*SAE TECHNICAL
PAPER SERIES*

1999-01-2177

Incubator Designs for Space Flight Application Optimization and Automation

A. Hoehn, J. B. Freeman, M. Jacobson and L. S. Stodieck
BioServe Space Technologies – University of Colorado

*The Engineering Society
For Advancing Mobility
Land Sea Air and Space®
INTERNATIONAL*

**29th International Conference
on Environmental Systems
Denver, Colorado
July 12-15, 1999**

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

The appearance of this ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition, however, that the copier pay a $7.00 per article copy fee through the Copyright Clearance Center, Inc. Operations Center, 222 Rosewood Drive, Danvers, MA 01923 for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Sales and Satisfaction Department.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

GLOBAL MOBILITY DATABASE

All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191
Copyright 1999 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Group.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Meetings Board, SAE.

Printed in USA

1999-01-2177

Incubator Designs for Space Flight Application Optimization and Automation

A. Hoehn, J. B. Freeman, M. Jacobson and L. S. Stodieck
BioServe Space Technologies – University of Colorado

ABSTRACT

Spaceflight life sciences research typically requires accurately controlled thermal environments to help isolate the effects of gravity on the development of living organisms or biochemical reactions. Given the power, mass and volume constraints of spaceflight experimental hardware, highly efficient temperature control is necessary to provide scientists with adequate tools for their research. The main focus is on 3 incubators, designed by the authors, for commercial space biotechnology research. While the simplest incubator allows for highly accurate temperature control above ambient only, the more sophisticated units use temperature-controlled liquid circulation systems for above and below ambient temperature control. The latest design variation provides eight individually controlled sample containers, where temperatures can be maintained constant or profiled for automated experiment initiation and termination, or preservation of samples on orbit.

INTRODUCTION

For the purpose of this paper, we will refer to any temperature-controlled containment and processing environment as an ‘incubator’, independent of the requirement to ‘heat’ or ‘cool’ (refrigerator) the environment with respect to the ambient environment. Robust temperature control is mandatory, both with respect to temperature accuracy as well as temperature consistency. Temperature fluctuations may have a large enough influence on the process being investigated in microgravity that isolation of gravity as the sole independent variable between flight and corresponding ground control samples may become impossible. In addition to temperature control, spaceflight incubators also typically provide the capability to perform process controls, such as experiment activation and termination, and often process monitoring through experiment-specific instrumentation such as optical density, pH, electric conductivity, or gas composition.

Maintaining temperatures above ambient (‘heating’) can be accomplished with fairly simple and power-efficient resistive heating elements. Uniform heating can be accomplished using large surface area film heaters placed around the entire incubator volume, minimizing or eliminating temperature gradients throughout the sample volume.

Achieving temperatures below ambient (‘cooling’) requires more complex engineering solutions employing heat pumps and associated support hardware. Design solutions are complicated due to spaceflight constraints such as mass, power and volume limits, as well as microgravity and safety considerations. Achieving an acceptable design with minimum temperature gradients within the incubator becomes even more challenging when heat sources within the incubator have to be accommodated. The dissipation of heat from within the incubator, from instrumentation, internal light sources or sample processing hardware, will induce temperature gradients across the incubator volume and the samples. Similarly, the localized geometry of the heat pump and heat transport in the coolant media will result in temperature gradients affecting the quality of the incubator (Table 1).

Table 1: Thermal Characteristics of Incubator Performance

- Setpoint accuracy (accuracy and calibration of sensor).
- Setpoint consistency (quality of control system).
- Thermal response time (heat capacity vs. heat pump capacity).
- Incubator-internal temperature gradients (heat sources, geometry, size of controlling heat exchanger).
- Setpoint range capability (limited by heat pump capacity and depends on ambient / setpoint temperature).

INCUBATOR DESIGN

The basic incubator consists of the sample volume, insulation between the sample volume and the ambient environment, a heat pump (heater or cooler or both), and some sort of thermal distribution system. Laboratory incubators attempt to minimize gravity-dependent vertical temperature gradients by adding forced convective air circulation throughout the incubator volume (fan). Air circulation can also minimize temperature gradients from heat sources throughout the incubator volume. Sufficient void spaces and air passageways are therefore necessary to allow for sufficient air circulation within the incubator, a luxury for the often ‘cramped’ spaceflight incubators (Figure 6). The temperature consistency can be further improved by using a water-jacketed incubator. The heat capacity of the water surrounding the incubator volume also provides some buffer capacity in case of power interruptions.

SPACE FLIGHT CONSTRAINTS – The ‘typical’ spaceflight experiment accommodation aboard the US Space Shuttle is the so-called Middeck Locker, a ‘box’ with usable internal volume of roughly W44.1cm x H25.3cm x D51.6cm (W17.377” x H9.969” x D20.320”, see Figure 1). Any ‘experiment insert’ inside a middeck locker has to be mechanically (vibration) isolated by a minimum of 1.27 cm foam (0.5”), further reducing the usable volume. The maximum power available to such a middeck locker is normally limited to 130 Watts at 28 VDC. This limit is not only driven by the available electrical power, but also by limitations on how to thermally dissipate that electric power once it is converted into ‘waste heat’. Limits on the maximum allowable noise emission, and the maximum allowable air exhaust velocities typically prevent the rejection of more heat using forced convection cooling fans. Water-cooling is not available to middeck lockers aboard the Space Shuttle. The maximum mass allowance for a locker insert is typically 24.5 kg (54 lbm.), limited additionally by the location of the center of gravity. An example of such a middeck locker-based incubator insert can be seen in Figure 1.

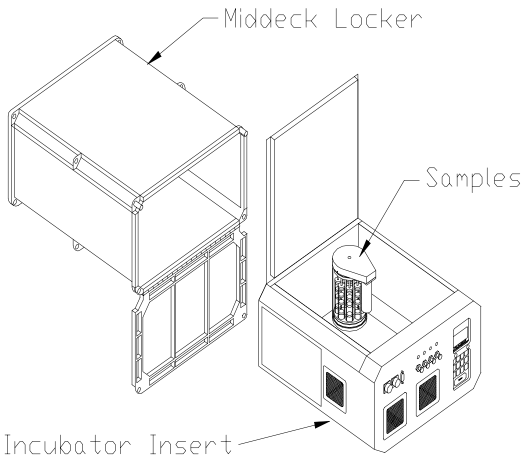

Figure 1. Middeck locker (left) and a typical spaceflight incubator payload ‘insert’ (BioServe’s Isothermal Containment Module, ICM, shown).

INSULATION – To minimize the required power for maintaining a desired setpoint temperature different than the ambient temperature (the Shuttle cabin temperature varies from typically as low as 20°C to as high as 32°C), the incubator volume requires thermal insulation. The spaceflight ‘standard’ foam, satisfying off-gassing, flammability, mechanical vibration isolation and thermal requirements, has been Pyrell‘, a Polyurethane foam with a thermal conductivity of kª0.035 W m^{-1} K^{-1}. Much of the usable incubator volume inside the middeck locker is retained since this foam can be used for both the required mechanical vibration isolation and the thermal insulation. Thermal properties could be improved by using vacuum-type insulators such as vacuum panels [1] or Aerogel [2, 3] panels. While advertised performance data for Aerogel panels suggest a potential k-value of as low as 0.003 W m^{-1} K^{-1}, a more realistic and achievable value could be around ª0.017 W m^{-1} K^{-1}, accounting for edge effects and deterioration of the insulating vacuum over time [2]. Such a vacuum insulator would still provide twice the insulating value for the same thickness as the Pyrell‘ foam insulation. However, vibration isolation foam would still have to be added to these vacuum panels to meet the mechanical interface requirement for vibration dampening.

HEAT PUMP – Assuming the typical incubator volume available with each Generic BioProcessing Apparatus (GBA) as an example, one can estimate the necessary heat pump capacity (heat or cool) for typical ambient Space Shuttle temperatures. With a usable internal incubator dimensions of W38.8cm, H19.7cm, D34.5cm (W15.275” x H7.75” x D13.579”, 26.3 liters), the incubator requires ª0.56 m^2 of insulation. With desired life sciences sample temperatures ranging from typically 4°C to 37°C, one can estimate the heat pump capacity, $Q_{pump.}$

$$Q_{pump} = k \bullet t^{-1} \bullet A_{insul} \bullet \Delta T$$

$\Delta T = T_{incubator} - T_{ambient}.$
k thermal conductivity
t thickness of insulation
A_{insul} surface area of insulation (1)

This is graphically represented in Figure 2 as a function of cabin temperature and a fixed insulation thickness of 1.27cm (0.5”) as used with the GBA payload family. For example, at a cabin temperature of 30°C and a desired incubator temperature of 4°C, the heat pump has to transport ª40 watts of parasitic heat.

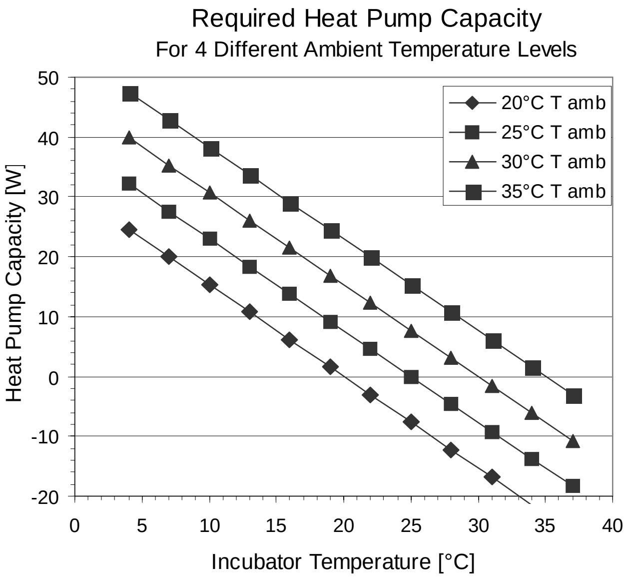

Figure 2. Required heat pump capacity for the Isothermal Containment Module (ICM) incubator, using 1.27 cm (0.5”) thick Pyrell foam insulation at four typical Shuttle ambient temperatures (20-35°C).

HEAT PUMP OPTIONS – The simplest ‘heat only’ incubator would employ large-sized foil heating strips to maintain an incubator temperature above ambient. These foil heaters can be located on all 6 sides of the incubator volume, covering the entire surface area, virtually guaranteeing temperature-gradient free (i.e., isothermal) sample temperatures at steady state, as long as no internal heat sources are present in the sample volume. When an incubator must also cool the sample volume below ambient temperatures, thermoelectric controllers (TEC) are typically used as heat pumps. No moving parts, no toxic or hazardous process fluids, and the high reliability offered with solid state technology make TECs a suitable candidate for spaceflight applications. Optimizing the use of TECs for spaceflight conditions to obtain the most efficient heat pump capacity for the consumed electric power is challenging. For the above-mentioned incubator at 4°C internal and 30°C ambient temperature, 40 Watts of heat have to be pumped (Figure 2). Electric power expenditure for this realistic 40-Watt heat pump example can vary widely from ª49 Watts (most efficient) to as high as 127 Watts for the least efficient system as depicted in Figure 3. The optimum design (least power) uses a total of 8 thermoelectric heat pumps, with two electrically parallel strands of 4 modules each in serial electrical connection (Figure 4).

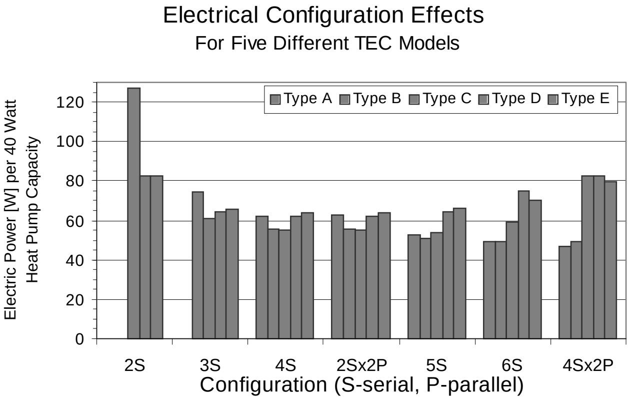

Figure 3. Electric power requirements for a thermoelectric, 40 Watt heat pump. The layout geometry (combiations of electrically serial or parallel) and pump characteristics (type A-E) can dramatically affect the total power requirements.

The design options graphed in Figure 3 favor multiple TEC module configurations with a combination of serial (S) and parallel (P) electric connection, allowing the use of higher supply voltage and lower currents. The use of unconditioned 28 VDC, supplied directly by the Space Shuttle, eliminates power losses in voltage converters. The lower electric currents reduce line losses and facilitate electronic component selection at low currents. A serial / parallel combination of TECs also enhances reliability in case one of the modules fails, providing some redundancy at reduced performance with the remaining string (Figure 4). The most efficient design (Figure 3) operates the TECs at approximately 50% of the manufacturer’s maximum allowable power (for more details, see [4]).

Table 2 further highlights the effects of electric arrangement of the thermoelectric coolers. For Table 2, one model of a TEC module is arranged in 6 different electrical configurations, all designed to pump 40 Watts of heat from a 4°C incubator volume to a 30°C heat exchanger (hot side) temperature. Each configuration has a different power requirement and a different efficiency. For space applications, the most efficient configuration is preferred, while another arrangement may be simpler and more economical if power efficiency is not the primary criteria. For example, the configuration with 4 serial modules (4S) nearly allows for the direct, unconditioned use of the 28 VDC Space Shuttle power, at minimum current (2.2 Amp.) and minimum power of approximately 54.9 Watt. The least efficient design layout, using 2 of the same modules in series (2S), would need 127.1 Watts to pump the same 40 Watts of heat.

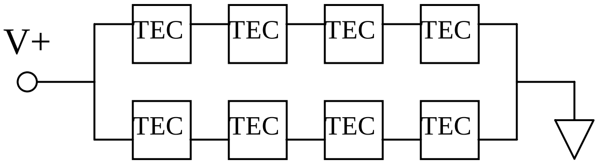

Figure 4. Example of electrical configuration of TECs. Using a combination of two parallel sets of four TECs in series (4Sx2P) still offers some heating or cooling if one TEC malfunctions.

Table 2. Electric power requirements for a 40 Watt heat pump as a function of serial (S) and parallel (P) electric configuration for a selected thermoelectric module, Type C, graphed in Figure 3. (Efficiency = Heat / Power.)

Units	**Config**	**Volt**	**Amp.**	**$P_{electric}$**	**Effic.**
2	2S	26.5	4.8	127.1	31.5%
3	3S	22.9	2.7	61.1	65.5%
4	4S	25.4	2.2	54.9	72.9%
4	2Sx2P	12.7	4.3	55.0	72.7%
5	5S	28.5	1.9	54.2	73.8%
8	4Sx2P	19.3	3.1	59.4	67.3%

HEAT REJECTION – Operating the thermoelectric coolers as well as the data acquisition and control system requires the rejection of not only the ‘parasitic’ heat conducted into the incubator, but also the ‘waste heat’, typically assumed to be equal to the electric power consumption [5]. If the incubator is operated below ambient temperatures, this additional heat can range from 25 to 47 Watt, depending on ambient cabin temperature and 1.27 cm insulation (Figure 2). For middeck locker type payloads, the only heat sink available is the cabin air, relying on forced convection from payload-internal cooling fans and air heat exchangers. With redesigns under way for Space Station operation, water-cooling as well as orbiter-provided avionics cooling air will become available. Heat transfer to cabin air is limited by the maximum allowable acoustic emissions associated with air flow and cooling fans, as well as the maximum allowable air exhaust velocity (crew discomfort) and air exhaust temperature (crew safety). Even with highly efficient air heat exchanger designs (minimum mass, maximum heat transfer) and fans designed for extreme low noise emission, the maximum heat rejection capabilities remain limited to approximately 130 Watt (single middeck locker) and 230 Watt (double middeck locker).

Surprisingly, thermal design seldom receives the attention necessary for a successful design, and many spaceflight experiment designs to date have experienced thermal problems on orbit, resulting in over-heating or the inability to maintain the desired setpoint temperature. Successful thermal designs typically are fully integrated in the overall payload design from the very beginning of the design process, designing the payload around the thermal system. Some key design features of successful thermal designs include: placing the cooling fans in locations that reduce the pressure drop through the cooling passage, keeping fans and their noise-emitting blades out of ‘line of sight’ to minimize noise emissions at maximum air flow, and using advanced designs for both fans (high air flow at high dead head pressures, low noise at NASA critical frequencies) and heat exchangers (lightweight, low thermal resistance, optimized geometry).

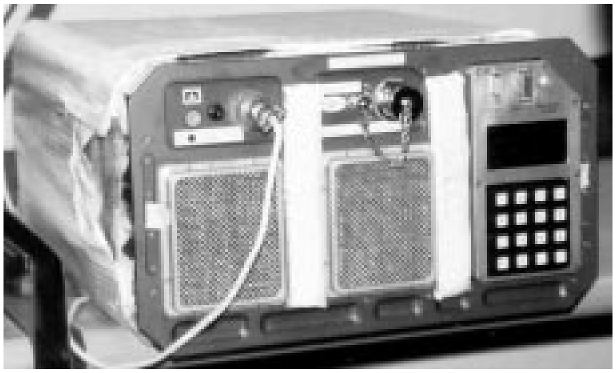

Figure 5. Air inlet, air outlet and computer interface of the Isothermal Containment Module (ICM-V2), a middeck locker insert incubator (6°C → 37°C).

TEMPERATURE UNIFORMITY – The ideal incubator should provide an isothermal environment throughout the entire incubator volume, and the actual sample temperature at steady state should be identical to the desired setpoint temperature. However, depending on how the temperature control system and the heat pump(s) are implemented, there may be temperature gradients across the incubator volume (Table 3). Any internal heat sources, such as instrumented samples, light sources, or powered sample manipulation hardware, will create temperature gradients. The effect of localized heat sources or radiant heat transfer can be minimized through additional heat transfer pathways within the incubator volume, such as forced convective mixing (fans), spot-cooling of heat sources, or adding additional material for heat conduction to the temperature controlled walls or the heat pump of the sample volume.

Table 3: Causes of Temperature Gradients

- Heat sources (instrumentation, process hardware)
- Radiative heat transfer (light sources)
- Localized heat pump geometry (size, location)
- Heat Transport (necessary for conduction, convection)

Internal mixing fans, as used in laboratory incubators, are not feasible in most spaceflight applications, since the experimenters tend to fill the available incubator volume with as many samples as possible (Figure 6). This leaves no space for air flow, and the minimal potential air flow would still not relieve large temperature gradients.

While a single thermoelectric heat pump with an air heat exchanger and internal circulation fan carries very little design risk, the expected performance of such a convection-based incubator will be very poor. Large temperature gradients within the incubator, insufficient temperature control for samples far away from the heat pump, inability to use the available volume efficiently, and poor setpoint accuracy will make experimental evaluation very difficult.

The authors therefore pursued a design that was to reduce temperature gradients throughout the incubator volume and to allow for a densely packed experiment package to be used inside the sample volume. The result was a water-jacketed incubator as shown in Figure 6.

Figure 6. Incubator filled with experimental samples for the STS-95 flight. To avoid thermal gardients across the incubator volume, all walls are water cooled and material thickness of sample containers are increased to provide thermal pathways.

The Isothermal Containment Module (ICM, Figure 5 and 6) uses a temperature-controlled coolant circulation system. The fluid (distilled water with alcohol additive) is temperature-controlled using thermoelectric modules and liquid heat exchangers. The temperature-controlled coolant is circulated through loops along all walls, creating a well-controlled barrier between the samples and the exterior. Foam insulation is provided between the loops and the surrounding middeck locker for thermal insulation and vibration isolation. One can quickly show that, without internal heat sources (lamps, instrumentation), and with all walls at essentially constant and uniform temperature, temperature gradients within the sample volume are minimal. The only potential cause of temperature gradients is the collection of heat by the coolant. At steady state, the water collects all of the heat introduced into the sample volume. This heat causes the temperature of the water to increase as it flows through the water jacket. The change in temperature of the water is a function of the mass flow rate through the jacket (Figure 7), as well as the heat removed from the sample volume. Appropriate geometry and routing of coolant loops, together with highly conductive incubator walls, will help to minimize the effect on the sample temperature deviation or gradient throughout the incubator. Coolant flow through parallel loops rather than through a single, sequential loop along all walls was evaluated. However, operational considerations, such as filling and priming of the loops, the removal of trapped air bubbles, the risk of having individual loops being blocked, and especially the effort necessary to guarantee uniform flow through each loop, all indicated that parallel loops would not be the best way to overcome or to minimize potential thermal gradients.

A water-jacketed design, such as used in high-performance laboratory incubators, first appears heavy. However, using a ‘snaked’ aluminum tube, bonded to the aluminum incubator walls, allowed for a compromise, where water and tube mass, as well as temperature gradients between individual loops were traded off. Figure 7 gives the rise in temperature along the tubing for various flow rates, which indicates the capacity for the water-jacketed design to reduce temperature gradients within the incubator. Related design risks remain, however, such as the fact that pumping water continuously leads to issues of fluid containment, seal deterioration, and potential corrosion. A typical Space Station ‘tour of duty’ of 120 days (2880 hours) could reach the life time limits of rotary seals, for example. The loss of the pump, a coolant leak or line blockage (freezing, ‘pinched’ lines, air entrapment) will all disable the incubator. For contingency purposes, the water heat exchanger of the ICM-series incubators was mounted against the front incubator wall. In case of coolant circulation failure, temperature control through conduction may limit adverse impacts on the science for samples in close vicinity to the water heat exchanger. However, science would likely be lost for all those samples located further away from the heat exchanger due to poor temperature control.

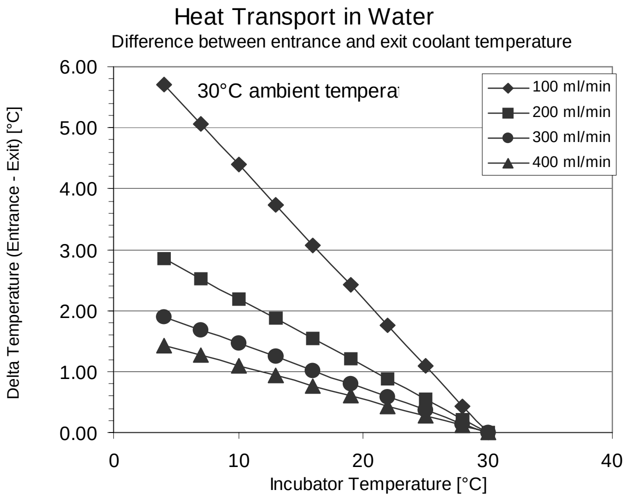

Figure 7. Temperature difference between water inlet and water outlet temperature (i.e., temperature gradient within the incubator) for the water-jacketed incubator. The gradient depends on the mass flow through the coolant loops ($DT = Q\ m_{dot}^{-1}\ Cp^{-1}$, where Q=heat flux, m_{dot}=mass flow rate, and Cp=specific heat).

AUTOMATION OF TEMPERATURE PROFILES – A majority of scientific experiments require the incubator to maintain a constant process temperature. Samples may be kept before and / or after the processing at storage and holding temperatures different than the process temperature. In an earth-based laboratory, a sample may be moved from the storage incubator (refrigerator, freezer) to the process incubator, where the sample is held for a desired period of time. After the experiment duration, the sample would either be analyzed or again stored at preservation temperature. The temperature transitions between storage and process temperature may need to be controlled actively to prevent damage from temperature shock. An automated system allowing pre-programmed temperature changes between storage, process and preservation temperatures is highly desirable for spaceflight applications, where space is at a premium and the crew is not always available for such a sample change-out between refrigerator and incubator, especially during early or late phases of a Space Shuttle flight. The thermal mass (Cp*DT) of the samples and their containment, as well as the heat pump capacity and the heat transfer between incubator and sample, will limit the speed at which the temperature can be changed between two setpoints.

CASE STUDY – For a NASA Ames supported research project, stacks of Petri dishes with fruit fly larvae are kept in a dormant state at 12°C during sample loading, payload installation and launch. As soon as possible after achieving microgravity, the samples are warmed to the process temperature of 25°C at a rate of 6.5°C/hr. Eight different stacks of Petri dishes are maintained at the process temperature for different periods of time before the sample temperature is returned to 12°C to slow development of the fly larvae during landing and post-flight deintegration. Therefore, the larvae in each stack of Petri dishes develop for a different amount of time while in microgravity. Each stack contains eight Petri dishes with larvae beginning at 2 to 4 different stages of development, providing 20 independent data points for development in space.

A new incubator was developed (ICM-V3, Appendix 1) that allows such an experiment configuration in a single middeck locker, with fully automated sample processing (Figure 8). Each stack of Petri dishes is enclosed in a watertight, but gas-permeable aluminum tube assembly, fitted with thermoelectric coolers on each end. The temperature of each of these aluminum tubes (Gas Exchange Group Activation Pack, GE-GAP) can be accurately controlled. The waste heat from the thermoelectric coolers is transported by a liquid coolant loop to the front of the payload, where an additional set of thermoelectric coolers maintains a constant coolant temperature and transfers the heat to the cabin atmosphere (Figure 8 top). Each tube can be controlled to any temperature between 4°C and 37°C. Temperature transition between two setpoints for the Aluminum tube (GE-GAP) can be achieved within 15-30 minutes, however, the internal sample temperature lags behind due to the thermal mass of the agar-filled Petri dishes and the limited heat transfer between the samples (Polystyrene Petri dishes) and the actively temperature-controlled aluminum tube enclosure (GE-GAP).

TEMPERATURE RANGE – One should keep in mind that the achievable incubator temperature depends on the heat pump capacity and the difference between the incubator and the ambient temperature. Due to the often unpredictable range of ambient temperatures, sometimes between 20°C and 32°C, the incubator temperature performance cannot be expressed in an absolute temperature, but only in how far below or above ambient temperature the incubator can maintain a desired setpoint (Table 4). Should the orbiter or space station ambient temperature rise (due to a system malfunction or limited performance), or the intake air temperature rises due to an adjacent ‘hot’ payload, the lowest possible incubator temperature at peak power will also rise. Prior to selecting a temperature profile for an experiment, one has to carefully verify sufficient performance safety margin under all possible environmental conditions. The example shown in Table 4 illustrates that the incubator capable of maintaining 8.4°C at 25°C ambient temperature will only be able to cool to 13.1°C as the ambient temperature rises to 30°C. With Shuttle temperatures typically ranging from 25°-32°C, the experimenter may not want to choose a setpoint below ª14°C for this model incubator to ensure accurate setpoint maintenance under fluctuating ambient temperatures.

Table 4. The lowest obtainable and maintainable incubator temperature depends on the ambient temperature. Parasitic heat transfer from the ambient into the incubator increases with increasing ambient temperature. Providing constant electric power to the thermoelectric coolers (17.4 Watt, 4 modules in series), the minimum obtainable temperature rises with the increasing ambient temperature. The increase in TEC efficiency at higher temperature increases the obtainable temperature differential between ambient and incubator temperature for the same electric power.

$T_{ambient}$	15°C	20°C	25°C	30°C	35°C
$T_{min\ incubator}$	-1°C	3.7°C	8.4°C	13.1°C	17.8°C
Q_c pumped	24.5 W	25.0 W	25.4 W	25.9 W	26.2 W
ΔT: $T_{amb} - T_{min}$	16°C	16.3°C	16.6°C	16.9°C	17.2°C

TEMPERATURE CONTROLLER – With a wide range of ambient and incubator setpoint temperatures, the temperature controller has to control the TEC current and vary the supply voltage or duty cycle to the thermoelectric coolers. To minimize the overall power consumption of the incubator, power conversion efficiencies of the controller have to be considered. Directly using the unconditioned 28 VDC Shuttle supply voltage and a simple on-off controller minimizes power conversion losses, but results in poor thermal efficiency, as the switched ‘OFF’ thermoelectric module acts like an ‘open refrigerator door’. A proportional controller that can control the current (and thereby voltage) to the thermoelectric modules at high conversion efficiencies allows for accurate temperature control using a proportional-integral-derivative (PID) control strategy. Obtainable power conversion efficiencies for an inductor-smoothed pulse-width-modulated (PWM) based system should be approximately 80%, but depend on the required duty cycle / power level when compared to the supply voltage. The PID controller is best implemented using software rather than hardware electronics due to the long time scales of integration (15 to 30 minutes) to reach steady state temperatures.

PROCESS CONTROL AND MONITORING – In addition to temperature control, it may be necessary to provide autonomous sample processing and data recording facilities within the incubator. The ICM-series incubators are controlled by a Pentium‘-based single board computer coupled with a separate analog and digital I/O board [6]. The digital outputs from the board switch solid-state relays to control power to different components of the payload. Additionally, an RS-485 addressable serial network allows the computer to communicate with microcontrollers of experiment-specific hardware within the sample volume. These microcontrollers can serve many functions such as: controlling motor-driven activation and termination, taking location-specific temperature measurements, and measuring other experimental variables such as pH and conductivity.

AUTOMATION – Experimenters typically desire the activation of their experiment as early and the termination as late as possible during a spaceflight. To provide the largest flexibility in experimental time line, the ICM-series incubators were fitted with an autonomous launch detection system (3-axis accelerometer and associated software) and, in most cases, motor-activated sample containers. Once a launch and subsequent microgravity environment have been verified, the samples are automatically processed by increasing the temperature to process levels or by activating the motor-driven sample injection system. Since the actual landing time is unknown prior to the mission due to possible delays or mission extensions, the crew can edit the computer-stored landing time to guarantee a timely experiment termination through sample preservation prior to the onset of gravity. An accelerometer-based system detecting the onset of gravity is not feasible to terminate samples before gravity effects alter the samples. All ICMs have data up- and downlink capabilities, but data links are not available in all orbiter locations and not during all mission phases. Data links within the Spacehab modules are currently not available during ascent and descent phases of the flight. The accelerometer-based launch detection system and pre-programmed landing times still provide the best compromise to maximize experiment time in microgravity.

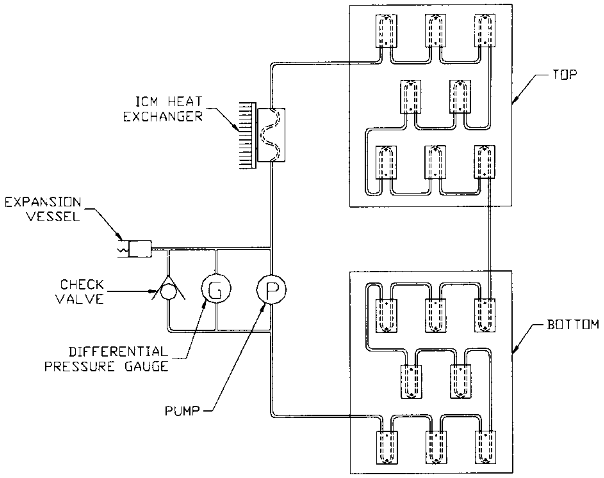

Figure 8. Incubator with 8 individually controlled sample containers. Each container has its own, independent proportional temperature controller and heat pump, allowing 8 different temperature environments simultaneously on the same space flight in the same incubator.

POWER LOSS – Continuos electric power is not available during transport to and installation into the Shuttle, or during transfer of experiments from the Shuttle to the Space Station. Battery backup for the entire payload during these times is not feasible. During power loss, it becomes necessary to minimize temperature deviations and to independently record actual temperatures of the samples. Increasing heat capacity and minimizing heat flux into the incubator are the best options to minimize temperature fluctuations during unpowered times. The addition of appropriately tailored phase change materials (PCM) can extend stable temperature durations dramatically. The addition of small, battery-powered independent temperature recorders provide a post-mission record of the actual temperatures while the main process control computer is offline.

GROUND CONTROL – Despite best efforts to design a perfect spaceflight incubator, the performance may be not quite as expected once on orbit. To minimize the impact on the science validity of mission-parallel ground control experiments, a ‘master-slave’ ground control system was developed for the ICM incubator series and the PGBA plant growth chamber operated by the authors [7]. The flight experiment is attempting to control to the desired temperature. Any deviation is sensed and recorded, and also transmitted to ground, if a data link is available. The ground control unit, an identical unit with identical samples operated on ground under 1-g conditions, will now be controlled to the actual on-orbit temperatures instead of the originally planned, desired fixed setpoint temperature. This ‘master-slave’ approach minimizes any differences between flight and ground control experiments and may allow the scientific use of experimental samples even if the setpoint temperature was not maintained as accurately as planned prior to the mission.

CONCLUSION

The capabilities of life sciences spaceflight incubators have steadily improved. Despite severe power, volume, and mass limitations, control capabilities and environmental characterization have been improved to the point that spaceflight incubators provide better experimental environments than are typically available in ground-based laboratories. Lessons learned from both ground based development work and on-orbit off-nominal conditions have been implemented in incubator design improvements. The operation of the International Space Station will further enhance operational capabilities by providing greater power and increased potential for heat rejection. Incubators will continue to play an important role not only for on-orbit experimentation, but especially for the temperature-controlled transport to and from the ISS.

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). Design and program support by NASA Ames for the latest incubator design (ICM-V3, Figure 8) is greatly appreciated (Debra Reiss-Bubenheim, Rudi Aquilina, Shawn Bengston, Steve Patterson).

The authors wish to thank Brian Biesterfeld for the excellent design work for the proportional current TEC controller, Dr. Kevin Gifford for the implementation and steady improvements on the exceptional software control code, and Jon Genova for the design and continued optimization of the Isothermal Containment Module incubator series.

Theoretical analysis of the thermoelectric modules was performed using the Melcor design software package Aztec [4].

REFERENCES

1. Glacier Bay: Barrier‘ High Performance Vacuum Insulation Products. Glacier Bay, Inc., 2845 Chapman St., Oakland, CA. 94601, http://www.glacier-bay.com/Insulation.htm.
2. Ernest Orlando Lawrence Berkeley National Laboratory: Silica Aerogels, http://eande.lbl.gov/ECS/aerogels/satoc.htm.
3. Aspen System Inc., 1996: Aerogel Super-Insulation, http://www.aspensystems.com/aerogel.html.
4. 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.
5. M.B. Horner, H. Ashraf, D.S. Hanna, A. Hoehn (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.
6. S. Kuzminsky (1997): “Linux Out of the Real World”. Linux Journal, Issue 39, July 1997, pp. 32-37, ISSN1075-3583.
7. A. Hoehn, J. Clawson, A.G. Heyenga, P. Scovazzo, K.S. Sterrett, L.S. Stodieck and P.W. Todd (1998). “Mass Transport in a Spaceflight Plant Growth Chamber“. SAE paper 98-1556, 28th International Conference on Environmental Systems ICES, 1998.
8. Flight Experiment Hardware for Space Life Sciences: http://www.reston.com/astro/hardware/flight.hardware/flight.hardware.html.
9. Spacehab, Inc.: Microgravity and Life Sciences Research Payloads and Facilities – Online Catalogue: http://www.spacehab.com/miclsrpf/index.htm.
10. NASA Ames: Life Sciences Laboratory Equipment (LSLE) On-line: http://lifesci.arc.nasa.gov:100/lsle/.
11. Links to Hardware Available for Space Research - Flight Hardware: http://peer1.idi.usra.edu/peer_review/nra/life_science/98_SCD_Section_4_websites.html.
12. Kennedy Space Center Life Science Flight Experiment Program Flight Hardware Handbook, point of contact: Guy Etheridge, NASA KSC, mail code NN-L1, Kennedy Space Center, Florida, 32899.

ADDITIONAL SOURCES

Characteristics of current and near-term spaceflight incubators have been collected from various sources [8, 9, 10, 11, 12] and are summarized in Appendix 1.

DEFINITIONS, ACRONYMS, ABBREVIATIONS

A	Ampere.
cm	centimeter.
C/RIM	Commercial Refrigerator Incubator Module.
CSC	NASA Center for Space Commercialization.
D	depth.
EVA	Extra-Vehicular Activity.
g	Earth gravity, 9.81 ms^{-2}.
GAP	Group Activation Pack.
GBA	Generic BioProcessing Apparatus, a series of middeck-locker based spaceflight incubators, designed and operated by BioServe Space Technologies, a NASA CSC.
GE-GAP	Gas Exchange Group Activation Pack.
H	height.
H_2O	Water.
Hr	hour.
ICM	Isothermal Containment Module, a middeck locker based spaceflight incubator.
I/O	Inout / Output.
ISS	International Space Station.
k	thermal conductivity in $W\ m^{-1}\ K^{-1}$.
KSC	NASA Kennedy Space Center.
Lbm.	Pound mass (1 kg = 2.2 lbm.).
LED	Light Emitting Diode.
MDLE	Middeck Locker Equivalent, maximum internal dimensions are D20.320”xW17.337”xH9.969”.
N/A	not available.
NASA	National Aeronautics and Space Administration.
OSRF	Oceaneering Spacehab Refrigerator Freezer.
P	parallel (electric connection).
PCM	Phase Change Material.
PID	Proportional Integral Differential (Controller).
PGBA	Plant Generic BioProcessing Apparatus.
psi	Pounds per Square Inch pressure.
PWM	Pulse Width Modulator (Controller).
rH	relative humidity.
RIM	Refrigerator Incubator Module.
S	serial (electric connection).
STS	Space Transportation System.
T	Temperature.
TEC	Thermoelectric Controller or Cooler.
UAB	University of Alabama at Birmingham.
US	United States of America.
VDC	Volts Direct Current.
W	Width or Watt.

Appendix 1

	RIM [8], [11]	**C/RIM** **UAB** [8], [9], [10], [12]	**GBA_INC** **BioServe Space Technologies**	**GBA_ICM V2** **BioServe Space Technologies**	**GBA_ICM V3** **BioServe Space Technologies**	**OSRF** **Oceaneering / Spacehab** [9]
Designated Carrier	Shuttle	Shuttle	Shuttle	Shuttle / ISS	Shuttle / ISS	ISS
Total Payload Mass	< 72 lbm.	< 72 lbm.	< 72 lbm.	< 72 lbm.	< 72 lbm.	120 lbm
Payload Power	N/A (<130 Watts)	N/A (<130 Watts)	35 Watt (at 37°C fixed)	35 – 130 Watt (setpoint dependent)	35 – 130 Watt (setpoint dependent)	380 Watt (freezer) <75 Watt (refrigerator)
Payload Size	1 MDLE (locker insert)	1 MDLE (locker insert)	1 MDLE (locker replacement)	1 MDLE (locker insert)	1 MDLE (locker insert)	2 MDLE (locker replacement)
Exterior Payload Dimensions	17.377" wide 9.969" high 20.32" deep	17.377" wide 9.969" high 20.32" deep	17.377" wide 9.969" high 20.32" deep	17.377" wide 9.969" high 20.32" deep	17.377" wide 9.969" high 20.32" deep	18.12" wide 21.55" high 20.56" deep
Flight Readiness	Flown	Flown (>40 missions)	Flown (>8 missions)	Flown (6 missions)	STS-93	Flown
Interior Incubator (Sample) Dimensions	N/A	10.19" wide 6.79" high 16.5" deep	15.275" wide 7.75" high 13.579" deep	15.275" wide 7.75" high 13.579" deep	15.275" wide 7.75" high 13.579" deep	N/A
Incubator Sample Volume	N/A	18.6 liter	26.3 liter	26.3 liter	26.3 liter	50 liters
Sample Mass Capacity	N/A	13 kg (28.5 lbm.)	9.7 kg (21.4 lbm.)	14.0 kg (31.0 lbm.)	14.0 kg (31.0 lbm.)	18.1 kg (40 lbm.)
Levels of Containment provided by Incubator	0	0	0	0	0	2
Temperature Control	Thermoelectric	Thermoelectric	Resistive Heater	Thermoelectric	Thermoelectric	Thermoelectric
Temperature Range	0°C → 40°C	4°C → 40°C	37°C	6°C → 45°C	6°C → 45°C	-22°C → +40°C
Setpoint Accuracy / Steps		±0.5°C	±0.25°C	±0.1°C	±0.1°C	N/A
Temperature Uniformity	Large gradient	Large gradient	< 0.5°C	< 0.5°C	< 0.5°C	N/A
Temperature Adjust and Profile capacity	Manual potentiometer	Computer based Temperature profiles	Fixed (potentiometer)	Computer-based temperature profiles	Computer-based temperature profiles	N/A
Heat Pump Capacity		20-25 Watt	28 Watt (heat)	≈ 40 Watt cooling	≈ 40 Watt cooling	N/A
Internal Lights	None	Custom, or Red LED	None	Fluorescent or Red LED	Fluorescent or Red LED	N/A
Atmosphere Control: CO2	None - ambient	None – ambient	None – ambient	None – ambient	None - ambient	None - ambient
Atmosphere Control: O2	None – ambient	None – ambient	None – ambient	None – ambient	None – ambient	None – ambient
Atmosphere Control: rH	None – ambient	None – ambient	None – ambient	None – ambient	None – ambient	Desiccant pack
Internal Power to Samples	None	0.8A @ 24-32 VDC	None	≈ 20 watt continuous	≈ 5 Watt continuous	N/A
Launch detection	N/A	N/A	N/A	3-axis accelerometer (launch and landing)	3-axis accelerometer (launch and landing)	N/A
Sample Activation	Manual - Astronaut	Manual – Astronaut	Manual – Astronaut	Automatic - Motor	Automatic - Motor	N/A
Process Monitoring	N/A	N/A	Optical density	Optical density, pH, EC, temperature, O2	Optical density, pH, EC, temperature, O2	N/A

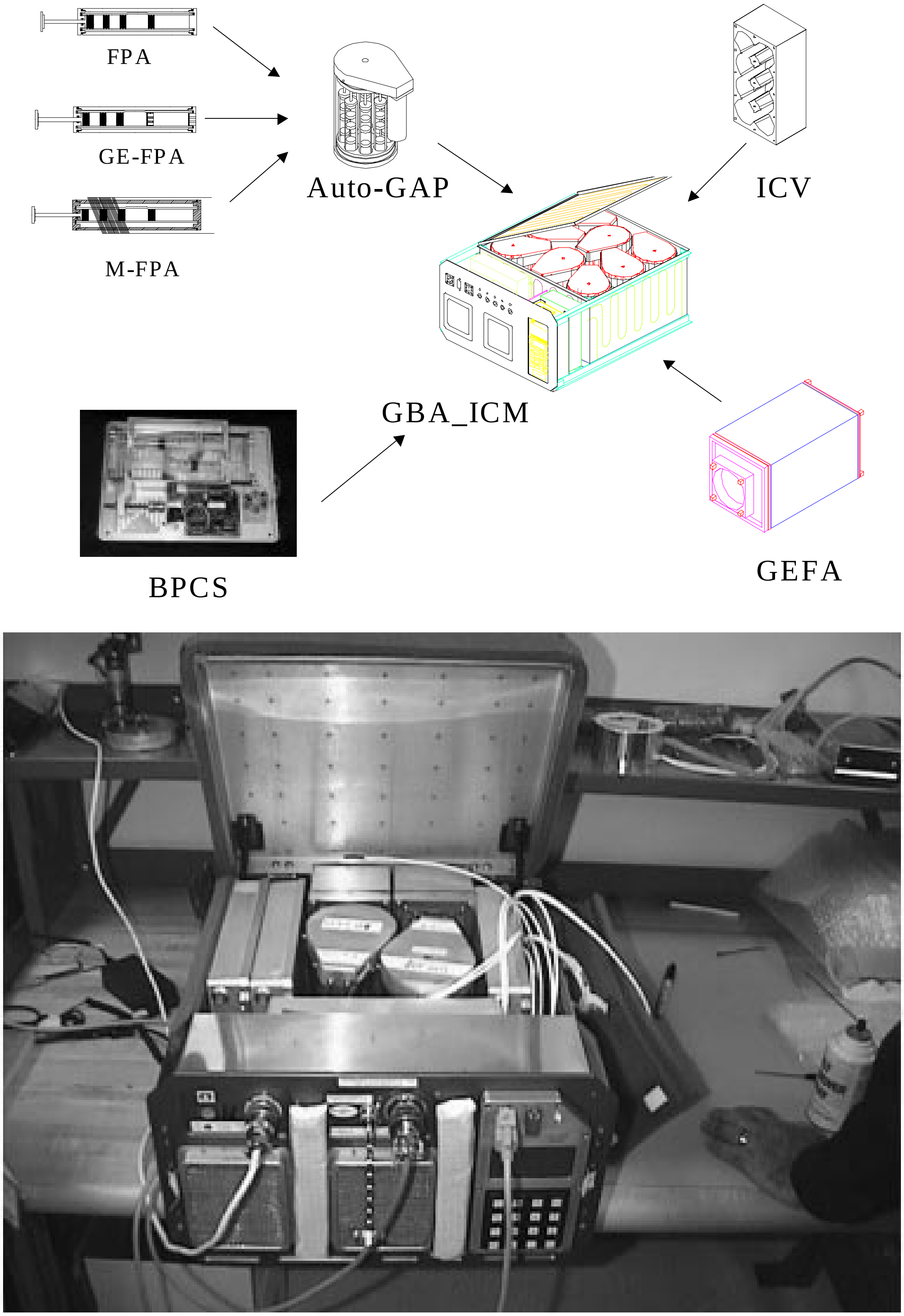

Figure 9.The CGBA Hardware Complement, showing the ICM incubator and a variety of potential experiment sample containment hardware. Samples can be contained inside the Fluid Processing Apparatus (FPA) and the Group Activation Pack (GAP) sample containment hardware. GAPs are automatically activated with a motor drive (Auto-GAP) once on orbit. Examples of other experiment-specific containment hardware include the Gas Exchange Fermentation Apparatus (GEFA – liquid and solid fermentation), the Illuminated Culture Vessel (ICV – plant tissue cultures under red LED light), and the automated BioSpace Protein Crystallization System (BPCS). All sample containers (GAP, FPA, ICV, GEFA, BPCS) are stored inside the temperature-controlled Isothermal Containment Module (ICM) cooler / incubator facility. The individual experiment assemblies are controlled using an RS-485 multidrop control network.