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PRINCIPLES OF LIGHT ENERGY MANAGEMENT

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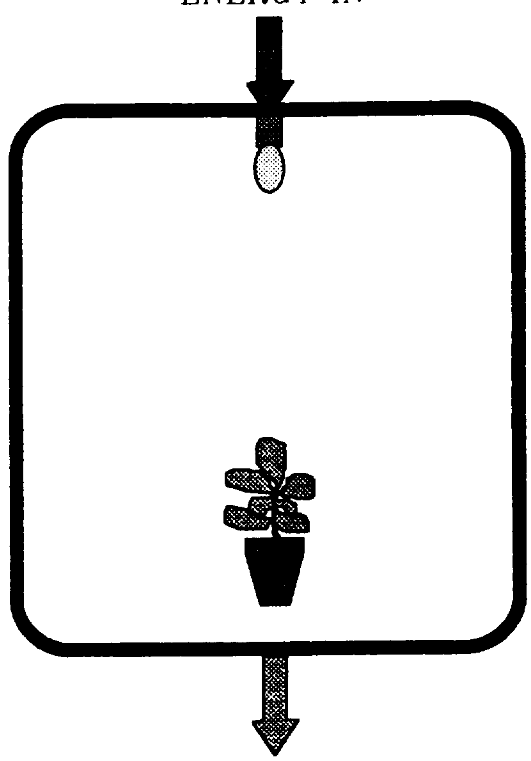
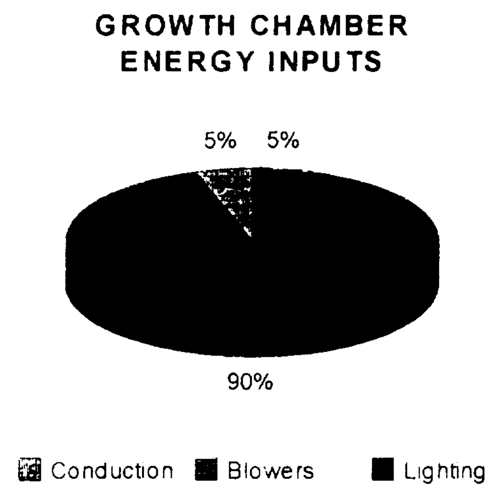
This paper presents a review of several methods of minimizing the effects of the excess energy associated with lighting systems for plant growth.



BASIC GROWTH CHAMBER

In these considerations the growth chamber is defined as an enclosure in which temperature, humidity and light can be maintained at one or more desired levels, an envelope in which the energy that goes in must come out. Some of the effects of the lighting energy on chamber and light source performance are identified and illustrated. Six methods of dealing with the lighting energy are reviewed.

Of all of the energy relations within a growth chamber those which are related to the lighting are dominant. The energy associated with wall transmission and chamber operating equipment are not considered. Experimental requirements such as fresh air and internal equipment are not considered. Only the energy associated with providing and removing the energy for lighting is considered.

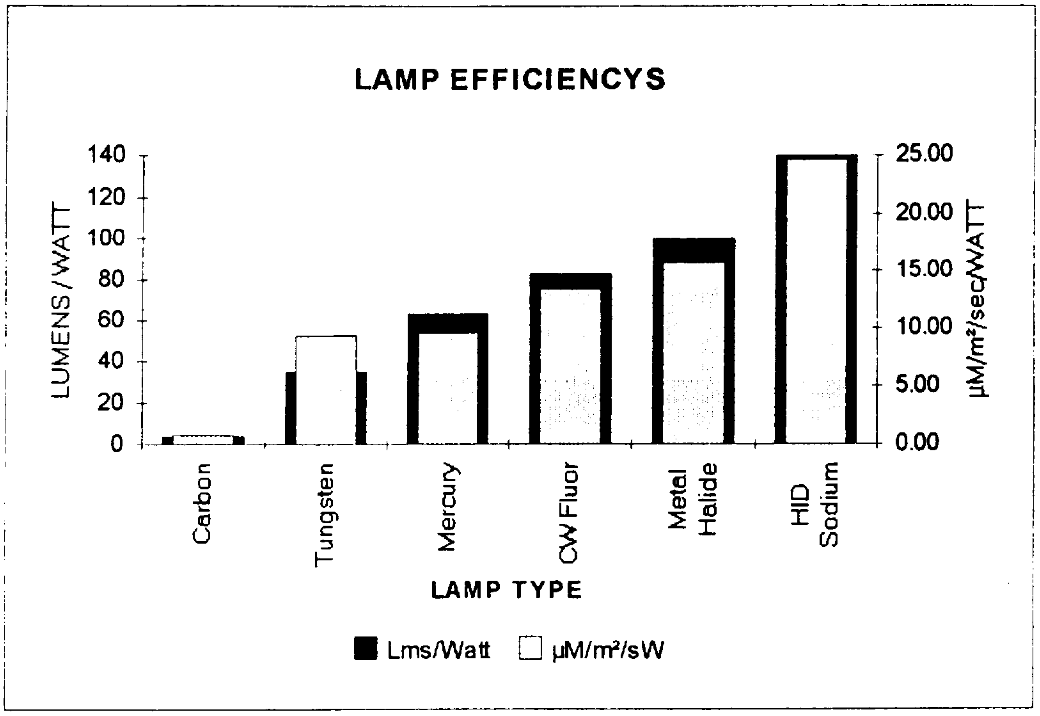


To provide radiation at any chosen level two separate factors must be considered. They are the means chosen to provide the radiation and the means chosen to remove the unwanted energy associated with that radiation. The energy associated with the delivery of the desired conditions must be balanced with the removal of the excess energy involved.

In all growth chambers energy gains and losses occur at varying levels at all times. It is desirable to maintain the closest possible desired conditions with the minimum of control and energy. The less energy required to maintain the controlled environment the more easily it is controlled. The more easily it is controlled the more evenly it will perform. The more evenly it performs the less control cycle is imposed on the mean conditions. The less control cycle the less maintenance it will require. The less maintenance it requires the longer it will meet its specifications.

Several controllable variables are available for obtaining the required radiation which if optimized can substantially lower the total energy required to obtain the necessary radiation and operate the chamber.

All lamps are not created equal. All lamps convert a portion of the energy they consume into radiation between the 400 and 700 nanometer wavelengths. This radiation varies between 10 and 40% of the total energy applied. Radiation between these wavelengths is measured in foot-candles for purposes of vision and in moles of quanta per meter² per second for plant growth. The following chart shows the relationship between a number of commercially available light sources.

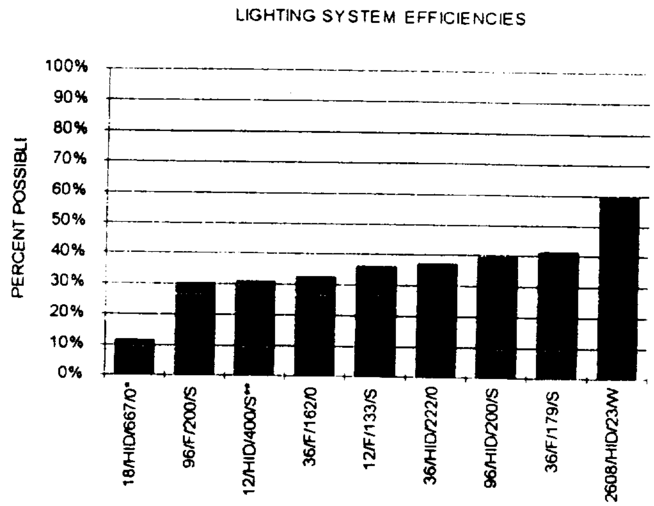


By choice of lamp type it is possible to reduce the input energy significantly for the same radiation. This choice must be consistent with the light quality that is necessary for the research objectives.

Also consistent with the objective of minimizing the energy required to provide the necessary radiation for plant growth, is the consideration of the system used to deliver the radiation from the source to the plants. Measurements of growth chambers with different light delivery systems show efficiencies varying from 30% to 60%. This efficiency is the ratio of the radiation measured at the growing surface to the manufacturer's rating of the radiation emanating from a standard lamp.

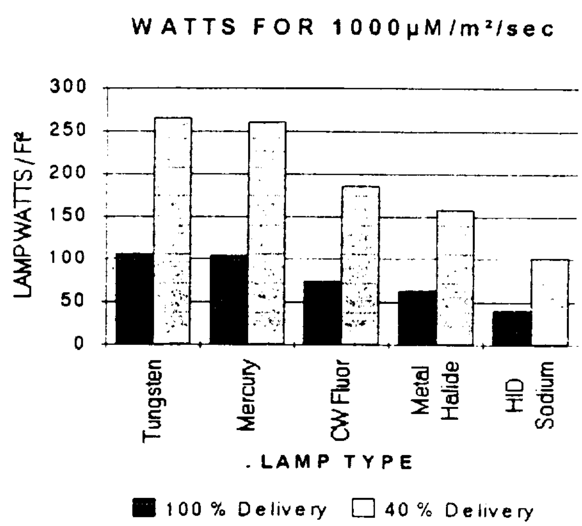
Selecting the most efficient light delivery system can reduce the required energy input by as much as 50%.

Combining the information in the two previous charts the input energy required to deliver an equal amount of radiation to a growing surface may be calculated for two different delivery systems. The systems selected are the ideal, or 100% of the source radiation and 40%, the high end of the range of most currently available growth chambers.



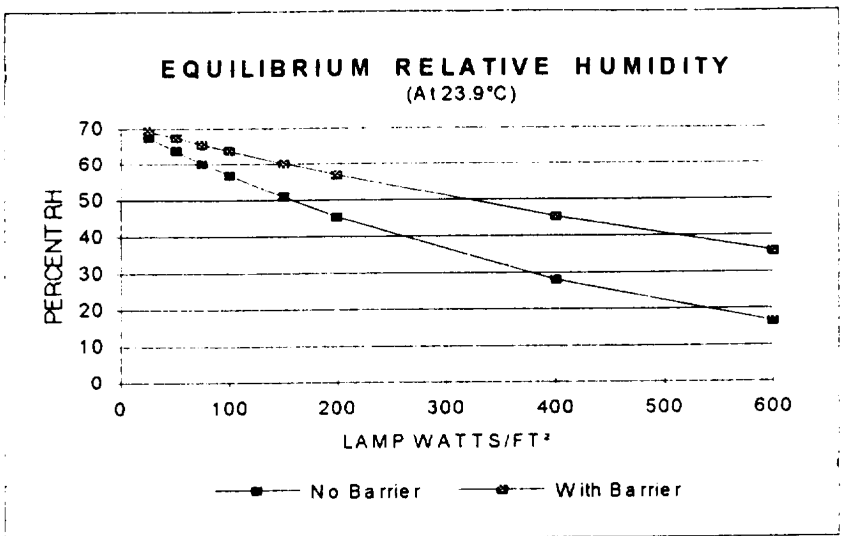
The indicated **Chamber Code** for the nine different growth chambers and rooms is as follows: Area (ft^2)/Light Type (Fluorescent or HID)/ Watts Ft^{-2}/Barrier Type. The Barrier Type is 0 (none); S (single); W (water)

* > 1500 μmol $m^{-2}s^{-1}$ **> 700 μmol $m^{-2}s^{-1}$.



Before choosing which method to use to remove the unwanted heat of lighting the effects of two interactions should be understood. First the effect on the system's equilibrium relative humidity which is dependent on the amount of energy that must be removed by the primary environmental control system and second the effect on the light output of the source which is dependent on the rate heat transfer from the lamps and their resulting operating temperature.

The equilibrium relative humidity of the system, is defined as that maximum relative humidity that would be maintained indefinitely in the system without the addition of moisture. This is established by the coldest part of the system which is in contact with the system air and becomes the controlling dew point. This temperature in turn is dependent on the amount of heat removal that is necessary by the primary environmental control system. The less lamp heat to be removed the less depression of the equilibrium dew point.

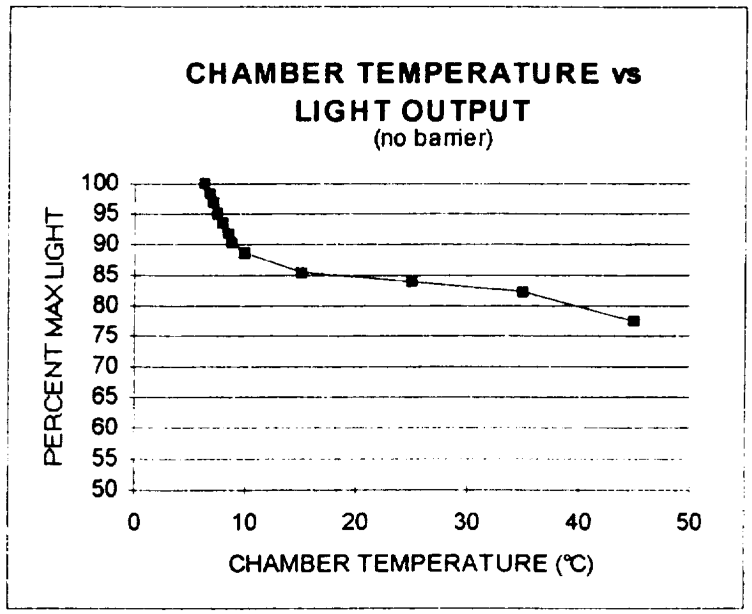


While the natural dew point, or minimum coil temperature, is primarily dependent on the amount of heat to be removed, it can be influenced by the rate at which chamber air is circulated over the cooling surfaces. In general practice commercial growth chambers have air moving at volumes per square foot between 30 and 60 cubic feet per minute. The preceding chart is based on an air flow of 50 cubic feet per minute. A simple, single layer barrier is considered providing a generic heat load reduction of 50%. The calculations for this chart assume chamber temperature of 23.9 C, a constant temperature cooling surface and a 5.5 C change in air temperature across the cooling coil. Loads not considered but capable of influencing dew point depression include heat gain from ambient, heat loads from equipment, fresh air heat and moisture loads and the temperature cycle of the cooling surfaces associated with control systems.

The range of lamp loads is taken from chambers built and operated over a period of years. The PhytoFarm in DeKalb, Illinois operated for 12 years with a light load of 23 watts/ft², the walk-in chambers designed in 1961 for the Cornell University Bio Climatic Laboratory project provided 200 watts/ft² and newer chambers reaching for ever higher light intensities have exceeded 600 watts/ft².

As can be seen from the chart the effect on humidifying requirements increases rapidly as the lamp wattage increases in response to the need for higher light intensities.

Another consideration of the energy management in a growth chamber relates to the temperature effect of the lamp environment on the lamp's output. The following chart illustrates this effect on closely spaced 1500 milliamp fluorescent lamps.

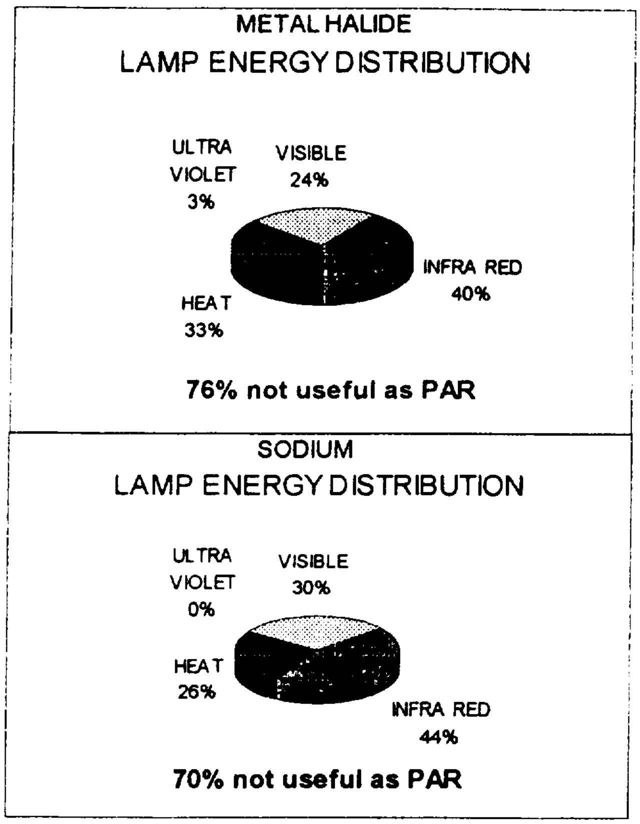


For this chart a 36 ft² growth chamber was operated with full lights. The initial temperature was 45 C. The temperature was reduced in steps while the light intensity was recorded. At lamp environment temperatures greater than 15 C the lamps are operating at 15 to 23% less than their optimum capability. The optimum lamp environment is seldom the temperature required for the experiment. This temperature light relationship in growth chambers was recognized and described in the early work on plant growth chamber development at Cornell University in 1958. More detailed information is available in US Patent Numbers No's. 3,393,728, Davis, N, 1968 and 3,604,500, Davis, N, 1971.

To reduce unnecessary humidification, maximize the light source efficiency and minimize the energy required for lighting and chamber operation it is important to manage the energy balances within a growth chamber.

After minimizing the input energy by selecting the most efficient light source and the most efficient delivery system appropriate for the application, the issue of minimizing the heating effect of the light energy on the growth chamber conditions may be addressed. In general 70% of the energy supplied to the lamps does not produce any Photosynthetically Active Radiation but impacts on heat removal requirements, dew point depression and lamp performance.

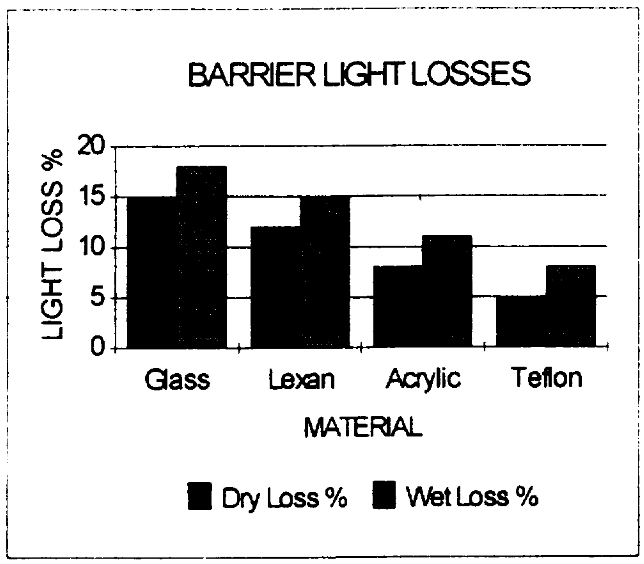
Using High Intensity Discharge, Metal Halide and Sodium lamps rated for 400 watts the energy available for removal can be illustrated.



With two of the most common light sources for supplying high light intensities in plant growth chambers all but 24 to 30% of the lamps wattage could be removed with out loss of light. Some of this light will be lost in barriers. Heat recovery, at best, has only 70% of the lamps wattage that can be recovered. Most secondary cooling systems can prevent up to 75% of this energy from entering the growing area. Temperature controlled, water filtered systems can prevent up to 90% from entering the growing area.
The methods for removal of this heat fall into two classifications. It may be absorbed into the primary environmental control system or it may be separated, to varying degrees, from the

primary system and removed by a secondary removal system. This secondary system may employ direct expansion refrigeration, cool water or air as a heat rejection medium.

Secondary heat removal systems use some form of light transmitting barrier to isolate the lamp environment from the growing environment. The choice of barrier material from a thermal separation concern is less important than the effect on light loss and spectral altering that may occur with some materials. The following chart illustrates the light loss of several materials suitable for use in growth chambers. When used in conjunction with a film of water the increase in heat recovery exceeds the loss in light.

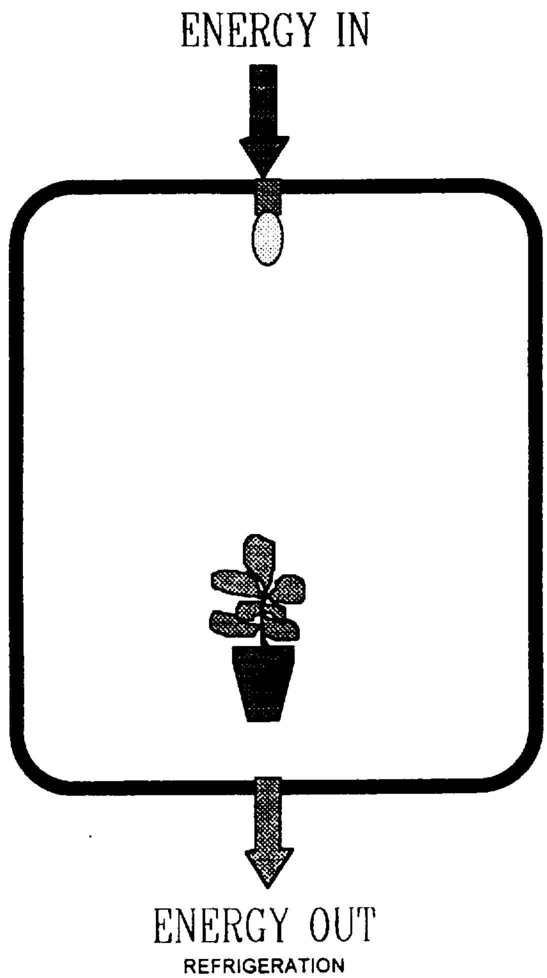


The following pages describe several methods for separating and collecting the unwanted heat in preparation for its removal by the secondary system.

NOTE:

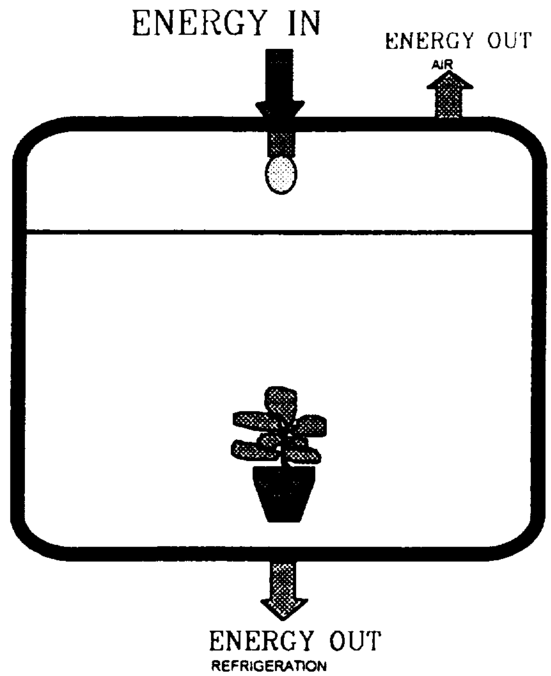
This paper is intended as a check list when considering light associated heat management in controlled environments. Before applying any of the described methods a careful analysis or consultation with an experienced source should be completed.

DIRECT ABSORPTION INTO THE PRIMARY COOLING SYSTEM



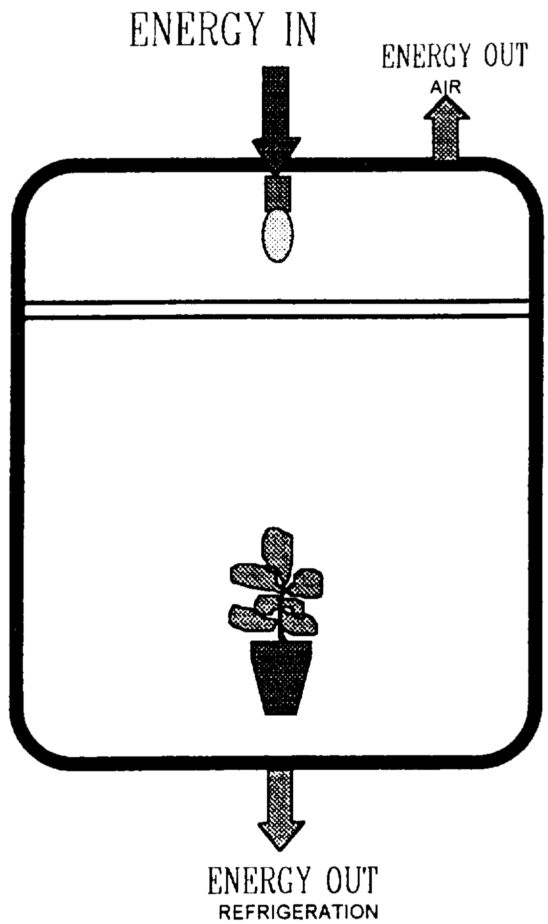
This system represents the base from which all energy management programs derive. The primary heat removal system is defined as that system which provides control of the environment in which the plants are located. In this case it must provide control of the growing environment while removing the full input energy of the lighting system. Even with the best choice of light sources and light delivery systems this system requires the most energy removal and the most humidificaton of all of the systems considered. It also represents the most temperature dependent lighting system in chambers which have variable lighted temperatures. This is the least complex, least flexible and the least efficient of the approaches considered for providing a controlled environment for plant growth.

ABSORPTION INTO A SECONDARY COOLING SYSTEM



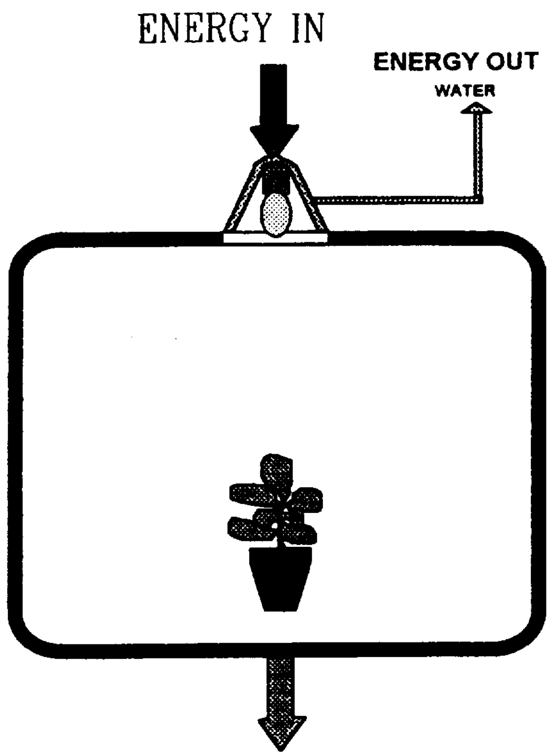
In systems utilizing a secondary cooling system for growth chamber heat removal some form of isolation of the lamps from the growing area is required. The earliest and still the most widely used is a single transparent membrane separating the lamp area from the growing area. This membrane is most frequently an acrylic plastic, obtainable as either Ultra Violet transmitting or Ultra Violet absorbing. It is described by its manufacturer as 'optically pure' and has the same transmission losses, 8%, in all thicknesses up to 1 full inch. It's losses are surface phenomena of 4% per surface. The early uses of this type of system employed a flow of outside air through the lamp area to remove the heat generated by the lamps. These systems, while reducing the cooling load on the growing area, were plagued with maintenance problems. Even good filters could not keep dust and bugs from littering the top surface of the membrane. They also suffered from a lack of temperature control as the seasons changed. An improved system was developed and described in the Cornell work. A closed system with recirculating air and separate cooling coils provided a temperature controlled, dust free method of removing the heat from the lamp area Light intensity and chamber temperature were more independent variables. As much as 50% of the lamp energy can be removed from the growing area. With the critical temperature for fluorescent lamps being higher than the cooling water available from most cooling towers it is possible to remove this heat without the requirement for more refrigeration. More detailed information on this method is available in US. Patent Number 3,393,728, Davis, N, 1968.

IMPROVED ABSORPTION INTO A SECONDARY COOLING SYSTEM



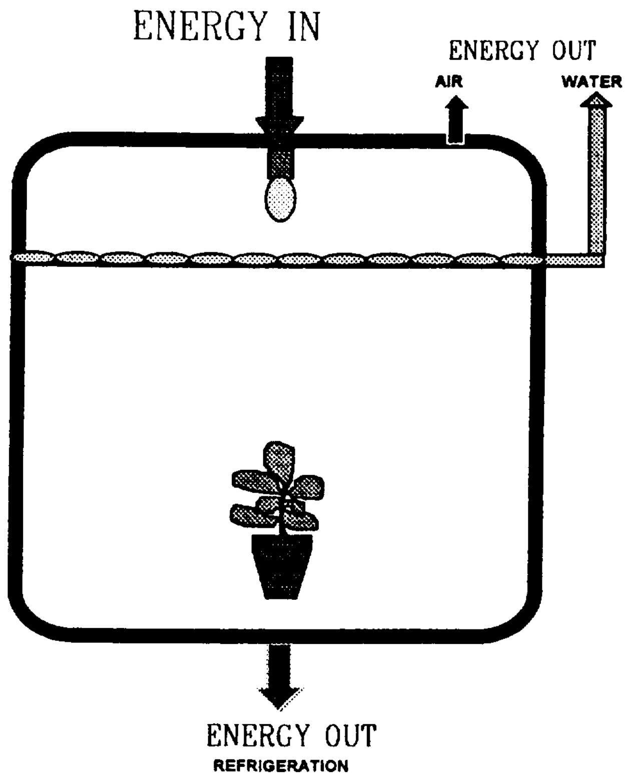
As growth chamber temperature requirements became lower and relative humidity requirements became higher the need for better isolation between the lamps and the growing area became more important. At low temperatures, where refrigeration efficiencies are declining, any lessening of the heat load is important. When the lights were off at high relative humidities and high temperatures it was possible to get condensation on the underside of a single barrier while at low chamber temperatures and high ambient humidities it was possible to get condensation on the top surface of the barrier. A double barrier reduces this tendency. By assuring a highly reflective housing for the lamp area surface reflection losses are minimized. This system is applicable for chambers requiring extreme conditions. More detailed information is available in US. Patent No. 3,447,595, Davis, N, 1969.

ABSORPTION INTO A WATER JACKETED REFLECTOR

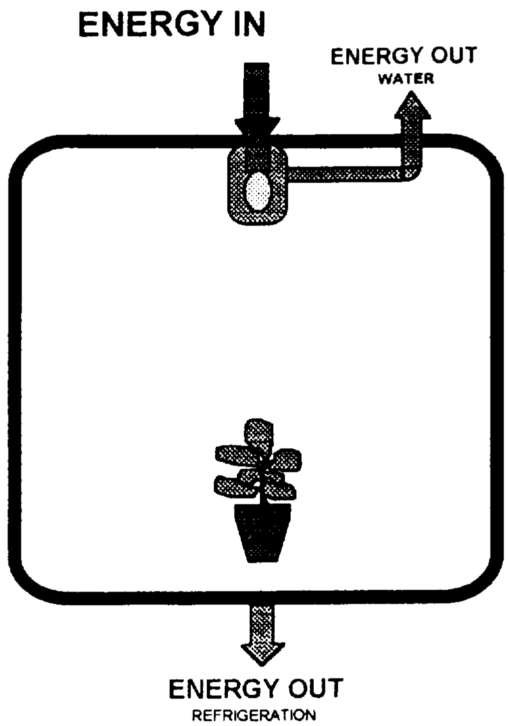


It is possible to remove a portion of the heat associated with lamps by enclosing them in a water cooled reflector. In this system a special porcelain is selected which will provide good reflection of radiation between 400 and 700 nanometers and transmit infrared radiation. This material is bonded with a good thermal joint to a backing that can be cooled by flowing water. The whole assembly is well insulated to maximize the amount of heat that can be collected by the water and minimize the heat load on the environment. The fixture can be operated with or without a barrier. Water temperatures can be extracted up to 220 F, depending on the flow rate and entering temperature of the input water. As much as 50% of the lamp wattage can be collected in the water depending on flow and input temperature. These fixtures have been made to accommodate two 400 watt HID lamps, one Metal Halide and one Sodium, in order to provide a blended light output. Water at cooling tower temperatures can be utilized, but careful filtering must be provided to prevent obstruction to the small diameter water passages in the cooling element. A closed water system for the fixtures is desirable. Fixtures of this type have been used for greenhouses, converting coolers and on growth chambers. More detailed information is available in US. Patent 3,869,605, Davis, N, 1975.

ABSORPTION INTO A PLANAR, FILTERING, SECONDARY COOLING SYSTEM



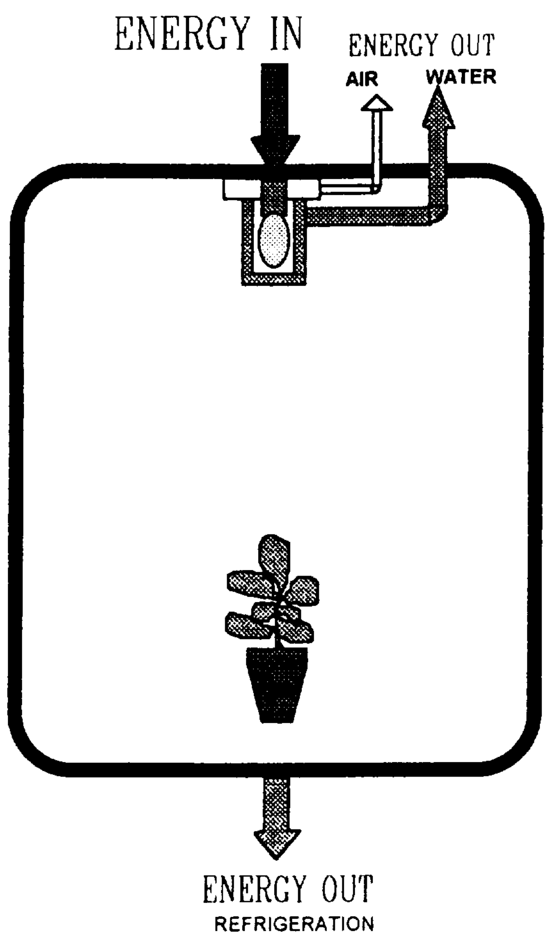
A flooded barrier adds the reduction of infrared radiation to the separation of the lamp heat from the primary growing area. An advantage of this system lies in the ability to control the water temperature and bring the barrier to the chamber temperature thus completely eliminating any thermal exchange between the two areas. This enables the highest relative humidities. It also requires special consideration to achieve equilibrium dew points more than a few degrees less than air temperature. The flooded barrier is a combination system requiring both a water cooling method and an air cooling method Both water and air systems require stringent filtering to prevent contamination of the barrier and loss of light. While the system offers some performance advantages, it requires particular consideration of the support of the barrier, the leak sealing of the barrier to the chamber and any chemical interactions between the cooling water and any system components. It is not recommended where chamber temperatures go below freezing. Flooded barriers are most applicable for smaller areas where structural support and maintenance can be are readily accomplished. Light transmission is a function of the barrier material, the depth of the water, any induced turbulence on the water surface and the clarity of the water.



A water jacketed lamp provides the heat collection advantages of the flooded barrier without some of the disadvantages. Using a closed water circuit and no secondary air the jacketed lamp reduces maintenance of the water and the barrier. Heat collection is consistently greater than 50% of the lamp wattage. The lamp water is presently restricted to temperatures between 37 C, the upper limit for algae growth, and 60 C, the lower limit for PVC pipe softening. Metal ions in the water will deposit on the lamp surface and require occasional cleaning. De-ionized water is recommended for contact with the lamp surfaces. Stainless steel heat exchangers and pumps are required. Heat can be collected at temperatures up to 55 C.

Lamps operating submerged in water have greater heat transfer than when operated in air. Lamps operating under these cooler conditions do not develop their full wattage or light output. Wattage and light output are reduced by 10 to 20%. With appropriate ballasts the wattage and light output can be returned to standard. Operations at reduced levels result in operating lives approaching 50,000 hours. Both Metal Halide and Sodium H.I.D. lamps can be operated in these fixtures. 1000 watt Metal Halide lamps require special construction. These fixtures can be operated in large areas without sacrifice of their heat control and recovery capabilities. More information is available in US Patent No. 4,1996,544, Davis, N.B. et al. 1980.

ABSORPTION INTO COMBINED SECONDARY COOLING SYSTEMS



A combination of air and water cooling of individual lamps represents the best of both systems. The lamps running in air will develop full wattage with no additional circuitry. The water jacket, separated from the lamp, can be operated with controls set to match chamber temperature when desired and eliminate any heat transfer between the lamps and the growing area. With the lamps insulated from the water algaecides can be used to allow water temperatures lower than the algae growth upper limit. The need for de ionized water is reduced or eliminated. With widely spaced fixtures the effect on dew point is minimized. This arrangement is suitable for large area illumination. The fixtures can be suspended from the structure internally or they can be dropped through holes in a solid ceiling. All connections can be made outside of the chamber. Maintenance and lamp replacement are minimized. More detailed information is available in US. Patent No's 3,624,380, Davis, N, 1971 and 3,777,199, Davis, N, 1973