp reached nearly 12%. This means that the current in the capacitor circuit of the lamp would be 77% higher than designed and could cause overheating and failure.

The use of the filter did not significantly alter the voltage in the system

2.3.4 New lighting technology

This project concentrated on current lighting technology in widespread use in the horticultural industry. However, even since the start of this project there have been several developments.

2.3.4.1 Gavita Internal Reflector lamp

Gavita have launched a lamp with an internal reflector (IR). The shape of the glass envelope surrounding the arc tube has been modified and the inside surface of the upper half coated in a mirror finish reflective coating so that a separate reflector is not required. By doing this the reflector is unaffected by dirt and chemical attack normally associated with aluminium reflectors which has been identified in this report as a significant factor affecting the drop in light intensity over time. However, practical experience with these lamps is limited and they are still subject to a drop in output due to ageing of the arc tube.

At the time of writing they are being sold in limited quantities into the Dutch market for final proving prior to widespread release.

2.3.4.2 Over power lamps

The effect of mains voltage on lamp output has already been discussed in some detail. Some luminaire manufacturers are developing and promoting luminaires that operate nominal 400W lamps at up to 550W and 600W lamps at up to 750W. This is outside the operating range specified by the lamp manufacturers and will have a significant impact on lamp life which is currently unknown. Two such luminaires capable of operating a

400W lamp either at 400W or 550W and a 600W at 600 or 750W were tested to gain an insight into their performance. The results are shown in Table 23 overleaf.

Table 23 – 'Over power' lamp test results

	400W SONT+ lamp		600W SONT+ lamp		400W Grolux SONT+ lamp	
Power setting – Watts	400	550	600	750	400	550
Actual power drawn – Watts	404	540	659	822	471	603
Total lumen output	54,610	70,610	90,420	107,900	61,720	74,930
PAR Watts	130	179	222	277	153	196
Micro-moles	640	884	1101	1375	755	973
Lumens / Watt	135.2	130.8	137.2	131.3	131	124
PAR Watts / Watt	0.32	0.33	0.34	0.34	0.32	0.33
Micro-moles / Watt	1.58	1.64	1.67	1.67	1.60	1.61
% Violet	1.7	1.8	1.1	1.3	1.4	1.5
% Blue	4.7	5.0	3.6	4.0	4.0	4.3
% Green	12.2	13.6	16.4	17.7	12.3	13.1
% Yellow	30.5	25.3	24.4	21.3	24.6	20.7
% Orange	36.7	35.9	35.2	33.6	33.4	31.1
% Red	14.3	18.6	19.3	22.2	16.4	19.6

As would be expected there were significant increases in total lamp output. Although the lumen efficiency is worse, the PAR watts efficiency is unaffected. This is because the lamp output has been shifted slightly towards the red end of the spectrum which remains in the 400-700 nm PAR region but moves away from the peak response of the human eye (555nm). At this point 'over power' lamps seem to have a lot of benefits, however the effect on lamp life and reduction in output over their lifetime is unknown. These need to be carefully assessed before committing to this, as yet, unproven method of lamp operation

Electrical gear

Electronic gear which combines all the required functions into one package have already been developed for smaller lamp powers and it is expected that such equipment will become available for 400 and 600W lamps in the near future. They offer a variety of benefits:

- Reduced weight
- Reduced losses
- Less sensitive to mains voltage variations
- Improved power factor
- Less harmonic distortion
- More controlled lamp starting potentially improving lamp life

Conclusions

It is clear that a variety of installation related factors can have a significant effect on the actual light intensity achieved compared to the intensity calculated by taking manufacturers data at face value. The combined effect of manufacturing tolerances, luminaire electrical gear and mains electricity voltage can easily result in a light intensity as much as 20% less than expected. A further 20% drop in light intensity can occur as a result of lamp and reflector ageing and soiling over 8,000 hours (4 years) operation even when an adequate maintenance procedure is in place.

The grower should be aware of the factors affecting lamp output so that the design specification takes their effect into account. Reductions in light intensity should be related to the value or cost of reduced crop quality and output to determine the initial design lighting intensity such that it is still adequate when the lamps are replaced. Once this has been decided it is the responsibility of the installer to provide a system that will achieve the required lighting intensity according to the conditions on site.

When considering high pressure sodium SONT+ lamps in isolation the relationship between lumens, PAR watts and micro-moles is relatively consistent. The maximum difference was 5%. PAR watts were shown to be the best compromise measurement, however performance data in this form is not readily available for all lamps. Using a standard conversion factor of 2.4 PAR watts per 1000 lumens for SONT+ lamps will not introduce significant errors when specifying light intensity. The same is not true for metal halide lamps, test results showed that this can vary from 2.8 to 3.5 PAR watts per 1000 lumens.

Although there are variations in the efficiency of different high pressure sodium SONT+ lamps, tests have shown this to be less than 4% (PAR watts / watt electrical energy). Subtle variations in spectral output of the ‘enhanced’ lamps in particular may be beneficial from a photo-morphic point of view but not for photosynthesis.

The reduction in reflector performance due to ageing effects has been shown to be of potentially greater significance than lamp ageing. As such replacement policies similar to those employed for lamps should be applied. Testing in this area was however limited. The potential for improved cleaning techniques or reprocessing of reflectors and new materials remains to be fully proven. Recent developments in lighting technology include lamps with built in reflectors that would help to address this issue. However there is currently little practical experience with them.

Areas for Further Investigation

1. Economic analysis of the sensitivity of horticultural crops to changes in supplementary lighting intensity and uniformity.

Many trials have been conducted on the response of chrysanthemum crops to supplementary lighting and a recent HDC publication on pot chrysanthemums provides a detailed technical and economic appraisal of the benefits of supplementary lighting[8]. While less detailed, there is also information available on the benefits of supplementary lighting for AYR chrysanthemums[9, 10]. Recent plant trials have highlighted the potential benefits of supplementary lighting for crops of begonia[11], New Guinea Impatiens[12] and for bedding plants in the plug phase[13]. However, full economic appraisals have not been conducted and hence clear guidelines cannot be given to growers on the sensitivity of the quality and throughput of these crops to changes in supplementary lighting intensity and uniformity.

There has been renewed interest in supplementary lighting of protected edible crops and a recent feature article in the trade press by Jack Vergeer of Hortilux Schreder[14] highlights the potential yield response of tomato crops to supplementary lighting. Such work does need further technical and economic appraisal before growers in the UK are likely to adopt the technology.

The lack of reliable economic sensitivity data on the response of some of the main horticultural crops to changes in supplementary lighting intensity and uniformity means that the impact of the findings of this study cannot be adequately quantified. It is therefore recommended that further work is directed towards understanding these effects and their economic impact.

2. The effect of degradation of aluminium reflectors on luminaire efficiency and final light intensity

It has become clear that the degradation of the reflective properties of aluminium reflectors during use can be as important as the drop in light output of lamps. Testing carried during this project showed that even after cleaning the efficiency of a 4 year-old reflector was 12% less than a new one. Reprocessing of reflectors offers a potentially lower cost route to returning them to ‘as new’ than by simply buying new ones. However this is only just being recognised by manufacturers and installers as an ongoing maintenance issue.

There is currently insufficient information to enable growers to accurately determine when reflectors should be replaced or refurbished and which method of refurbishment is most cost effective. It is therefore recommended that further work is directed towards identifying the factors that affect reflector ageing and how they can be minimised, the effectiveness of different reprocessing and cleaning techniques and how growers can cost effectively and accurately assess the performance of their reflectors.

3. Merits of new technologies in supplementary lighting

Several new and improved lighting technologies and materials have recently been developed. These include over powering lamps, lamps with built in reflectors and new reflective materials. This project has investigated new technologies and materials to only a limited degree and these areas may warrant further work to prove their benefits.

4. Electrical installations

In the area of electrical installation, this study has set out a foundation of sound basic rules for most applications. However, as commercial systems continue to increase in size, a deeper understanding, and the development of better design tools, needs to be explored. This is especially important with regard to installations over 1MW and those fed from on-site generation plant (i.e. combined heat and power) where practical experience is limited and current technology has yet to be proven.

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Appendix 1 – Detailed lamp data

The following tables combine the results from tests carried out as part of this project and data provided by manufacturers. The following points help to clarify the content of the tables:

- The 'Test' column contains data derived from the tests carried out
- The 'Man.' column contains data supplied by the manufacturer
- The '%' column is the percentage of the test data relative to the data provided by the manufacturer
- Where a cell is empty this means that either the lamp was not tested or the data was not available from the manufacturer
- McCree Watts are the product of the spectral composition line for the lamp (watts) and the plant response curve as measured by McCree (see Figure 2 page 14)
- DIN5031 Watts are the product of the spectral composition line for the lamp (watts) and the plant response curve as defined in DIN5031-10 (see Figure 2 page 14)
- Table 26 and Table 29 give the output of each lamp as a percentage of the total PAR watts output in each colour band.

Table 24 – 400W lamp total output

Lamp	Lamp power Watts			Total lumens (x1000)			PAR Watts			Micro-moles/sec			McCree Watts			DIN5031-10 Watts		
	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%
High pressure sodium SONT+ lamps																		
Philips SONT+	358	400	89.4	49.1	55.0	89.2	113.4	132	85.9	560.9	647.4	86.6	91.5	105.7	86.6	68.3	80.1	85.3
Philips SONT Agro		400			55.0			134			651.0			107.0			82.2	
GE Lucalox HO		400			56.5			139			686.5			112.4			84.8	
Osram NAVT Super	375	400	93.9	50.7	55.5	91.4	121.7			605.5			99.1			73.8		
Sylvania Grolux	400	425	94.2	54.8	58.0	94.4	130			647.2	713	90.8	106.1			79.1		
Osram Planta		400			52.0													
Metal Halide lamps																		
Philips HPI T	392	445	88.1	33.0	38.0	86.9	91.5			416.7			61.3			58.6		
Osram HQI BT	393	420	93.6	30.0	32.0	93.7	104.0			484.3			70.6			69.0		

Table 25 – 400W lamp efficiencies

Lamp	**Lumens / Watt**			**PAR Watts / Watt**			**Micro-moles / sec / Watt**			**McCree Watts / Watt**			**DIN5031-10 Watts /Watt**		
	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%
High pressure sodium SONT+ lamps															
Philips SONT+	137.2	137.5	99.8	0.32	0.33	95.8	1.57	1.62	96.9	0.26	0.26	98.1	0.19	0.20	95.5
Philips SONT Agro		137.5			0.34			1.63			0.27			0.21	
GE Lucalox HO		141.3			0.35			1.72			0.28			0.21	
Osram NAVT Super	135.2	138.8	97.4	0.32			1.61			0.26			0.20		
Sylvania Grolux	137.0	136.5	100.4	0.33			1.62	1.68	96.3	0.27			0.20		
Osram Planta		130.0													
Metal Halide lamps															
Philips HPI T	84.2	85.4	98.6	0.23			1.06			0.17			0.15		
Osram HQI BT	76.3	76.2	100.2	0.26			1.23			0.18			0.18		

Table 26 – 400W lamp spectral output

Lamp	**Output in this wavelength band as a percentage of the total PAR watts output**																	
	Violet 400-435nm			Blue 440-495nm			Green 500-565nm			Yellow 570-590nm			Orange 595-625nm			Red 630-700nm		
	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%
High pressure sodium SONT+ lamps																		
Philips SONT+	1.6	1.5	106.7	4.2	4.0	105.0	11.3	10.0	113.0	33.4	32.9	101.5	36.7	38.0	96.6	12.8	13.5	94.8
Philips SONT Agro		2.1			4.9			9.2			31.6			39.9			12.3	
GE Lucalox HO		1.2			3.5			11.4			30.8			36.4			16.7	
Osram NAVT Super	1.2			3.6			13.3			28.5			36.3			17.1		
Sylvania Grolux	1.5			3.9			12.0			30.0			37.1			15.5		
Osram Planta																		
Metal Halide lamps																		
Philips HPI T	12.1			16.5			27.7			21.0			15.1			7.9		
Osram HQI BT	11.4			16.5			28.9			9.2			13.4			21.4		

Table 27– 600W lamp total output

Lamp	Lamp power Watts			Total lumens (x1000)			PAR Watts			Micro-moles/sec			McCree Watts			DIN5031-10 Watts		
	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%
Philips SONT+	565	600	94.2	79.3	90.0	88.1	191.2	213	89.8	944.7	1045	90.4	154.5	173	89.3	114.5	129	88.8
GE Lucalox HO ballast 1	557	600	92.8	77.1	90.0	85.7	181.8	224	81.2	898.7	1107	81.2	146.6	202.1	72.5	108.3	138	78.5
GE Lucalox HO ballast 2	622	600	103.7	85.9	90.0	95.4	205.9	224	91.9	1021	1107	92.2	166.4	202.1	82.3	123.5	138	89.5
Osram NAVT Super		600			90.0													
Sylvania Grolux		615			87.0						1090							
Osram Planta		600			81.0			188			922			152			114	

N.B. All high pressure sodium SONT+ lamps

Table 28 – 600W lamp efficiencies

Lamp	Lumens / Watt			PAR Watts / Watt			Micro-moles / sec/ Watt			McCree Watts / Watt			DIN5031-10 Watts /Watt		
	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%
Philips SONT+	140.4	150.0	93.6	0.34	0.36	93.9	1.67	1.74	96.1	0.27	0.29	94.1	0.20	0.22	92.3
GE Lucalox HO ballast 1	138.4	150.0	92.3	0.33	0.37	88.1	1.61	1.85	87.2	0.26	0.34	77.4	0.19	0.23	84.3
GE Lucalox HO ballast 2	138.1	150.0	92.1	0.33	0.37	89.5	1.64	1.85	88.7	0.27	0.34	78.8	0.20	0.23	86.1
Osram NAVT Super		150.0													
Sylvania Grolux		141.5													
Osram Planta		135.0			0.31			1.54			0.25			0.19	

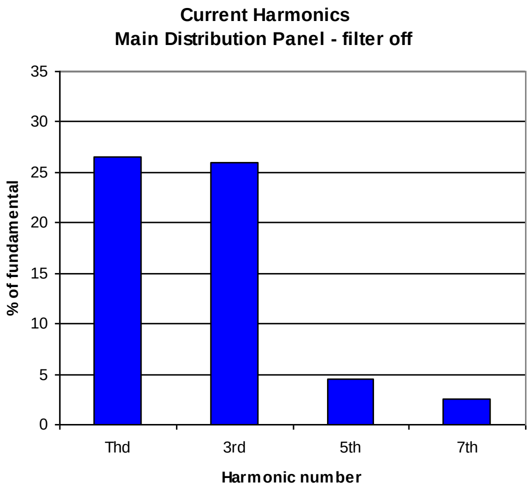
N.B. All high pressure sodium SONT+ lamps

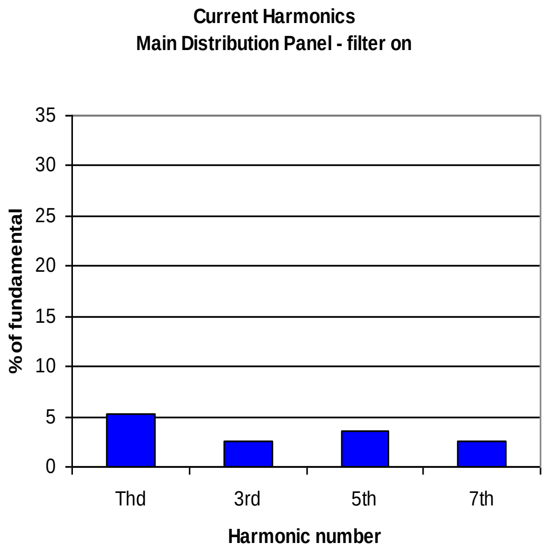
Table 29 – 600W lamp spectral output

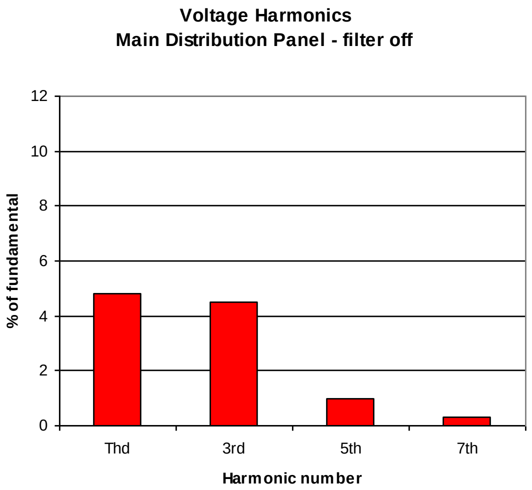
Lamp	**Output in this wavelength band as a percentage of the total PAR watts output**																	
	Violet 400-435nm			Blue 440-495nm			Green 500-565nm			Yellow 570-590nm			Orange 595-625nm			Red 630-700nm		
	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%	Test	Man.	%
Philips SONT+	1.3	1.2	108	3.8	3.1	123	13.0	10.8	120	30.9	33.4	93	36.3	37.5	97	14.9	14.2	105
GE Lucalox HO ballast 1	1.1	1.0	110	3.2	2.8	114	14.6	13.1	111	28.6	29.1	98	36.2	35.0	103	16.4	19.0	86
GE Lucalox HO ballast 2	1.1	1.0	110	3.4	2.8	121	15.3	13.1	117	26.9	29.1	92	35.8	35.0	102	17.6	19.0	93
Osram NAVT Super																		
Sylvania Grolux																		
Osram Planta		1.5			3.6			10.4			34.8			37.6			12.1	

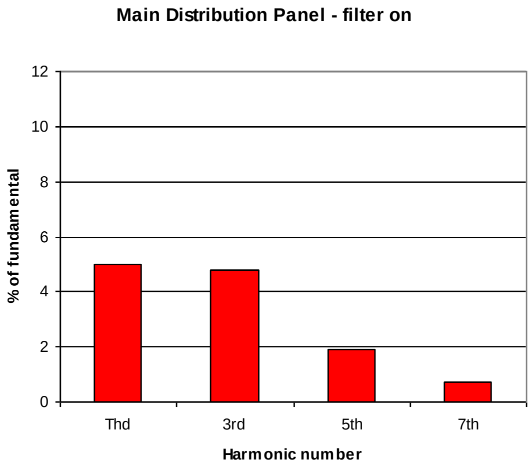
N.B. All high pressure sodium SONT+ lamps

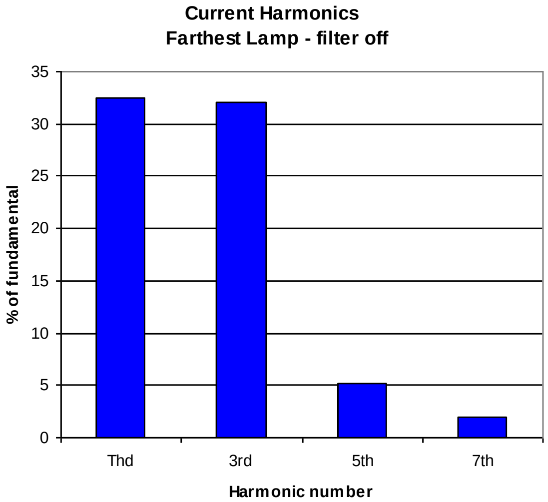
Appendix 2 Harmonic Current and Voltage Measurements

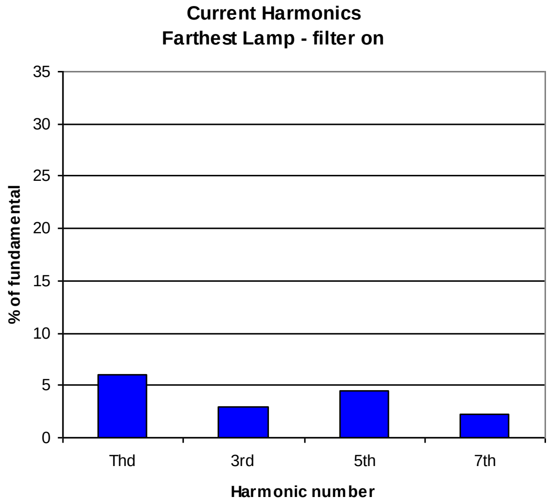


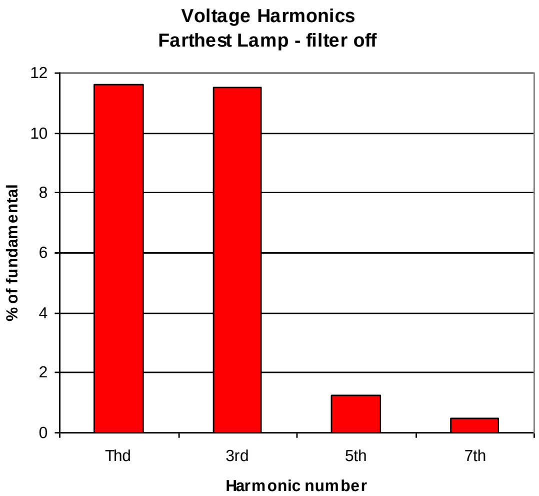


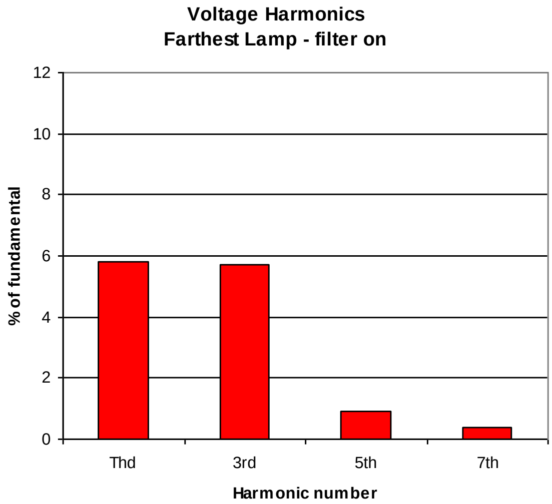





Current Harmonics
Farthest Lamp - filter off
% of fundamental
Harmonic number
Thd
3rd
5th
7th
0
5
10
15
20
25
30
35


Current Harmonics
Farthest Lamp - filter on
% of fundamental
Harmonic number
Thd
3rd
5th
7th
0
5
10
15
20
25
30
35


Voltage Harmonics
Farthest Lamp - filter off
% of fundamental
Harmonic number
Thd
3rd
5th
7th
0
2
4
6
8
10
12


Voltage Harmonics
Farthest Lamp - filter on
% of fundamental
Harmonic number
Thd
3rd
5th
7th
0
2
4
6
8
10
12