Investigation of the Thermal Regime of a Cultivation Structure Following an Emergency Shutdown of the Heating System

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Abstract. Maintaining favorable microclimatic conditions in cultivation facilities is directly linked to the stable operation of the heating system. An emergency shutdown of the heating system in a cultivation facility, especially during the winter, can lead to the death of the plants being grown. Thus, the issue of predicting the thermal regime of the cultivation facility following a cessation of heat supply is practically significant. Research object: cultivation facilities intended for year-round plant growth. Research subject: the patterns of temperature changes in the internal air (both in dimensional and dimensionless forms), the rate of temperature decline, and the loss of thermal energy during an emergency heating system shutdown. Research objective: to predict the thermal regime of the cultivation facility after an emergency shutdown of the heating system. Research methods: classical theory of thermal stability of building envelope structures; the theory of regular thermal regime, according to which the temperature field in all points of the cooling body (in this case, the heating system) changes uniformly, following an exponential law; computational software simulations. Research results: in an industrial greenhouse, the internal air temperature will reach the critical mark of 8 °C within 36 minutes after an emergency shutdown of the heating system and will reach zero degrees after 1 hour and 9 minutes. Based on the conducted scientific research, it can be concluded that the cooling of the heating system in an industrial greenhouse occurs quite rapidly, as the heating elements have a high cooling rate. The structural design of the enclosure does not allow for the accumulation of thermal energy. Therefore, heating systems in cultivation facilities intended for year-round plant growth must meet stringent reliability requirements.

Keywords: Thermal Regime of Cultivation Facility; Internal Air Temperature; Rate of Temperature Decline; Thermal Stability of the Structure; Specific Thermal Characteristic of the Structure; Heat Accumulation Coefficient; Cooling Rate Index; Regular Thermal Regime; Emergency Heating System Shutdown.

1 Introduction

Optimal climatic conditions in a cultivation facility, along with the necessary level of illumination [1–3], not only protect plants from potential damage but also influence the quality, quantity, and timing of the harvest [4, 5]. When considering the energy consumption balance of a cultivation facility, approximately 90% of all energy is used for heating purposes [6, 7]. In contrast, in residential buildings, around 45% of the consumed energy is allocated to heating [8, 9]. Therefore, the shutdown of the heating system in an industrial greenhouse, designed for year-round plant cultivation, can quickly lead to crop loss, as such structures are typically built with glass or polycarbonate that has low thermal insulation properties [10–12]. Enhancing the thermal protection of enclosing structures [13–16], along with finding optimal spatial planning solutions [17, 18] and creating energy-efficient air and soil heating systems [19–21], is one of the key areas in the design of cultivation facilities. The study of the effectiveness of ventilation and air conditioning systems in greenhouses is generally characteristic of countries with warm or hot climates [22–26].

Current research is focusing on refining existing methods for calculating the thermal regime of buildings following an emergency heating system shutdown. New factors affecting the internal air temperature are being considered, such as variable outdoor air temperature [27] and the thermal stability of multilayered enclosing structures [28, 29]. The subjects of such scientific studies include not only residential and cultivation facilities [30, 31] but also industrial enterprises, where the specific features of technological processes are taken into account [32]. Significant attention is also given to forecasting the impacts of centralized heating system outages on populated areas [33–37].

Research object: cultivation facilities designed for year-round plant growth.

Research subject: patterns of internal air temperature change (both dimensional and dimensionless), temperature drop rate, and thermal energy loss during an emergency heating system shutdown.

Research objective: to forecast the thermal regime of a cultivation facility following an emergency heating system shutdown.

Research tasks:

1. To develop a method for calculating the key parameters that characterize the thermal regime of a cultivation facility in the event of an emergency heating system shutdown.
2. To validate the proposed calculation method using the example of an industrial greenhouse intended for year-round plant cultivation.
3. To determine the period of emergency heating system shutdown after which the thermal regime of the industrial greenhouse reaches its characteristic critical values.

2 Methodology

To evaluate the reliability of heat supply at the consumer level, the following formula can be used to determine the internal air temperature after an emergency heating system shutdown:

$$T_{int.air} = T_{out.air} + \frac{Q_{heat}}{q_{heat}V} + \left(T'_{int.air} - T_{out.air} - \frac{Q_{heat}}{q_{heat}V}\right) e^{-t/\beta}, \text{°C}, \quad (1)$$

where $T_{out.air}$ is the average outdoor air temperature during the period of emergency heating system shutdown, °C; Q_{heat} is the thermal flux entering the heated space, W. For a cultivation facility Q_{heat} is numerically equal to the heating system's thermal power, as solar long-wave radiation, heat gains from occupants, and technological equipment are not considered in the thermal balance of the space; q_{heat} is the specific thermal (or heating, according to some sources) characteristic of the space, $\text{W}/(\text{m}^3 \cdot \text{°C})$; V is the volume of the heated space (by external measurement), m^3; $T'_{int.air}$ is the indoor air temperature at the moment of the emergency heating system shutdown, °C; t is the duration of the emergency heating system shutdown, h; β is the heat accumulation coefficient, h.

In classical thermal stability theory, when thermal energy is supplied intermittently to a space (an emergency heating system shutdown can be considered a specific case of intermittent thermal energy supply with an unknown duration period), the heat accumulation coefficient in formula (1) is typically determined as follows:

$$\beta = \frac{(c\rho AL)_{wall}}{2} \frac{1}{q_{heat}V} \cdot \frac{1}{3600}, \text{h}, \quad (2)$$

where c_{wall}, ρ_{wall}, A_{wall} and L_{wall} denote the specific heat capacity, $\text{J}/(\text{kg} \cdot \text{K})$, density, kg/m^3, surface area, m^2, and thickness, m, of the building's enclosing structure, respectively.

It can be demonstrated that the desired coefficient β in equation (2) is numerically equal to the product of the heat capacity of half of the building's enclosing structure (by the principle of symmetry) and its equivalent thermal resistance.

The variable thermal flux Q_{heat} in equation (1) will gradually decrease during the emergency shutdown of the heating system (eventually reaching zero). If the heating system is considered as a body being cooled in an environment with a conditionally constant temperature $T_{int.air}$, then, according to the first kind of regular thermal regime, the following relationship holds:

$$Q_{heat} \approx Q'_{heat} e^{-mt}, \text{W}, \quad (3)$$

where Q'_{heat} is the initial thermal power of the heating system (prior to the emergency shutdown), W; and m is the cooling rate of the heating system, $1/\text{h}$.

In this context, the parameter m from expression (3) will be equal to:

$$m \approx \frac{h_{conv} A_{heat}}{C_{metall} + C_{water}} \cdot 3600, 1/\text{h}, \quad (4)$$

where h_{conv} is the convective heat transfer coefficient (heat dissipation), $\text{W}/(\text{m}^2 \cdot \text{K})$; A_{heat} is the total surface area of the heating system, m^2; C_{metall} and C_{water} are the specific heat capacities of the heating system (excluding the heat carrier) and the heat carrier, respectively, J/K.

The greater the value of m, the faster the cooling (or the rate of cooling) of the heating system occurs. The reciprocal of m, which has units of time, serves as a measure of the thermal inertia of the system.

At this stage of the research, the heat transfer coefficient h_{conv} is assumed to be constant, i.e., the parameter m is considered constant. In the theory of heating system design and in the design calculations of heating devices, it is known that the heat transfer coefficient $h_{conv} \propto (T_{surf} - T_{int.air})$, where T_{surf} is the average surface temperature of the heating element, °C. In the current situation, the temperature difference $T_{surf} - T_{int.air}$ during the emergency shutdown of the heating system is difficult to predict, as T_{surf} is a variable and $T_{int.air}$ is the unknown quantity.

Based on the equation used to calculate the thermal load required for heating a building or structure, which is commonly applied in the design of centralized heating systems for residential areas and enterprises, we will express formula (1) incorporating expression (3) in the following form:

$$T_{int.air} = T_{out.air} + (T'_{int.air} - T_{out.air})\left[e^{-mt} + (1 - e^{-mt})e^{-t/\beta}\right], \text{°C}. \quad (5)$$

In its dimensionless form, equation (5) can be written as follows:

$$\Theta = \frac{T_{int.air} - T_{out.air}}{T'_{int.air} - T_{out.air}} = e^{-mt} + (1 - e^{-mt})e^{-t/\beta}. \quad (6)$$

The rate of temperature decrease of the internal air in the event of a heating system failure, according to equation (5), will be:

$$\Delta_T = \left|\frac{dT_{int.air}}{dt}\right| = (T'_{int.air} - T_{out.air})\left[(1 - e^{-mt})\frac{e^{-t/\beta}}{\beta} + \left(1 - e^{-t/\beta}\right)me^{-mt}\right], \text{°C/h}. \quad (7)$$

The amount of thermal energy lost by the building or structure during the heating system failure will be:

$$\Delta Q_{heat} = Q'_{heat}\int_0^t \Theta dt = Q'_{heat}\left[\frac{1 - e^{-mt}}{m} + \beta\left(1 - e^{-t/\beta}\right) - \frac{1}{m + \frac{1}{\beta}}\left(1 - e^{-\left(m + \frac{1}{\beta}\right)t}\right)\right] \cdot 3600, \text{J}. \quad (8)$$

In equations (5)-(8), the relationship between the parameters m and $\frac{1}{\beta}$ is of interest. If the condition $m \gg \frac{1}{\beta}$ holds (the heating system cools down an order of magnitude faster than the building or structure's envelope) or $m \ll \frac{1}{\beta}$ (the building or structure's envelope cools down an order of magnitude faster than the heating system), then simplified (reduced) forms of equations (5)-(8) can be derived.

Figure 1 illustrates the schematic diagram of heat exchange in the cultivation facility.

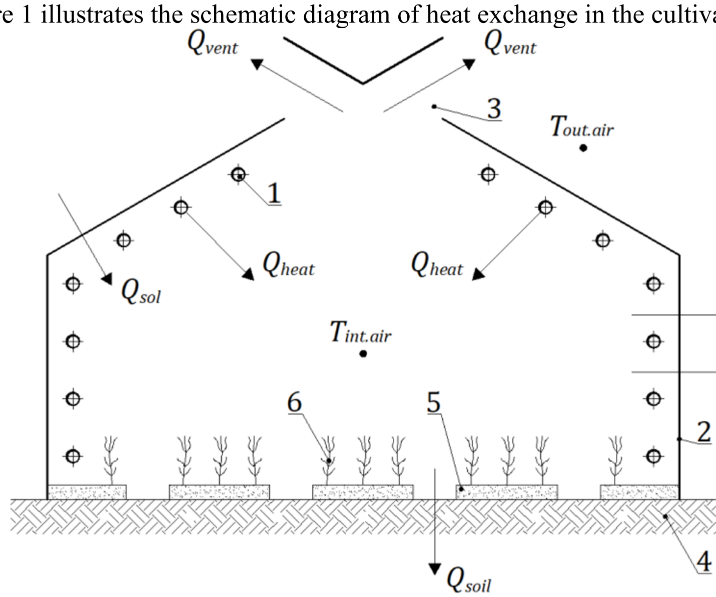

Fig. 1. Major thermal energy flows in a cultivation structure: 1 – heating system; 2 – enclosure; 3 – exhaust ventilation openings (vents); 4 – soil; 5 – earth; 6 – plants.

In the cultivation facility (Figure 1), the primary source of heat energy Q_{heat} is supplied by the heating system 1, which in this case consists of air heating pipelines. The positive component of the heat balance of the cultivation facility also includes the long-wave solar radiation Q_{sol}, penetrating through the barrier 2, which is not accounted for in the heating design due to its irregular thermal energy flow. Negative heat flows include: heat losses due to heat transfer and infiltration of external air through the leaks in the barrier 2 – denoted as

Q_{wall} and Q_{inf}; respectively; heat losses from heat exchange with external air at temperature $T_{out.air}$ through exhaust ventilation openings (transoms) 3 and the soil 4 – denoted as Q_{vent} and Q_{soil}, respectively. The temperature of the internal air $T_{int.air}$ will also be influenced by its interaction with the soil 5 and plants 6, which occurs through convective heat exchange and moisture evaporation (transpiration).

In the calculation of the heating system's thermal performance for the cultivation facility, Q_{heat} does not account for solar radiation Q_{sol} (during nighttime operation) or the thermal energy used for ventilation Q_{vent}. Therefore, for the initial growth period of the plants, the thermal balance equation of the cultivation facility will be expressed as follows (prior to the emergency shutdown of the heating system):

$$Q'_{heat} = Q'_{wall} + Q'_{inf} + Q'_{soil}, \text{W}. \quad (9)$$

3 Results and Discussion

Consider, as an example, an industrial greenhouse designed for year-round plant cultivation, and analyze the thermal regime of the cultivation facility under the specified conditions following an emergency shutdown of the heating system (Figure 2).

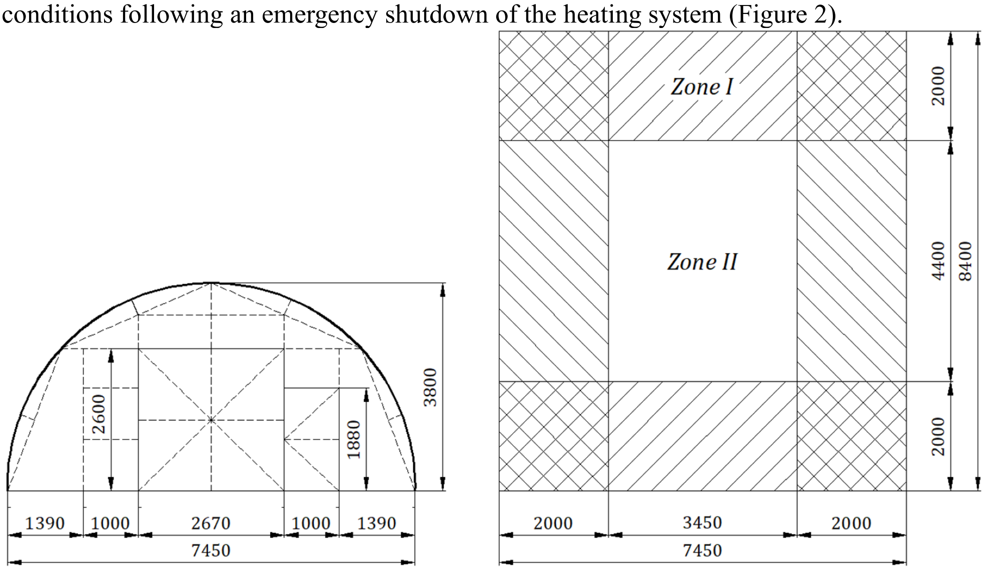

Fig. 2. Industrial greenhouse for year-round plant cultivation with zoned soil division.

Input data for the calculation (Figure 2):

1. Room parameters. The dimensions of the industrial greenhouse are as follows: width $a_{greenhouse} = 7.45$ m; length $b_{greenhouse} = 8.4$ m; height at the highest point $h_{greenhouse} = 3.8$ m. Soil surface area $A_{soil} = 62.58\ \text{m}^2$. The volume of the space $V_{greenhouse} \approx 183.108\ \text{m}^3$.

2. Enclosure parameters. The enclosure of the industrial greenhouse, with a thickness of $L_{wall} = 10$ mm is constructed from honeycomb polycarbonate. The density and specific heat capacity of the honeycomb polycarbonate are $\rho_{wall} = 0.55\ \text{kg/m}^3$ and $c_{wall} = 1000\ \text{J/(kg} \cdot \text{K)}$, respectively. The total surface area of the enclosure is $A_{wall} \approx 140.29\ \text{m}^2$. The thermal resistance of the honeycomb polycarbonate is $R_{T,wall} = 0.51\ \text{m}^2 \cdot \text{K/W}$. The proportion of additional heat losses for heating infiltrating air entering the industrial greenhouse is taken as $\beta_{inf} = 0.2$.

3. Soil parameters. The thermal resistance values for the soil in zones I and II are $R_{T,\mathrm{I}} = 2.1\,\mathrm{m}^2 \cdot \mathrm{K/W}$ (with an area of $F_\mathrm{I} \approx 63.40\,\mathrm{m}^2$) and $R_{T,\mathrm{II}} = 4.3\,\mathrm{m}^2 \cdot \mathrm{K/W}$ (with an area of $F_\mathrm{II} \approx 15.18\,\mathrm{m}^2$).

4. Indoor air parameters. The initial temperature of the indoor air in the industrial greenhouse is taken as $T'_{int.air} = 22\,°\mathrm{C}$ (for cucumbers in the winter-spring cycle, prior to fruiting).

5. Outdoor air parameters. The calculated temperature of the outdoor air is assumed to be constant during the period of heating system failure and is set at $T_{out.air} = -15\,°\mathrm{C}$.

6. Heating system parameters. The heating system consists of steel air heating pipes with dimensions $D \times L = 51 \times 2.5\,\mathrm{mm}$. The total length of the pipes in the industrial greenhouse is $l_{heat} = 120\,\mathrm{m}$. The total surface area of the heating elements is $A_{heat} = 19.20\,\mathrm{m}^2$. The volume of the heat carrier (water) in the heating system is $V_{water} \approx 0.199\,\mathrm{m}^3$. The mass of the heating system, excluding the heat carrier, is $m_{metall} \approx 358.8\,\mathrm{kg}$. The specific heat capacity of the metal (steel) is $c_{metall} = 500\,\mathrm{J/(kg \cdot K)}$. The density and specific heat capacity of the heat carrier (water) are $\rho_{water} = 1000\,\mathrm{kg/m}^3$ and $c_{water} = 4190\,\mathrm{J/(kg \cdot K)}$, respectively. The average surface temperature of the heating system in the industrial greenhouse under the given conditions is $T_{surf} = 82.5\,°\mathrm{C}$. The convective heat transfer coefficient is $h_{conv} \approx 11.6\,\mathrm{W/(m^2 \cdot K)}$. The thermal power of the heating system before the emergency shutdown is $Q'_{heat} = 13500\,\mathrm{W}$. The specific thermal (heating) characteristic of the room is $q_{heat} = 1.993\,\mathrm{W/(m^3 \cdot °C)}$.

According to Equation (2), the heat accumulation coefficient $\beta \approx 0$. The cooling rate of the heating system, calculated using Formula (4), is $m \approx 0.791\,1/\mathrm{h}$. Given the mathematical condition $m \ll \frac{1}{\beta}$, Equations (5) through (8) can be expressed in their simplified (particular) form:

$$T_{int.air} = T_{out.air} + (T'_{int.air} - T_{out.air})e^{-mt},\ °\mathrm{C}. \quad (10)$$

$$\Theta = e^{-mt}, \quad (11)$$

$$\Delta_T = (T'_{int.air} - T_{out.air})me^{-mt}, \quad (12)$$

$$\Delta Q_{heat} = \frac{Q'_{heat}}{m}(1 - e^{-mt}) \cdot 3600. \quad (13)$$

Figure 3 illustrates the graphs of the internal air temperature $T_{int.air}$ and the dimensionless temperature Θ in the industrial greenhouse during the period of emergency heating system shutdown.

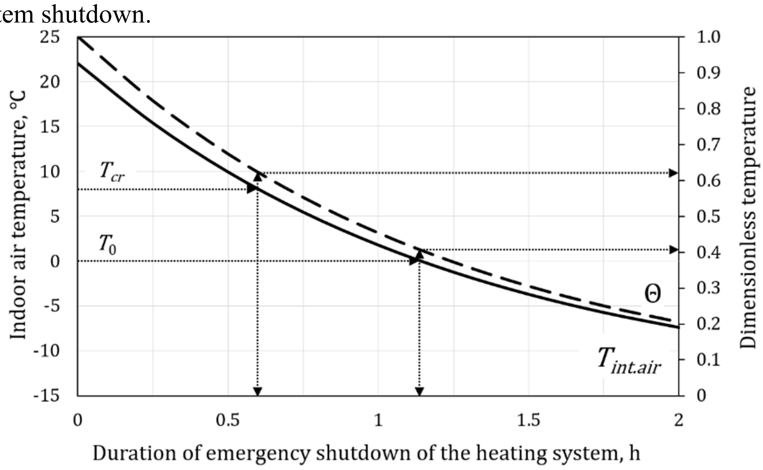

Fig. 3. Evolution of internal air temperature in an industrial greenhouse following an emergency shutdown of the heating system: solid line – dimensional representation; dashed line – dimensionless representation.

In the event of an emergency heating system shutdown, cucumbers can tolerate a temporary reduction in internal air temperature to $T_{cr} = 8$ °C for no more than six hours. Prolonged exposure to low temperatures can cause cucumbers to freeze and die. It is known that cucumbers are highly sensitive to internal air temperature, particularly during the fruit maturation stage. For example, at an internal air temperature of $T_{int.air} = 15$ °C, cucumbers may "freeze" and nearly cease to grow. According to Figure 3, the internal air temperature in the industrial greenhouse will reach the critical value of $T_{cr} = 8$ °C ($\Theta_{cr} \approx 0.62$) approximately $t_{cr} \approx 36$ min after the heating system is turned off. During the emergency heating system shutdown period $t_0 \approx 1$ h 9 min, the internal air temperature will fall to zero $T_0 = 0$ °C ($\Theta_0 = 0.405$).

Figure 4 presents the graph of the rate of temperature decrease Δ_T and the thermal energy loss ΔQ_{heat} from the industrial greenhouse during the emergency heating system shutdown period.

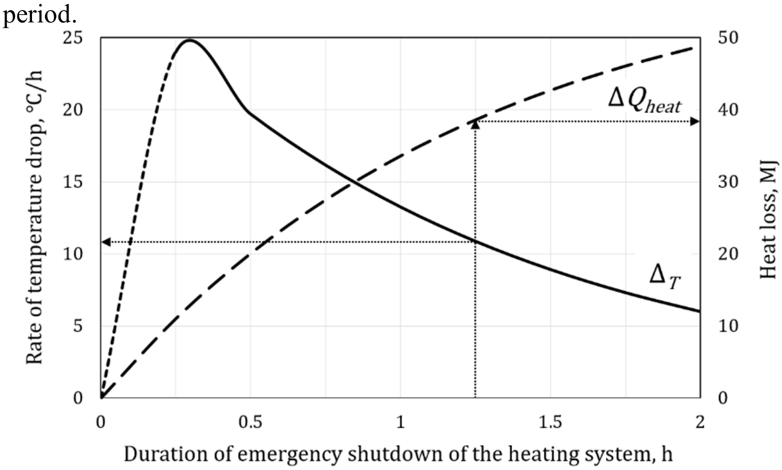

Fig. 4. Evolution of internal air temperature drop rate (solid line) and heat loss from an industrial greenhouse (dashed line) following an emergency shutdown of the heating system.

For instance, at the time $t = 1$ h 15 min the rate of temperature decrease of the internal air and the loss of thermal energy during the considered period, according to Figure 4, were $\Delta_T \approx 10.9$ °C/h and $\Delta Q_{heat} \approx 38.6$ MJ, respectively. It is noteworthy that the rate of temperature decrease Δ_T exhibits indeterminate behavior in the initial period: starting from the origin, it rapidly reaches a maximum value, after which there is a period of gradual reduction in Δ_T. Therefore, the segment of the $\Delta_T = \Delta_T(t)$ curve for the time interval $t \in [0; 0.25]$h curve for the time interval $t \approx 20$ min the rate of temperature decrease reaches its maximum value of $\Delta_{T,max} \approx 24.9$ °C/h.

Based on the system of mathematical equations (5)-(8), a program was developed in the Mathcad mathematical editor to determine the internal air temperature in the cultivation facility following the shutdown of the heating system.

4 Conclusions

For cultivation facilities with relatively thin enclosing structures (e.g., the thickness of honeycomb polycarbonate ranges from 4 to 16 mm, and organic glass is no less than 5 mm, with a recommended thickness of 10-15 mm), the mathematical condition $m \ll \frac{1}{\beta}$ applies (indicating that the enclosing structure cools an order of magnitude faster than the heating system). For predicting the thermal regime of a cultivation facility following an emergency shutdown of the heating system, it is permissible to use the system of equations (10)-(13).

In an industrial greenhouse (Figure 2), it was determined that the internal air temperature will reach the critical point of 8 °C within 36 minutes after an emergency shutdown of the heating system, and will drop to zero degrees within 1 hour and 9 minutes. The average rate of temperature decline over a period of 2 hours is 14.7°C/h, with total thermal energy losses amounting to 48,8 MJ.

Thermal accumulation in enclosing structures plays a crucial role in maintaining the required thermal regime of the room in the event of an emergency shutdown of the heating system. Given the relatively low heat capacity and high heat dissipation associated with the significant temperature gradient of the heating elements, the cooling of the heating system occurs rapidly (with a high cooling rate index). Consequently, heating systems for cultivation facilities, where the microclimate is a fundamental factor for the optimal growth and development of plants, must meet stringent reliability standards.

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