American Society of Agricultural and Biological Engineers

ASABE is a professional and technical organization, of members worldwide, who are dedicated to advancement of engineering applicable to agricultural, food, and biological systems. ASABE Standards are consensus documents developed and adopted by the American Society of Agricultural and Biological Engineers to meet standardization needs within the scope of the Society; principally agricultural field equipment, farmstead equipment, structures, soil and water resource management, turf and landscape equipment, forest engineering, food and process engineering, electric power applications, plant and animal environment, and waste management.

NOTE: ASABE Standards, Engineering Practices, and Data are informational and advisory only. Their use by anyone engaged in industry or trade is entirely voluntary. The ASABE assumes no responsibility for results attributable to the application of ASABE Standards, Engineering Practices, and Data. Conformity does not ensure compliance with applicable ordinances, laws and regulations. Prospective users are responsible for protecting themselves against liability for infringement of patents.

ASABE Standards, Engineering Practices, and Data initially approved prior to the society name change in July of 2005 are designated as "ASAE", regardless of the revision approval date. Newly developed Standards, Engineering Practices and Data approved after July of 2005 are designated as "ASABE".

Standards designated as "ANSI" are American National Standards as are all ISO adoptions published by ASABE. Adoption as an American National Standard requires verification by ANSI that the requirements for due process, consensus, and other criteria for approval have been met by ASABE.

Consensus is established when, in the judgment of the ANSI Board of Standards Review, substantial agreement has been reached by directly and materially affected interests. Substantial agreement means much more than a simple majority, but not necessarily unanimity. Consensus requires that all views and objections be considered, and that a concerted effort be made toward their resolution.

CAUTION NOTICE: ASABE and ANSI standards may be revised or withdrawn at any time. Additionally, procedures of ASABE require that action be taken periodically to reaffirm, revise, or withdraw each standard.

Copyright American Society of Agricultural and Biological Engineers. All rights reserved.

ASABE, 2950 Niles Road, St. Joseph, MI 49085-9659, USA, phone 269-429-0300, fax 269-429-3852, hq@asabe.org
Lighting Systems for Agricultural Facilities

This Engineering Practice combines and therefore supersedes ASAE R286, Lighting for Dairy Farms, and ASAE R332, Poultry Industry Lighting, developed by the joint Illuminating Engineering Society—ASAE Farm Lighting Committee, EPP-46. R286 was adopted by ASAE June 1965; R332 was adopted by ASAE December 1969. This document was approved by the ASAE Electric Power and Processing Division Standards Committee and adopted by ASAE as ASAE Recommendation R344 February 1971; revised editorially and reclassified as an Engineering Practice December 1975; reconfirned December 1980; revised March 1982; reconfirmed July 1986, December 1987; revised July 1988; reaffirmed December 1993, December 1998; December 1999; revised editorially March 2000; revised January 2005; reaffirmed January 2010; revised January 2014.

Keywords: Facilities, Lighting

1 Purpose and Scope

1.1 This Engineering Practice is intended to guide those responsible for or concerned with the design of lighting installations on or within agricultural facilities.

1.2 This Engineering Practice applies to the effective performance of workers as they accomplish specific tasks requiring various levels of illuminance and it applies to lighting installations used to change the physiological or biological properties of livestock, birds, fish and plants to alter their production capabilities.

1.3 The lighting recommendations are based on information obtained from search of current literature, from people and organizations active in this field, and from field measurements of lighting requirements for difficult seeing tasks. This document is in accordance with the latest knowledge and practice of the lighting field, and conforms to all official IESNA reports. However, future progress in agriculture and lighting will undoubtedly make revisions desirable.

1.4 Lighting systems must be installed safely. In all cases, the National Electrical Code and Building Codes, plus local codes, will take precedence. This document is primarily for effective, efficient production in agriculture.

2 Definitions

2.1 diffuser: A device used to redirect the illumination by the process of diffuse transmission.

2.2 candela: The SI unit of luminous intensity. One candela is one lumen per steradian. Formerly known as Candle. For more information on this term, see the IESNA Lighting Handbook Reference Volume.

2.3 footcandle (fc): The unit of illuminance when the foot is the unit of length. It is the illuminance on a surface one square foot in area on which is uniformly distributed a flux of one lumen. It equals one lumen per square foot.

2.4 general lighting: Lighting designed to provide a uniform level of illuminance throughout the area involved.

2.5 glare: The effect of brightness or brightness differences within the visual field sufficiently high to cause annoyance, discomfort, or loss in visual performance.
2.6 illuminance: The density of the luminous flux incident on a surface; it is the quotient of the luminous flux by the area of the surface when the latter is uniformly illuminated.

2.7 local lighting: Illuminance provided over a relatively small area or confined space without any surrounding general lighting.

2.8 louver: A series of baffles used to shield a source from direct view at certain angles or to absorb unwanted light.

2.9 lumen (lm): The unit of the time rate of flow of light (luminous energy) equal to the energy emitted through a unit solid angle (one steradian) from a uniform point source of one candela.

2.10 luminaire: A complete lighting unit consisting of a lamp or lamps together with the parts designed to distribute the light, to position and protect the lamps, and to connect the lamps to the power supply.

2.11 lux (lx): The unit of illuminance when the meter is the unit of length. It is the illuminance on a surface one square meter in area on which is uniformly distributed a flux of one lumen. It equals one lumen per square meter.

2.12 Photosynthetically Active Radiation (PAR): the equivalent of illuminance when lighting for plant growth, equal to the number of micromoles of photons in the 400–700 nm wavelength range reaching a 1 m² target per second (μmol m⁻² s⁻¹)

2.13 reflector: A device used to redirect the light from a source primarily by the process of reflection.

2.14 refractor: A device used to redirect the illuminance primarily by the process of refraction. (The bending of a ray of light as it passes obliquely from one medium to another in which its velocity is different.)

2.15 shielding angle (of a luminaire): The angle between a horizontal line through the light center and the line of sight at which the base source first becomes visible.

2.16 supplemental lighting: Lighting used to provide a specific amount or quality of illuminance which cannot be readily obtained by the general lighting system, and which supplements the general lighting system.

2.17 visual task: Conventionally designates those details and objects that must be seen for the performance of a given activity, and includes the immediate background of the details or objects.

2.18 work plane: The plane at which work is done, and on which, illuminance is specified and measured. Unless otherwise indicated, this is assumed to be a horizontal plane 0.75 m (2.5 ft) above the floor.

3 References

Agriculture and Agrifood Canada. 1993. Recommended Code of Practice for the Care and Handling of Farm Animals. Ottawa, ON.

Albrecht, J. 1996. Personal Communication on Lighting Needs for Swine. Professor and Extension Swine Specialist, Department of Animal and Veterinary Sciences, Clemson University, Florence, SC.


Hudson, L. 1996. Personal Communication on Effects of Photoperiod on Estrus in Brood mares and Sperm Production in the Stallion. Professor and Extension Equine Specialist, Department of Animal and Veterinary Sciences, Clemson University, Clemson SC.


Skewes, P. 1996. Personal Communication on Lighting Programs Used for Broiler and Egg Production. Professor and Extension Poultry Specialist. Department of Poultry Science, Clemson University, Clemson SC.
4 Introduction

4.1 Lighting equipment

4.1.1 Lamps. Light sources available for agriculture lighting applications include incandescent, fluorescent, low pressure sodium and high intensity discharge (HID). HID sources include mercury, metal halide and high-pressure sodium lamps. HID lamps are more efficient, have longer rated lives, and generate 2 to 5 times more light than the incandescent filament for the same amount of electrical energy. Refer to IESNA Lighting Handbook, Part II Lighting Engineering, Chapter 6 Light Sources.

Incandescent Lamps. These lamps come in a variety of types and sizes. They are a high brightness source and should be used in appropriate luminaire to minimize glare. No auxiliary electrical equipment is required. These lamps can be dimmed.

Fluorescent Lamps. These lamps provide a large light source. Even though surface brightness is relatively low, fluorescent lamps should always be housed in a suitable luminaire to minimize glare. In high humidity environments or areas subject to wash down, gasketed or weatherproof housings are required to prevent corrosion and premature failure of the light system. Fluorescent lamps are available in different sizes, types, and colors, which can provide good color rendering, cool or warm colors. Light output is highly dependent on operating temperature.

At very high or extremely low ambient temperatures, light output drops. Cold start or low temperature starting ballasts along with an enclosure to maintain to temperature should be used in cold areas. Refer to IESNA Lighting Handbook, Part II Lighting Engineering, Chapter 6 Light Sources.

High Intensity Discharge Lamps. HID lamps are used both outdoors and indoors. Ballasts are required for their operation. HID lamps differ in their color rendering ability, generally being lower than fluorescent or incandescent lamps. These lamps are not suited to applications where lights operate intermittently for a short duration due to their slow warm up time.

Light Emitting Diodes. LED lamps are relatively new to the lighting market, and can provide either colored or white light at efficacies exceeding those of incandescent lamps. As they are an emerging technology, their performance characteristics continue to develop.

4.1.2 Luminaires. Light is emitted from most lamps in many directions. A luminaire is designed to control the direction at which light is emitted so glare will be reduced and light directed more effectively on the objects to be seen. In most cases, luminaires should direct light downward to minimize losses. In some applications, it is desirable to have a portion of the light directed toward the ceiling. Some of the light striking a light-colored ceiling is reflected back to the visual tasks.

Luminaires control light distribution with reflectors (enamel, aluminum, glass, or plastic), refractors (glass or plastic diffusing lenses), or diffusers (glass or plastic diffusing shields). One or more of these devices might be used in the same luminaire. Reflectors and refractors direct light for more efficient utilization. Reflectors, refractors, and diffusing shields prevent glare. Refer to IESNA Lighting Handbook, Part II Lighting Engineering, Chapter 6 Light Sources.

A luminaire prevents water from striking hot lamps when used in damp locations, outdoor areas or areas which are washed. Weatherproof or gasketed housings are available for lamps used in humid environments, areas where water spray is a problem or when lamps are exposed to the weather.

4.1.3 Controls. Electric lighting systems in agricultural applications can be controlled electronically. There are several reasons for equipping a lighting system with an electronic control.

- Visual and Production Performance: match light intensity to the application. Occupant visual performance may depend on the quantity and quality of the light; for example, visually inspecting livestock for health or produce for quality purposes is a demanding visual task. The application may be specific to the reproductive, growth or behavioral needs of the plant or livestock.
- Energy Management: matches light application to demand; thereby, reducing unnecessary energy, time of use and/or demand charges.
A wide variety of controls are used in agricultural operations depending on the application. These controls include switches, dimmers, photosensors, occupancy sensors, and timers. The information provided in this section comes from IESNA Lighting Handbook, Part V Special Topics, Chapter 27 Lighting Controls. For details on any of the areas discussed, please refer to the Handbook.

**Switching.** Switching control allows lights to be switched on and off manually with simple wall-box switches, or remotely with relays, switchable circuit breakers, a control system, or occupancy sensors. The choice of switching control will depend on the application. Local manual switching controls give control over light levels according to their needs or the task are inexpensive.

Central switching controls are well suited to scheduled activities such as occupation of a space during prescribed hours of the day and week. Control systems are ideal for applications with multiple zones and changing lighting requirements over time. Greenhouse operations, for example, employ lighting control systems to match light requirements to the crop being grown in a particular zone.

Occupancy or motion sensors are used in applications where lights are required only during occupancy of a space. These sensors are ideally suited to walkways, hallways, entrances to buildings, or to spaces where the user's hands are not free to activate a switch.

**Dimming.** Dimming control allows the illuminance in an area to be adjusted smoothly and continuously to meet the lighting requirements of the occupants. Dimming systems are employed in the poultry industry for example to control daily light levels and light levels during the growout period of a crop of broiler chickens for instance.

Most incandescent lamp dimmers currently rely on solid-state switching components. These components can generate electromagnetic and audible noise as well as harmonic distortion, which requires filtering. The light output, life and color temperature of the lamp are affected by dimming. By reducing light output by 25%, lamp life triples. The lamp color appears warmer with reduced voltage.

Fluorescent lamps can be controlled with dimmers. Dimming is not as simple as reducing the input voltage, which eventually extinguishes the arc and reduces lamp life. Dimmers are available for lamps operated with standard magnetic ballasts, magnetic dimming ballasts, or electronic dimming ballasts. There are many factors affecting the reliability, stability and cost of dimming systems.

High intensity discharge lamps can be dimmed; however, the restrike delay, long warm-up, and color shift limit their use in agricultural applications. Multi-level ballasts allow illuminance to be changed in steps. Continuous dimming to less than 20% full light output is available with certain equipment. Metal halide lamps shift color toward blue-green, and high-pressure sodium to yellow. The color shifts become noticeable below 60% of rated lamp power for metal halide and 40% for high-pressure sodium lamps.

**Timing Devices.** Timers control lighting based on known or scheduled events, ideal for poultry, swine and dairy operations. They range from simple integral timers (spring-wound) to microprocessors. Microprocessors can be programmed for a sequence of events or multiple events and lighting effects for years in advance. An override is required in order to deviate from the preset schedule.

**Sensing Devices.** Sensing devices include photosensors and occupancy or motion sensors. A photosensor transforms visible radiation (light) into an electrical signal, which controls a lighting system or lamp. The photosensor generally does not respond to UV and IR radiation. Design, placement, and calibration of interior photosensors are critical to ensure high quality lighting.

Occupancy or motion sensors provide local on-off control of luminaires automatically based on the presence or absence of occupants. Energy consumption is reduced and demand may be reduced as well.

**4.1.4 Energy Efficient Lighting.** Energy efficiency varies with the type of light source. Table 1 shows the approximate efficiency of a number of light sources compared to a regular life incandescent source. Fluorescent, metal halide, and high-pressure sodium lighting systems have significantly higher first costs compared to incandescent. However, the energy cost savings combined with longer lamp life offsets the higher initial costs for energy efficient lighting systems. The energy efficient alternative will typically pay for itself in two years or less in applications where the lights are operated 8 hours per day or more (Chastain, 1992).
4.1.5 Starting Characteristics. The two starting characteristics that influence lamp selection are starting temperature and warm-up period.

Starting temperature generally is only important when selecting a lighting system for unheated spaces in cold climates, such as naturally ventilated structures. Incandescent, high-pressure sodium, and LED lamps perform well at cold temperatures (-29°C or colder). The minimum starting temperatures for standard T12 fluorescent lamps and ballasts is 10°C while T5 and T8 fluorescent lamps and ballasts is -17°C. Ballasts are available that allow fluorescent lamps to start at -29°C.

Incandescent, halogen and LED lamps do not have a warm-up period. Standard fluorescent lamps have a slight starting delay, but it is not significant in most applications. Quick starting ballasts can be purchased if required. All of the high intensity discharge lamps have a significant warm-up period. The warm-up period can range from 1 to 15 minutes.

4.1.6 Emergency Lighting. The need for emergency lighting must be evaluated during the design phase of the building. If the facility does not have an automatic start generator, emergency lighting units may be required, to illuminate the exit passageways in the building(s) in the event of a power outage. Be sure to consult federal, state, provincial and local codes that may apply. NFPA (National Fire Protection Association) 101 — The Life Safety Code can be used as a reference along with the State Fire Marshal’s Office in the State where the facility will be built. Even if not required, the Engineer designing the building must always consider how to get people out of the building(s) in the event of an emergency. Auxiliary Generators must be installed in accordance with NFPA (National Fire Protection Association) 70, the National Electrical Code, NFPA 110 Standard for Emergency and Standby Power Systems and any other federal, state, provincial and local codes that may apply. The local electrical utility also must approve any installation and the equipment used. The appropriate NFPA, federal, state, provincial and local codes must be followed with regard to the installation of fuel tanks. In some instances, fuel tanks may be located inside the building, if the appropriate codes are followed and authorities such as State Fire Marshal’s Offices are consulted. Be sure to check and see if the insurance company insuring the facility has any guidelines that must be met.

4.1.7 Codes. Many federal, state, provincial and local codes govern the use of lighting equipment. Some public health codes specify minimum illuminance levels required in processing plants, egg handling areas, milking and milk handling areas to maintain health standards. These required levels address the concern for proper sanitation and often are below those recommended for efficient performance of visual tasks. Agriculture facilities include many types of environments, which may be wet, damp, corrosive, dirty, surrounded by combustible materials, or saturated with gasoline fumes. It is mandatory to follow the National Fire Protection Association Standard No. 70, National Electrical Code, and any local regulations that may be in effect when installing lighting equipment. Contact a local electrician, electric power supplier for assistance or refer to the Agricultural Wiring Handbook published by the Rural Electricity Resource Council (US) as well as the Wiring Handbook for Rural Facilities published by the Midwest Plan Service.
4.2 Lighting System Performance Characteristics

4.2.1 Lighting Quantity

**General Comments.** “General Lighting” systems provide a uniform light level throughout a facility, and are the most common approach to designing lighting for agricultural industries. “Task Lighting” systems, on the other hand, provide light to a specific location to allow for a specific task. These systems are also used selectively in agricultural facilities — i.e. for milk tank inspection on dairy farms.

Modern agriculture facilities need a high quality work environment to optimize plant, animal and worker efficiency, and comfort. Proper lighting is an environmental factor that is often overlooked, or given little attention during the planning, construction, and maintenance of a facility. However, it is just as important as ventilation, heating, or cooling. In the case of plant growth facilities, light provides the energy input for plant growth, and in the case of animal production facilities, it can strongly influence animal comfort and physiological responses. The amount of light needed in agriculture facilities varies depending on the type of production and the tasks performed in the work area.

**Units of Measure.** Light levels for human occupied or animal facilities are generally expressed in terms of average lux (lumens m\(^{-2}\)) at the work plane. Plant lighting systems utilize units of PAR (\(\mu\text{mol m}^{-2} \text{s}^{-1}\)), which more closely matches a plant’s photosynthetic sensitivity to light. Light levels can be reported as initial (with new lamps and clean luminaires), average (over the life of the equipment), or maintained (the lowest expected light level, when considering losses due to dust accumulation and lamp aging) – this distinction should be made when reporting light levels. Unless otherwise noted, recommended light levels in this document refer to the maintained light level. This value can be calculated for a lighting system design as follows:

\[
E_{\text{maint}} = E_{\text{init}} \times BF \times LLD \times LDD \times RSDD
\]

where:

- \(E_{\text{maint}}\) = maintained light level (lux)
- \(E_{\text{init}}\) = initial light level (new lamps and clean surfaces)
- \(BF\) = ballast factor (decimal)
- \(LLD\) = lamp lumen depreciation factor (0.0 to 1.0)
- \(LDD\) = luminaire dirt depreciation factor (0.0 to 1.0)
- \(RSDD\) = room surface dirt depreciation factor (0.0 to 1.0)

**Daylighting.** Lighting can come from daylight or electrical lighting systems depending on the task and quality of light required. Daylighting is well suited to work areas where tasks can be adequately lit during the daytime, such as open feedlots, greenhouses, naturally ventilated facilities, or areas within buildings that can be illuminated by windows.

Daylight may be supplemented with electrical light for some tasks. In these cases, supplemental light might be required to maintain adequate light quality and photoperiod. Photoperiod refers to the duration of the light period. Many animals and plants require specific photoperiod (light) and scotoperiod (dark) phases for reproduction and growth. Daylight is significant in naturally ventilated, curtain-sided buildings. Winter light levels ranging from 200 lux on a cloudy day to as much as 53,000 lux on a clear day have been measured in curtain-sided dairy facilities (Chastain, et al., 1997). In these types of buildings, electrical lighting supplements the natural day length. A timer and photocell control the supplemental light system’s operation.

Use of daylight to replace or augment electrical lighting is recommended whenever practical, as it generally conserves energy if appropriately designed and operated.
4.2.2 Lighting Quality

**General Comments.** The quality of light in a work area must be considered in addition to the quantity. An installation’s light quality is influenced by the color rendering characteristics of the light source, illuminance uniformity, glare, flicker, horizontal and vertical illuminance, the environment and other factors. Maintenance of the lighting system keeps both the quality and quantity of light at acceptable levels over time.

**Color Rendering.** The color rendering capability of the light source is an important light quality factor in agricultural facilities. Certain specialized visual tasks, notably color discrimination processes and some inspection activities, depend on appropriate light source color. Color also has certain psychological effects upon people. These factors should be considered when selecting light sources to obtain quality lighting. One measure of the color of a light source is the Color Rendering Index (CRI). The CRI and other typical characteristics are presented in Table 2. Incandescent and halogen lamps provide the greatest color rendition and have a CRI of 100. A CRI of 80 or more is recommended for office, milking, washing, product inspection, plant growth and animal treatment areas. High quality fluorescent or metal halide lamps can provide an energy efficient light source when a CRI of 80 or greater is needed.

<table>
<thead>
<tr>
<th>Lamp Type</th>
<th>Lamp Power (W)</th>
<th>CRI</th>
<th>Efficacy (lm/W)</th>
<th>Typical Lamp Life (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incandescent</td>
<td>34–200</td>
<td>100</td>
<td>11–20</td>
<td>750–2,000</td>
</tr>
<tr>
<td>Halogen</td>
<td>50–150</td>
<td>100</td>
<td>18–25</td>
<td>2,000–3,000</td>
</tr>
<tr>
<td>White LED</td>
<td>1–200</td>
<td>70–90</td>
<td>50–100</td>
<td>25,000–100,000</td>
</tr>
<tr>
<td>Fluorescent</td>
<td>32–100</td>
<td>70–95</td>
<td>75–98</td>
<td>15,000–20,000</td>
</tr>
<tr>
<td>Compact fluorescent</td>
<td>5–50</td>
<td>80–90</td>
<td>50–80</td>
<td>10,000</td>
</tr>
<tr>
<td>Metal halide</td>
<td>70–1,000</td>
<td>60–80</td>
<td>60–94</td>
<td>7,500–20,000</td>
</tr>
<tr>
<td>High-pressure sodium</td>
<td>35–1,000</td>
<td>20–80</td>
<td>63–125</td>
<td>15,000–24,000</td>
</tr>
</tbody>
</table>

**Uniformity.** The uniformity of illuminance is typically expressed as a uniformity ratio (maximum measured illuminance ÷ minimum measured illuminance), or as the coefficient of variation (CV = standard deviation ÷ mean). The CV provides a normalized measure of the interval about the mean, and can be expressed in units of percentage by multiplying by 100; therefore, CV = (standard deviation / mean) × 100.

One method of designing for uniformity in a general lighting system is to lay out the luminaires such that the “spacing-to-mounting-height ratio” divided by the luminaire’s published “Spacing Criterion” (SC) value does not exceed a recommended value (often 1.0).

The location of the work plane for calculating mounting height depends on the application, and could correspond to the top of the plant canopy (in greenhouse applications) or the height of the animal’s eye (in animal lighting applications). In the absence of spacing criterion data for a luminaire, the following guidelines can be used.

<table>
<thead>
<tr>
<th>Task Classification</th>
<th>Maximum CV (%)</th>
<th>Typical s/mh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visually intensive (i.e., milking)</td>
<td>25</td>
<td>0.87</td>
</tr>
<tr>
<td>Handling of livestock and equipment</td>
<td>45</td>
<td>1.57</td>
</tr>
<tr>
<td>General low-intensity lighting</td>
<td>55</td>
<td>1.92</td>
</tr>
<tr>
<td>Greenhouse lighting, research facility</td>
<td>5</td>
<td>0.8</td>
</tr>
<tr>
<td>Greenhouse lighting commercial facility</td>
<td>10</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Note: s/mh = luminaire spacing divided by mounting height above workplane
Additional luminaires around the perimeter of the space should also be considered as a means of improving uniformity. Light sources should be located to minimize shadows cast on the work area by workers and obstructions. Objects should receive illuminance from more than one direction to minimize the density of shadows and to provide uniform illuminance.

**Glare.** Glare is any brightness within the field of vision that causes discomfort, annoyance, reduction in vision, or eye fatigue. It usually is the result of uncontrolled light emitted directly by a luminaire, or reflected from a glossy surface that is in the normal line of sight in the work area. Proper selection and mounting of the luminaires (above the line of sight), and use of reflective matte finishes on interior surfaces will greatly reduce glare. Luminaires that distribute most of their light downward (within 45 degrees of vertical) rather than laterally tend to be less prone to glare.

**Environment.** Room surfaces should have high reflectance, matte finishes to help prevent excessive glare. The ceilings, walls and floors can increase the utilization of light within a room by acting as a secondary large-area light source. Luminaires that direct some light upward toward a ceiling having a relatively high reflectance will help create a comfortable visual environment. Recommended reflectance values for general lighting systems are presented in Table 4.

Maintenance is necessary to ensure that a high quality light environment is provided. Lamps, luminaires and room surfaces in production facilities tend to become quite dirty. Regular cleaning is required to maintain illuminance levels.

### Table 4 – Recommended room surface matte reflectance values

<table>
<thead>
<tr>
<th>Surface</th>
<th>Reflectance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ceiling</td>
<td>80 to 90</td>
</tr>
<tr>
<td>Wall</td>
<td>40 to 60</td>
</tr>
<tr>
<td>Desk and bench top, equipment</td>
<td>25 to 45</td>
</tr>
<tr>
<td>Floor</td>
<td>20 minimum</td>
</tr>
</tbody>
</table>

### 5  Lighting for General Work Areas

Illuminance levels recommended for general facility work areas within buildings are presented in Table 5. The IESNA lists recommended lighting levels for general workplace lighting in offices and industrial facilities. An attempt has been made to provide a fairly comprehensive list of tasks that might be performed in agricultural facilities. In the event that a task is not listed in Table 5, please refer to IESNA Lighting Handbook, Part IV Lighting Application, Chapter 11 Office Lighting, and Chapter 19 Industrial Lighting for further information.
6 Livestock

Lighting system requirements vary with the housing and livestock type. The housing system and task will determine whether daylighting and/or supplemental lighting is required. In totally enclosed buildings, electrical lighting alone must provide the needed light quality and day length.

6.1 Dairy and Beef Cattle Facilities

High quality light at adequate levels and duration is required in facilities housing dairy and beef cattle. Based on a field study of lighting in dairy buildings, a CV of 25% or less represents a high degree of uniformity (Chastain, 1994). The coefficient of variation was found to correlate well with respect to the ratio of the average fixture spacing and mounting height above the work plane (s/Hp) (Chastain et al., 1997). The recommended uniformity criteria for livestock facilities are summarized in Table 2.

Research trials indicate that supplementing lactating cows with 16 to 18 hours of light per day increases milk production by 5 to 16% as compared to cows exposed to 13.5 hours or less of light per day (Peters, 1994; Dahl et al., 2000). The expected result of supplemental lighting for a commercial herd is a 5 lb increase in milk production coupled with a corresponding increase in feed intake. The response to supplemental lighting however is not immediate. The cows will require several weeks to adapt, and the increase in milk production precedes the increase in feed intake (Dahl et al., 2000).

In order to stimulate milk production, the lighting system must provide the following:

1) 150 lux of illuminance throughout the barn.

2) 16 to 18 hour continuous block of light. Providing illuminance for 24 hours a day does not produce a sustainable increase in milk yield, and operating the lighting system more than necessary wastes energy.

In contrast to extended light in lactating cows, recent evidence suggests that reduced photoperiod is of benefit to cows during the dry period (Miller et al., 2000). Cows that received 8 hours of light and 16 hours of darkness each day when dry produced 7 lbs more milk per day in the next lactation than contemporaries exposed to 16 hours of light per day. Furthermore, reduced photoperiod during the dry period improves immune function and health in cows as they transition into lactation relative to cows on longer photoperiods (Dahl et al., 2003).

Improved daily gains have also been observed for beef steers and dairy heifers (Peters, 1994). The lighting period needed is similar to that for lactating cows.

Recommended illuminance levels for dairy facilities are presented in Table 6.

<table>
<thead>
<tr>
<th>Work Area or Task</th>
<th>Illuminance (lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parlour, pit and near udder</td>
<td>500</td>
</tr>
<tr>
<td>Parlour, stalls and return lanes</td>
<td>200</td>
</tr>
<tr>
<td>Parlour, holding area</td>
<td>100</td>
</tr>
<tr>
<td>Milk room, general</td>
<td>200</td>
</tr>
<tr>
<td>Milk room, washing</td>
<td>750–1,000</td>
</tr>
<tr>
<td>Dairy housing and feeding area</td>
<td>250</td>
</tr>
</tbody>
</table>

Note: if daylight is available to supplement the lighting system during work hours, a lower supplementary light level of 150 lux is permissible, provided that the daylight is sufficient to augment visibility in spaces used by workers.
In addition to providing adequate levels and duration of illuminance for production, a high level of uniformity is required in the parlour pit, office, and milk room washing area. These areas require high uniformity to perform demanding visual tasks.

### 6.2 Open Lot Facilities

Important considerations in lighting beef and dairy cattle feedlots include comfort for the workers and cattle, production efficiency of the cattle, and feedlot security. Principles of selection for cattle feedlot lighting systems consist of:

A) using the lowest lamp wattage to yield acceptable lighting levels in various areas

B) selecting an efficient type of lamp/luminaire

C) providing automatic control of lighting/lamp operation

D) providing adequate lighting system maintenance.

#### 6.2.1 Feed Pen Lighting

Feedlot and dairy cattle feed pen lighting is provided for several production reasons. Feed pen lighting allows the animals to "see" where the food and water sources are as well as feel more comfortable during dark periods since cattle are inherently nervous in the dark. During high temperature periods, cattle are more likely to eat during the coolest part of the day so providing light over the food source helps maintain production. The lighting also allows workers to move about during the night and not scare or spook the animals, allowing various work activities to be performed at every hour of the day.

Lighting sources should be located over or very near feed bunks, which generally are located adjacent to the alleyways along which feed trucks move to deposit feed into the feed bunks. Common lamp types used in cattle feed pens include metal halide and high-pressure sodium, while induction and LED lighting is often suitable as well. The mounting pole height influences the lamp size, which in turn affects energy efficiency of the lamp. Lamp efficiency increases with lamp wattage and taller poles allow larger, more efficient lamps to be used. The use of taller poles, larger wattage lamps and good directional control will reduce the number of poles and luminaires required. Taller poles may cost more, but the extra expense may be offset by a reduction in the number required and energy savings from the increased lamp efficiency. Most feed yard lighting systems are operated with single-phase 120-volt service; however, higher voltage 240 and 277-volt systems can also be found. Individual photoelectric control on each light generally is used to turn individual lights on and off when light levels change. Individual photocell control allows for better continuity of service when photocells fail.

#### 6.2.2 Loading Pens and Chutes

A higher level of illuminance for worker convenience is required in loading areas and chutes where cattle may be moved, visually evaluated, and/or treated for illness. It is important to provide light from several directions in these areas so that the potential for shadows is reduced.

#### 6.2.3 Feed Mill/Office

Many larger feedlots operate the feed milling facilities at night to take advantage of lower time-of-day electricity rates. Lighting recommendations for general offices and commercial grain elevators or similar work areas and tasks will generally apply with these types of facilities.

#### 6.2.4 Recommended Lighting Levels

The Illuminating Engineering Society and ASAE have developed standards for various industries and tasks, including various components of cattle feedlots. A summary of recommended lighting levels in cattle feedlots is presented in Table 7. Good color rendition is necessary in feedlot offices, cattle sorting, feed processing, and veterinary service areas, but is not as essential in feed pens.
Table 7 – Recommended lighting levels in areas of feed yards

<table>
<thead>
<tr>
<th>Feed Yard Area or Task</th>
<th>Illuminance (lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed processing</td>
<td></td>
</tr>
<tr>
<td>Scales</td>
<td>50</td>
</tr>
<tr>
<td>Commodity receiving area</td>
<td>100</td>
</tr>
<tr>
<td>Hay and grain storage</td>
<td>50</td>
</tr>
<tr>
<td>Concentrate storage</td>
<td>100</td>
</tr>
<tr>
<td>Feed processing</td>
<td>200</td>
</tr>
<tr>
<td>Special pens and chutes</td>
<td></td>
</tr>
<tr>
<td>General</td>
<td>100</td>
</tr>
<tr>
<td>Sick animal treatment</td>
<td>500</td>
</tr>
<tr>
<td>Feed pens</td>
<td></td>
</tr>
<tr>
<td>Feed bunk area</td>
<td>10–30</td>
</tr>
<tr>
<td>Waterer area</td>
<td>2.5</td>
</tr>
<tr>
<td>Center and rear of pens</td>
<td>2.5</td>
</tr>
<tr>
<td>Security Lighting</td>
<td>2</td>
</tr>
</tbody>
</table>

6.2.5 Lighting System Maintenance. Lighting system maintenance at cattle feedlots should be performed once every three months. All automatic control equipment should be checked to ensure it is functioning properly and not leaving the lights on during daylight periods. Faulty lamps should be replaced, and dirty lamps/fixtures should be cleaned.

7 Swine Facilities

7.1 General Recommendations

Lighting plays a significant role in reproductive and overall swine production performance. The cost of electricity for lighting is a small percentage of the cost of production for swine; however, it is possible to reduce energy costs, increase lighting levels and actually improve performance with well designed, energy efficient lighting systems. A good lighting system should provide proper light levels economically with low maintenance costs.

Pigs require light for a variety of reasons, including seeing each other and finding feed and water. Pigs’ eyes, when confined, are sensitive to bright light, so point sources with poor quality diffusers and spot lights will not be a good choice. Pigs have poor color perception compared to humans and in particular a reduced sensitivity to the red end of the spectrum (Taylor, 2010). Otherwise there is little research into the effect of light color on pig production. In cases where red light has been used, pigs respond as though in darkness.

There is currently little research into pigs’ flicker sensitivity, but it is unlikely that pigs can see flicker from correctly functioning fluorescent tubes (Taylor, 2010). However, the use of electronic ballasts has eliminated fluorescent flicker.

Pig’s reproductive performance is sensitive to both heat and light photoperiod. Controlling day-length in pig units can affect reproductive behavior and success. However, lighting only plays a minor part in this subject with the real impact coming from sire line traits.

Other important effects of seasonality:

- Increasing day length (15–18 hours) increases piglet suckling.
• Increasing day length increases food intake in growers/finishers.

• Twenty-four hour light can increase stress levels and disruptive behavior can reduce productivity (especially in young pigs).

• Twenty-four hour light can increase stress levels in pigs. Bright luminance can also result in eye damage and weight loss. Aside from these issues, generally, pig behavior is affected very little by lighting factors and they are highly tolerant/adaptable to artificial lighting regimes.

All fixtures should be dust and vapor tight, U.L. listed for wet locations in an NSF approved housing with polycarbonate (or other suitable alternative) lamp enclosure.

Incandescent lighting is seen very rarely in modern facilities, with fluorescent systems providing the vast majority of light. This can be in the form of compact fluorescent (C.F.) lamp and ballast systems, which provide good energy efficiency and are easily retrofitted into incandescent fixtures.

Another option, for barns with a ceiling height of less than 3.6 m should install T-8 fluorescent lamps with matching electronic ballast or LED lamps, mounted in a weatherproof fiberglass or plastic housing with gasketed diffuser. Refer to Table 2 for relative system efficiencies and lamp life.

Where barn ceiling height exceeds 3.6 m, efficient fluorescent T5 or T8 (with multiple lamps), LED or high intensity discharge (HID) fixtures should be considered. They are easier to install, maintain and require fewer fixtures to provide the same level of light.

Ceilings and walls should be white to maximize reflectance and reduce the number of lighting fixtures required.

7.2 Light Levels and Photoperiods for Swine

Each period of production requires different light levels and photoperiods. See Table 8. The 1993 Recommended Code of Practice for the Care and Handling of Farm Animals — Pigs (Publication 1898/E, Agriculture and Agri-Food Canada) recommends at least 8 h of light per day, at a level adequate to observe pigs. Fifty lux are adequate and will be at least twice as much light as typically is found in many older swine barns. Design is critical to maximize light efficiency and minimize over lit or under lit areas.

Table 8 – Recommended light levels and photoperiods for swine housing (Allmond, 1986; Brandt et al., 1990; Claus et al., 1985; Evans et al., 1996; Feddes et al., 1988; Hoagland et al., 1981; Mutton, 1987; Ntunde et al., 1979; Perara et al., 1984; Petchey, 1987; Stevenson et al., 1983; Wheelhouse, 1982)

<table>
<thead>
<tr>
<th>Type of Housing</th>
<th>Light Levels (lux)</th>
<th>Photoperiod (hrs/day)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breeding/gilts</td>
<td>&gt;100</td>
<td>14–16</td>
<td>Necessary for estrus cycling</td>
</tr>
<tr>
<td>Gestation</td>
<td>&gt;50</td>
<td>14–16</td>
<td>To assist missed cycles, bring estrus on again</td>
</tr>
<tr>
<td>Farrowing</td>
<td>50–100</td>
<td>8</td>
<td>If no heat lamps, light in room 24 h/d</td>
</tr>
<tr>
<td>Nursery</td>
<td>50</td>
<td>8</td>
<td>Light in room 24 h/d</td>
</tr>
<tr>
<td>Grower-finisher</td>
<td>50</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Breeding/gestation barns require lighting photoperiods from 14–16 hours per day, to bring on more quickly and extend breeding sow estrus. Nursery pigs, particularly those in SEW, should have 24 hours of light at low levels and higher levels for day time feeding, inspection, etc. Farrowing rooms also should have 24 hours of light per day, particularly where heat lamps are not used. Again, it can be low level during night time.
8 Poultry Facilities

8.1 General Recommendations

Poultry farms and processing plants vary in function, size, layout and degree of mechanization; however, there are some areas common to most facilities. The following are brief discussions describing the operations in the major areas. Lighting requirements vary with the type of production and the task. The amount and duration of light required by the birds is significantly different from worker requirements. See Table 9 for light levels and photoperiod requirements directly associated with affecting production. Table 10 Lighting Guide for Poultry Industry Tasks provides information on tasks associated with but not directly affecting production.

<table>
<thead>
<tr>
<th>Type of Poultry</th>
<th>Age (weeks)</th>
<th>Minimum Light Level (lux)</th>
<th>Photoperiod (hrs/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chickens</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broilers</td>
<td>0–0.5</td>
<td>30–50</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>0.5–1.5</td>
<td>30–50</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>1.5 to market</td>
<td>5</td>
<td>18–20</td>
</tr>
<tr>
<td>Breeders</td>
<td>0–3</td>
<td>30–50</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>4–20</td>
<td>30–50</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>20–64</td>
<td>30–50</td>
<td>15</td>
</tr>
<tr>
<td>Layers</td>
<td>0–6</td>
<td>10–30</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>6–18</td>
<td>5–10</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>18–80</td>
<td>5–10</td>
<td>15</td>
</tr>
<tr>
<td>Turkeys</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grow out</td>
<td>0–2</td>
<td>30–50</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>3–5</td>
<td>30–50</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>6–9</td>
<td>30–50</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>10 to market</td>
<td>30–50</td>
<td>16</td>
</tr>
<tr>
<td>Breeder hens</td>
<td>0–5</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>5–8</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>8–22</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>22–30</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>30 and up</td>
<td>20</td>
<td>13–15</td>
</tr>
<tr>
<td>Breeder toms</td>
<td>0–5</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>5–30</td>
<td>20</td>
<td>13–15</td>
</tr>
<tr>
<td></td>
<td>30 and up</td>
<td>30</td>
<td>13 – 15</td>
</tr>
</tbody>
</table>

Footnote: Due to the wide variety of commercial production facilities and management style, it is difficult to design a lighting program to work for all situations. It is beneficial to give a dark period to reduce aggressiveness and improve overall performance.
Table 10 – Lighting guide for worker tasks in the poultry industry

<table>
<thead>
<tr>
<th>Area and Visual Tasks</th>
<th>Minimum on Task (lux)</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brooding, production, and laying houses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inspection and cleaning</td>
<td>20–50</td>
<td>Provided by a lighting circuit separate from the circuit used to stimulate production and growth.</td>
</tr>
<tr>
<td>Charts and records area</td>
<td>300</td>
<td>Localized lighting is needed where charts and records are kept (often in a separate room).</td>
</tr>
<tr>
<td>Thermometers, thermostats, and light controls</td>
<td>500</td>
<td>Localized lighting is needed to accurately determine readings or setting.</td>
</tr>
<tr>
<td>Hatcheries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General area and loading platform</td>
<td>200</td>
<td>Needed for operators to move about readily. Needed for cleanliness of the general area.</td>
</tr>
<tr>
<td>Inside incubators</td>
<td>300</td>
<td>Portable or localized lighting is needed for inspection and cleaning inside incubators.</td>
</tr>
<tr>
<td>Sexing</td>
<td>10,000</td>
<td>Needed for sex sorting of baby chicks. Supplementary lighting should be used in a closed area to prevent excessive luminance ratios between the task area and the immediate surrounding area.</td>
</tr>
<tr>
<td>Egg handling, packing, and shipping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General lighting</td>
<td>500</td>
<td>General illuminance is needed to keep area clean and to detect any unsanitary conditions, as well as to examine and grade eggs. Note: Canding and other special grading equipment are used as separate devices for examining and grading eggs.</td>
</tr>
<tr>
<td>Loading platform, egg storage area, etc.</td>
<td>200</td>
<td>Needed for easy operator movement, and for operation of mechanical and loading equipment.</td>
</tr>
<tr>
<td>Egg processing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General lighting</td>
<td>700</td>
<td>Should meet food preparation area cleanliness requirements. Includes liquid processing, pasteurizing, and freezing of raw eggs.</td>
</tr>
<tr>
<td>Fowl processing plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>General (excluding killing and unloading area)</td>
<td>700</td>
<td>General lighting for cleanliness, inspection, and sanitation. Should meet food preparation area requirements.</td>
</tr>
<tr>
<td>Government inspection station and grading stations</td>
<td>1,000</td>
<td>Needed to detect diseases and blemishes. Vertical illuminance is needed if birds are hanging.</td>
</tr>
<tr>
<td>Unloading and killing area</td>
<td>200</td>
<td>Needed to move about readily.</td>
</tr>
<tr>
<td>Charts and records</td>
<td>300</td>
<td>If detailed records or charts are kept in the feed room, localized lighting in this area is needed.</td>
</tr>
</tbody>
</table>

8.2 Broiler and Turkey Houses

Chicks and poults are placed into large houses inside which they move about freely. The structures may utilize daylight with electrical supplement or rely totally on electrical light. The light levels and photoperiod are adjusted during the growing period to maximize growth, minimize aggression, and control losses. Light control is provided by a dimmer and timer system. Higher levels of supplemental lighting may be required occasionally in the confinement area for workers to perform tasks such as reading charts or controls, inspecting the birds and equipment, and cleaning. Often, a dimmer circuit is used to provide different light levels for bird production vs worker tasks. In many facilities, monitoring and control equipment as well as records are housed in a separate room. Localized, higher illuminance levels are needed in this area for record keeping, observation and adjustment of alarm and control systems and monitoring equipment. Extremely low light levels (1–2 lux) are needed while birds are being harvested to minimize bird activity.
8.3 Breeder Barns

Breeder birds are placed in separate facilities, which generally are totally enclosed blocking out all daylight. Electrical lighting on timing circuits controls the perceived day length. The hours of light per day stimulate reproduction and control the breeding process.

8.4 Laying Houses

Facilities housing laying hens may range in size from a few thousand to several hundred thousand birds. There are basically two types of laying houses, the floor type house and the cage type house. In floor type houses, the hens are free to move about the floor area. In cage type houses, hens are confined to cages with three to four hens per cage — thus the lighting system must be designed to deliver light to each cage, relative to the arrangement of the cages.

8.5 Egg Handling, Packing and Shipping

The egg handling area may be located in a separate or adjoined building. When the eggs arrive at the egg processing area, they are either stored in a refrigerated area or loaded directly onto a washer. After the eggs have been washed, they are sorted and graded. Rough shells, cracked shells, and dirty or stained eggs are removed at the grading table. Candling equipment is used inside an enclosed booth to sort eggs that have internal defects such as blood spots or meat spots. If mechanization is used, the eggs are sorted according to size by a machine and placed in an egg carton for shipment. The cartons are held in refrigerated storage until they are ready for shipment to retail outlets. General lighting is needed to keep the area clean and detect any unsanitary conditions. Higher intensity, task specific lighting is necessary to examine and grade eggs. In the loading platform and egg storage areas, general lighting is needed for operation of mechanical and loading equipment.

8.6 Raw Egg Processing

Eggs, which are to be marketed as liquid, frozen, or powdered products, are processed in this area. The area must meet the sanitary requirements of a public food preparation area as set up by the health department. Cracked eggs, eggs with shell defects and stains, plus grade A eggs, are utilized in the processing of liquid eggs. The eggs are broken out of their shells and pumped into a holding tank. The liquid eggs for interstate shipment are pasteurized and packaged. Some states also require all broken-out eggs to be pasteurized for intrastate shipment. In addition, liquid eggs may be frozen at the processing area and shipped as a frozen product. General lighting must supply adequate light levels and uniformity to ensure that cleanliness requirements for a food preparation area are met.

8.7 Hatchery

Fertile eggs are brought to the hatchery, loaded onto trays and placed in incubators. The incubators maintain a temperature required for embryo development. After twenty-one days, the chick is hatched. When hatched, baby chicks are sorted according to sex. The male chicks are disposed of and the females are marketed as layers. Most of the female chicks have their combs dubbed, a process whereby the top of the comb is clipped off. As a result, the mature bird has a smooth comb, which helps prevent the comb from catching in the wires of the laying cages. Broiler chicks are handled in much the same manner except they are not sex-sorted or dubbed.

General lighting is needed for cleaning and easy movement of operators. Supplementary lighting is required for inspecting and cleaning inside incubators, and at dubbing stations to prevent cuts and injuries to chicks. Task specific lighting is necessary for sex sorting and should be provided in a closed area to prevent excessive luminance ratios between task area and the immediate surrounding area.

8.8 Poultry Processing Plant

The birds are brought to the plant in crates of about 20 per crate. Crates are unloaded and the birds hung by the feet on a continuously revolving overhead carriage. They pass by an area where they receive a slight electrical shock, which stuns them just before killing. They move through a bleeding area and then into the scalding tanks. Feathers are then removed by machine and the birds move on to the processing area. All birds
are government inspected for wholesomeness after eviscerating, are thoroughly washed, inspected again, and sorted according to grade. Generally, the processed birds are then packed in ice and shipped to retail outlets.

General lighting is needed for cleanliness, inspection and sanitation. Supplementary lighting is required to detect diseases and blemishes (vertical illuminance if the birds are hanging).

9 Equine Facilities

9.1 Brood Mare

Day length is the primary environmental factor that regulates the seasonal reproductive cycle of the mare (King, 1993; Evans et al., 1990). Since all foals are given a birthday of January 1, it is a relatively common practice to manipulate the estrous cycle in the mare to produce a foal as close to January 1 as possible. Due to an 11 month gestation period, this requires that the mare be bred out of season in winter. Provision of 14 to 16 hours of light followed by darkness has been shown to stimulate estrous. The minimum amount of light needed is 22 to 32 lux (Vogelsang, 1993; Evans et al., 1990). Since 10 lux are needed in a box stall (Table 11), this light requirement can be satisfied by controlling the stall fixture with a timer.

9.2 Stallion

Day length also influences sperm production in the stallion. Sperm production in the winter is typically half of that produced in the summer breeding season (King, 1993). Controlling the photoperiod for the stallion in the same way as for the mare will improve off-season breeding performance (Hudson, 1996). Table 11 lists light intensities for different work areas in a horse barn.

<table>
<thead>
<tr>
<th>Work Area or Task</th>
<th>Illuminance (lux)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Box stalls</td>
<td>10</td>
</tr>
<tr>
<td>Tack room</td>
<td>300–400</td>
</tr>
<tr>
<td>Breeding</td>
<td>150–200</td>
</tr>
</tbody>
</table>

10 Lighting for Indoor Aquaculture

Indoor aquaculture is a relatively new industry. The lighting needs for fish production are limited. Lighting however can play a crucial role in the productivity of a facility and as such must be considered in the overall design.

10.1 Effects of Lighting on Fish Production

Lighting effects on fish populations can be classified in three categories: growth rate effects, maturation effects, and vigour.

**Growth Rate Effects.** Photoperiod and light intensity in many species influence growth rate. Often, only a very low light level difference is needed (<1 lux) to induce photoperiod responses in fish, which include increased activity and time spent feeding. Fish can be extremely sensitive to environmental shock — including sudden changes in light level. The resulting stress can negatively affect feeding and growth of the fish. Thus, dimming circuits or banked lamps on a slow ramp-up and down may be needed to prevent stress and insure proper growth.

**Maturation Effects.** Manipulating the photoperiod can control speed of maturation of some fish species. One method is to vary the photoperiod above the fish tanks from day to day so as to simulate the natural
fluctuations in day length from season to season. In selected species, the annual maturation cycle of the fish can be compressed to 9 or even 6 months by compressing the day length cycle to that period.

**Vigour.** Fish vigour, or survival rate, also is dependent on lighting. Generally, increased photoperiods will result in greater vigour of the fish crop.

### 10.2 Specific Species Recommendations

The following recommendations need to be used with some caution. Current research is insufficient for many species; as a result, the recommendations regarding lighting are based on limited data. Combining these recommendations with the knowledge and desires of the grower will assist in the design of a system that optimizes production.

**Atlantic Salmon.** Long photoperiods during the freshwater period result in an increased growth rate relative to shorter photoperiods (Sigholt et al, 1989) and continuous light results in a higher growth rates than the use of a simulated daylight cycle (Krakenes et al., 1991). Long photoperiods interrupted by 2 months of short photoperiods results in faster maturation and higher survival rates, compared to constant long photoperiods (Duston et al., 1995).

**Coho Salmon.** Absence of a dark period (24 hr light/day) results in reduced growth rate, silverying index, and seawater adaptability (Thorarensen et al., 1989).

**Pink Salmon.** Mature faster by accelerating the seasonal photoperiod (Beacham et al., 1993).

**Greenback Flounder.** Absence of lighting results in death of the species. An 18–24 hour photoperiod is recommended for optimum production (Hart et al., 1996).

**Silver Carp.** A light level of 100 lux at the water surface is recommended for raising larvae of this species (Radenko et al., 1992).

**Rainbow Trout.** A long photoperiod (16 hr) results in increased growth and feed conversion (Mason et al., 1991).

**Striped Bass.** Reproductive cycles can be compressed to 6 or 9 months by compressing the photoperiod cycle, but reproductive success diminishes as a result (Blythe et al., 1994).

### 10.3 Lighting Other Areas in the Facility

Lighting systems for walkway, processing, packaging, and shipping areas should be designed according to recommendations in the General Work Areas section. Often, lighting requirements for operation of the facility will not be compatible with the needs of the fish. Thus, care must be taken to ensure that lighting for human needs does not negatively affect the fish population.

### 11 Greenhouse Lighting System Design

The use of electrical light sources to supplement natural light or to modify the natural photoperiod in greenhouse production systems is a common practice. The successful application of lighting systems in greenhouses depends on the types of plants grown, the local incidence of natural sunlight, the light spectrum provided, the availability and price of electric energy, and the availability of control systems to maximize system operation for enhanced plant performance. While the term “light” typically applies only to visible electromagnetic radiation (approximately 380 to 770 nm), it will be used in this discussion also to refer to electromagnetic radiation that is useful for growth and development of plants (defined as Photosynthetically Active Radiation, “PAR”, and covering the waveband between 400 and 700 nm). See the photobiology section of the Illuminating Engineering Society handbook for a discussion of specific plant responses to electromagnetic radiation.
Supplemental lighting in greenhouses generally is designed to either enhance crop photosynthesis (assimilation lighting), or to control flowering and fruiting (photoperiod lighting).

Supplemental lighting provides a number of advantages to the grower:

- reduced dependency on sunlight
- increased productivity
- higher plant quality
- shorter growing times
- opportunity for controlled seedling production
- control over timing of flowering of plants/shrubs
- control over timing of plant production (to best meet market needs).

11.1 Design Objectives

Greenhouse lighting systems generally are designed to meet three main objectives:

- instantaneous light level (sometimes converted to the daily light integral)
- photoperiod
- uniformity (important for both instantaneous and photoperiod lighting).

For plant growth and development purposes, the instantaneous light levels are generally reported as PAR readings (µmol m\(^{-2}\) s\(^{-1}\)) or as a total daily dosage (mol m\(^{-2}\) d\(^{-1}\)). One mole equals Avogadro’s number of photons and one micromol equals one millionth of a mole. The terms Photosynthetic Photon Flux (PPF) or Photosynthetic Photon Flux Density (PPFD) are sometimes also used. PAR measurements approximate the absorption spectrum of an average plant leaf (McCree, 1972; Sager et al., 1988), and sensors are readily available to measure in this unit. Conversion factors between PAR (µmol m\(^{-2}\) s\(^{-1}\)) and illuminance (lux) depend on the light source, and are shown in Table 12. Conversion between units becomes more challenging when multiple light sources provide radiation simultaneously. Note that Table 12 does not include conversions for Light Emitting Diode (LED) sources. LEDs are a newly emerging technology that can provide a range of light spectra (from individual colors, color combinations, to white light), have different thermal characteristics, and potentially have higher electric conversion efficiencies. Therefore, LEDs provide exciting opportunities for plant lighting. However, limited information is available at this time to accurately characterize and describe the use of LEDs for plant lighting (Mitchell et al., 2012). Additional light conversion factors are presented in Table 13.

### Table 12 – Converting light units for several different light sources

<table>
<thead>
<tr>
<th>Light Source</th>
<th>PAR 400–700 nm (µmol m(^{-2}) s(^{-1}))</th>
<th>Visible 380–770 nm (lux)</th>
<th>Visible 380–770 nm (fc)</th>
<th>Solar Radiation 280–2,800 nm (W m(^{-2}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunlight</td>
<td>100</td>
<td>5,600</td>
<td>520</td>
<td>48.3</td>
</tr>
<tr>
<td>High-pressure sodium (HPS)</td>
<td>100</td>
<td>8,500</td>
<td>790</td>
<td>44.4</td>
</tr>
<tr>
<td>Metal halide (MH)</td>
<td>100</td>
<td>7,100</td>
<td>660</td>
<td>48.3</td>
</tr>
<tr>
<td>Incandescent (INC)</td>
<td>100</td>
<td>5,000</td>
<td>465</td>
<td>48.3</td>
</tr>
<tr>
<td>Fluorescent, cool white (FCW)</td>
<td>100</td>
<td>7,400</td>
<td>688</td>
<td>44.4</td>
</tr>
<tr>
<td>Low-pressure sodium (LPS)</td>
<td>100</td>
<td>10,600</td>
<td>985</td>
<td>45.2</td>
</tr>
</tbody>
</table>

Note: For example, for sunlight: 100 µmol m\(^{-2}\) s\(^{-1}\) (PAR) = 520 (fc) (visible radiation) = 5,600 lux (visible radiation) = 48.3 W m\(^{-2}\) (solar radiation). The last conversion assumes that 45% of the solar radiation occurs in the PAR waveband.
Table 13 – Additional useful light conversion factors

<table>
<thead>
<tr>
<th>Conversion Factor</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar radiation (280–2,800 nm):</td>
<td></td>
</tr>
<tr>
<td>1 Langley (Ly) = 1 cal cm(^{-2})</td>
<td></td>
</tr>
<tr>
<td>1 cal cm(^{-2}) = 4.184 J cm(^{-2})</td>
<td></td>
</tr>
<tr>
<td>Visible radiation (380–770 nm):</td>
<td></td>
</tr>
<tr>
<td>1 fc = 10.76 lux</td>
<td></td>
</tr>
<tr>
<td>Conversion from integrated solar radiation to integrated PAR:</td>
<td></td>
</tr>
<tr>
<td>1 MJ m(^{-2}) = 2.08 mol m(^{-2}) (Ting and Giacomelli, 1987)</td>
<td></td>
</tr>
<tr>
<td>100 Ly d(^{-1}) = 8.70 mol m(^{-2}) d(^{-1})</td>
<td></td>
</tr>
</tbody>
</table>

Optimum PAR or daily integrated PAR levels are not always readily available for many crops. The designer must ascertain from the client or from published data what design values to select, and also adjust for incoming solar radiation at the site (Spaargaren, 2001). A general guideline for research greenhouses is that the natural sunlight plus supplemental lighting supply a minimum daily light integral of 26 moles per m\(^{2}\) per day (Dietzer et al., 1994). Estimation of the available daylight in a greenhouse can be based on analyzing local weather data or by using percentile criteria (Ciolkosz, 2006). Generally, supplemental PAR levels for commercial greenhouses are in the range of 50–200 \(\mu\)mol m\(^{-2}\) s\(^{-1}\). However, if the lighting system is used only for photoperiod control, then much lower PAR levels in the range of 1–3 \(\mu\)mol m\(^{-2}\) s\(^{-1}\) are usually suitable (Mpelkas, 1991; Weir, 1975). These values are measured on a horizontal plane at the surface of the crop canopy. Ideally, the PAR level at the top of the crop canopy would be perfectly uniform. However, luminaire spacing and intensity distributions, combined with economic considerations, require the acceptance of a degree of variation in the PAR level (Albright and Both, 1994; Both et al., 2002; Ciolkosz et al., 2001). In research greenhouses, a maximum variability of ± 15% from the average light level is considered acceptable (Both, 1994), while commercial greenhouses tend to vary somewhat more. Photoperiod requirements of a lighting system can be best thought of in terms of the length of the dark period plants are exposed to during a 24-hour period. Thus, if a plant requires a minimum photoperiod of 17 hours, the corresponding dark period is 7 hours. If the night length at the site is naturally 12 hours long, then photoperiod control can be obtained by turning the lighting system on for 30 minutes in the middle of the night, thus effectively reducing the maximum dark period to just under 6 hours. Some species have a maximum allowable dark period in order to grow and develop properly, while some require a dark period that is longer than a certain minimum amount. It is important to take the length of the dark period into consideration when assimilative lighting is to be used during nighttime hours. Also, it is important to evaluate the site for sources of stray light from neighboring structures. Stray light, if bright enough, may have an unwanted photoperiodic effect on the crop.

### 11.2 System Selection

Lamps for greenhouse lighting generally are selected for their electrical efficiency because of the systems’ typically high electricity consumption. Compact size also is a positive attribute because smaller lamps and luminaires tend to create smaller shadows. Currently, the high-pressure sodium lamp is preferred because the conversion efficiency typically ranges between 25 and 30% and the light spectrum is adequate for most plant species. While they often have higher conversion efficiencies, low pressure sodium lamps are generally not used because their light spectrum is inadequate for most plant species and their large reflector size tends to block a significant amount of incoming sunlight.

Often, the spectral quality of a light source is less important because the high proportion of sunlight received by the plants tends to overcome any spectral deficiencies in the light sources (Ehret et al., 1989). Some plant species however, show slightly different growth responses under different light sources. In these installations, a less efficient light source may result in better economic value for the crop (Clarke and Devine, 1984).

Photoperiodic lighting systems historically have used incandescent lamps because of their relatively low installation cost; and even though they are electrically inefficient, they are needed only for a few minutes each night an energy and cost efficient alternative to incandescent lamps are the compact fluorescent lamps (deGraaf-van der Zande and Blaquiere, 1992). Additional cost savings may be possible with the use of LED lamps for photoperiod control.
Greenhouse luminaires are specially designed for operation in the greenhouse environment. Other luminaire types should not be considered unless they can perform well in the hot, humid, and corrosive environment. Factors to consider in luminaire selection include optical efficiency, electrical efficiency (Both et al., 1997), reflector size, mounting height, ease of installation and maintenance, and ballast location. Occasionally, it can be desirable to locate the ballasts remotely in order to reduce the shading effect of the luminaire.

Switching and controls usually are a component of a greenhouse environmental control system, which is supplied separately from the lighting system. Communication with the controls provider is imperative to ensure that the client receives the type of system control needed, and that either the electrical or controls contractor provides all system components. Manual override controls should be included as part of the control system. Dimming controls are rarely an economic alternative for greenhouse lighting systems. This may change when LED lighting systems are further developed for plant lighting applications. The control of supplemental lighting can be integrated with the control of the shading system (Albright et al., 2000), particularly when control of the daily integrated PAR level is desired.

11.3 Layout and Design

Luminaire layout generally is done on a rectangular grid above the plant canopy (Mpelkas, 1984). Alternatively, luminaries can be mounted in a staggered grid in an attempt to improve light uniformity (Ciolkosz et al., 2001). When possible, locate the luminaires on structural members of the greenhouse to reduce the need for additional support. Luminaires should be located below thermal screens so that the screens may be drawn at night even when the lamps are operating. The effect of any screens or curtains in the greenhouse needs to be taken into account during the design process, provided that they will be drawn while the lamps are operating. Decreasing PAR levels at the edges of the greenhouse can be countered by increasing the number of luminaires along the greenhouse perimeter (Both, 1994). The amount of thermal radiation produced by the various lighting systems should be taken into account when designing lighting systems. The amount and location of the thermal radiation can have a significant impact on plant growth and development as well as the resulting environmental control strategies employed. Some experimental LED lighting systems provide the opportunity to place lamps within the plant canopy (particularly in tall crop canopies such as tomatoes, peppers and cucumbers) in an attempt to further improve plant growth and development. Hybrid systems with High Intensity Discharge (HID) lamps (such as HPS and/or MH) overhead and LED lamps inside the crop canopy are also being evaluated.

11.4 Maintenance

System maintenance generally consists of regular luminaire cleaning, and relamping as needed. The client should be informed of the importance of these tasks. Depending on the specifics of the design, scheduled (sub)group relamping may be an economical alternative. For example, one third of the lamps could be replaced every other third year.

11.5 Headhouse Lighting

The headhouse is a structure used for plant handling procedures such as planting, grading, and shipping plant material. It usually is located directly adjacent to the greenhouse. Lighting requirements for the headhouse correspond to the activities taking place in the various areas. Generally, these activities include potting, sorting, packing, shipping, and (cold) storage. The design for these areas should be conducted based on the client’s needs and the appropriate design criteria for those tasks, as set forth in Table 10.

12 Fruit and Vegetable Processing and Storage

Fruit and vegetable sorting operations can benefit from lighting changes that match the characteristics and color output of the light with the color of the produce being sorted. Most defects on produce are in the brown or gray tones. Light provided for inspection must have both the right illuminance level and spectral quality to reveal these defects. Proper lighting design also reduces worker fatigue and eyestrain, resulting in better sorting efficiency. Many operations currently use cool white or warm white lights, which researchers say can mask defects. High CRI fluorescent lights are recommended for most fruit and vegetable inspection areas. They are more expensive than cool white, but their relative light output and color rendering are superior.
Tungsten halogen quartz lighting also produced good color recognition and enhanced the ability to see brown defects, but is much less energy efficient.

The average illuminance level needed at the produce level for effective visual sorting is between 2,500 and 5,000 lux. The lower levels are adequate for light-colored produce and the higher level is needed for dark-colored produce.

The color of the sorting surface is also important. Using black or gray (but not glossy) belts is beneficial.

Select dark colors for equipment parts and employee clothing. It is important to screen task lights so they do not glare in the workers’ eyes. Minimize the influence of natural, stray, and general area lighting in the sorting area. Luminaires in coolers should be rated for wet environments per the National Electric Code.