

Thermal Design of a Spaceflight Plant Chamber Payload

Alex Hoehn, James Clawson, Jake Freeman, Jon Genova, Kevin Gifford, Louis Stodieck
BioServe Space Technologies, NASA Research Partnership Center, University of Colorado at Boulder, USA

Copyright © 2003 Society of Automotive Engineers, Inc.

ABSTRACT

PGBA, a 0.08m² / 27 liter spaceflight plant chamber payload employs two temperature-controlled liquid coolant loops to control the temperature and humidity of the sealed plant chamber independently. Cabin-air cooled thermoelectric heat pumps control the temperature of the water-alcohol coolant fluid in each loop, which is circulated by small, low-power, magnetically-coupled positive displacement gear pumps, designed to meet NASA safety requirements. Pulse-width-modulated DC current control circuits, controlled by two PI software controllers, maintain temperature and humidity accurately. The coolant loops feature bellows-based expansion vessels to accommodate thermal expansion and pressure fluctuations. Pressure sensors monitor the proper function and performance of the system. Pressure decay tests and unique fill procedures should ensure leak and air bubble-free operation.

INTRODUCTION

Biological / chemical experiments typically require accurate temperature control, as the processes under investigation show a strong dependency on temperature. Especially for life sciences experiments, temperature outside a predefined range may render the experiment useless, or may kill the organism. Nominal payload operation may also require time-dependent temperature profiles, such as cold stowage for preservation / stasis, and growth at a controlled, constant higher temperature. Growth temperatures typically range between 18-25°C for plants and many life sciences experiments, and 37°C for mammalian cell cultures. Often the experiment itself has additional internal heat sources (lights, motors, sensors) and requires heat removal for steady state temperature. The authors have developed several spaceflight life sciences incubators (Hoehn et al., 1999) and plant growth chambers (Hoehn et al., 1998, 1994) for microgravity research aboard the Space Shuttle, Space Station and Satellites. These experiments are designed with lowest mass, power and volume in mind. While earlier designs attempted air-to-air heat pump designs, it became increasingly difficult to remove the heat from the distributed sources within these tightly integrated science payloads. Originally, the only available heat sink was cabin air (typically 25° to 35°C),

and only the International Space Station now provides cooling water for individual science payloads. The first liquid coolant circulation system was implemented in the Isothermal Containment Module (ICM) / Commercial Generic BioProcessing Apparatus (CGBA, Hoehn et al., 1999; Figure 12). Thermoelectric heat pumps (Peltier elements, TEC) control the liquid coolant temperature while rejecting the waste and pumped heat through a forced-convection air heat exchanger to ambient cabin air. The coolant fluid (water/alcohol mixture) is circulated by a low-power, low-mass, high-reliability gear pump to distributed areas within the incubators or plant chambers with minimal thermal gradient (typ. <1°C, i.e., <±0.5°C). Science payloads of this geometry (single or double middeck locker equivalent, MDLE; <54.5 kg, <125 liter volume, <0.5x0.5x0.5m) have less than 230Watt (double MDLE, 130Watt for single MDLE) of power available. With good thermal insulation (Pyrell foam, 0.035W·m⁻¹·K⁻¹, 12.5mm, also required for vibration dampening) from the ambient environment / crew cabin, and careful design layout of the life sciences experiment chamber, the typical heat pump requirement is on the order of 35 Watts. At a maximum allowable gradient across the temperature controlled experiment chamber of ΔT=1°C (±0.5°C), the minimum coolant flow rate for water as the heat transport media can be estimated as:

$$\dot{m} = \frac{Q}{C_P \times \Delta T_{\max}} = \frac{35\text{Watt}}{4183 \frac{\text{J}}{\text{kgK}} * 1\text{K}} \approx 500\text{mL} / \text{min}$$

The typical MDLE experiment geometry with Ø6 mm ID tubing, including fittings and water heat exchangers, results in a pressure drop of between 33 and 100 kPa (≈5-15 psi_{id}) at 500mL/min flow rate. Experiment duration can be from several days aboard the Space Shuttle, up to typically 1 year (≈8,760 hours) aboard the International Space Station of autonomous operation without servicing. The payloads under consideration are all designed for the relatively benign crew cabin environment (nominal 101kPa, 10-45°C, 50%rH, microgravity, acceleration <3g, vibration <8g_{rms} on launch, low radiation exposure), and are not required to operate under, but may be exposed to, space vacuum conditions. With these parameters in mind, the liquid coolant systems could be designed according to science, engineering and payload safety requirements.

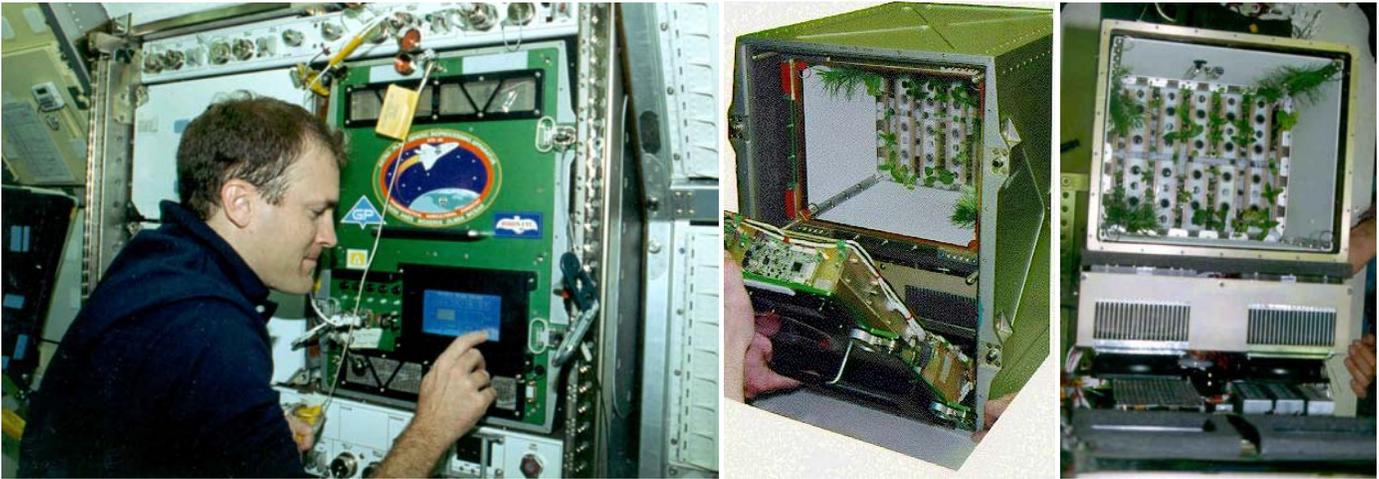


Figure 1. PGBA operated inside an EXPRESS rack on STS-94. Cabin air is used to cool the two thermoelectric heat pumps and payload waste heat. One heat pump each is used for temperature control and humidity control within the sealed plant growth chamber.

DESIGN REQUIREMENTS

- Lowest mass, power, volume, to maximize science volume and mass.
- ≤ 500 mL/min at ≤ 101 kPa (14.7 psi_a) delta pressure.
- Typically 0°C to 45°C coolant temperature, constant or temperature profiling, $\Delta T \leq \pm 0.5^\circ\text{C}$ / 1°C gradient.
- Pump ≈ 35 Watt to/from cabin air.
- Heat or cool depending on science experiment.
- Safe if exposed to space vacuum (cabin depress.).
- Meets NASA safety / interface requirements.
- $\approx 9,000$ hrs (≈ 1 year) operational life.

COOLANT LOOP DESCRIPTIONS

As a design example, the coolant loops of the PGBA spaceflight greenhouse will be analyzed (Figure 1-3). For proper plant growth, the plant chamber is sealed from the crew cabin environment and controlled independently for temperature, humidity and carbon dioxide (Figure 2). Major heat sources include the light radiated into the chamber, as well as internal fans, sensors and parasitic heat transferred from the areas surrounding the plant chamber (Horner et al., 1997). Due to limited power (230 Watt for entire payload) and the large heat capacity of the system (3kg water in root zone, 5kg structure), the thermal response of the entire system is very slow (15-120 minutes for steady state temperature/humidity under typical conditions).

Heat exchange between the chamber and the external environment is accomplished via an air-heat pump-water heat exchanger system. Independent systems of identical design and capacity manage the heat transfer to/from the plant chamber (temperature control) and the chamber humidity (Figure 3). Cabin air is used as the heat sink, but payload-internal heat transport is accomplished using temperature-controlled water circulation.

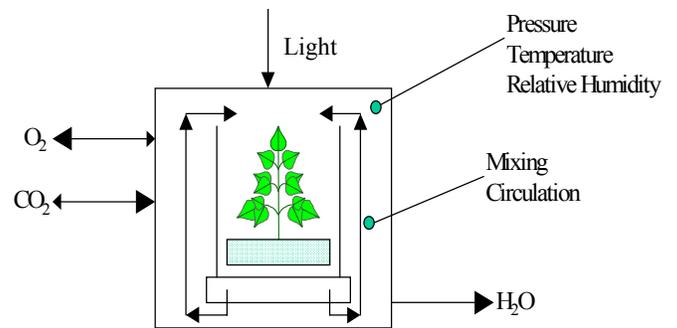


Figure 2. Environmentally sealed plant chamber with temperature-controlled walls for temperature control, and temperature-controlled dew point system for humidity control.

TEMPERATURE CONTROL

The temperature of the plant chamber is primarily maintained by temperature-controlled water circulation through the chamber walls (5 of 6 walls; transparent lid cooled on edges only). Internal air circulation along the walls ensures forced convection heat transfer for temperature control (typically 18°-25°C for plants), while also providing good air mixing for atmosphere composition control. The chamber is insulated with foam (12.5mm, $0.035\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, necessary for thermal insulation and launch vibration isolation) from the ambient (hot, typically 35°C) environment to minimize the heat pump load, but heat radiated from the lamps, located external to the chamber, and internally dissipated heat from fans and sensors must be transferred from the chamber to the thermoelectric heat pumps and to cabin air. Internal heat sources have been limited to the absolute minimum. Further improvements, at the expense of complexity and chamber seal integrity, would be to move the motors of the internal circulation fans to the outside, and to further reduce the heat radiated into the chamber through hot mirror coatings and/or improved light transmission through the clear Polycarbonate chamber lid.

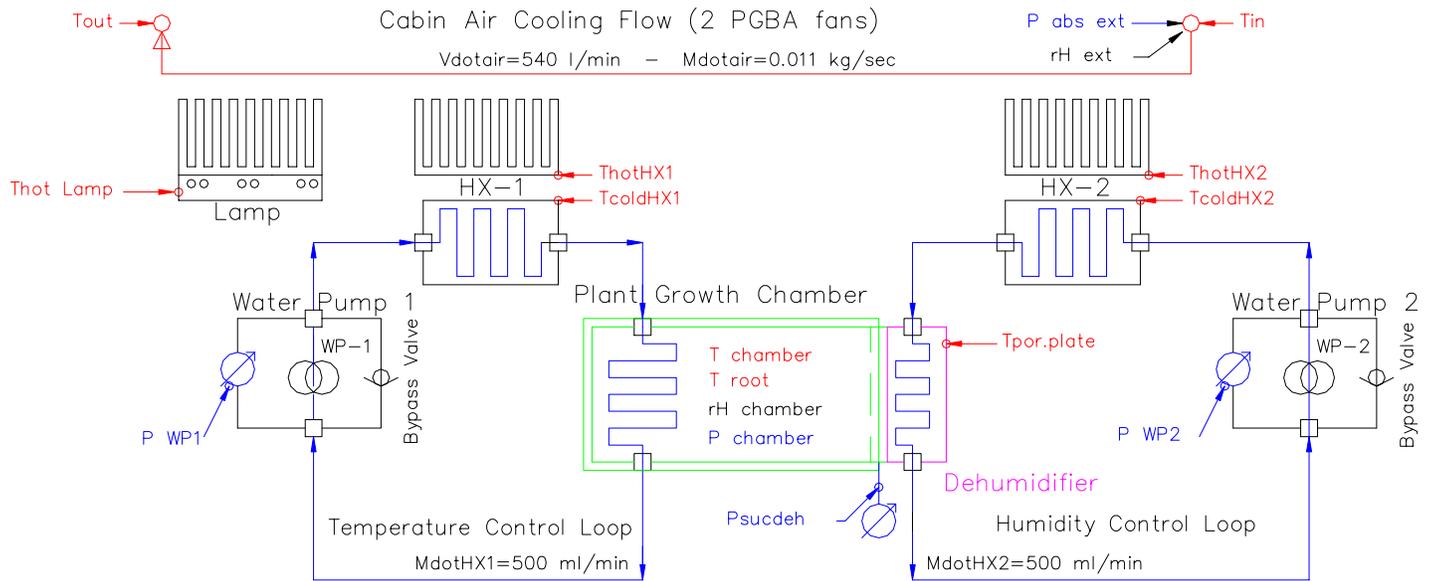


Figure 3. PGBA Thermal System. The PGBA controls the temperature of the two coolant loops (shown on the diagram in blue) as needed for temperature (left) and humidity (right) control. The waste heat from the thermoelectric coolers is rejected to cabin air together with the waste heat from the lamp box by forced convection (top). Diagram shows variables measured by the computer (P =pressure, T =temperature, $Mdot$ =mass flow, rH =humidity).

HUMIDITY CONTROL

The humidity of the plant chamber is controlled by the temperature of a porous, sintered, stainless steel, phase-separating dew point dehumidifier. Condensed water is returned to a reservoir or pumped back to the plants (root tray filled with a matrix such as soil, Figure 4; see also Hoehn et al., 2003; Scovazzo et al., 1999).

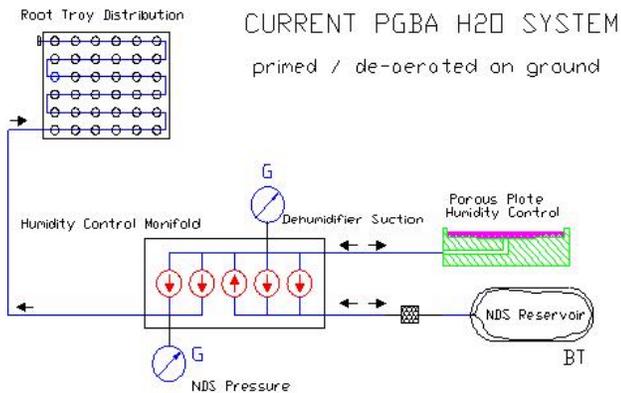


Figure 4. Humidity control – cooling the porous plate below the dew point results in condensation of water on the porous plate, from where it can be pumped back to the root tray (soil, hydroponics matrix) and/or a holding tank. The primed porous plate provides phase separation. Five micro-dispensing pumps ($50\mu\text{L}$) allow independent and redundant pressure control of the porous plate (de-humidify, re-humidify) and water delivery to the plants.

The chamber humidity is a function of the chamber temperature and the temperature of the dew point controller, which is controlled by an independent coolant circulation system (Figure 3). The coolant fluid for the

humidity controller is separated from the humidity condensate. The dew point humidity controller affects the overall temperature control system capacity, and temperature control relies on heat transfer through both the temperature and humidity control systems for best performance due to overall integrated system and resource limitations. The obtainable temperature range also depends on the amount of water condensed and the humidity setpoint of the chamber. Lowest temperatures can be obtained at low humidity and high condensation / evapo-transpiration. The dehumidifier contributes to the heat removal due to its large surface area and low temperature, and the temperature controller may need to heat the chamber to compensate, especially at night without the heat addition from the lights.

COMMON COOLANT LOOP COMPONENTS

The PGBA Plant Growth Chamber and the CGBA Spaceflight Incubator (Hoehn et al., 1999) share the same fundamental liquid coolant system design (Figure 5). PGBA contains two circulation loops for independent temperature and humidity control (Figure 3), while the CGBA Life Sciences Incubator (Figure 12) only contains one coolant loop for temperature control.

Pressure Ratings

In order to overcome the typical system backpressure of 101 kPa ($=\text{MOP}$, maximum operating pressure, $\approx 15\text{psi}_d$), and based on the hysteresis and variance in the bypass valve setpoints and current trip limits, the highest

pressure in the system could reach ≈ 220 kPa (=MDP, maximum design pressure; 32 psi_d), including thermal expansion. This includes potential exposure to space vacuum in case of cabin depressurization, at which point the payload would not be required to be operational. NASA safety requirements impose a proof and leak test to 1.5 times MDP, i.e., 330 kPa (50 psi_d) for this design, with Factors of Safety of 2.5 to 4.0.

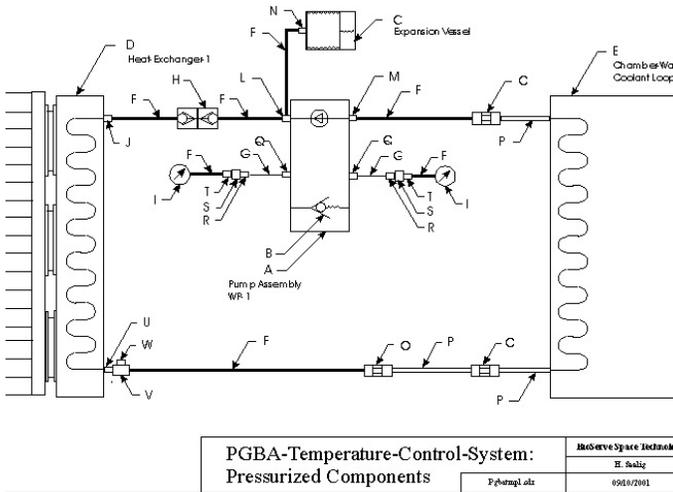


Figure 5. Generic coolant loop components: thermoelectric heat pumps, cooled by cabin air (left), control the coolant water temperature through finned water heat exchangers (D). The circulation pump assembly (A) contains an over-pressurization bypass valve (B), and circulates temperature-controlled water for temperature or humidity control (shown here: plant chamber, E). Expansion vessel (C) shown on outlet to further limit the system gauge pressure and to account for volumetric / pressure changes.

Circulation pump

The final choice for the coolant pump is a low-power (<5 Watt) magnetically-coupled positive displacement gear pump without dynamic seals, reducing the risk of leakage and extending the life time appreciably when compared to shaft seal pumps (Micropump, Inc.). The brushless DC pump motor (hot, power dissipation) is thermally isolated from the potentially cold (4°C) pump head to reduce heat pump requirements. A safety bypass valve (150 kPa, ≈ 22 psi_d) within the pump head limits the maximum possible differential output pressure. The dead head pressure of the pump without bypass valve is ≈ 500 kPa (75 psi_d, magnet decoupling), too high for the flexible tubing and fittings used in the design.

Two individual gauge pressure sensors are employed to measure the pump inlet and outlet pressures, from which the computer determines the differential pressure. Safety software assesses the presence of flow ($\Delta P > 0$), or a potential over-pressurization / blocked flow ($\Delta P > P_{max,allowed}$). Software is not the primary safety control, i.e., the payload software is not 'safety critical'. Instead, the system relies on passive / mechanical parts (bypass valve, motor over-current resettable fuses; Figure 7) to

ensure the system operates safely during malfunctions, even without computer control.

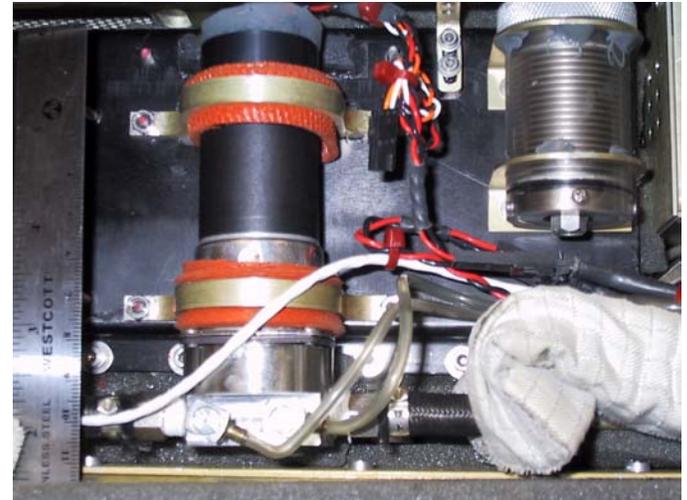


Figure 6. Coolant Circulation Pump (left): positive displacement gear pump ($\approx 8,000$ hrs) with brushless DC motor (20,000 hrs., 3-5 Watt) on left with pressure sense ports. Pump motor is fitted with a microprocessor-based time counter for lifetime tracking. Bellows-based expansion vessel (accumulator) is seen on upper right. Fluid components are insulated with closed-cell foam to avoid condensation while running below cabin dew point (not shown).

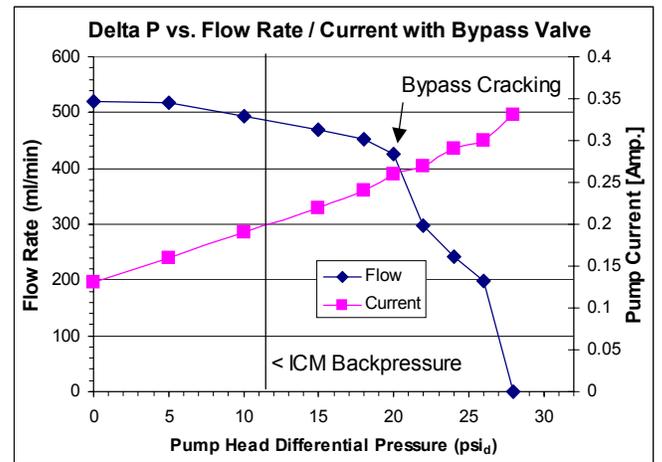


Figure 7. Pump performance as a function of pressure, and pressure limiting safety bypass valve. A Raychem Polyswitch™ resettable fuse ($I_{hold}=200$ mA, $I_{trip}=400$ mA) and the mechanical bypass valve ensure that the system pressure will not exceed ≈ 200 kPa (30 psi_d). During nominal operation, the pump performance is also monitored by the computer (P_{in} , P_{out} , $\Delta P=P_{out}-P_{in}$).

Bellows Expansion Vessel

The closed coolant circulation system with approximately 500ml of coolant is designed for use between nominal 4°C and 37°C (0° - 45°C, including tolerances and safety limits). Over this temperature range of 45°C, the water volume changes from a nominal 'as loaded' volume by as much as $\Delta V = V \cdot \beta \cdot \Delta T = 500\text{ml} \cdot 0.2 \cdot 10^{-3} \text{K}^{-1} \cdot \pm 22.5\text{K} = \pm 2.25$ ml. The

expansion vessel accommodates this volumetric change, and must be rated for the maximum design pressure (MDP), and must be testable to 1.5 x MDP.

To allow for thermal-driven volume changes in the cooling system, and to address pump-dynamics, a semi-rigid bellows-type expansion vessel was designed. The expansion vessel is constructed of two custom-made electro-less nickel-plated aluminum end caps, soldered to a standard electro-formed nickel bellows (Servometer, Inc.), using Kester #44 60/40 Tin-Lead rosin core solder. An outer containment consisting of a sealed polycarbonate tube provides a second level of containment, while also allowing access to the unit's bleed port via an O-ring-sealed cap. In operation, the expansion vessel accommodates up to ± 6 ml volume change in the system (Figure 8). The flexible hoses between the various coolant loop components provide additional system expansion.

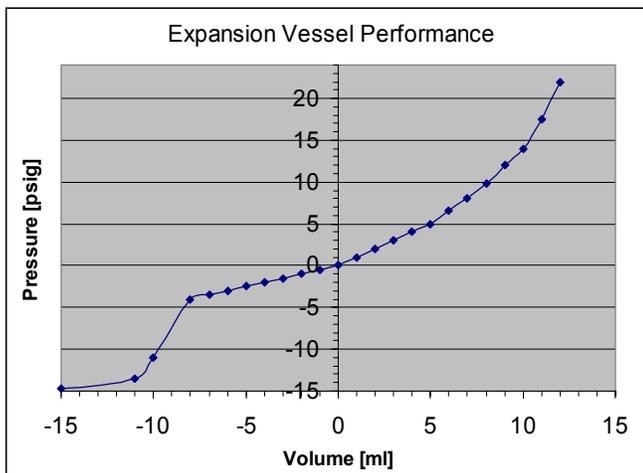


Figure 8. The current bellows-based expansion vessel exhibits a volume-dependent spring constant. Typically, the positive travel is limited by the second level of containment (Polycarbonate body) at 6 ml positive expansion. To some limited extent, the expansion vessel also serves as a reservoir to compensate for water losses (diffusion through flexible tubing).

Thermoelectric Heat Pump and Controller

The heat pump (concept, Figure 9) consists of 3 serially connected Peltier elements that can be operated at up to 48 VDC, however the maximum possible supply voltage to the elements is limited to ≈ 24 VDC, i.e., the TECs are operated always at $<50\%$ of max. allowed power for highest efficiency (Melcor). A PWM closed loop current controller (4 MOSFET H-Bridge, 20 kHz) is used in conjunction with the payload control computer to provide proportional current control (proportional heat or cool). Inductors in series with the Peltier heat pumps reduce ripple and essentially provide proportional DC current control.

The computer runs Proportional-Integral (PI) control software based on sensor feedback. In addition to the

primary temperature and humidity sensors inside the chamber, each system also has a backup control scenario in case damage to the primary sensor is detected. The backup sensors are the temperature of the wall of the chamber for temperature control and the temperature of the dehumidifier plate for humidity control. In each case, a distinct, appropriate set of controller gains is used when controlling to the backup sensor value. Inductors were added on both sides of the TECs, reducing the ripple to less than 10%. This guarantees adequate lifetime of the Peltier heat pumps. The proportional current controller, when compared to a simpler on-off (bag-bang) control, is necessary to maintain adequate lifetime of the Peltier heat pumps due to the long required operating life (years). High ripple or frequent on-off switching under full load would reduce the lifetime dramatically. For missions with limited power availability, the controller can be current-limited (range, heat only, cool only, payload power budgeting). Under normal operation, the supply voltage limits the maximum possible current through the TEC resistance. At full PWM duty cycle (100%), the TECs operate at 50% of maximum allowable current for highest efficiency, limited by the available supply voltage.

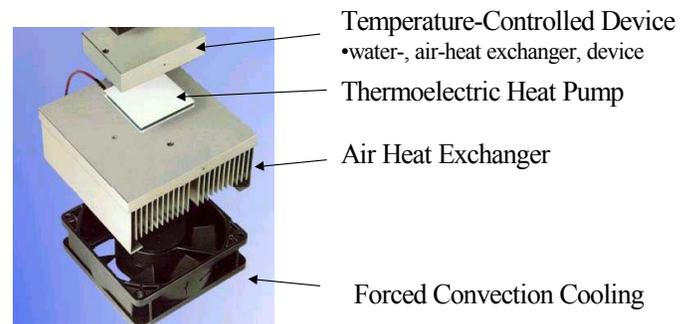


Figure 9. Fundamental building block of the thermoelectric heat pump system (Melcor). Waste and pumped heat are rejected to cabin air by forced convection. The thermoelectric heat pumps use a proportional current controller, which can be switched to heat (typically at night, or to re-humidify) or cool (dehumidification, day-time heat removal).

For missions with temperature profile requirements (launch cold for stasis, warm up at a certain rate, remain steady for incubation, then cool for preservation), the computer will vary the PI temperature setpoint accordingly to achieve the desired profile.

During normal plant growth operation, and based on plant evapo-transpiration rates, the dehumidifier is typically always cooled to maintain a constant humidity. Under certain conditions (no plants, immediately after chamber access in a dry environment), the dehumidifier may need to heat to increase the chamber humidity. At night, without the addition of the radiant energy from the lamps, but still with evapo-transpiration from the plants, the temperature control system will heat to compensate for the heat removed by the cooling dehumidifier.

Safety Overrides

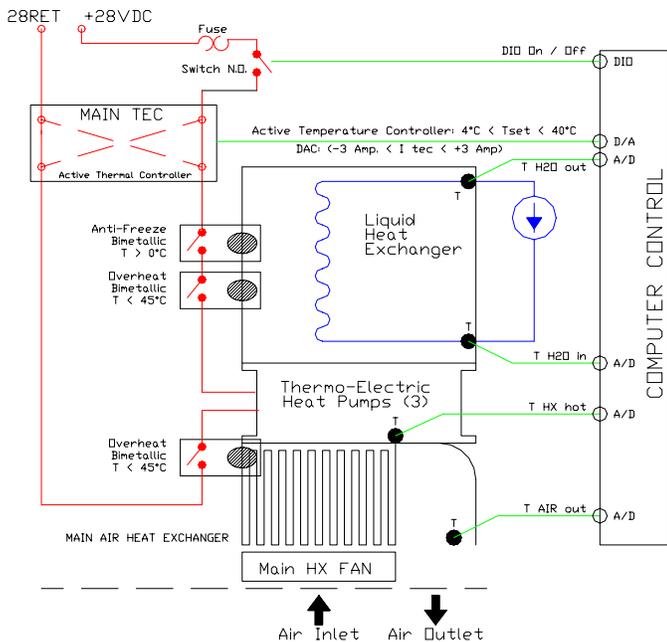


Figure 10. Temperatures monitored by the computer and by passive bi-metallic thermal switches for safe operation, shown for one coolant loop. Both sides (air, water) are protected from over-heating due to controller or fan failure, and the liquid side is protected from freezing (controller failure). Air exhaust is limited to $<49^{\circ}\text{C}$ due to crew safety concerns.

NASA safety requirements mandate that steps be taken to insure the integrity of the coolant system and to keep any surface that astronauts could contact within safe temperature limits. The air exhaust temperature may not exceed 49°C , and the coolant water shall not freeze (flow blocked / over-pressurization, cracked lines), nor overheat (boiling, thermal damage to biological samples). These requirements are met both actively by computer control and passively by bi-metallic temperature switches. As a sensor value approaches a safety limit, the allowed power to the TEC controller is reduced in order to preempt an exceedance. Should the sensor value exceed the safety limit despite the reduced power dissipation (blocked airflow, fan failure, high cabin temperature), the thermal system, and ultimately the entire payload, will be shut down. The bi-metallic switches act as a backup safety measure to ensure safe operation in case of a controller malfunction (e.g., computer crash). Therefore, the software is not safety-critical.

Mandatory fire detection (over-temperature) for ISS operation is accomplished using parameter monitoring, and a health and status byte is sent to the EXPRESS rack computer once a second to broadcast nominal or potentially off-nominal conditions. The crew can be alerted and assist in case of a perceived malfunction, or the payload is shut down remotely and/or automatically.

Water Heat Exchangers

Initially, O-ring-sealed, custom-made aluminum heat exchangers with a high internal fin density were employed. The outer body was low thermal conductivity, glass-filled Polycarbonate to further reduce parasitic heat transport into the typically cold water heat exchangers. However, this design was prone to leakage, and was replaced with Nickel-plated aluminum heat exchangers, that were soldered after plating, eliminating O-ring seals and screw compression. These heat exchangers consist of a 6061-T6 aluminum body, incorporating a cavity of machined, high surface area serpentine heat exchange passages, a simple aluminum cover, and integrated piping ports. All elements are plated with $13\ \mu\text{m}$ of electro-less nickel and joined by a solder process. All other aluminum components are alodined (MIL-C-5541B, a.k.a. Iridite, chromate conversion) for corrosion protection. The thermoelectric heat pumps are mounted in parallel, on thermal grease, and compressed through thermally isolated screw joints. The thermoelectric heat pumps and all electric connections are sealed and waterproofed, and all cold surfaces are insulated using closed-cell foam to minimize condensation.

Wall-embedded Coolant Loops

The PGBA coolant system consists of $\varnothing 6\text{mm}$ diameter 3003 aluminum tubing fashioned into a serpentine loop and bonded within five of the six honeycomb chamber walls. The 3003 series aluminum has good corrosion resistance. Pumping a commercial chromate conversion coating solution through the length of the formed coolant loop further prevents corrosion of the inner walls of the tube, which will be in constant contact with the coolant.

Air Heat Exchangers and Fans

The air heat exchanger system consists of two identical custom Fabfin[®] 6063T5 aluminum heat sinks (R-Theta, Inc.), housed in a specially designed, angled duct, which provides optimum impingement airflow across the heat exchange fins. The duct also provides a mounting surface and noise-suppression for the two tube-axial fans. The low-noise fans are located such that their primary noise emissions are projected into the payload rather than out into the crew cabin (EBM-Papst, 4212H brushless 12VDC, 112 mmx38mm, 49 dB(A), 5.3 Watt). At the system backpressure of $\approx 75\ \text{Pa}$, each fan delivers approximately 540 L/min flow rate. Stringent noise limits onboard ISS require the additional use of noise-suppression mufflers while on orbit. Future designs will replace the noisy cabin air heat exchangers with water heat exchangers, utilizing the ISS-provided water coolant system. Payloads that require power on ascent and descent will continue to use air-cooling.

Air inlet and outlets of the payload are protected from particle ingestion by stainless steel screens (71.9% open

area, 1.3x1.3mm opening, Ø0.23 mm wire, Figure 1). In microgravity, and especially in the more crowded Space Shuttle, large amounts of lint may accumulate, requiring daily air inlet cleaning by the astronauts. In addition, floating run-away objects may block the air inlet. The computer monitors air inlet and exhaust temperatures to prevent overheating in case of reduced, blocked or missing airflow (fan failure). The maximum air outlet temperature is limited to 49°C due to crew safety concerns. With a maximum of 230 Watt of power dissipation, the PGBA payload can therefore safely operate at ambient temperatures of up to 30-35°C, before the computer would reduce power consumption to avoid exceeding the air exhaust temperature limit of 49°C.

Under extreme operating conditions (very cold crew cabin), the air heat exchangers may be approaching cabin dew point temperatures, while the Peltier heat pumps heat the plant chamber. No provisions have been made to address cabin humidity condensation on the air heat exchangers themselves, as the circumstances for such an operational mode are not realistic, and any potential condensate would evaporate in the airflow. However, all payload-internal components that are cooled below the cabin dew point (typ. 17°C), such as the water heat exchangers, dehumidifier, pump heads, tubing, require adequate airtight (closed cell foam) insulation to prevent cabin air condensation and water accumulation during operational times of months or years. All electric components (sensors, heat pumps) are waterproofed. The crew cabin is typically maintained at 25°C / 50%rH / 17°C dew point, but possible environmental conditions span a wide range.

OPERATIONS AND FLIGHT PERFORMANCE

Leak testing

To ensure reliable operation and to satisfy safety requirements, the entire system must be proof- and leak-tested. Additionally, the system is vibration tested to typical Space Shuttle launch vibration loads to ensure system integrity. Due to the use of flexible tubing and COTS quick disconnect fittings, the system will always exhibit some small amount of leakage or pressure decay over time. Acceptable pressure decay criteria have been developed to ensure safe and reliable operation of the system over the nominal 1-year lifetime. In addition to unavoidable small leakage across interfaces, the flexible tubing will show some water loss over extended periods of time.

The MDP of 220 kPa (32 psi_d) is determined and limited by the pump bypass valve, a current-limiting fuse and pressure sensor feedback through the computer, and includes exposure of the system to space vacuum in case of crew cabin depressurization. The integrated system is proof- and leak-tested to 1.5*MDP=330kPa (50 psi_d).

Coolant Fluid Fill

Distilled water with <10% ethanol (to reduce the risk of biological contamination, and as a lubricant) is used as the heat transport media. De-ionized water is not compatible with the system and must not be used, as it leaches metal ions from the stainless steel fittings and Nickel-plated water heat exchangers. While alcohols are not allowed in the ISS cabin atmosphere due to incompatibilities with the ISS environmental control system, dissolved alcohol in the sealed coolant loops is permissible. At the 10% concentration, the water-alcohol coolant is assessed as a hazard level 0 fluid (one level of containment only).

Pressure Decay

After long periods of operation, both the system pressure (small leakage) and the pump differential pressure (wear) will decay. The system pressure drops due to unavoidable water loss over time as discussed before. Despite the use of a 'suction shoe' design (Micropump, Inc.), the differential pressure, and thus the flow rate, have been observed to drop over long operating times. To date, all pumps operated nominally in excess of 10,000 hours, without leaks or performance drops below acceptable levels. None of the pumps have ever failed.

Operation with Expansion Vessel on Outlet

To limit the system pressure (safety concern), the expansion vessel had originally been installed on the pump outlet, resulting in large portions of the circulation system to run below ambient pressure. While this design feature reduces the leak potential of water from the system, air can now be drawn into the system over time, creating an air-water coolant mixture, and potentially disabling the circulation system. This also increases the risk of cavitation due to low pump inlet pressures. Especially for longer mission duration, to make up for any potential water loss, the expansion vessels have now been enlarged and moved to the pump inlet, to also serve the function of a make-up reservoir. As water may be lost, replacement coolant can be drawn from the expansion vessel (accumulator), extending the operational life of the payload. The coolant system is currently not designed for on-orbit refill. Without refill, and with ingested air due to water evaporation, the system ultimately may no longer transport sufficient amounts of heat. If the pump cannot establish sufficient flow, measured as a function of the pump differential pressure, the computer will power-cycle the pump several times and potentially re-establish flow. Alternatively, the computer will ultimately turn off the pump and thermal system, and the experiment will no longer be able to perform the assigned function, typically resulting in payload and science failure.

Pressure Dynamics

The payload computer monitors the inlet and outlet pressure sensor continuously, but stores data only once a minute. The data in Figure 11 shows pressure fluctuation as a function of external pressure swings (shown simultaneously on both P_{in} and P_{out}), but also exhibits pressure dynamics that are not fully understood.

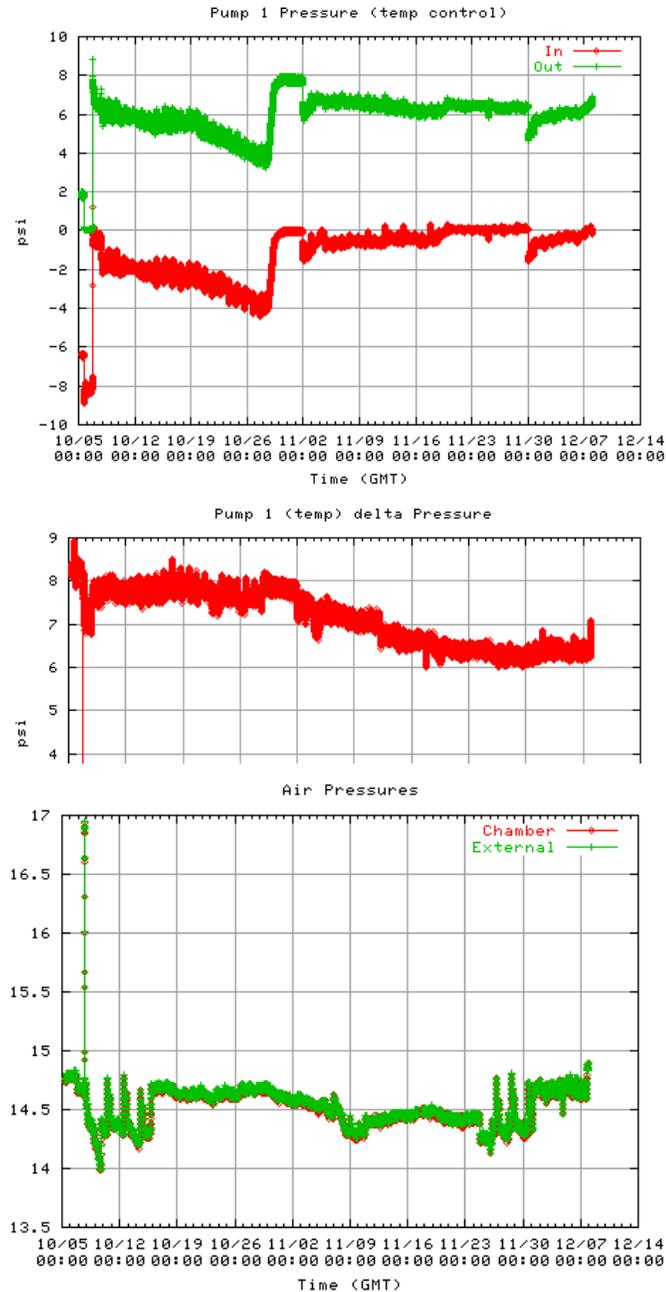


Figure 11. Pressure curves for 2 months operation on ISS.9A (launch STS-112, landing STS-113). The gauge pressures show diurnal changes due to heat loads changing daily (day/night cycle), as well as differential pressure decay over time. The 'sudden' simultaneous changes of the gauge pressures at certain mission increments are not fully understood (i.e., they do not coincide with cabin pressure changes or large thermal changes).

The use of flexible 'soft' tubing as well as the expansion vessel somewhat limit the response to ambient pressure changes, for example, the cabin pressure reduction from 101 kPa to 70 kPa during an Extra-Vehicular Activity (EVA) is partially absorbed by the expansion of the tubing.

CONCLUSION

The use of liquid coolant circulation loops within the middeck locker-type payloads allows for efficient temperature control and heat transfer within highly integrated and 'cramped' assemblies. The use of liquid coolant circulation systems increases the complexity and risk when compared to simpler air-to-air heat pump designs, but enhances the capabilities of the life sciences payloads dramatically. The availability of coolant water on the International Space Station further enhances payload capabilities and helps reduce power consumption through more efficient heat transfer and reduces acoustic noise emissions through elimination of the forced convection cooling fans. The small available volumes and limited power typically prevent the integration of redundant systems, creating multiple single-point failure points, and requiring high reliability components. New ISS mission durations with continuous operation of up to years challenge the designer.

CONTACT

Dr. Alex Hoehn is the associate director of engineering of BioServe Space Technologies, a NASA Research Partnership (formerly: Commercial Space) Center, located at the University of Colorado, Aerospace Engineering Sciences, in Boulder. He can be reached at: BioServe Space Technologies - University of Colorado, 429 UCB, Boulder, CO 80309-0429, USA. Tel: +1-303-492-5875. Fax: +1-303-492-8883. email: alexander.hoehn@colorado.edu.

ACKNOWLEDGMENTS

This research and space flight program is supported by NASA grants: NASA-MAR: NCC8-131 (NASA MSFC cooperative agreement) and NASA-NCC2-5290 (NASA Ames cooperative agreement). The authors wish to thank Brian Biesterfeld for the development of the proportional current TEC controller. Theoretical analysis of the thermoelectric modules was performed using the Melcor design software package Aztec.

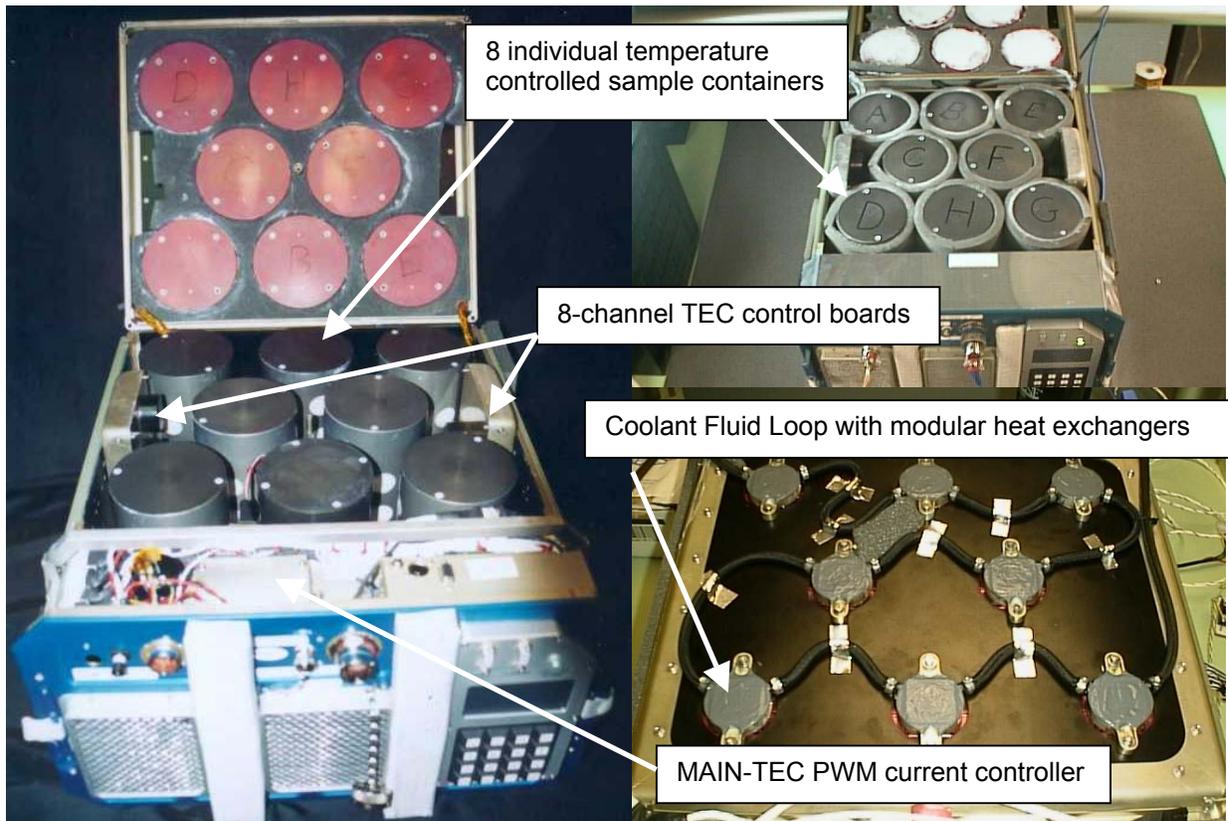


Figure 12. This Cell Culture / Space Biology Incubator utilizes the same coolant loop components to provide 8 individually temperature-controlled zones. Each zone has its own thermoelectric heat pump. The waste heat from each thermoelectric heat pump is transferred into the coolant fluid loop, which is located on the outside of the lid and base within the thermal insulation foam (bottom right). The coolant transports the heat to the front of the payload, where the main heat pump rejects the heat to cabin air. This two-stage heat pump approach was implemented to provide temperature control from 4°C to 37°C for each sample containment cylinder at a wide range of ambient crew cabin temperatures.

REFERENCES

1. Ebm Industries, Inc., 100 Hyde Road, Farmington, CT 06034, USA. <http://www.ebm.com/home.html>.
2. Hoehn, A., Clawson, J., Geissinger, T., Kalinowski, W., Pineau, J., Scovazzo, P. (2003): "Design, Testing and Operation of Porous Media for Dehumidification and Nutrient Delivery in Microgravity Plant Growth Systems". SAE-paper 03ICES-157(155), 32nd International Conference On Environmental Systems (ICES), July 2003, Vancouver, Canada
3. Hoehn, A., Freeman, J.B., and Stodieck, L.S. (1999). "Incubator Designs for Space Flight Application - Optimization and Automation". SAE paper 1999-01-2177, 29th International Conference on Environmental Systems 1999, Denver, Colorado, USA, July 1999.
4. Hoehn, A., Clawson, J.M., Heyenga, A.G., Scovazzo, P., Sterrett, K.S., Stodieck, L.S., Todd, P., and Kliss, M.H. (1998). Mass transport in a spaceflight plant growth chamber. *SAE Technical Paper Series 98-1553*. SAE International, Warrendale, PA.
5. Hoehn, A., Kliss, M.H., Lutges, M.W., Robinson, M.C. and Stodieck, L.S. (1994) P-MASS and P-GBA: Two New Hardware Designs for Growing Plants in Space. *24th International Conference on Environmental Systems (ICES)*. SAE-94-1545.
6. Horner, M.B., Ashraf, H., Hanna, D.S., Hoehn, A. (1997): "Optimizing and Integrating Thermal Control Systems for Space Life Sciences Hardware". SAE paper 97-2543, *27th International Conference on Environmental Systems (ICES)*, July 14-17, 1997, Lake Tahoe.
7. Melcor, 1996 "AZTEC - A Thermoelectric Design / Selection Guide" was developed for MELCOR by: ScillaSoft Consulting, 102 Holiday Court, Mount Laurel, NJ 08054, 1996. Free download at: <http://www.melcor.com/>.
8. Micropump Inc., 1402 NE 136th Avenue, Vancouver, WA 98684-0818, Office Phone: +1 (360) 253-2008, www.micropump.com.
9. Scovazzo, P., Illangasekare, T.H., Hoehn, A., and Todd, P. (2001): "Modeling of two-phase flow in membranes and porous media in microgravity as applied to plant irrigation in space". *Water Resources Res.* 37(5): 1231-1243.

10. R-Theta, 6220 Kestrel Road, Mississauga, Ontario, Canada, L5T 1Y9, <http://www.r-theta.com/>.
11. Servometer Precision Manufacturing Company, LLC, 501 Little Falls Rd., Cedar Grove, NJ 07009, USA, <http://www.servometer.com/>.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

A	Ampere.
cm	Centimeter.
CGBA	Commercial Generic BioProcessing Apparatus, a series of middeck-locker based spaceflight incubators, designed and operated by BioServe Space Technologies, a NASA CSC.
COTS	Commercial of the Shelf.
CSC	NASA Commercial Space Center, now Research Partnership Center (2003).
EVA	Extra-Vehicular Activity.
g	Earth gravity, 9.81 ms^{-2} .
H ₂ O	Water.
I	Current.
ICM	Isothermal Containment Module, a middeck locker based spaceflight incubator.
I/O	Input / Output.
ISS	International Space Station.
k	thermal conductivity in $\text{W m}^{-1} \text{K}^{-1}$.
KSC	NASA Kennedy Space Center.
L	Liter.
Lbm.	Pound mass (1 kg = 2.2 lbm.).
MDLE	Middeck Locker Equivalent, maximum internal dimensions are D20.320"xW17.337"xH9.969".
MDP	Maximum Design Pressure.
mL	Milli-liter.
MOP	Maximum Operating Pressure.
N/A	not available.
NASA	National Aeronautics and Space Administration.
PID	Proportional Integral Differential (Controller).
PGBA	Plant Generic BioProcessing Apparatus.
PGC	Plant Growth Chamber.
psi	Pounds per Square Inch pressure.
PWM	Pulse Width Modulator (Controller).
rH	Relative humidity.
STS	Space Transportation System.
T	Temperature.
TEC	Thermoelectric Controller or Cooler.
VDC	Volts Direct Current.
W	Watt.