PGF-SP CDR
Part Two

Prepared by: Bionetics

Date:09/09/2002

Agenda

Part Two

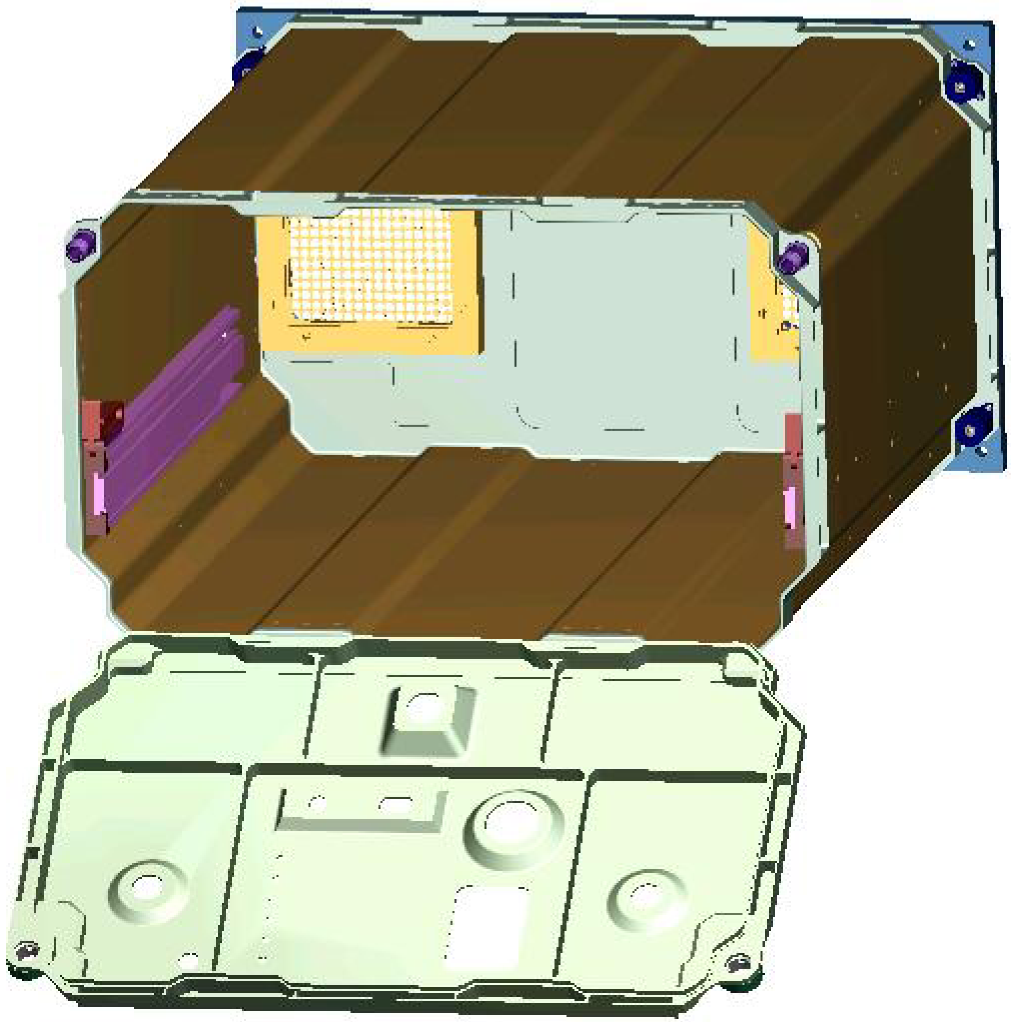
- Subsystem Design and Analysis 12:30 - 4:30
  - Single Locker Design
  - Double Locker Design
  - Tray Insert Assembly
  - Plant Growth Chambers
  - LED Light Module
  - Air Filtration System

  Day Two 8:15 - 9:15
  - Electronic Control System
  - Front Interface Panel
  - Green Fluorescent Protein Imager

Subsystem Design

APML Design

- Structural Interface to Middeck and Express Rack
- EMI and Environmental Enclosure
- Drawer Slides to allow for removal of TIA
- Rear cooling vents



APML Requirements

- Safety Critical Structure
- Contain and support payload in Middeck launch and landing environments and ISS on-orbit environment
- Prevent air leakage between avionics and cabin air in Middeck
- Allow easy on-orbit access to experiment
- Allow for status and power control at front panel
- Act as EMI/EMC enclosure with front door closed

APML Interfaces

- Middeck/VPMP mounting features
- Middeck/VPMP air inlet/outlet
- Express Rack mounting features
- Express Rack air inlet/outlet
- Tray Insert Assembly/drawer slides
- IVA Handles
- Crew
- Door mounted assemblies
  - Front Interface Board/Data Connectors
  - Main Power Connectors/Main Power Breaker
  - MTL quick disconnects
  - Nutrient Reservoirs

APML Goals

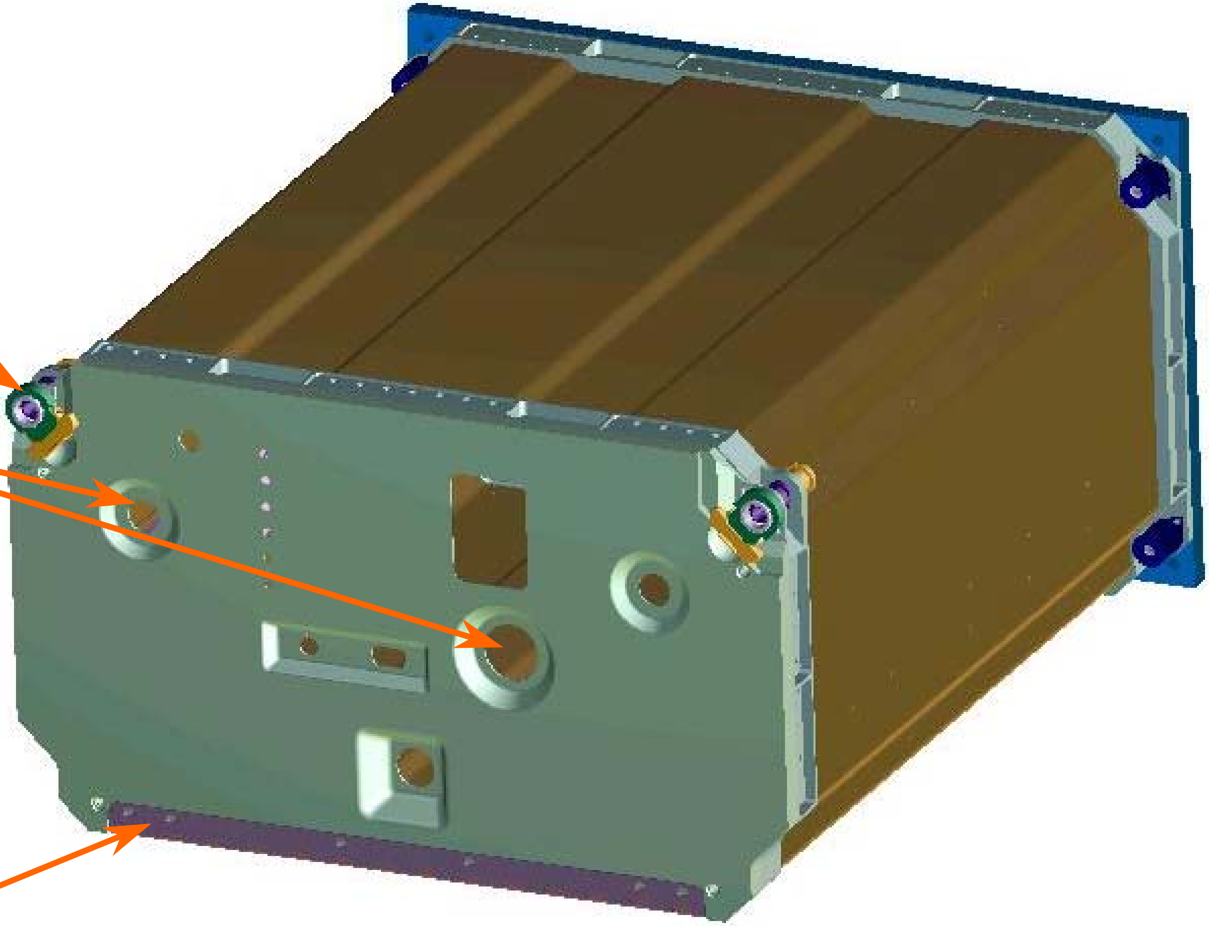
- **Generic locker for payloads requiring on-orbit transfer to ISS**

APML Features

Standard Locker Latches (PGC's)

Cutouts for interfaces

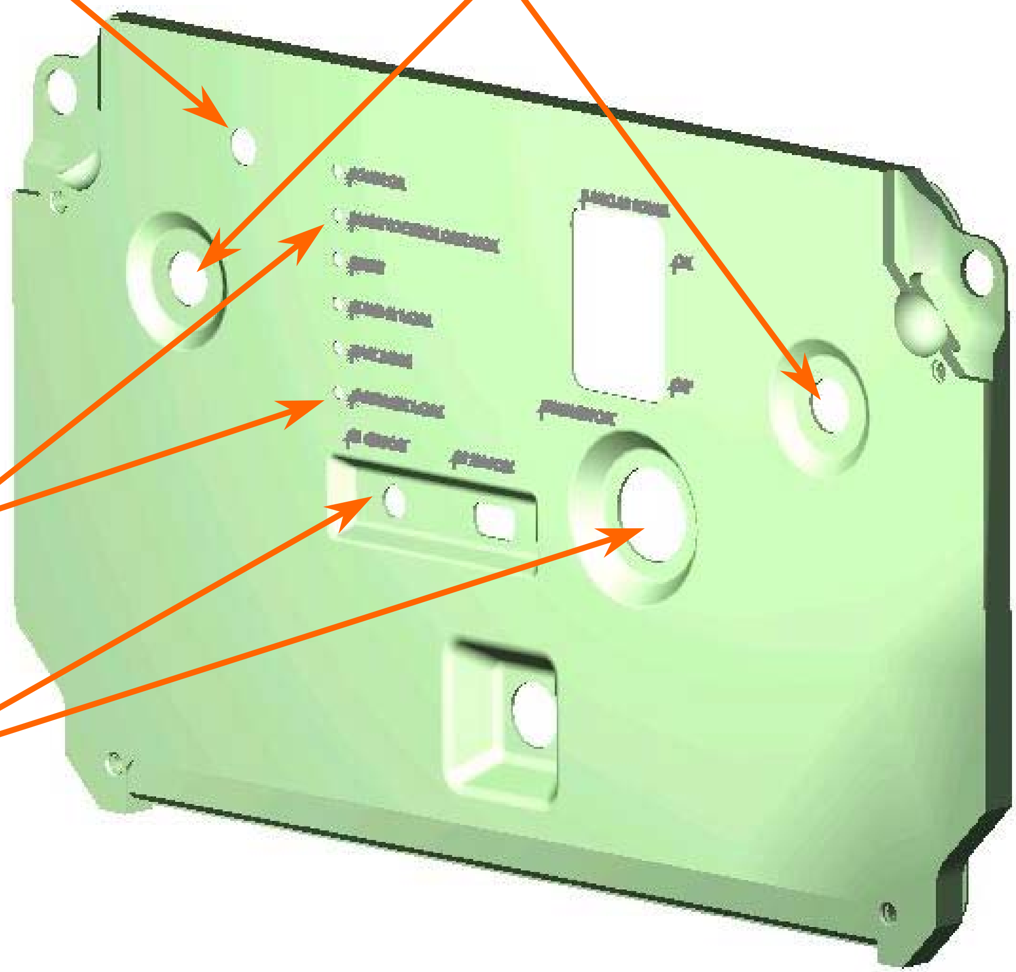
Hinged Door



Door Features

Portable Fire Extinguisher access

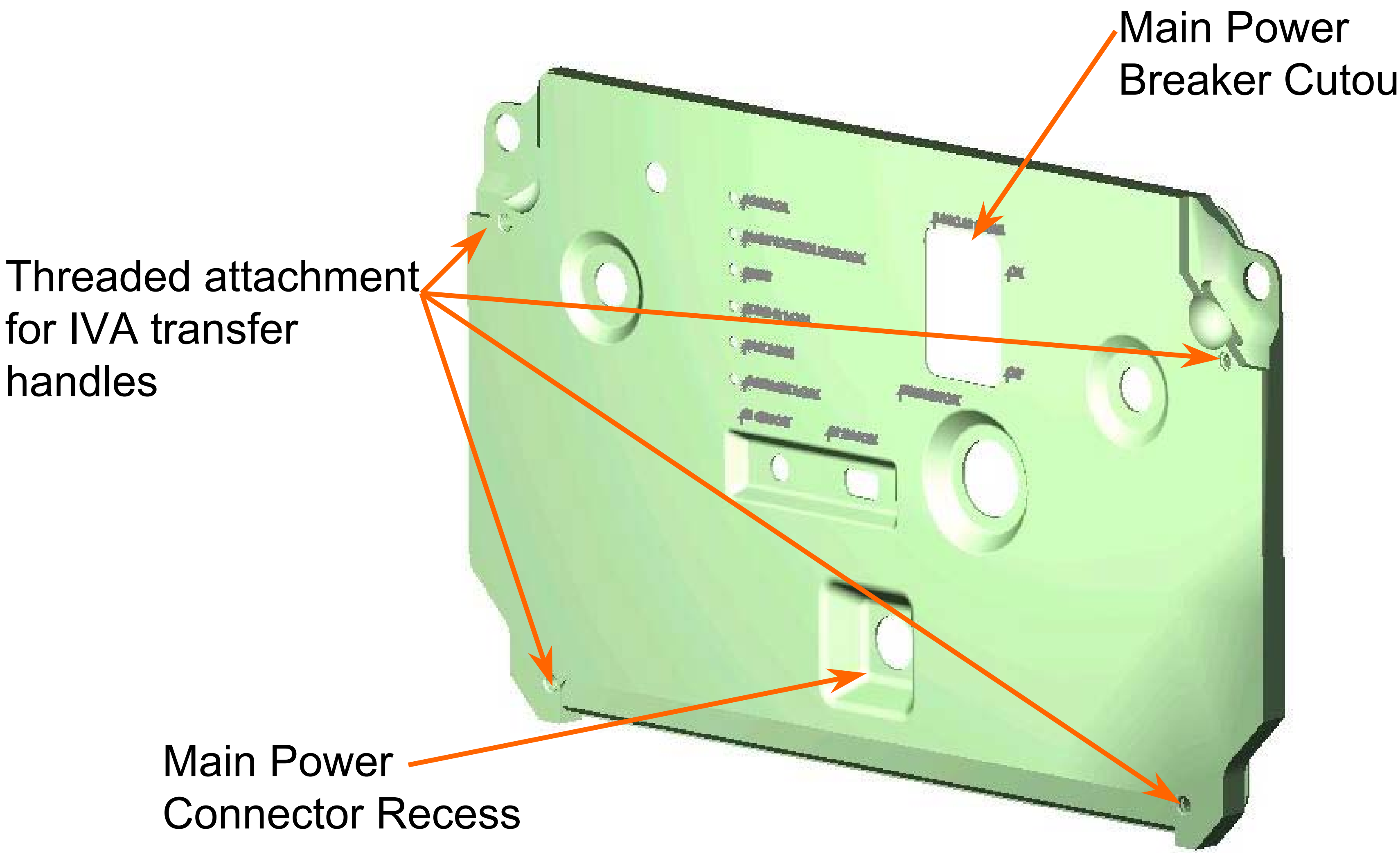
Cutouts for MTL Connectors



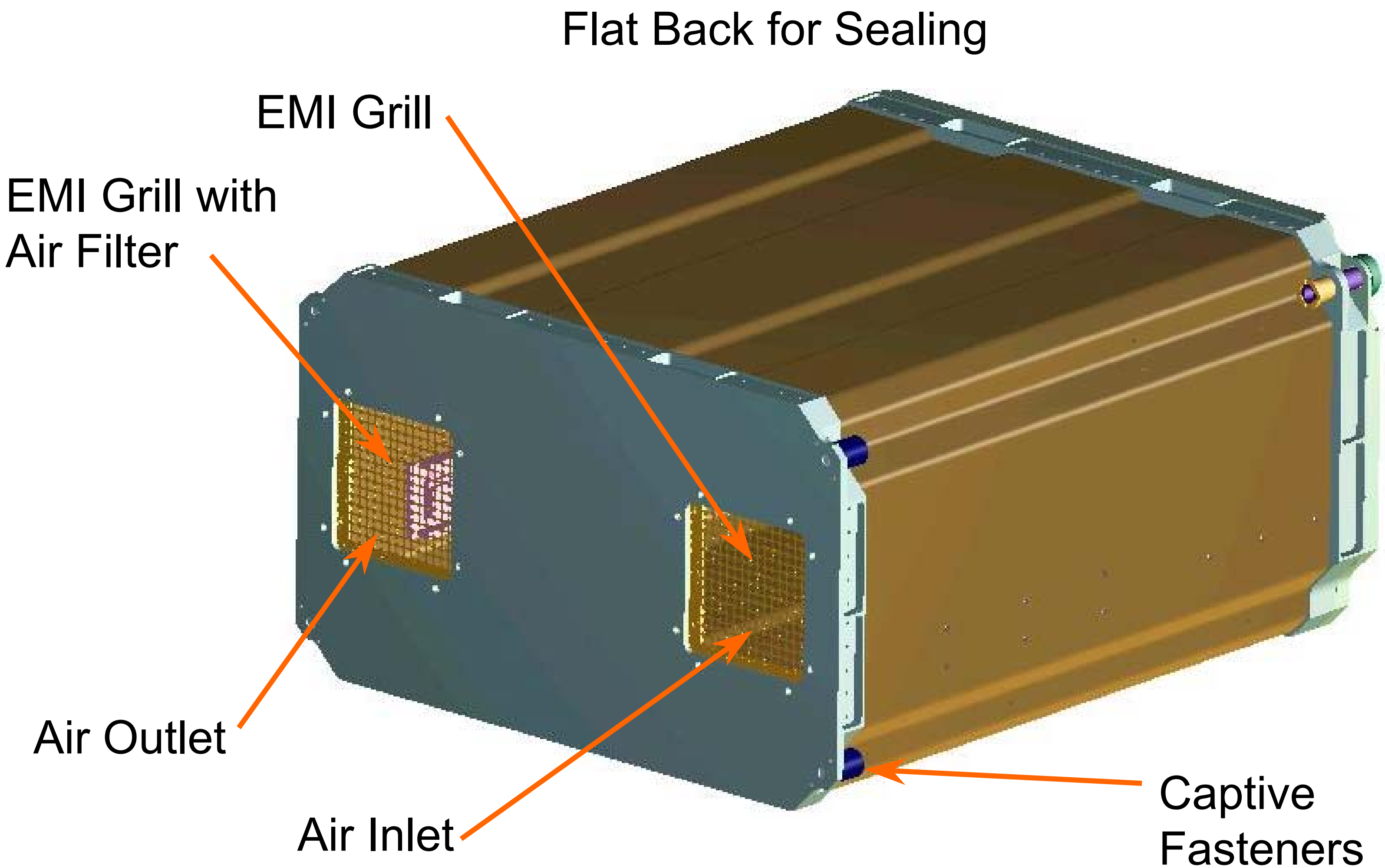
Status LED Windows

Cutouts for Data Connectors

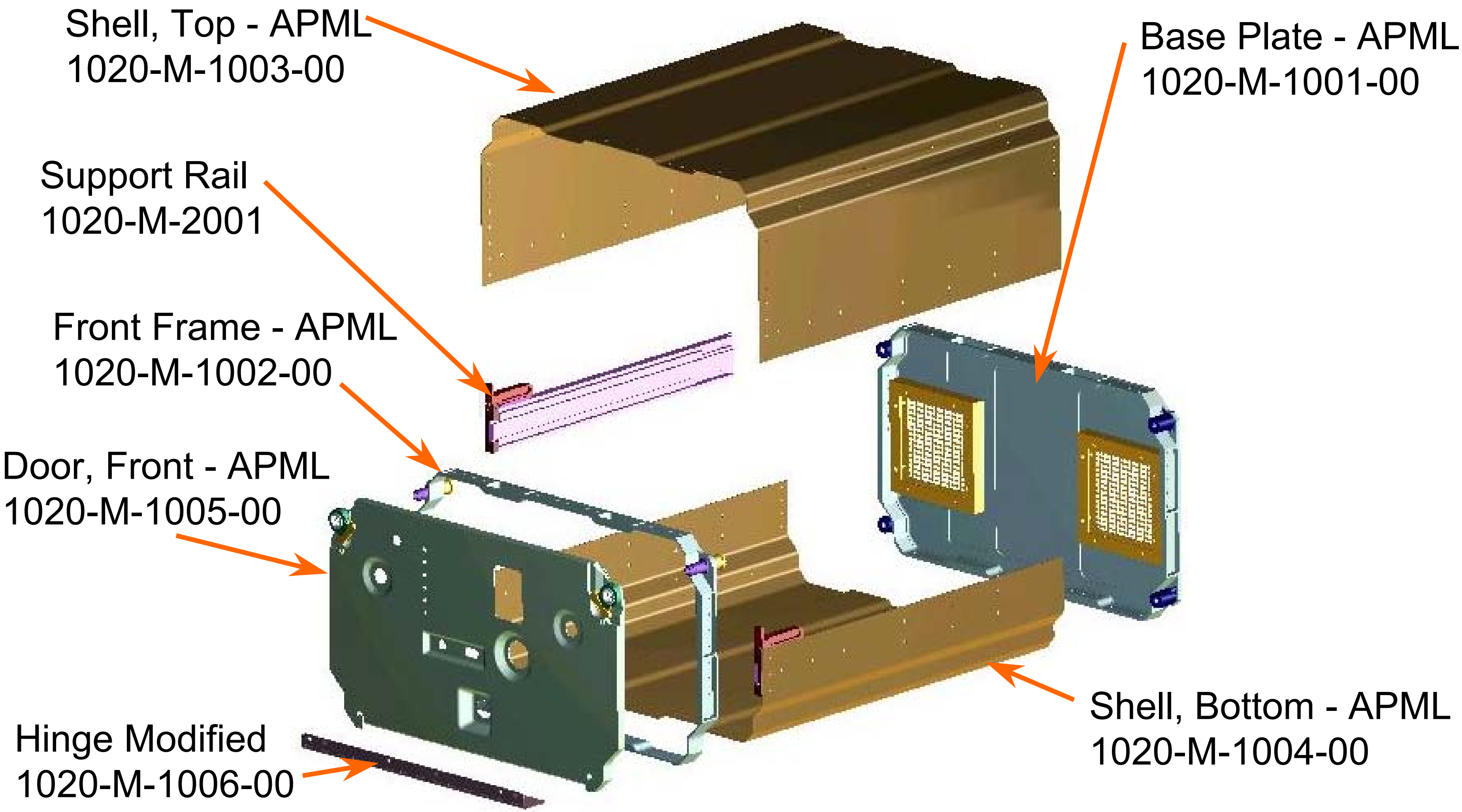
Door Features



Locker Features



APML Components



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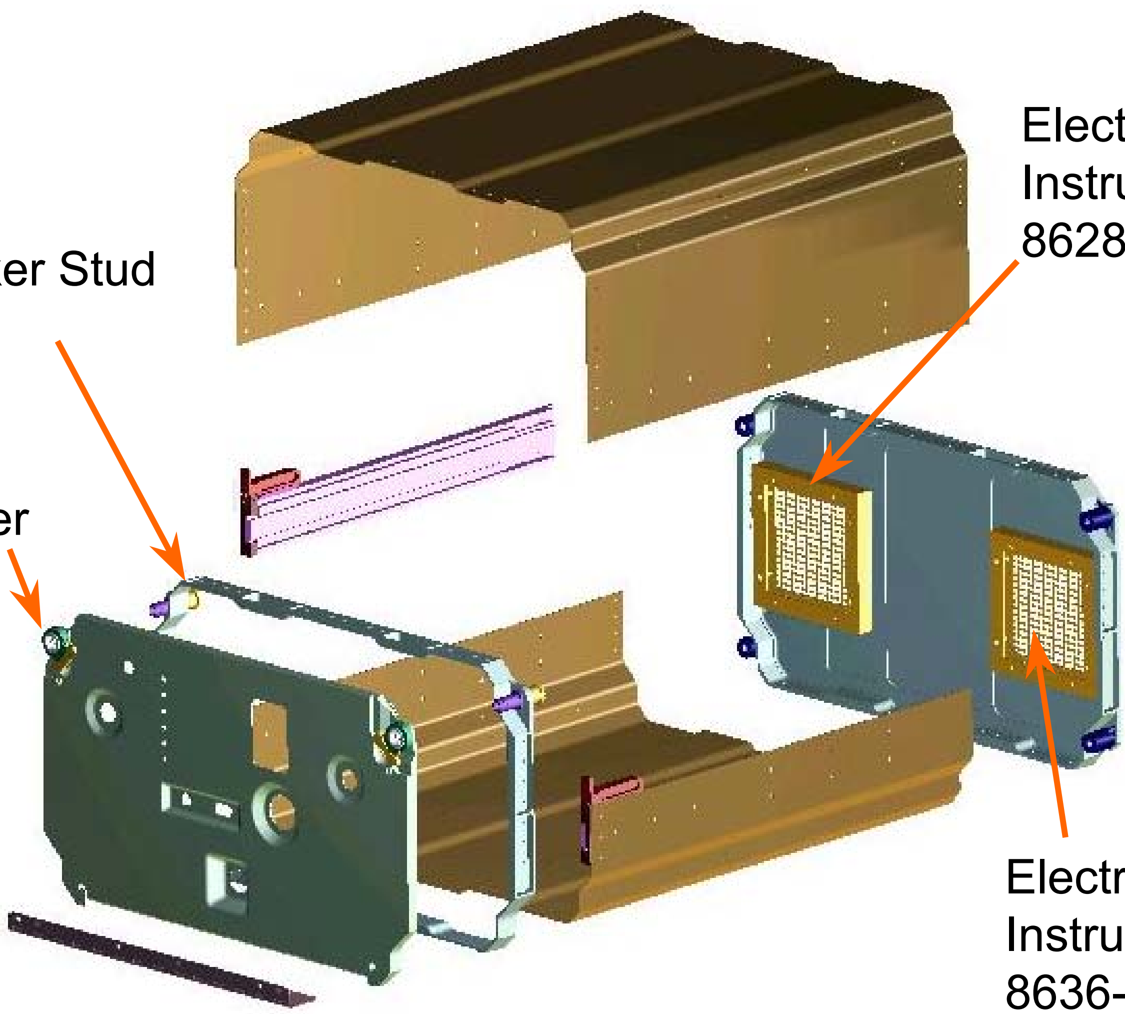
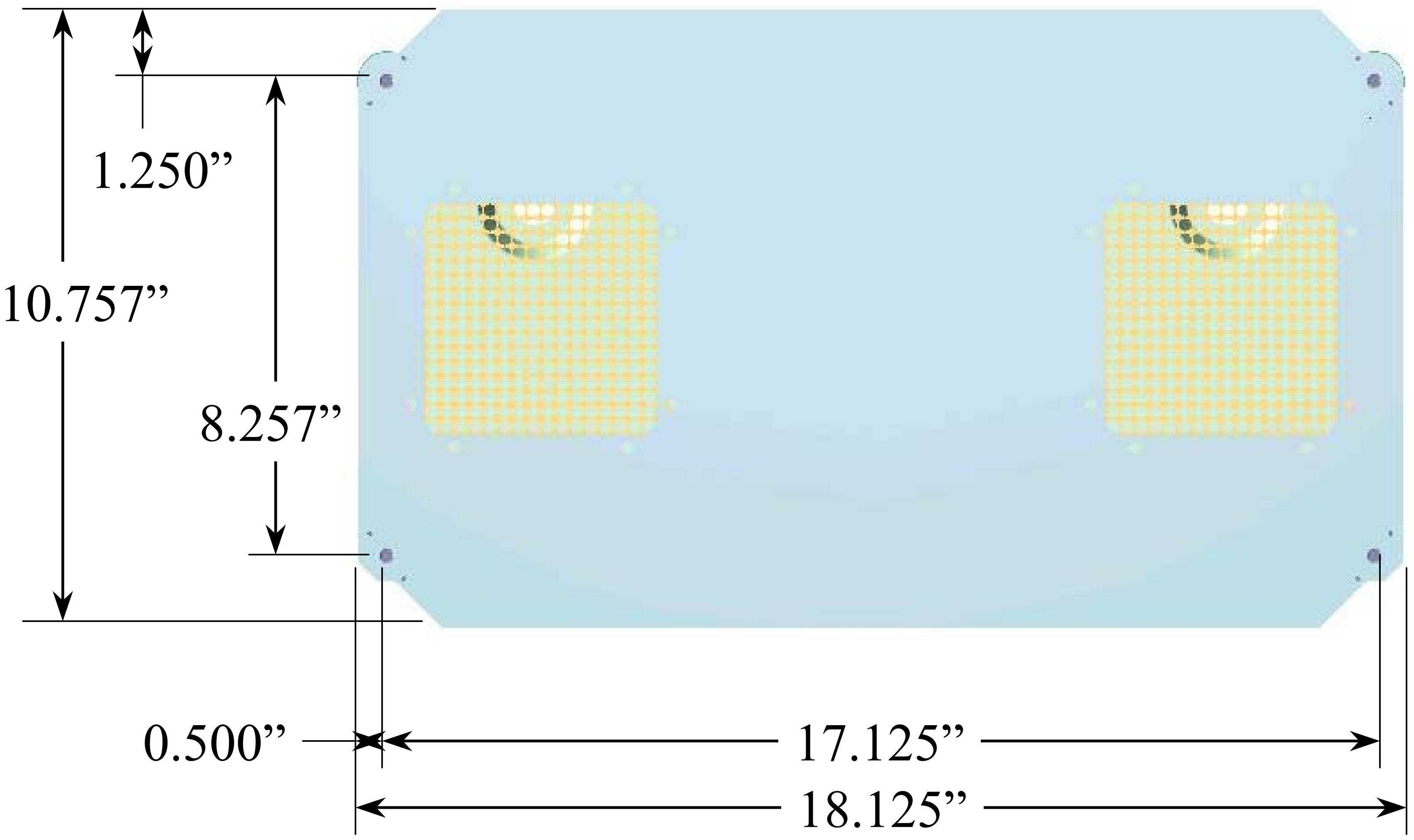


APML External Dimensions



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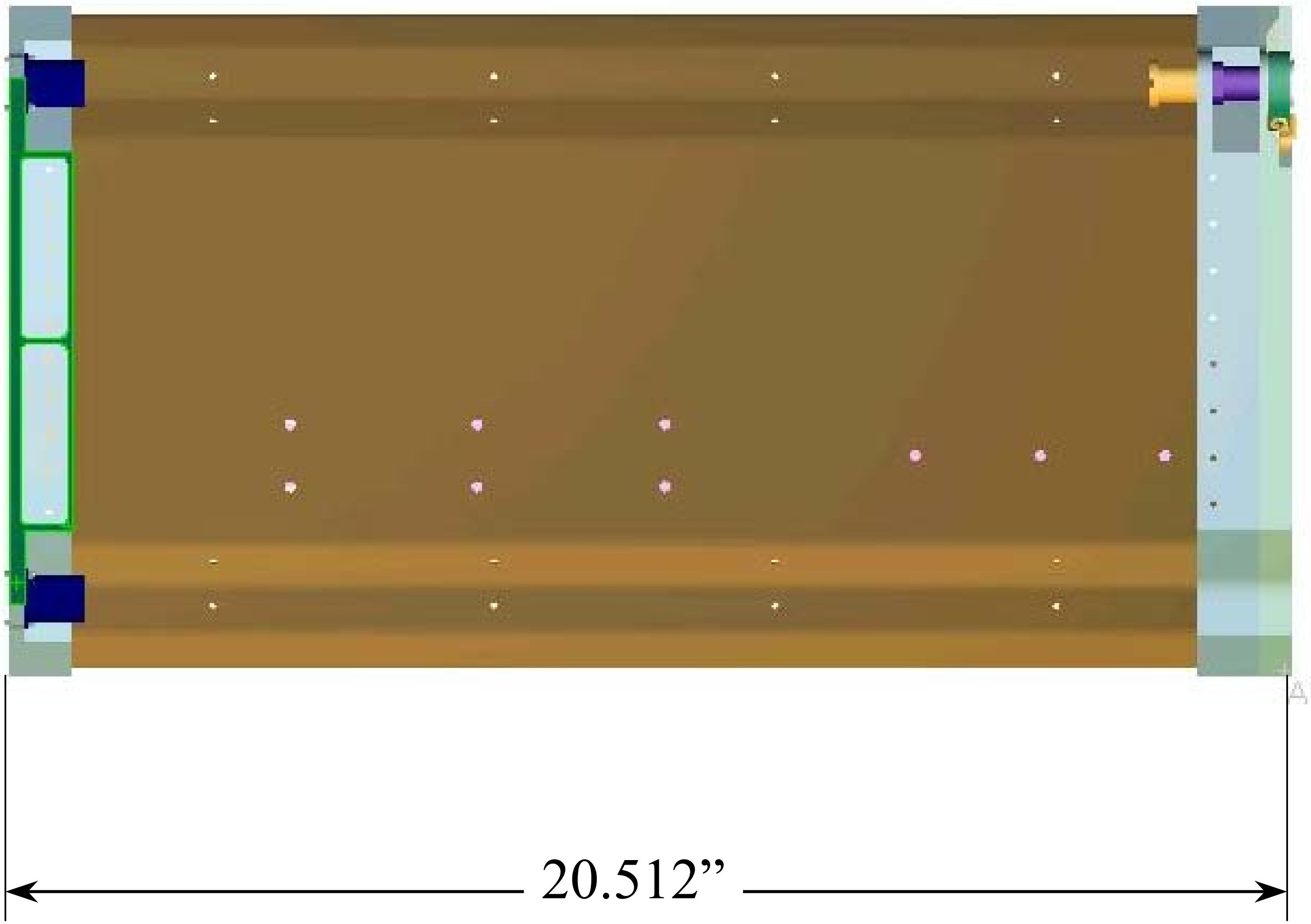
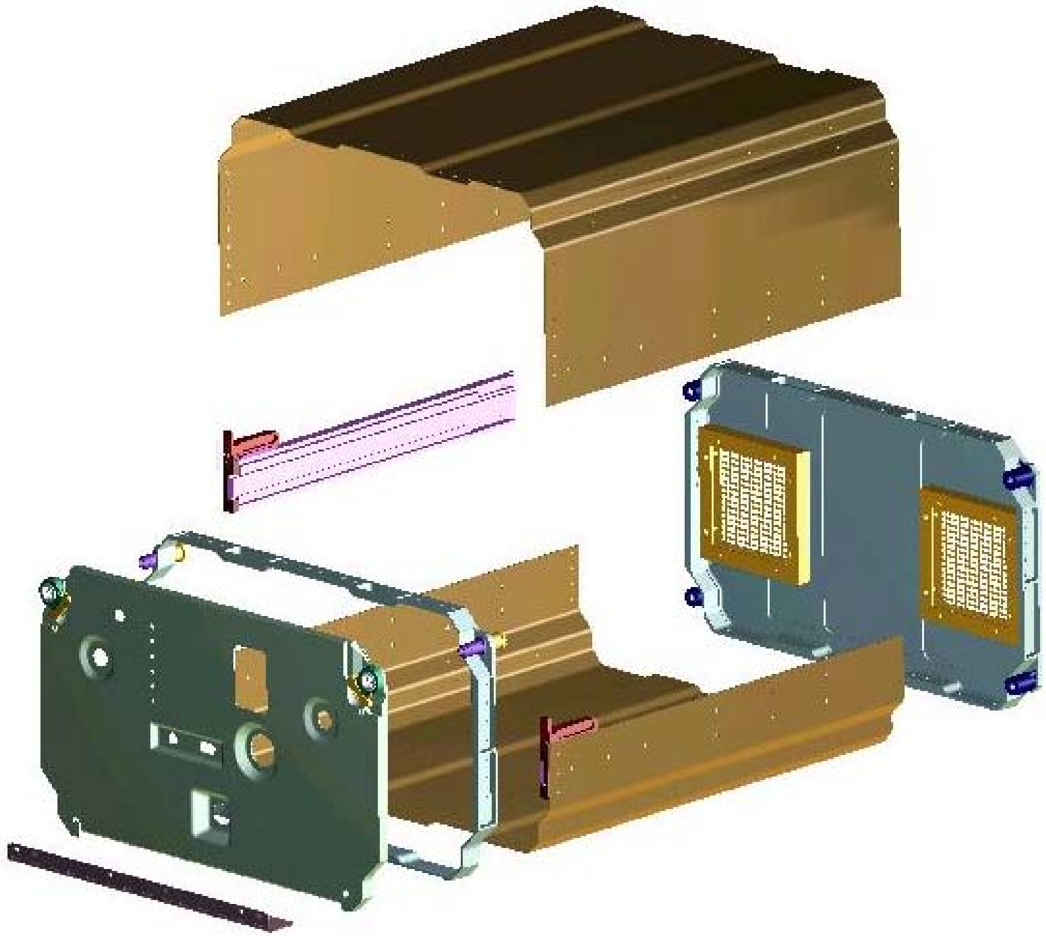


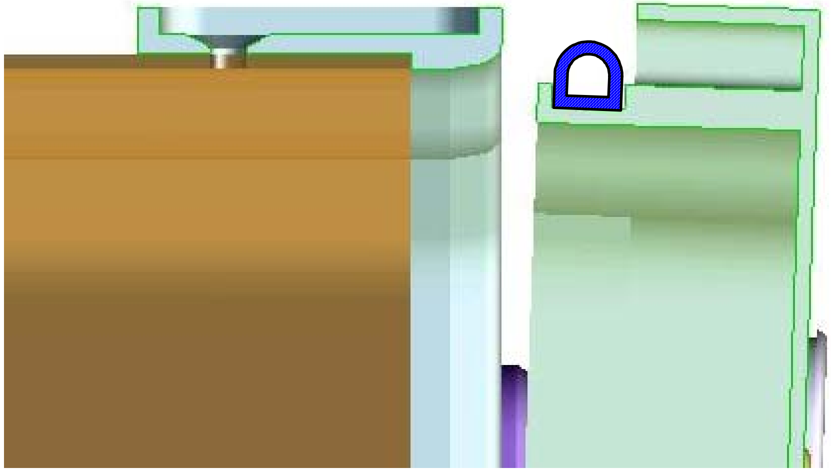
APML Construction

- **7075-T73 Aluminum Sheet and Plate**
- **Chemical Conversion Coating**
- **Riveted construction**
  - **3/32” 7050 Rivets**
- **Hinge and slides attached with bolts and nuts for adjustment**
- **Seams and rivets filled with RTV 3145 to eliminate leakage**

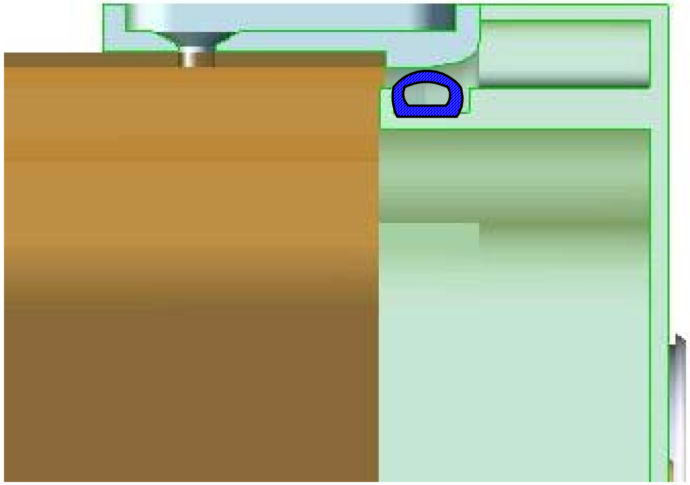


APML Sealing

- All rivets and fastener holes sealed
- Hollow D-ring EMI/Air seal on front door
- All cutouts sealed with EMI gaskets where possible



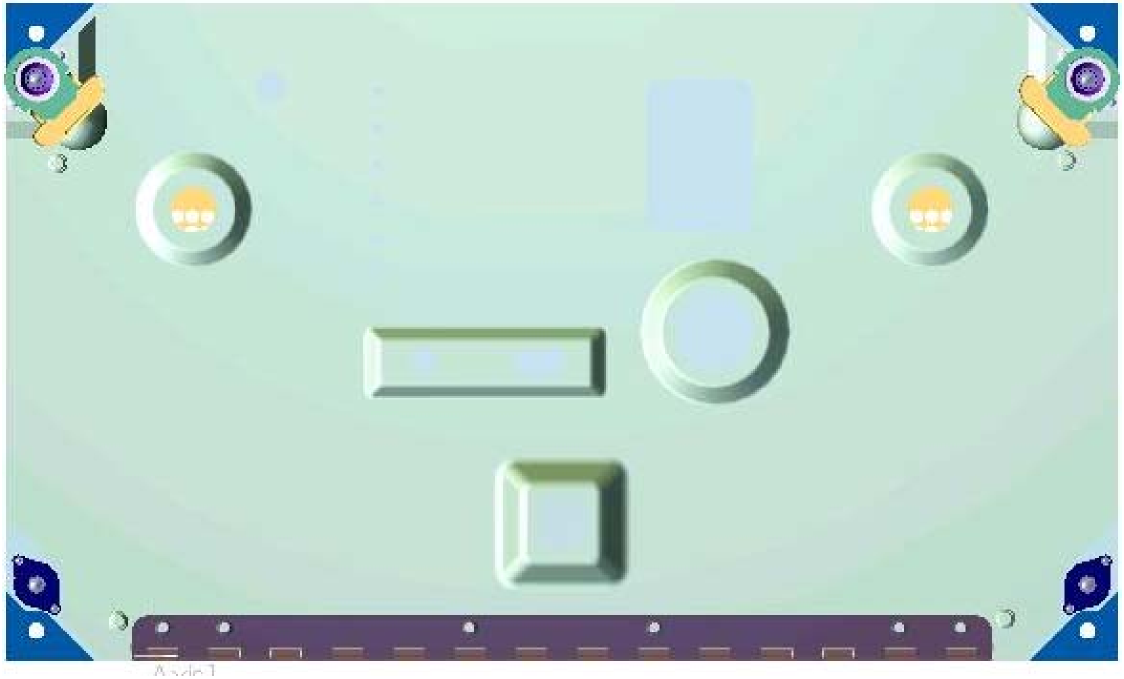
Cross-section of Door Seal - Door Open



Cross-section of Door Seal - Door Closed

Fastener Access

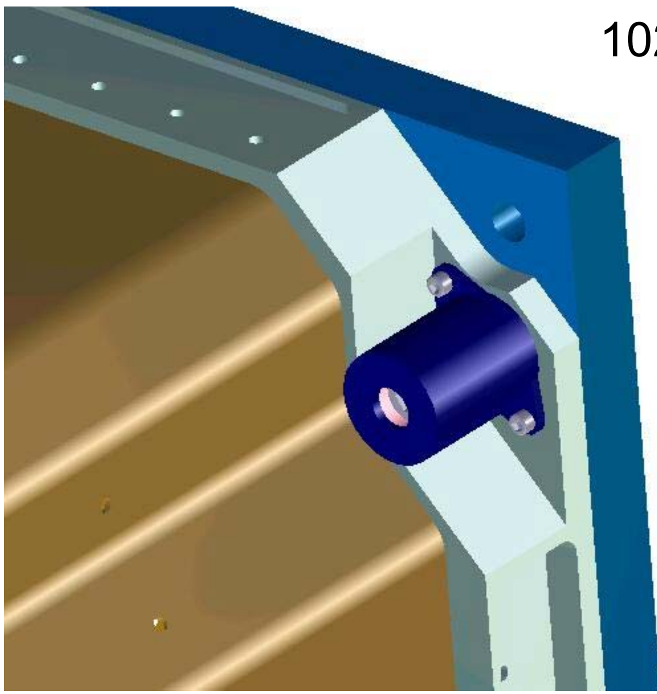
- Clear access to Wire Tray attachment hardware a
- Access to captive fasteners on Locker through standard latches
- Guide brackets not shown

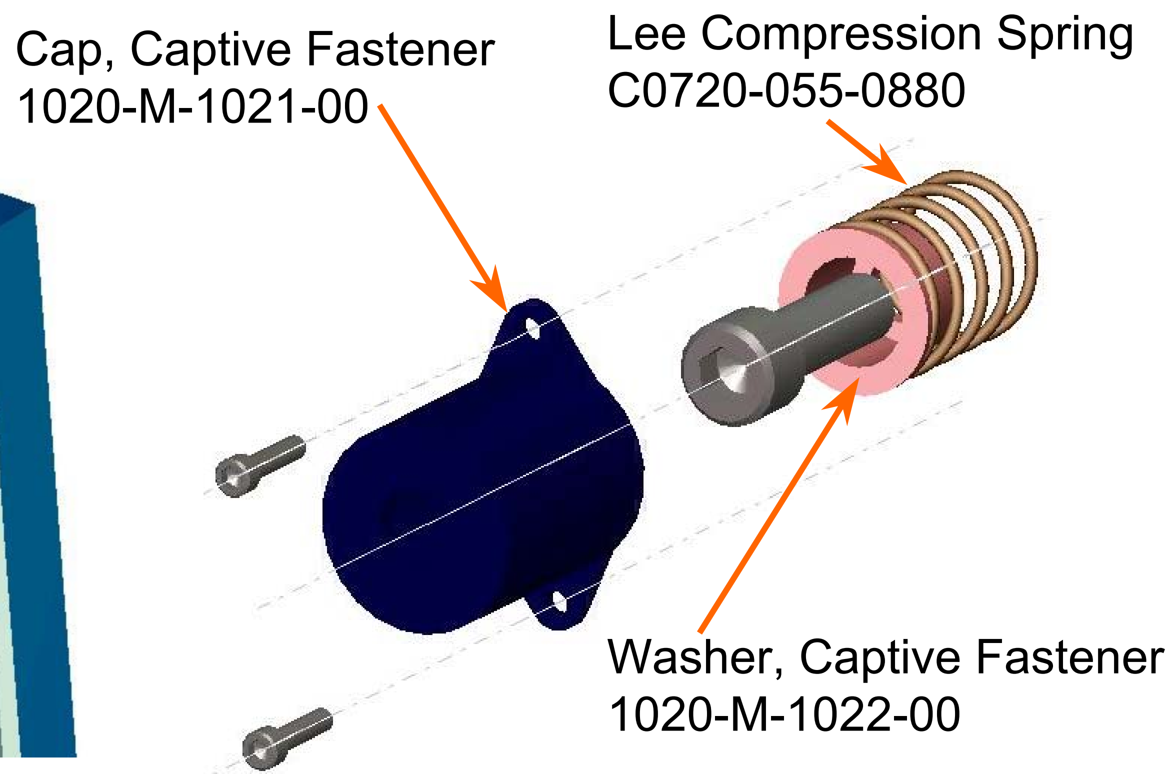


Locker Front View with VPMP in Blue

Captive Fasteners

- **Structural Attachment to VPMP**
- **Unmodified 1/4-28 UNRF A-286 Socket head cap screw with thread locking insert**



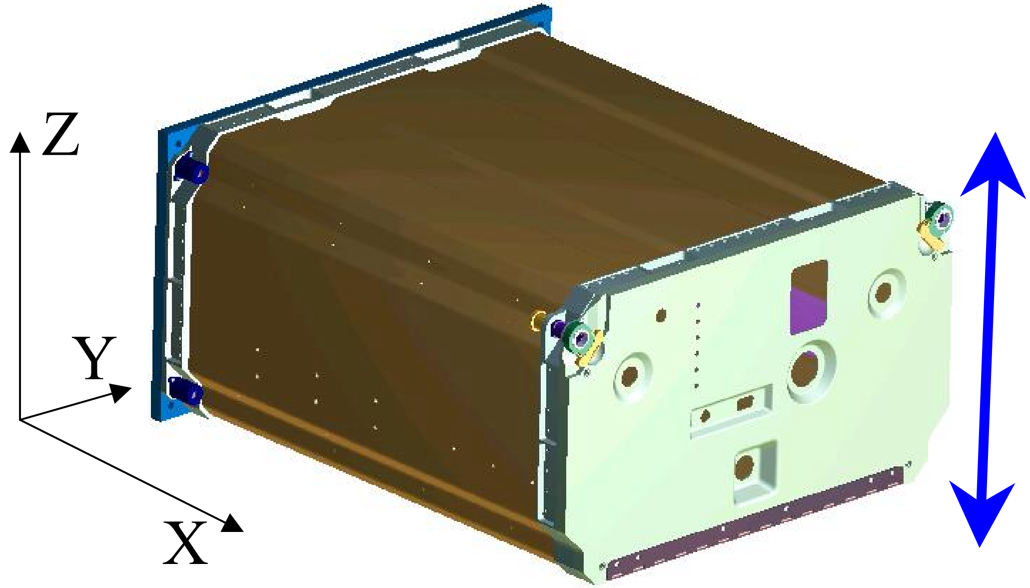


APML Structural Analysis

- Performed finite element analysis of locker directly from imported solid models
  - Fundamental natural frequencies
  - Ultimate and yield stress during launch, landing and crash landing in Middeck
  - Buckling in crash load case
  - Fatigue life after four missions
- Analysis based on SSP 52005 - Safety Critical Structures
- Load environment based on Middeck only
- Design load factors (quasi-static) and random vibration applied separately

Fundamental Natural Frequencies

- **Tray Insert Assembly modeled as lumped mass rigidly attached at drawer slides**
- **Total weight set to maximum payload weight of 69 lbs.**

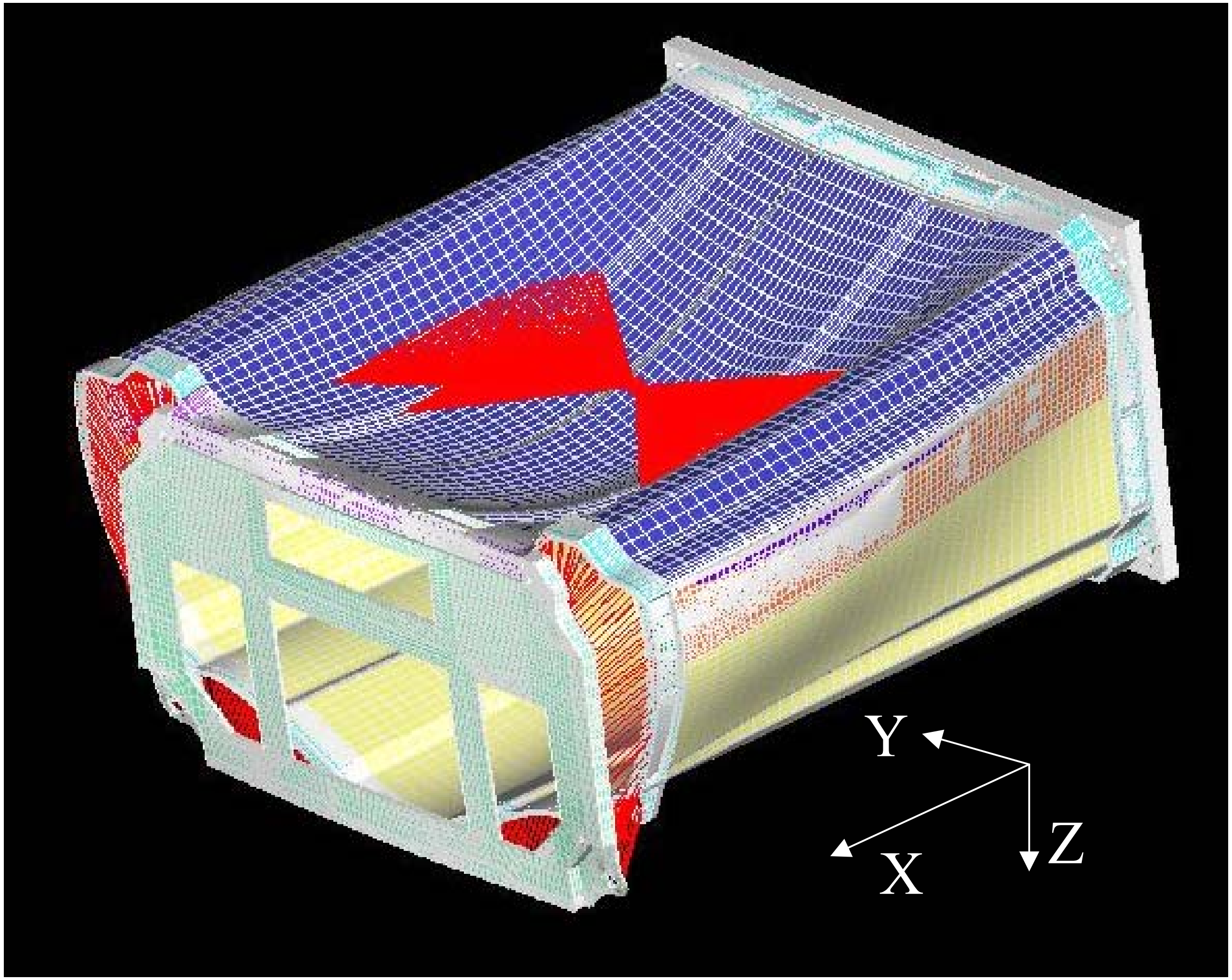


F_{N1} = 98Hz in Z

F_{N2} > 2000 Hz

Fundamental Natural Frequencies

- **FEA Output of modal response at 98 HZ**
- **First modal response**
- **Motion greatly exaggerated**

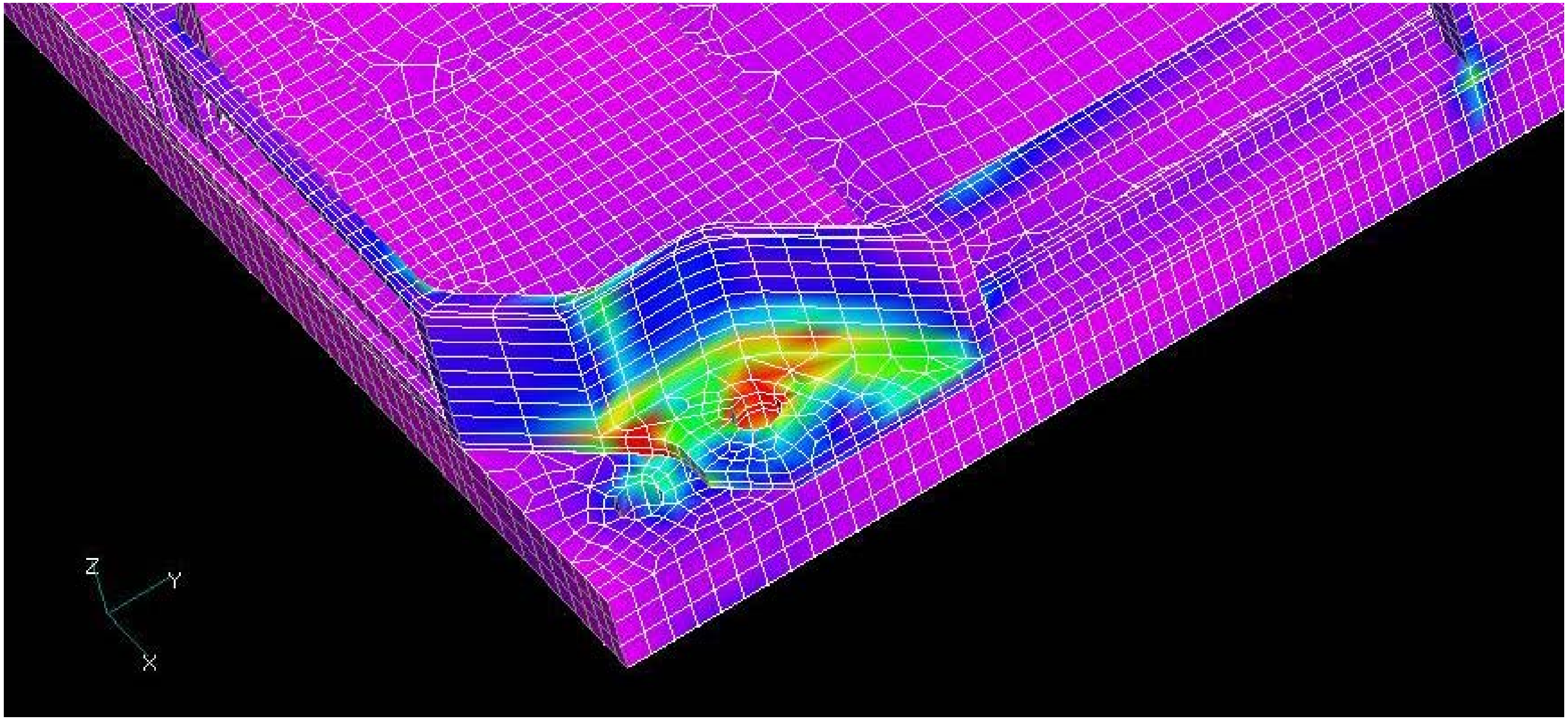


APML Stress

- Developed maximum von Mises stresses for each load case including ground handling, kick loads and installation
  - Other load cases result in negligible stresses
- Maximum stress experienced during launch quasi-static acceleration
- Maximum stress located in base plate near mounting bolts

APML Stress

- Maximum model stress at bolt interface
  - Unrealistic due to true bolt to plate interface
  - Next highest stress in corners nearby

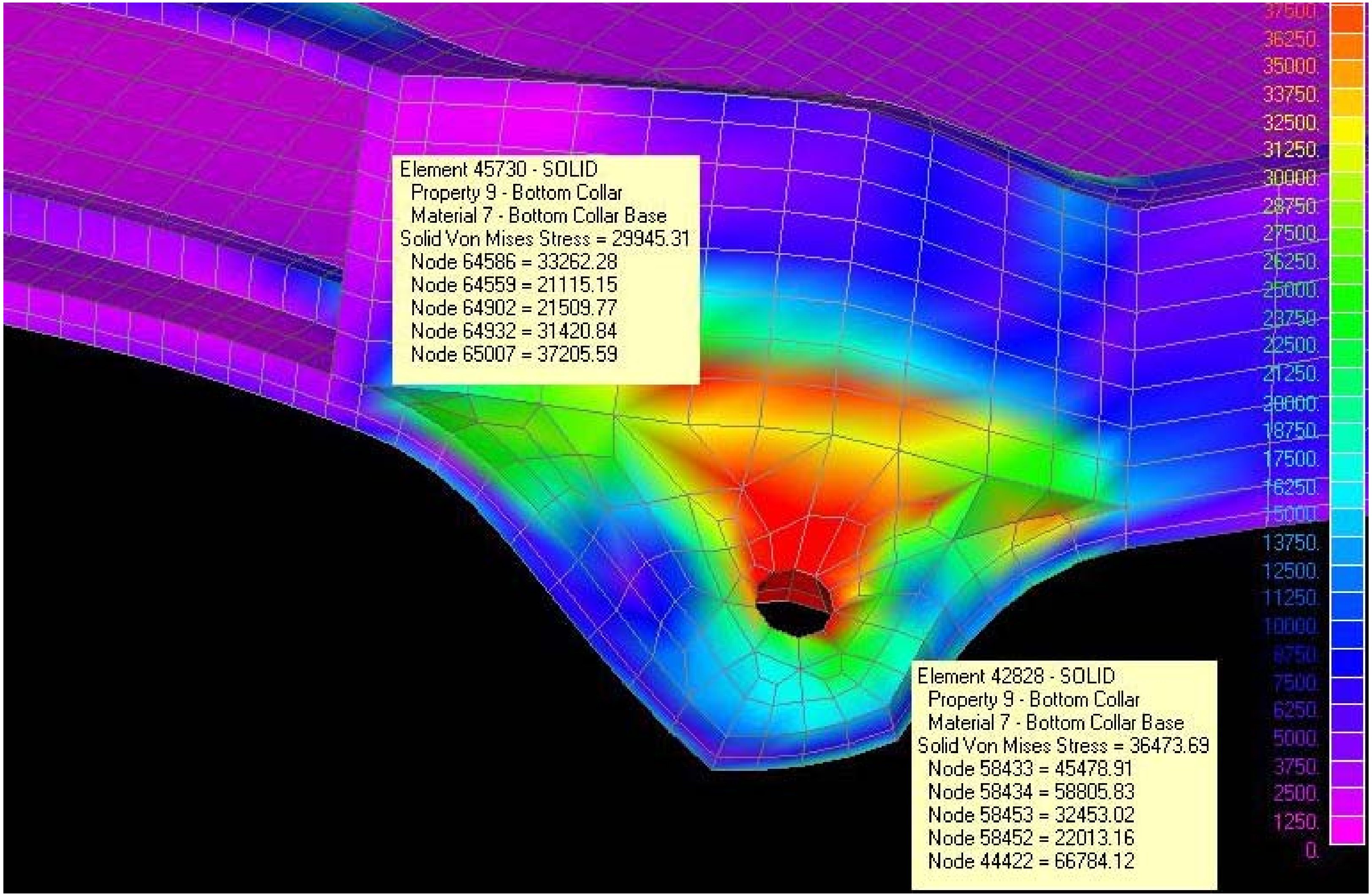


Maximum Stress

- Results of finite element analysis using maximum model stress
- Locker Material: 7075-T73X
- FEA indicates negative margins

Load Case	Maximum Von Mises Stress (psi)	Yield Margin of Safety	Ultimate Margin of Safety
Launch Loads	50,514	-6.5%	-30%
Landing Loads	49,054	-3.7%	-28%
Emergency Landing Loads (2x FS included in loads)	56,606	N/A	25%

FEA Sources of Error



FEA Sources of Error

- Constraints at attachment bolt hole do not distribute stress in a realistic manner
- Stresses in nearby section are 18% lower
- No fillet modeled for tab
- Fillet would reduce stress concentration

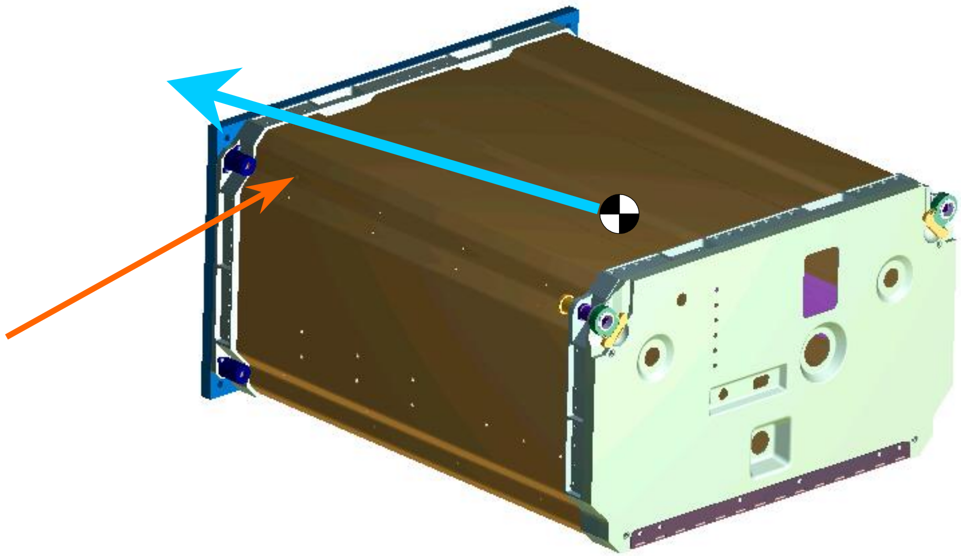
Design Modifications and Analysis

- Fillet will be added to tab
- Tab will be thickened to increase strength
- Hand analysis will be performed
  - Analysis will take into account launch, landing and emergency landing load cases
  - Stresses will be used for yield, ultimate and fatigue calculations
- Additional modifications will be made to achieve positive margins

APML Buckling

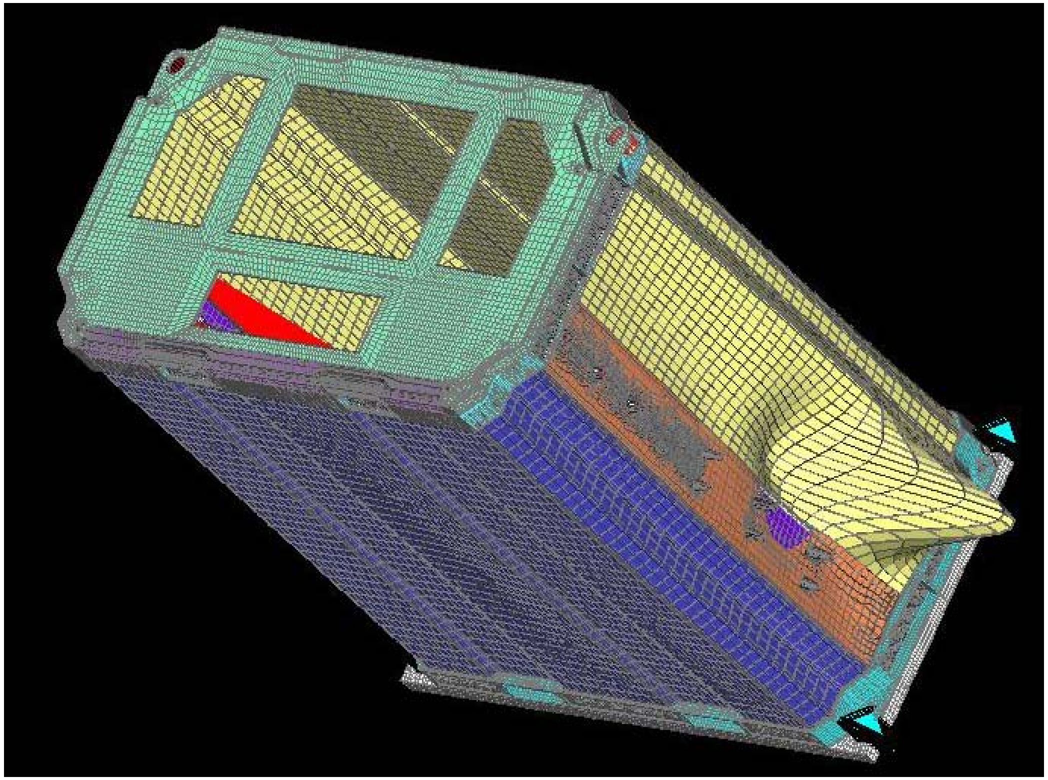
- **Elastic buckling analysis performed on locker with lumped mass representing maximum allowable locker weight of 69 lbs.**
- **Analyzed for crash load case, one combination of directions**
  - **Expected to load the weakest section in compression**

Thin shell in compression



APML Buckling

- **In direction of load buckling would not occur until 106 g's compared to max load of 22 g's**
- **Buckling margin of 3.8**
- **Buckling Shape**
  - **Greatly exaggerated**



APML Payload Containment

- Locker nominal skin thickness is based on past locker designs
- Nominal skin thickness of 0.040”
- Initial analysis indicated this was adequate for containment
- Additional analysis required for specific PGF-SP component designs

APML Risks

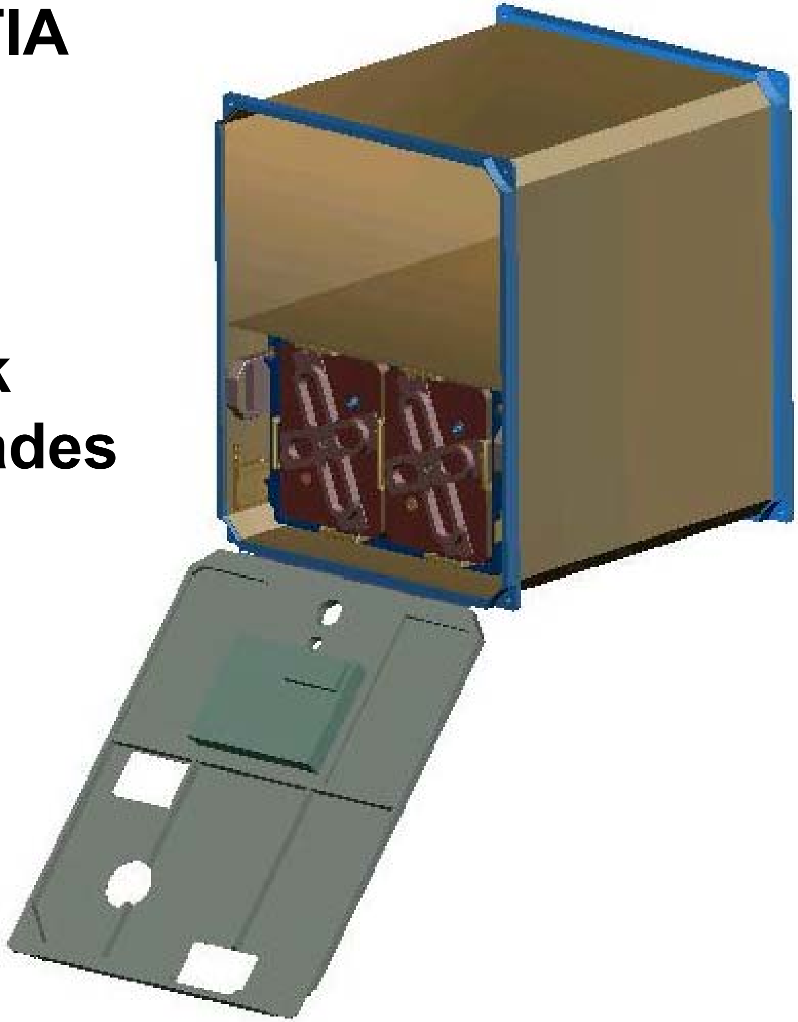
- Natural frequency may be significantly different with payload installed
  - Lockers will be tested for random vibration response prior to launch
- Failed to show positive margins with FEA
  - Minor changes and hand analysis will improve results
- Locker sealing to 2 scim may be difficult
  - Careful construction and leak testing should eliminate most leaks
  - Waiver may be required and could effect manifesting

APML Summary

- Single locker design based on past locker designs
- Design modifications and additional analysis required
- Lockers will undergo random vibration with integrated equipment to verify payload natural frequency
- Total locker weight is approximately 13.25 lbs
  - Including full drawer slides
  - Not including VPMP
- APML is passive structure and does not use power

CCDL Overview

- Drawer Slides to accept TIA with minor modifications
- Upper portion used for stowage/mini-freezer
- Allows for use in Middeck prior to rear cooled upgrades to shuttles
- Current design only conceptual



CCDL Requirements

- Safety Critical Structure
- Contain and support payload in Middeck launch and landing environments
- Supply Ducting from back of PGF-SP to front of locker
- Allow easy on-orbit access to experiment
- Allow for status and power control at front panel
- Act as EMI/EMC enclosure with front door closed

CCDL Interfaces

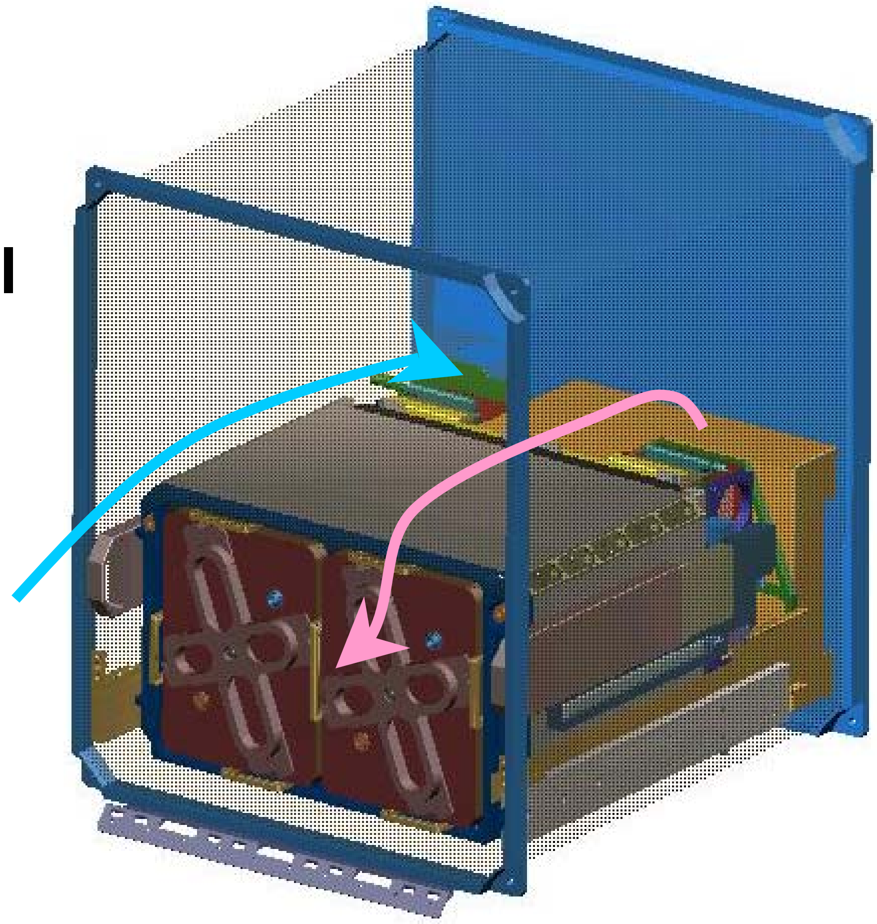
- Middeck/Double Payload Mounting Plate mounting features
- Cabin Air
- PGF-SP Tray Insert Assembly/drawer slides
- Crew
- Door mounted assemblies
  - Front Interface Board/Data Connectors
  - Main Power Connectors/Main Power Breaker
  - MTL quick disconnects
  - Nutrient Reservoirs

CCDL Goals

- **Maximize stowage area for Kennedy fixed tubes, expendables water and min-freezer**

CCDL Design

- **Conceptual Design only**
- **Divider in locker Provides support for ducts**
- **Air ducted to front panel with EMI and Dust screens**
- **Inlet fan built into locker/ducts**

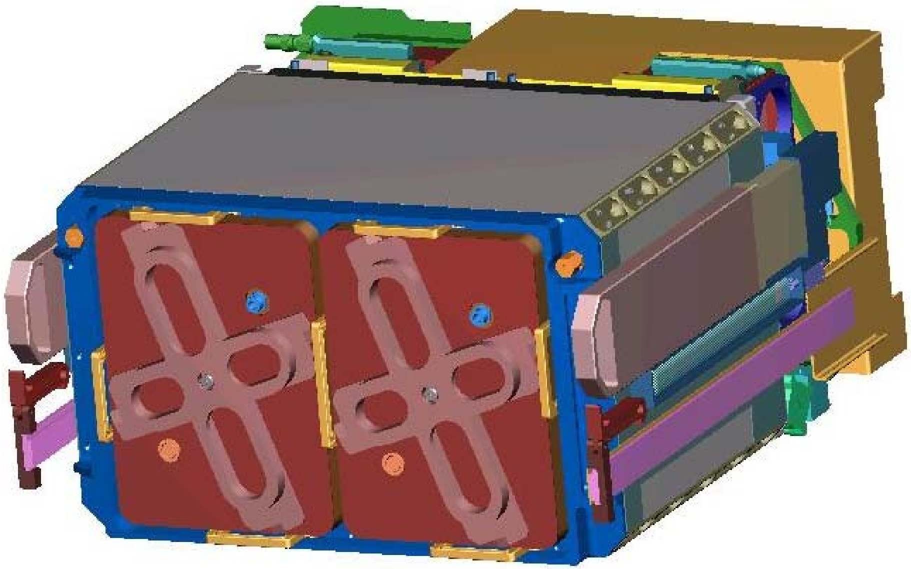


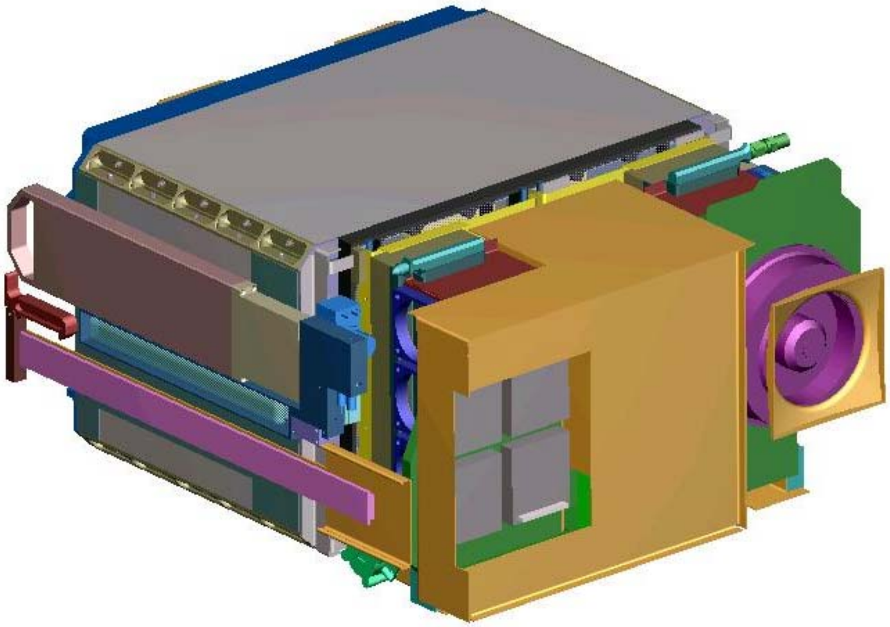
CCDL Summary

- Allows PGF-SP to fly as front breather in Middeck
- Additional work required for design and analysis

Tray Insert Assembly Design

- Modular assembly
- Drawer Slides for insertion into locker
- Allows for access to subsystems for easy maintenance





TIA Requirements

- **Modular assembly of PGF-SP subsystems**
- **Provide structural support of majority of payload**
- **Allow for easy access to payload for ground and on-orbit operations**

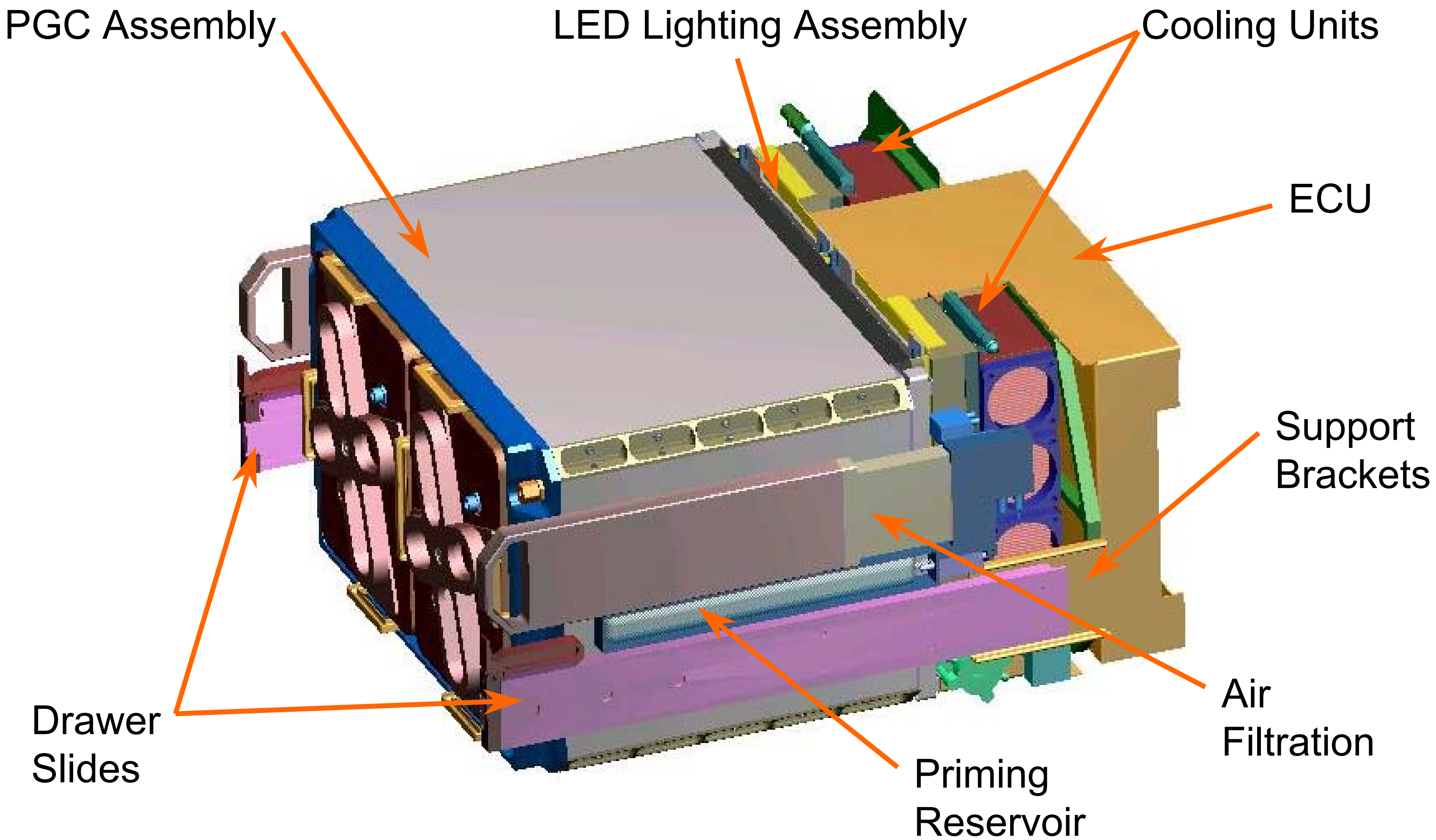
Interfaces

- APML and CCDL through drawer slides
- PGC assembly
- Filtration System
- Priming reservoir
- Electronics Housing

Goals

- **Minimize Weight**
- **Maximize access to subassemblies**

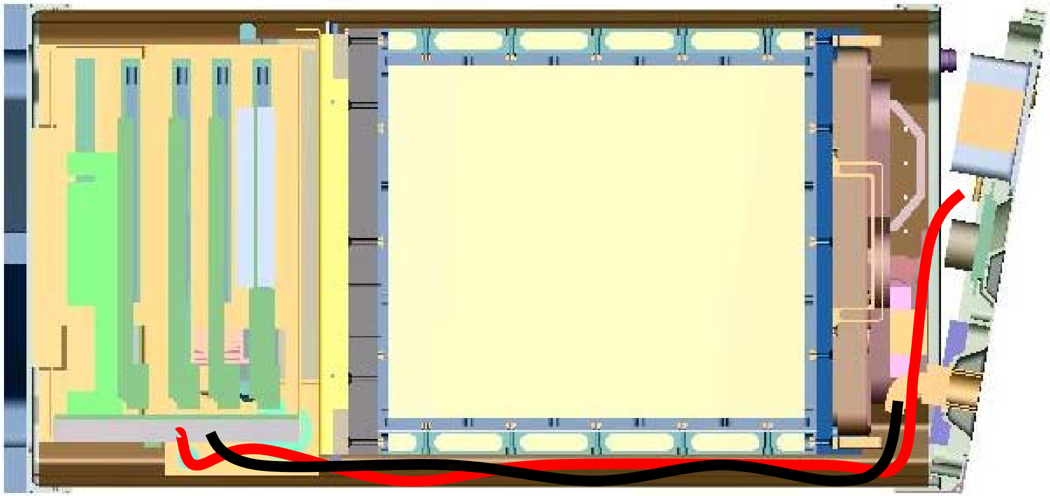
TIA Features



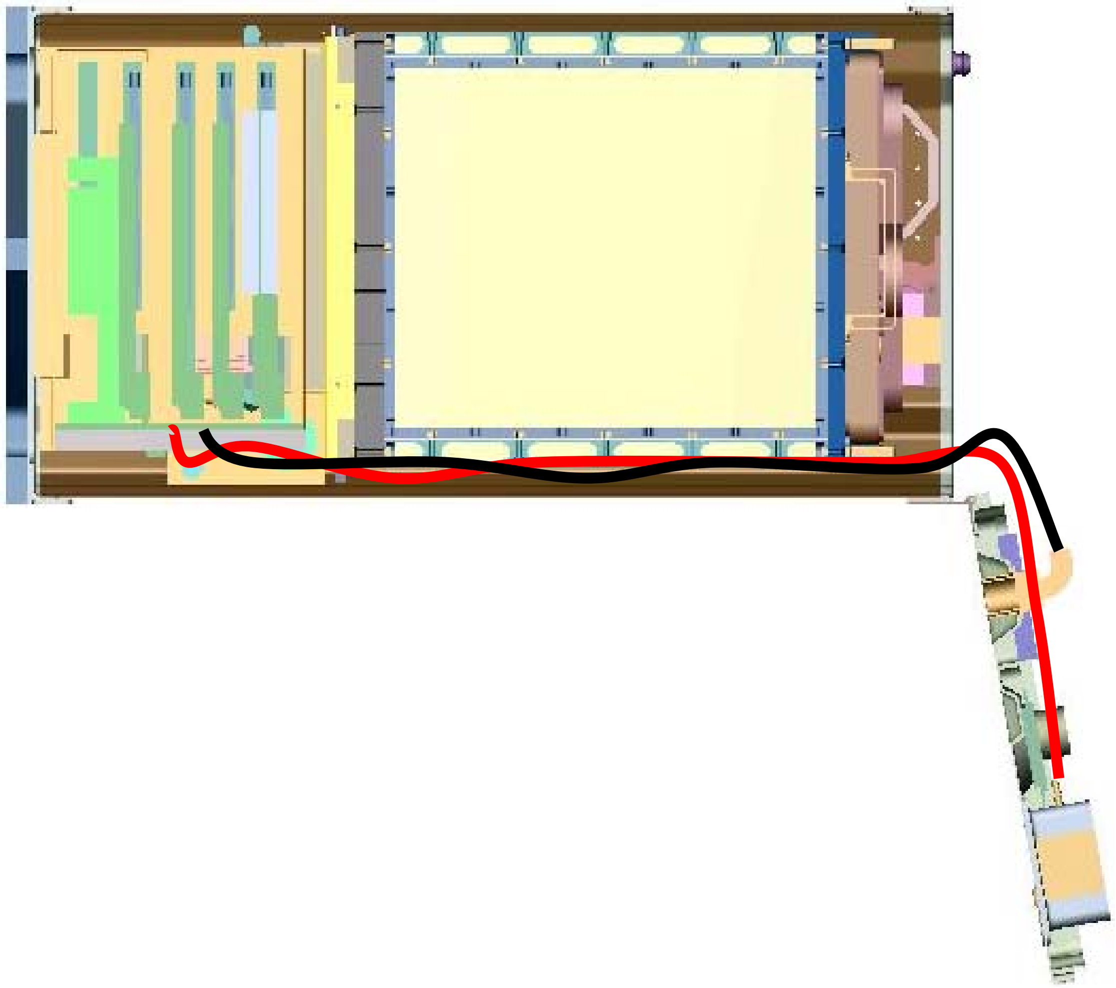
Front Door Connections

- Some equipment mounted to front door
  – Power Connector and Breaker
  – Data ports and front interface processor
  – MTL hookups
- Wires and cables routed below TIA and back to ECU housing and cooling units
- Cable and hose routing allow for door opening and extending of TIA
- Jackets and tie downs used to support and protect cables during movement

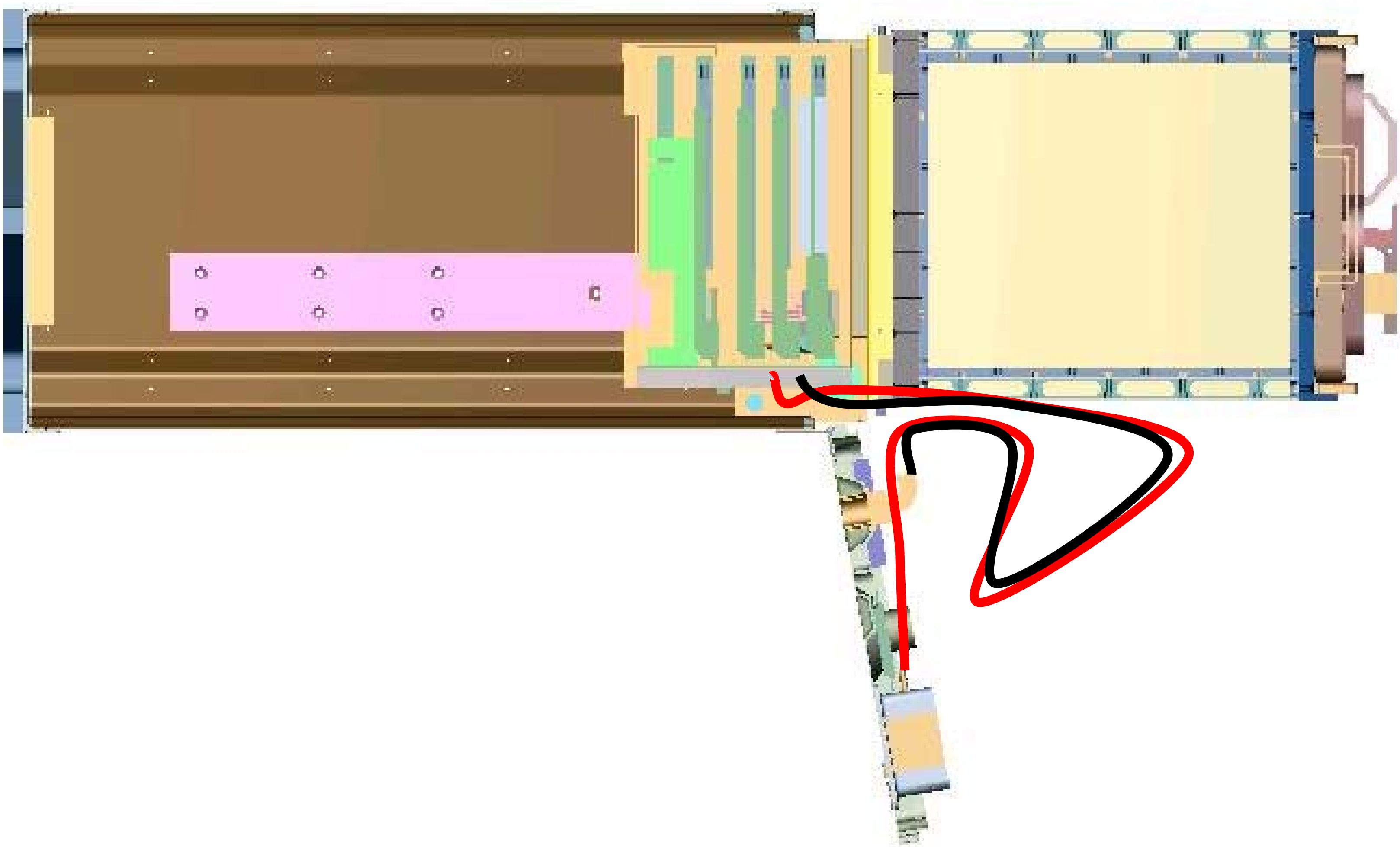
Front Door Connections



Front Door Connections

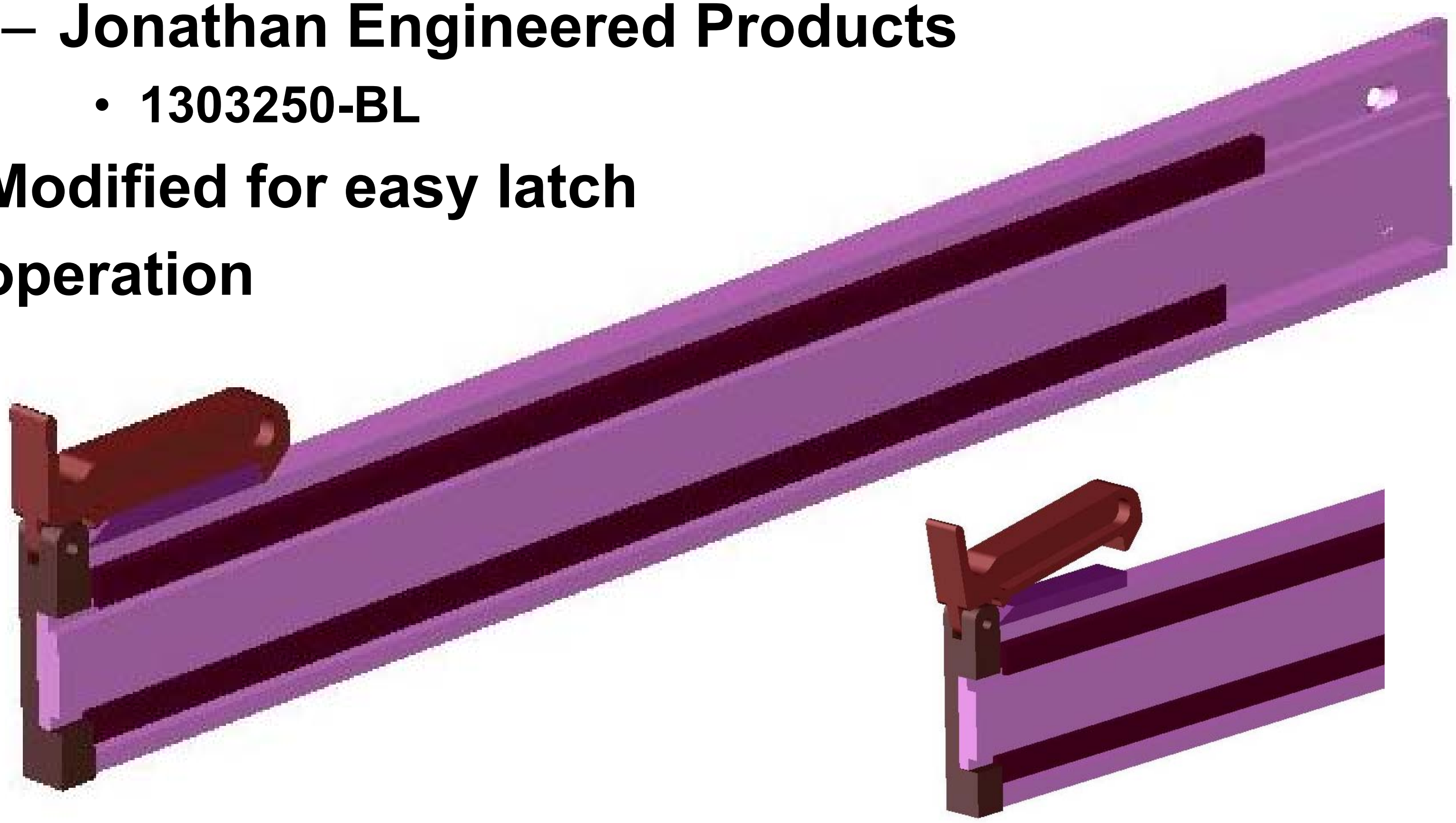


Front Door Connections



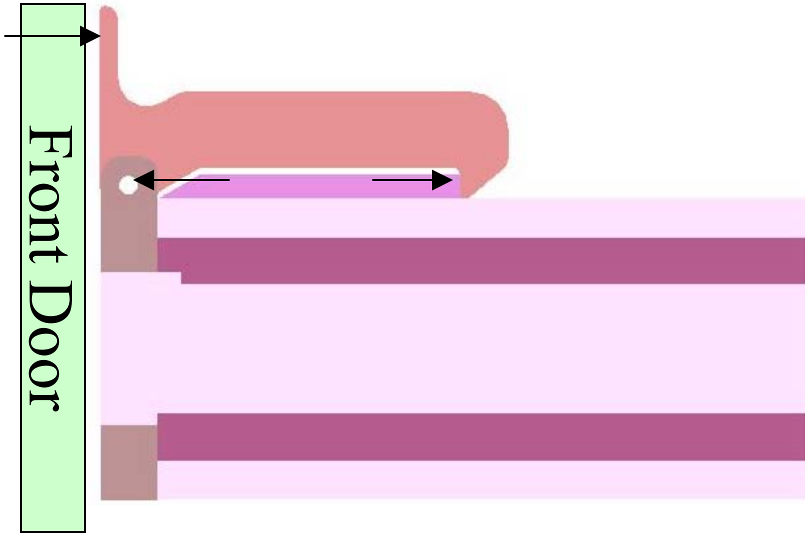
Drawer Slides

- **Modified COTS product**
  - **Jonathan Engineered Products**
    - **1303250-BL**
- **Modified for easy latch operation**



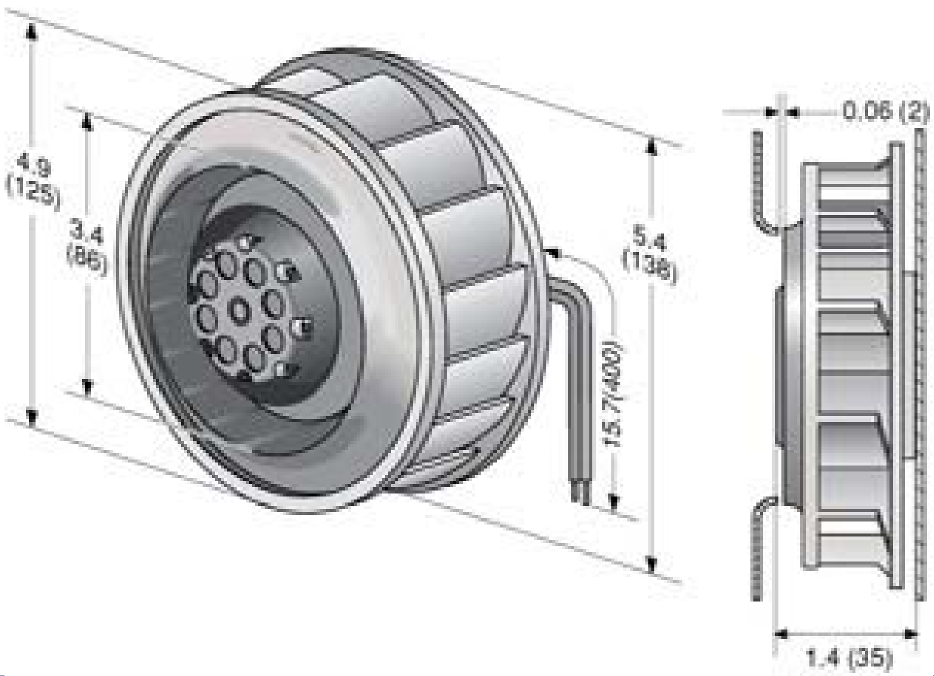
Latch Design

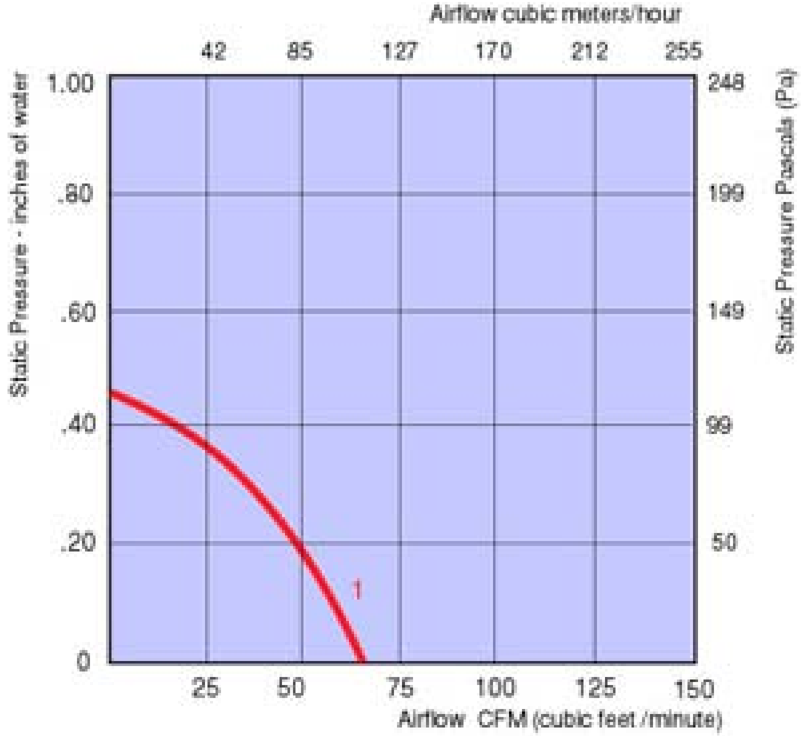
- Latch geometry will not open under load due to pivot point location
- High strength stainless construction for structural strength
  - 15-5PH H1025
- Closing front door prevents opening during vibration



Inlet Fan

- **COTS motorized impeller**
  - **EBM RER-19/14N**
  - **24 Volts**
  - **4.5 Watts**



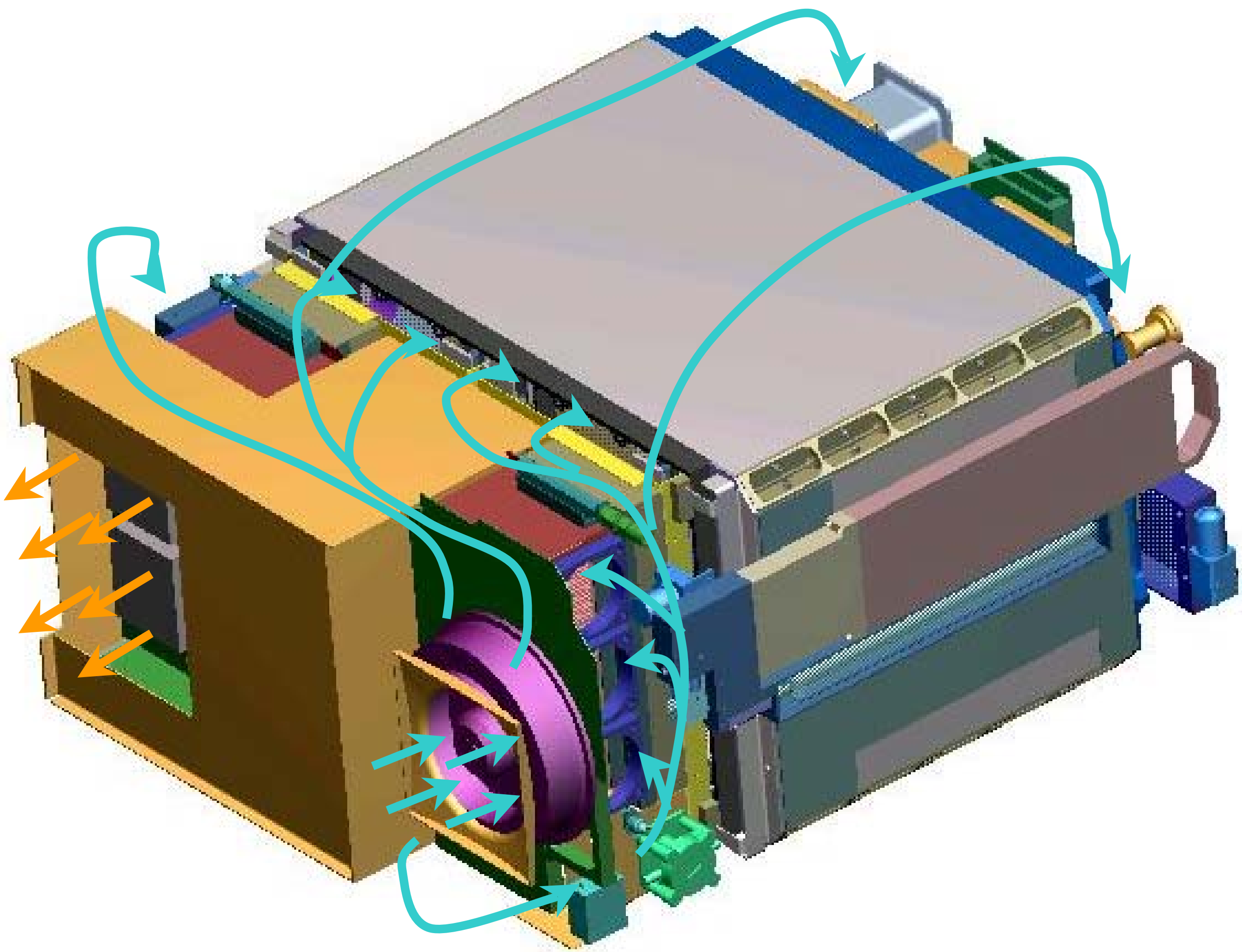


Avionics Air Flow

- Overall TIA layout and additional baffles used to control and distribute air flow in PGF-SP
- Change in Air flow for EXPRESS Rack achieved by shutting off fans on Cooling Units

	Middeck	EXPRESS Rack
Total Air Flow	36 CFM	15 CFM
Air flow to each Thermoelectric Cooling Units	12	1.6
Air Flow to each LED light module	5	4
Flow past front interface board	2	3.7
Flow through ECU housing	36	15

Avionics Air Flow



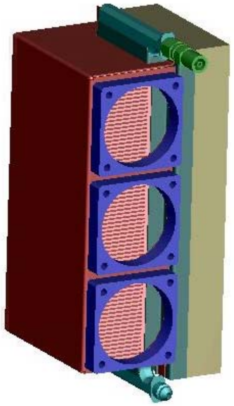
TIA Summary

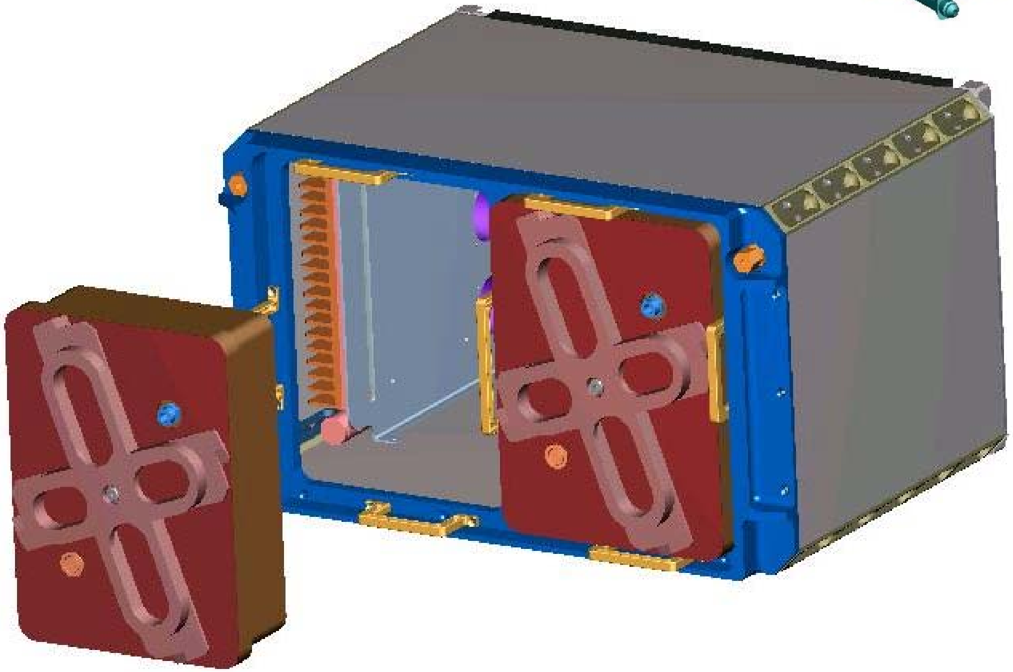
- Risks
  - TIA may not provide enough drawer motion to access lint filter at air inlet
- Weight (TIA brackets only)
  - 1.62 lbs without drawer slides
  - 4.42 lbs with slides
- Power Consumption
  - 4.5 watts for inlet fan

Plant Growth Chamber Assembly (PGC)

- Two independent Plant Growth Chambers
- Environmental control of temperature and humidity
- Condensate collection and recovery for watering
- Insulation Panel

  Construction





PGC Requirements

- Contain Plants in controlled environment
- Maintain air temperature to a set point between 23 and 26°C with an accuracy of +/-0.5°C
  - Compared to sensor reading
  - Will result in less than 1.0 °C difference in measured chamber temperatures when set points are same - Intended to meet RASTA Requirement
- Control Humidity to a set point between 60 and 80%RH to an accuracy of +/-5%
  - Compared to sensor reading
  - RASTA Requirement of 5% difference between chambers may not be met

PGC Requirements

- **Allow for Growth Lighting**
- **Provide automated condensate collection**
- **Provide condensate recirculation and watering**
- **Allow for easy access on orbit**
- **Circulate air to prevent temperature, humidity and air quality variations**
  - **Temperature - +/-0.5°C - Meets RASTA**
  - **Humidity - +/- 5%RH - Meets RASTA**
- **Collect environmental data**
  - **Temperature Sensor Accuracy +/-0.2°C**
  - **Humidity Accuracy +/-2% RH**
  - **CO_2 concentration +/-(20 ppm and 2% of reading)**

PGC Requirements

- Collect overall images of plant growth
- Allow for special imaging equipment like GFP Imager
- Control air leakage with outside environment to less than 10 ml/min of air to aid in Carbon Dioxide control
- Constructed of materials which meet Flammability, Odor, Off gassing and Biocompatibility

PGC Interfaces

- Plants
  - Biocompatibility, Volume
- Experiment specific hardware
  - GFP Imager
  - Growth media and water distribution system
- LED Light Module
- TIA structural brackets
- ECU
  - Control, power, data
- Avionics air and ISS MTL

PGC Goals

- Maximize growth volume
- Maximize experiment flexibility
- Air temperature control to 20°C in some cases
- Minimal air leakage
- Minimum weight

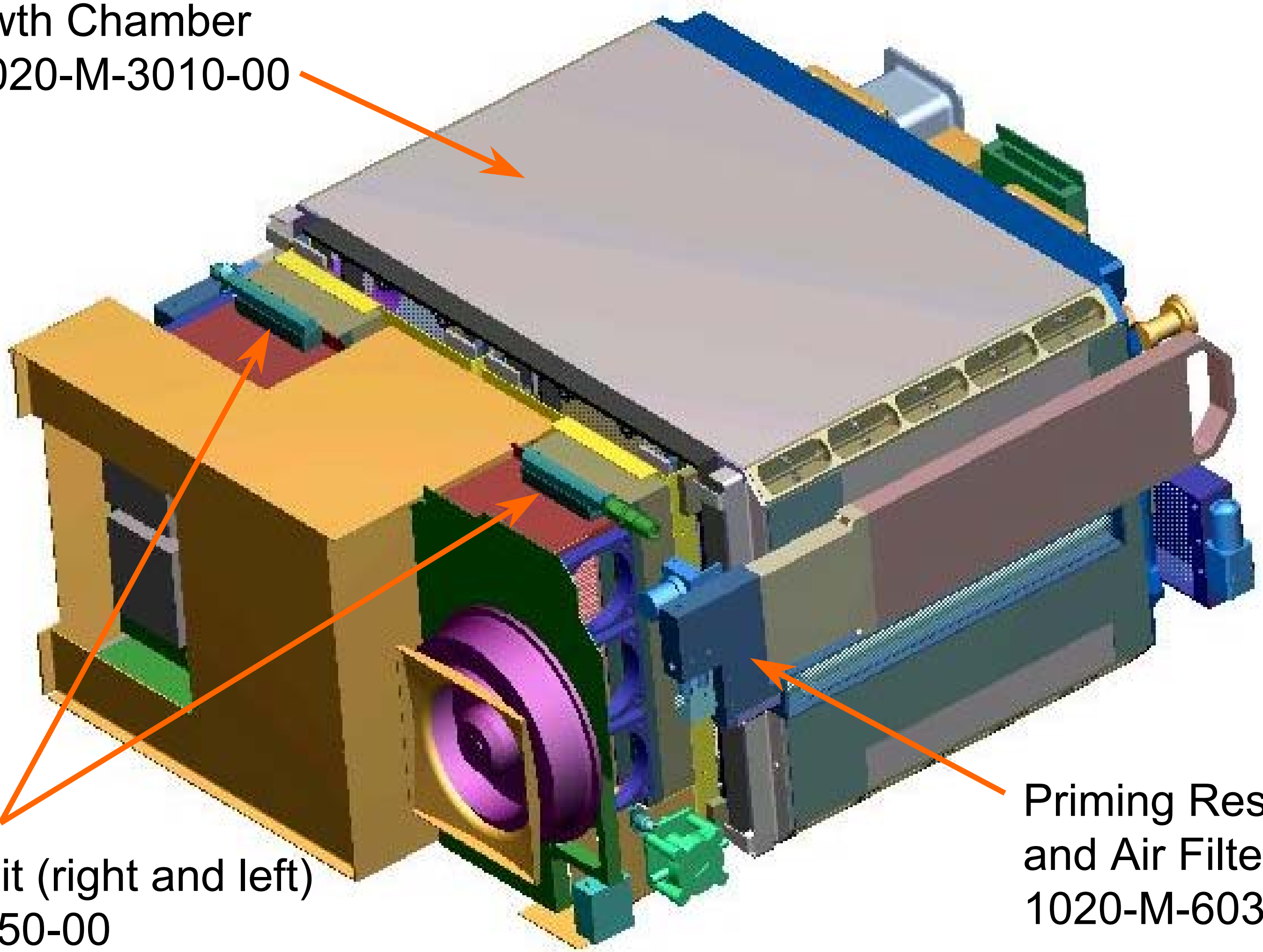
PGC Subassemblies

- PGC Housing
  – Provides enclosure for plants
  – Provides support for Environmental Control Panel and GFP Imager
- Root Tray
  – Removable tray with growth media for easy harvesting
- Environmental Control Panel
  – Supports cold sink, fans condensate collection and sensors in PGC

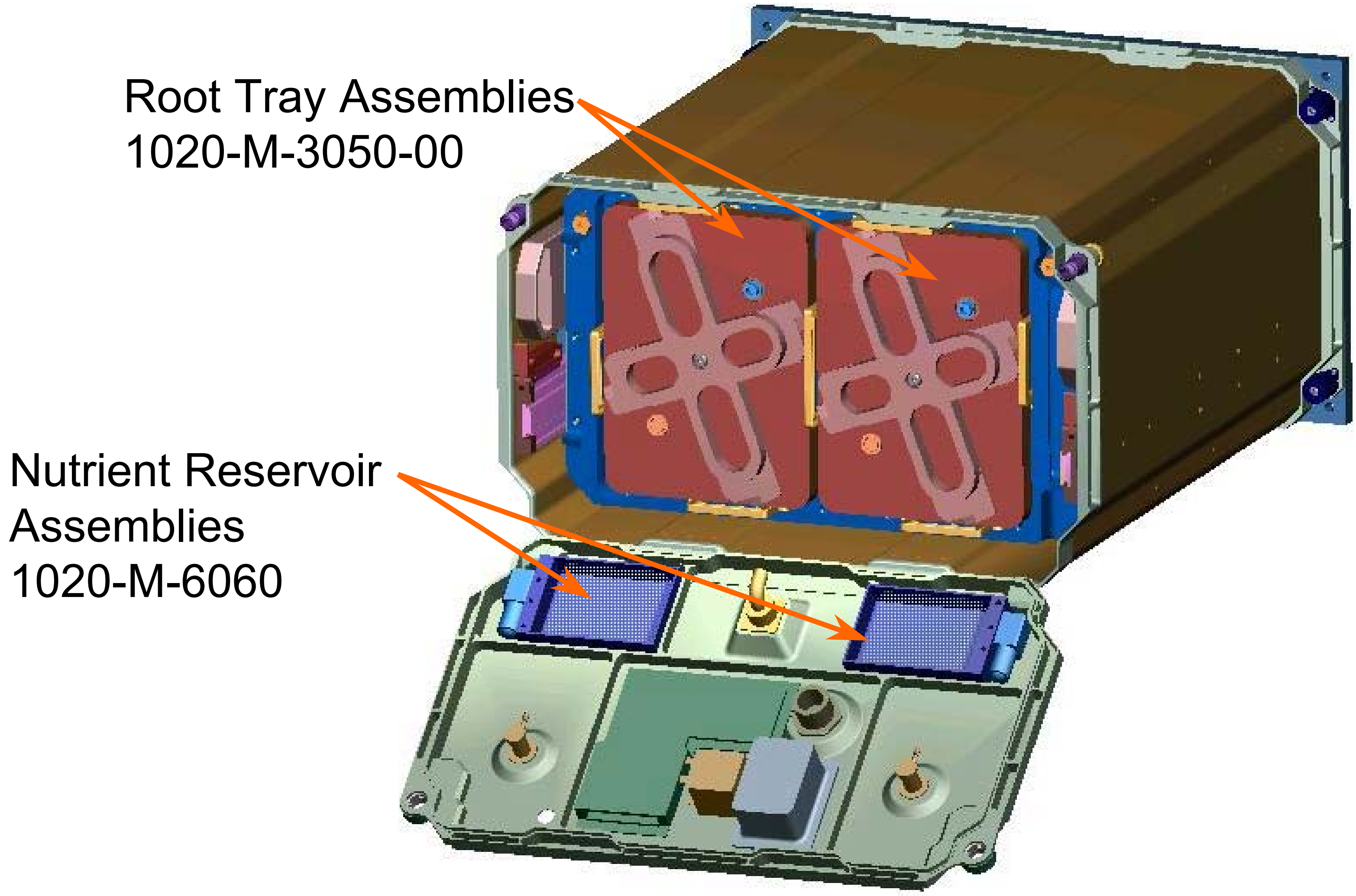
PGC Subassemblies

- Cooling Unit
  - Generates cold water using TECs for cooling PGCs
- Priming Reservoir and Manifold
  - Stores water for maintaining prime in condensate collection system
- Nutrient Reservoir and Watering system
  - Holds stored nutrient solution and recovered condensate
  - Pumps water back to root modules
- Analog Cameras
  - General plant growth imaging

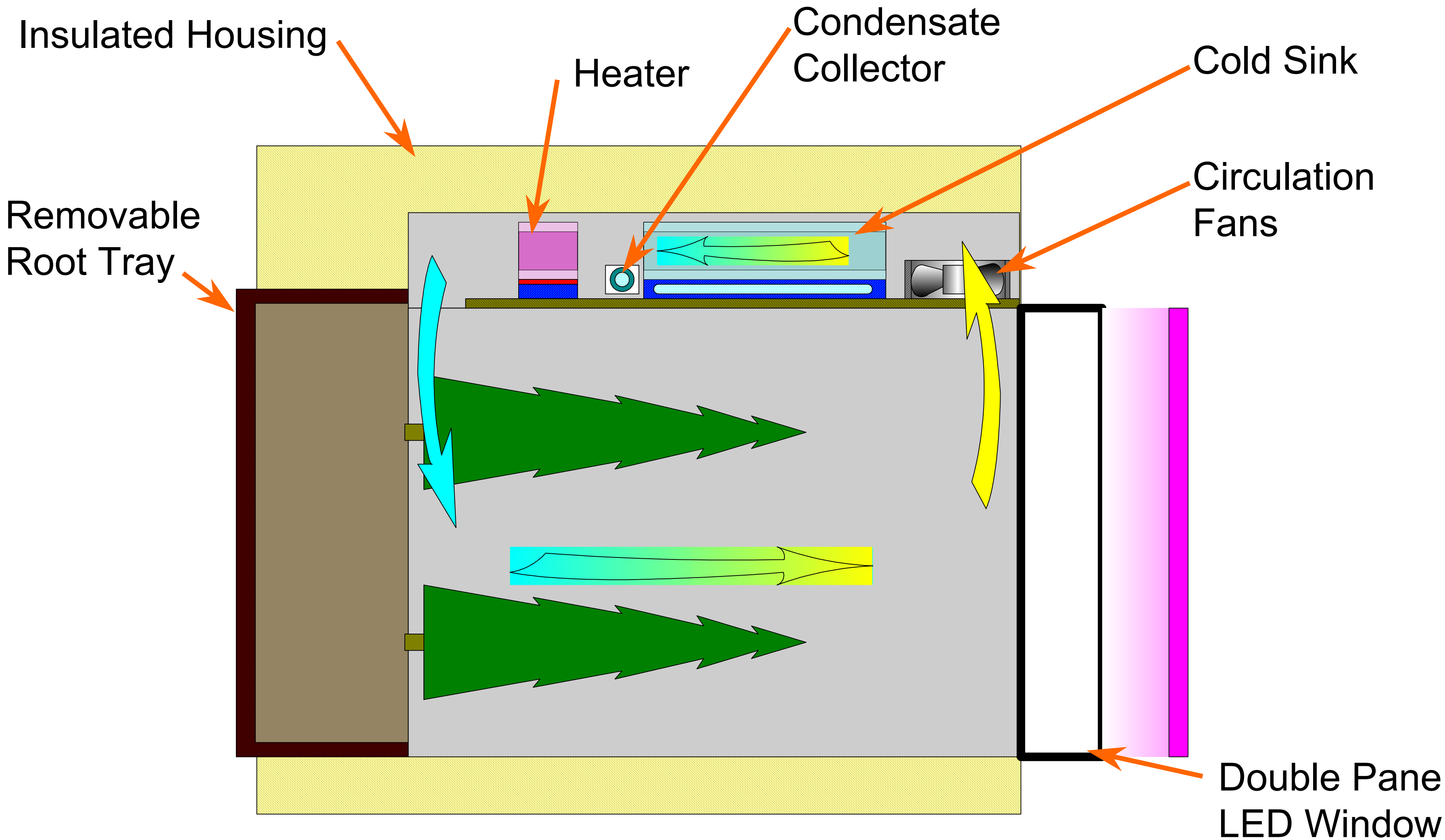
PGC Subsystem Design



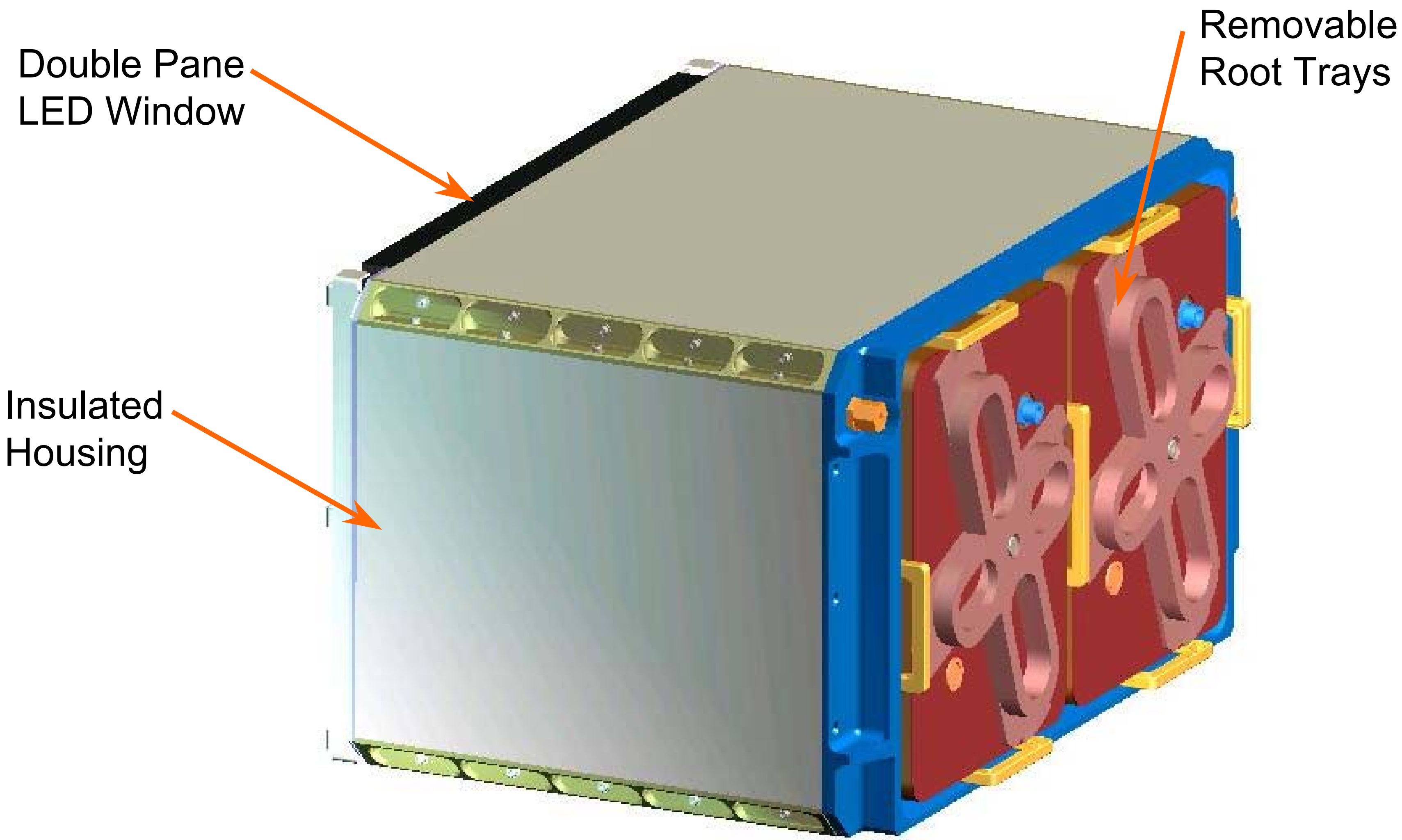
PGC Subsystem Design



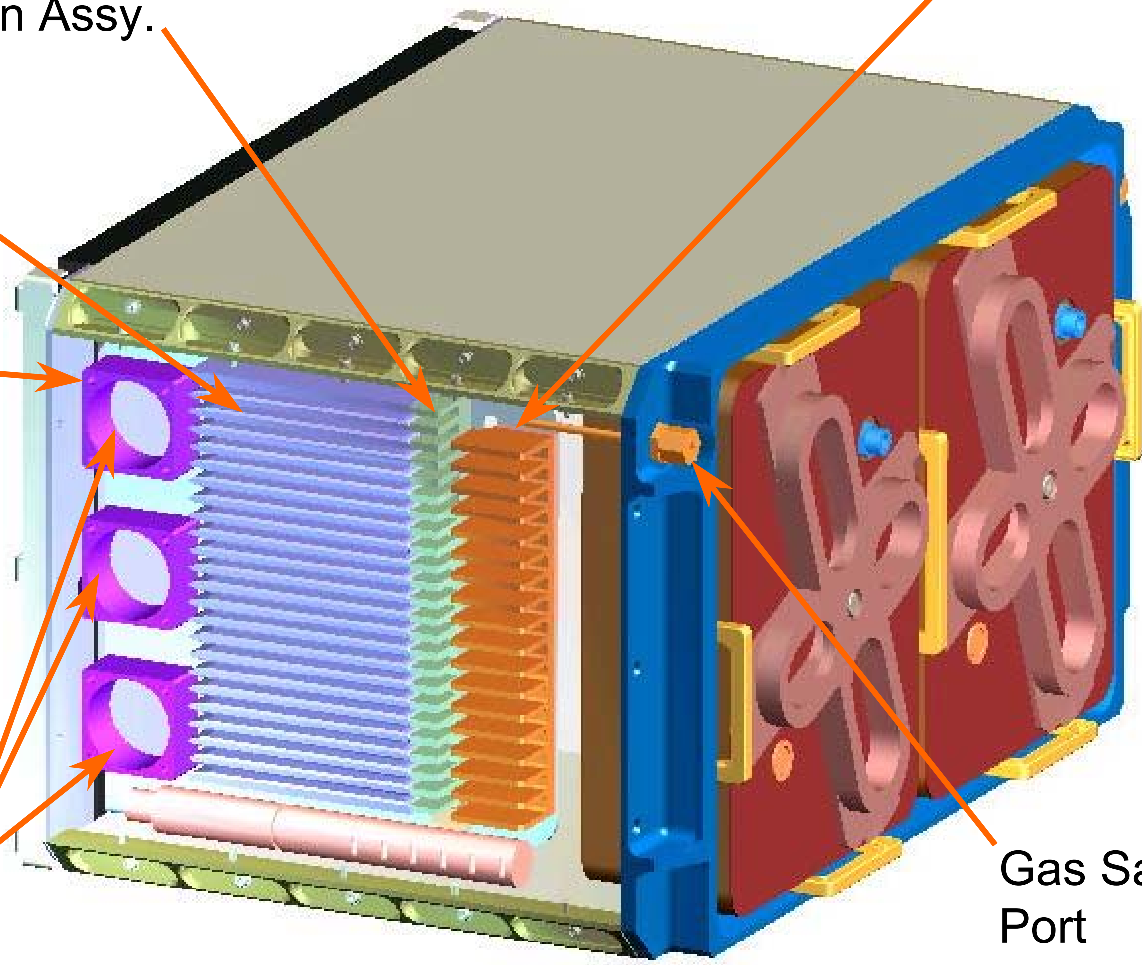
PGC Subsystem Design



PGC Subsystem Design



PGC Subsystem Design

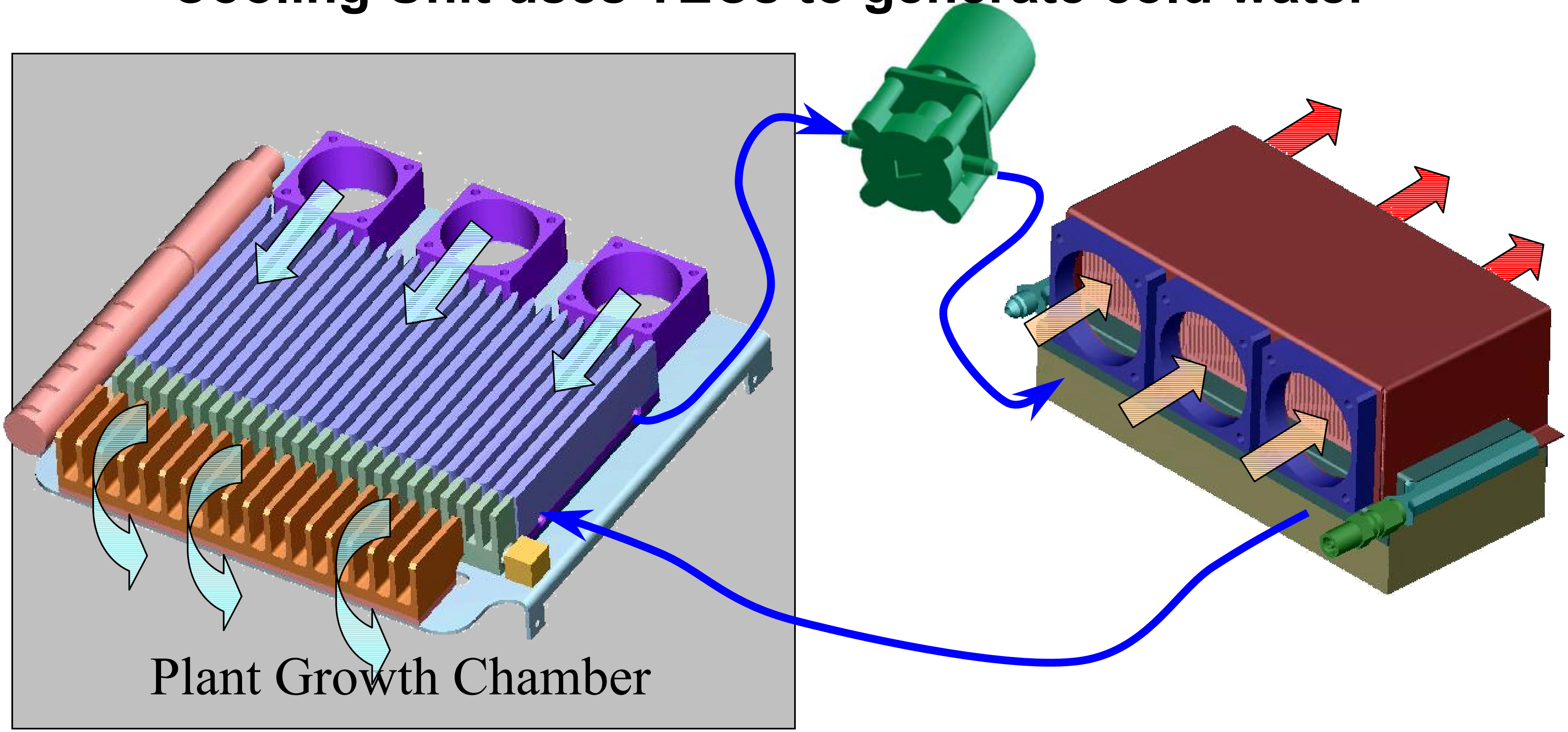


Temperature Control

- Growth chambers cooled by cold water loop
- Separate Cooling Units supply cold water to each side
- Deionized water in cooling loop, 60ml per side
  - 400 ml/min Flow Rate
- Water circulated by gear pump running at half rated speed
  - B&D Pumps UPG-8000
- Cooling Unit insulated and placed in direct air path near inlet and outlet
  - 12 CFM of avionics/cabin air in Middeck per cooling unit
  - 25 lbm/hr MTL water and 1.6 CFM of avionics air per cooling unit in EXPRESS Rack

Temperature Control

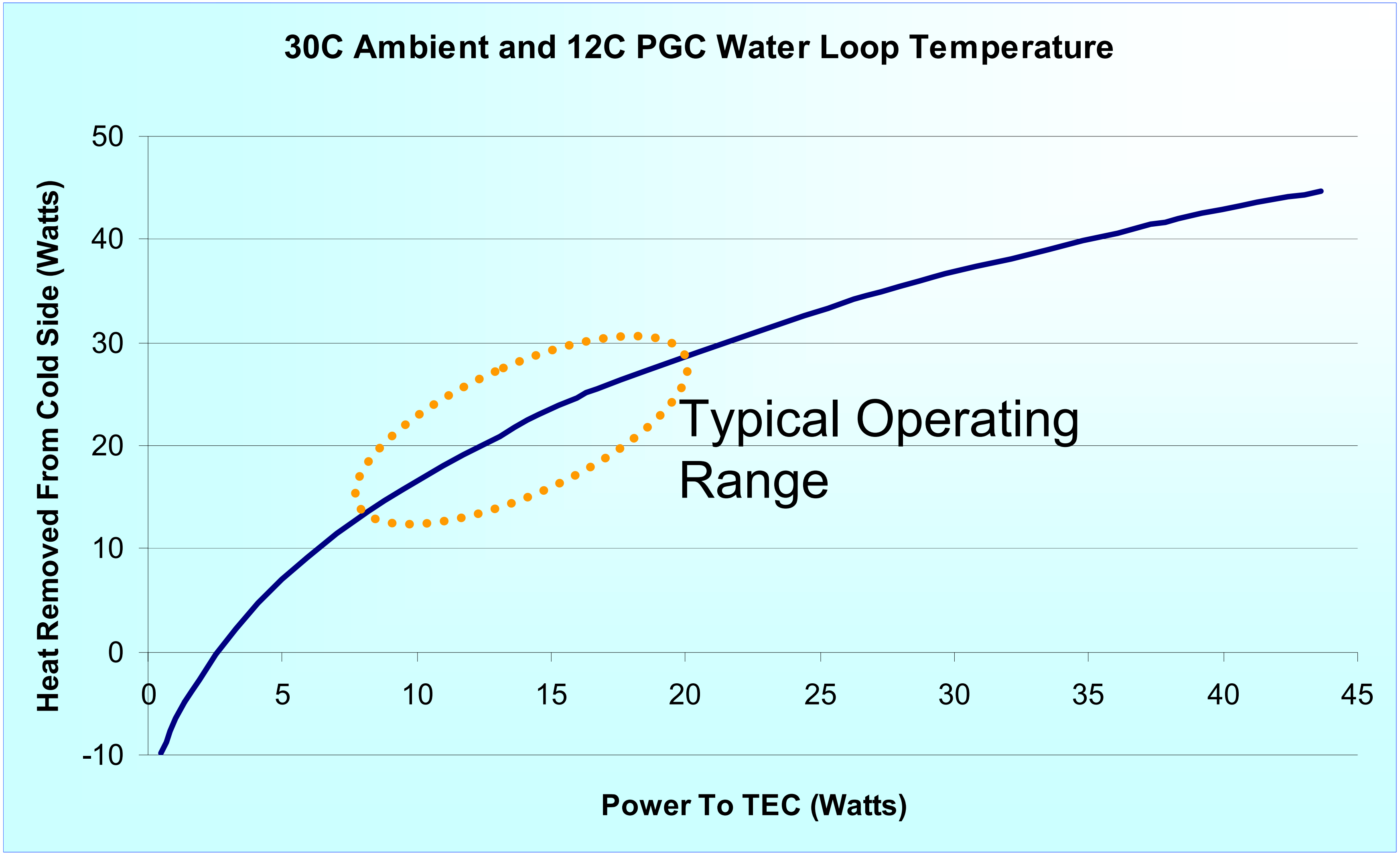
- Water loop provides cooling to Cold Sink in PGC
- Cooling Unit uses TECs to generate cold water



Temperature Control

- Power to cooling unit is closed loop PID control based on PGC temperature sensor reading
- Cooling system uses three (3) Thermoelectric coolers (TECs) electrically in series to provide large cooling capacity
- TECs nominally operate in low end of capability to improve efficiency, life and dynamic response
- Cooling limited by total heat rejected to avionics air

TEC Performance



PGC Thermal Design

- Thermal performance depends on
  - Heat entering growth chamber from environment
  - Heat generated in PGC by fans and electronics
  - Cold sink performance (in chamber heat exchanger)
  - Energy from water pump
  - Cold Side Heat Exchanger Performance (cooling unit water heat exchanger)
  - TEC Performance
  - Heat Rejection Fin Performance

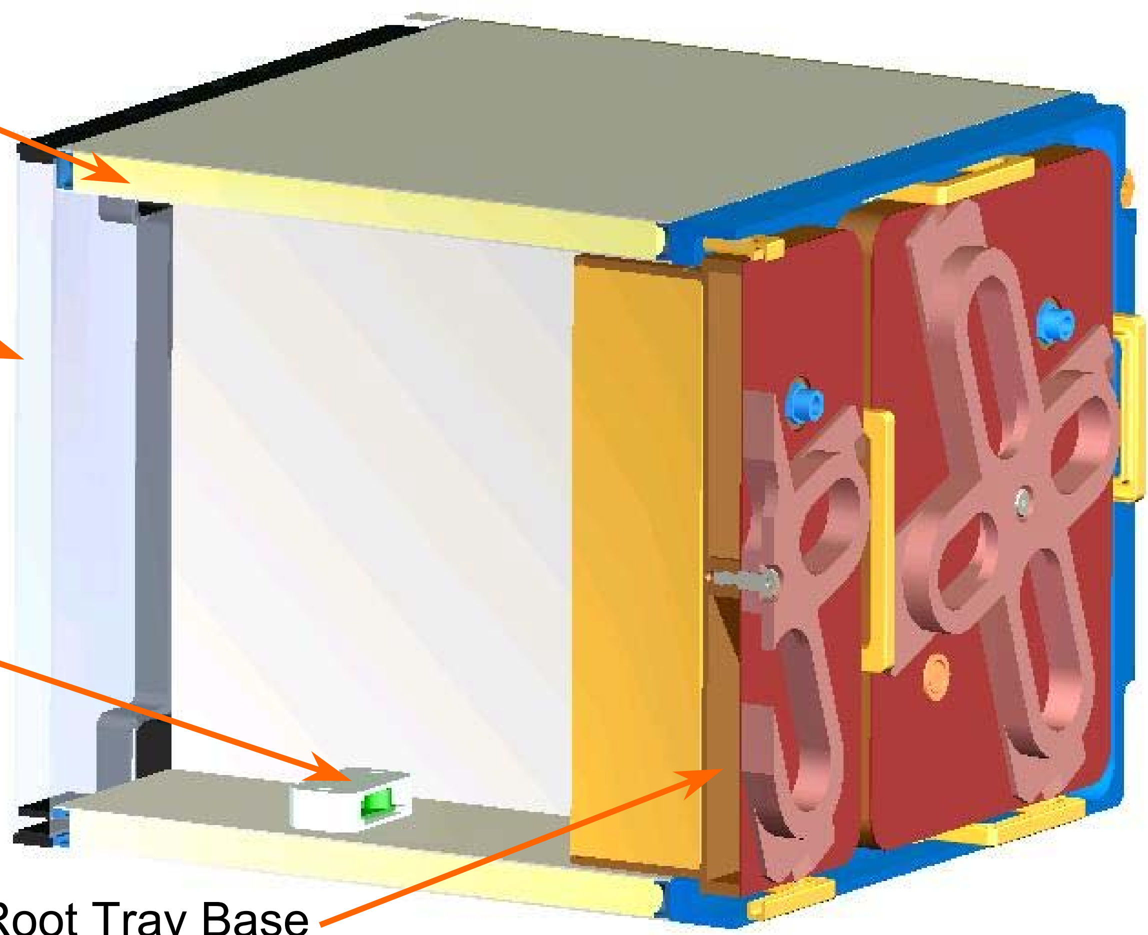
PGC Insulation

Estimated Thermal Conductance to Locker Air is 2.25 °C/watt

0.5” Foam Insulation in sandwich panel

0.5” Air Gap in Double Pane LED Window

Chamber Temperature and Humidity Sensor



0.5” Foam Insulation in Root Tray Base

Heat Transfer into PGC Air

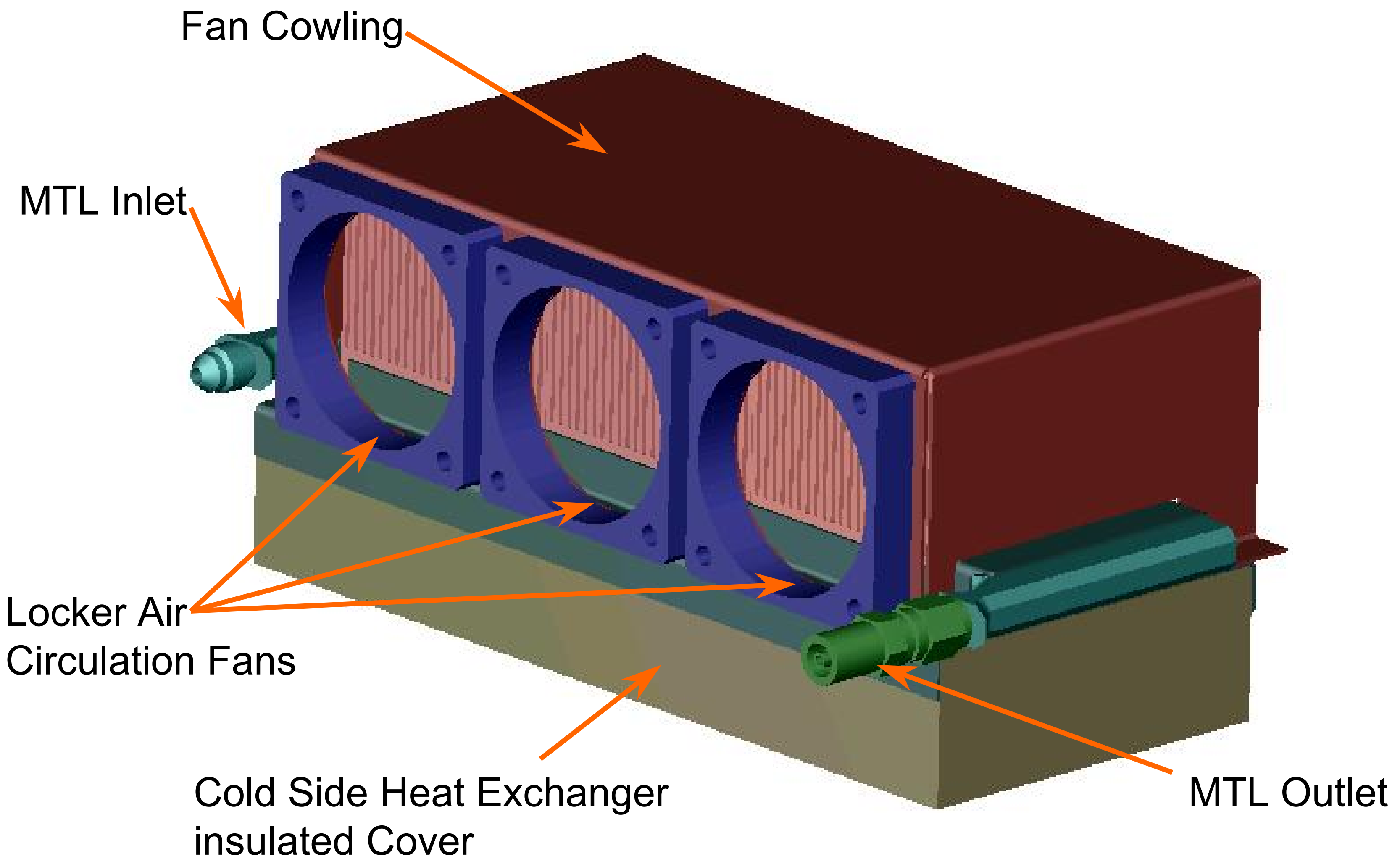
	Heat into PGC Air (Watts)	Conditions
Convection From Locker Air	4.2	30°C Locker Air 22°C PGC Air
Convection from LLM	1.0	31 Watts to LLM ~350 μmoles/m2/s
Radiated from LLM	7.0	31 Watts to LLM
Generated by fans	4.0	All fans on for 80%RH set point
Sensors/Cameras	<1.0	Average usage
Total Heat to be removed	~17.2	Represents extreme usage case

Water Loop

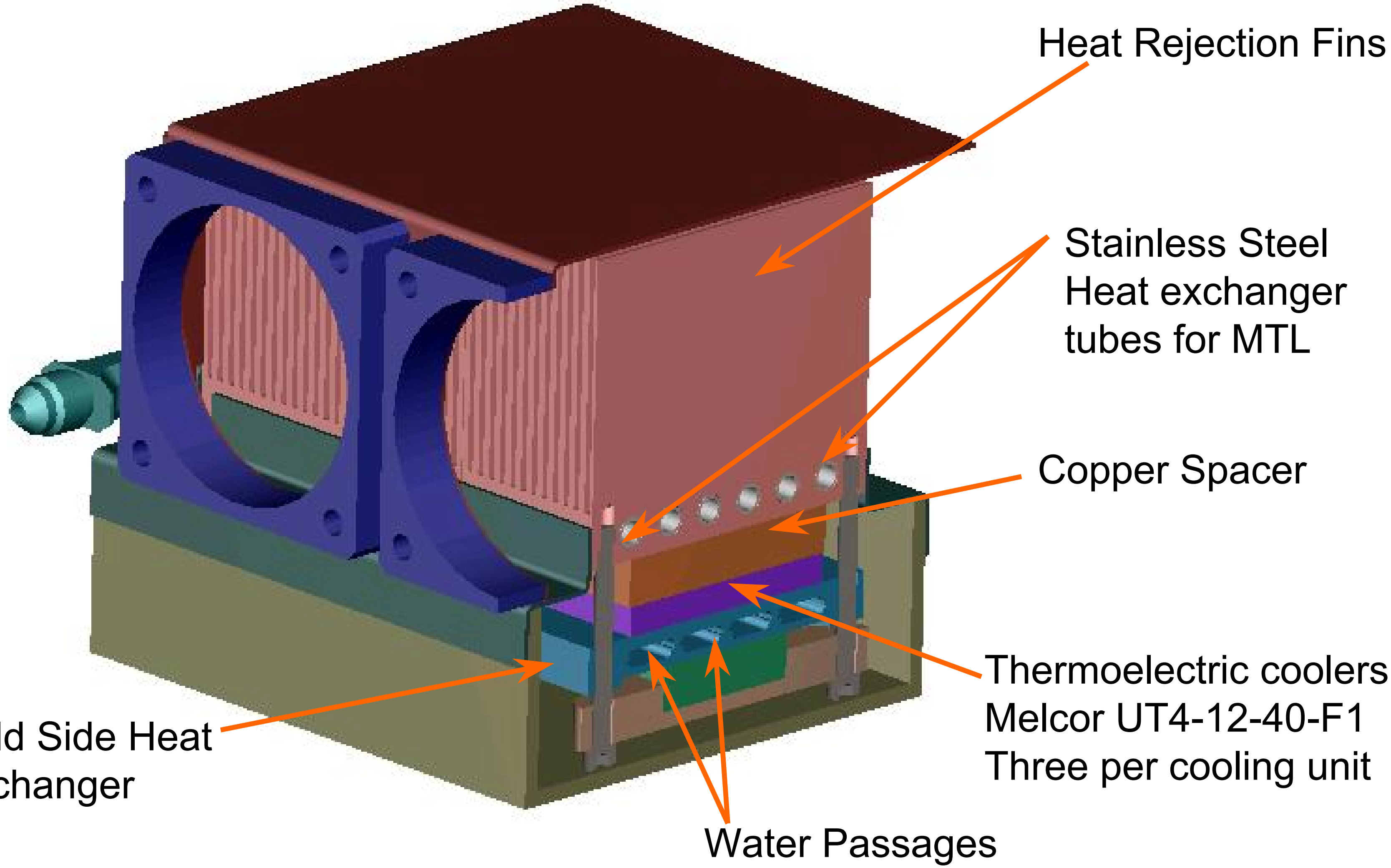
- Water loop performance based on 17.2 watts of heat into PGC Air

	Heat into PGC Air (Watts)	Units
Thermal Conductance of Cold Sink to water	.27	°C/Watt
Water to Air temperature difference	4.6	°C
Water Flow Rate	400	ml/min
Heat into water from circulation pump	3.5	Watts
Water temperature at Cold Side Heat Exchanger in Cooling Unit	16.8	°C

Cooling Unit



Cooling Unit



Heat Removal

- **TEC and Cooling Unit performance based 17.2 watts of heat into PGC air**

	Heat into PGC Air (Watts)	Units
Thermal Conductance of Cold Side HX to water	.18	°C/Watt
Water to TEC Cold Side Temp. Diff.	3.7	°C
Power to TEC's	15	Watts
Thermal Conductance of Heat Rejection Fins	.046	°C/Watt
Heat to cooling air	35.7	Watts

Locker Air Temperature Rise

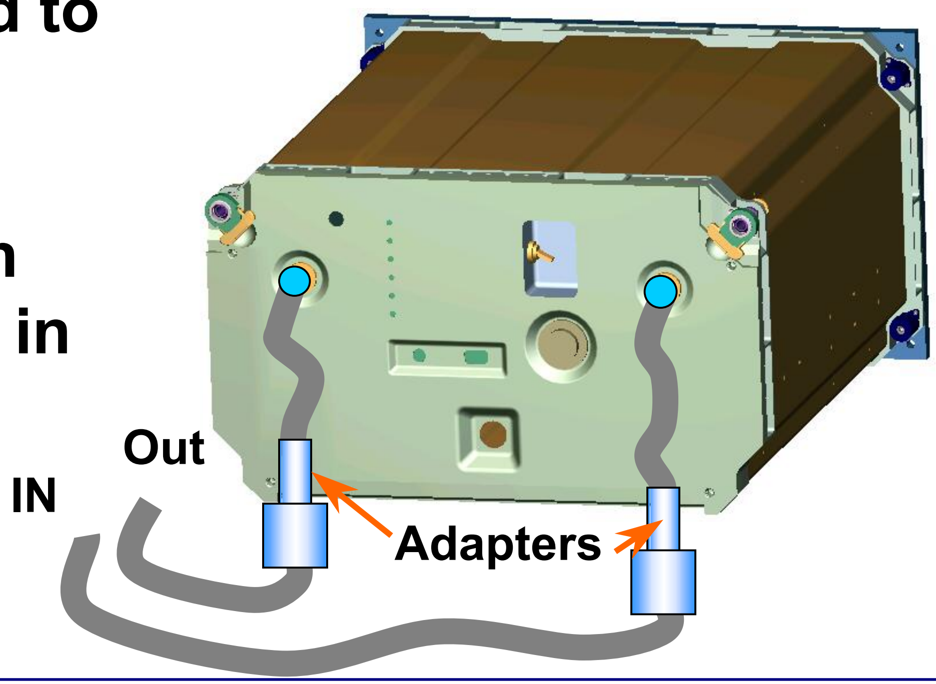
- **Assuming EVA operation thermal capacity of 12 cfm of air is ~4.6 Watts/°C**
- **Assuming locker air temperature of 30°C air temperature after Cooling Unit is ~ 38°C**
- **Estimated heat rejection fin temperature is ~40°C (104°F)**

MTL Water Temperature Rise

- **Assuming 25 lbm/hr flow the heat capacity of water is ~13.2 Watts/°C**
- **Assuming locker entering MTL water temperature of 23°C exit temperature is 28.2°C**
- **Estimated heat rejection fin temperature is ~36°C (97°F)**

MTL Conceptual Design

- Custom quick disconnects at front of locker
  - Reduce weight and volume
- Adapter section external to Payload installed on orbit
- Water split and routed to cooling units using flexible hose
- Water passes through stainless steel tubing in heat rejection fins



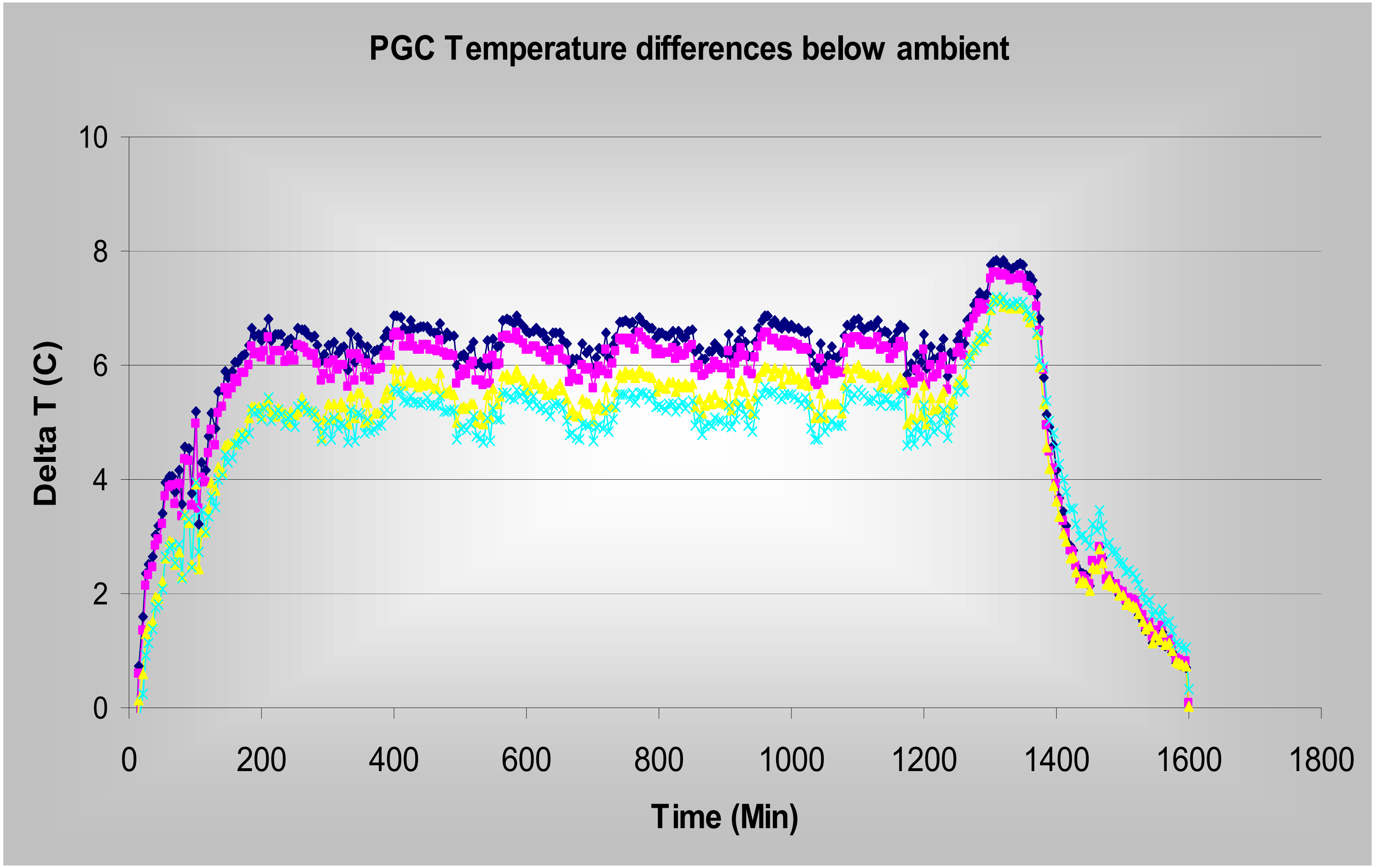
Thermal Design/Analysis

- **Each PGF-SP system was evaluated in thermal analysis**
  - **Heat generated**
  - **Thermal Resistance**
  - **Air flow Resistance**
- **Calculations were based on text book formulas for conduction, convection and air flow**
  - ***Fundamentals of Heat and Mass Transfer*, Incropera and Dewitt**
- **Formulas were used to design and optimize heat sinks and select fans and TECs**

Thermal Design/Analysis

- **Based on formulas and estimates the breadboard thermal control unit was fabricated and tested.**
- **Achieved 6°C below ambient with lighting in bench top testing**
- **Detailed measurements were used to adjust formula predictions and improve accuracy of analysis**

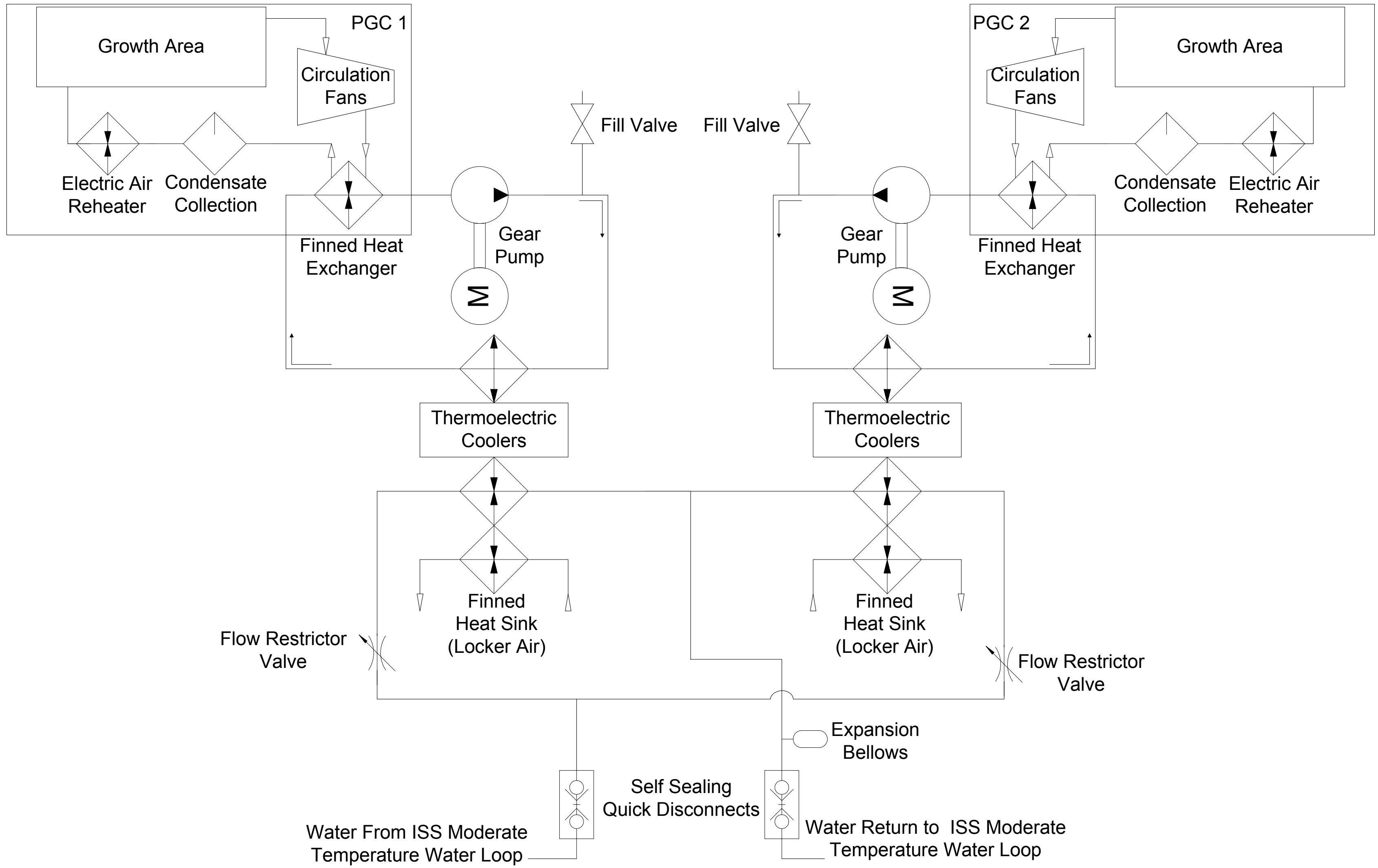
Thermal Design/Analysis



Improvements to Breadboard

- **Added double wall LED Window**
- **Increased thickness and quality of insulation**
  - **Was .375” silicone foam**
  - **Is .50” Urethane foam**

Cooling Loop Diagram



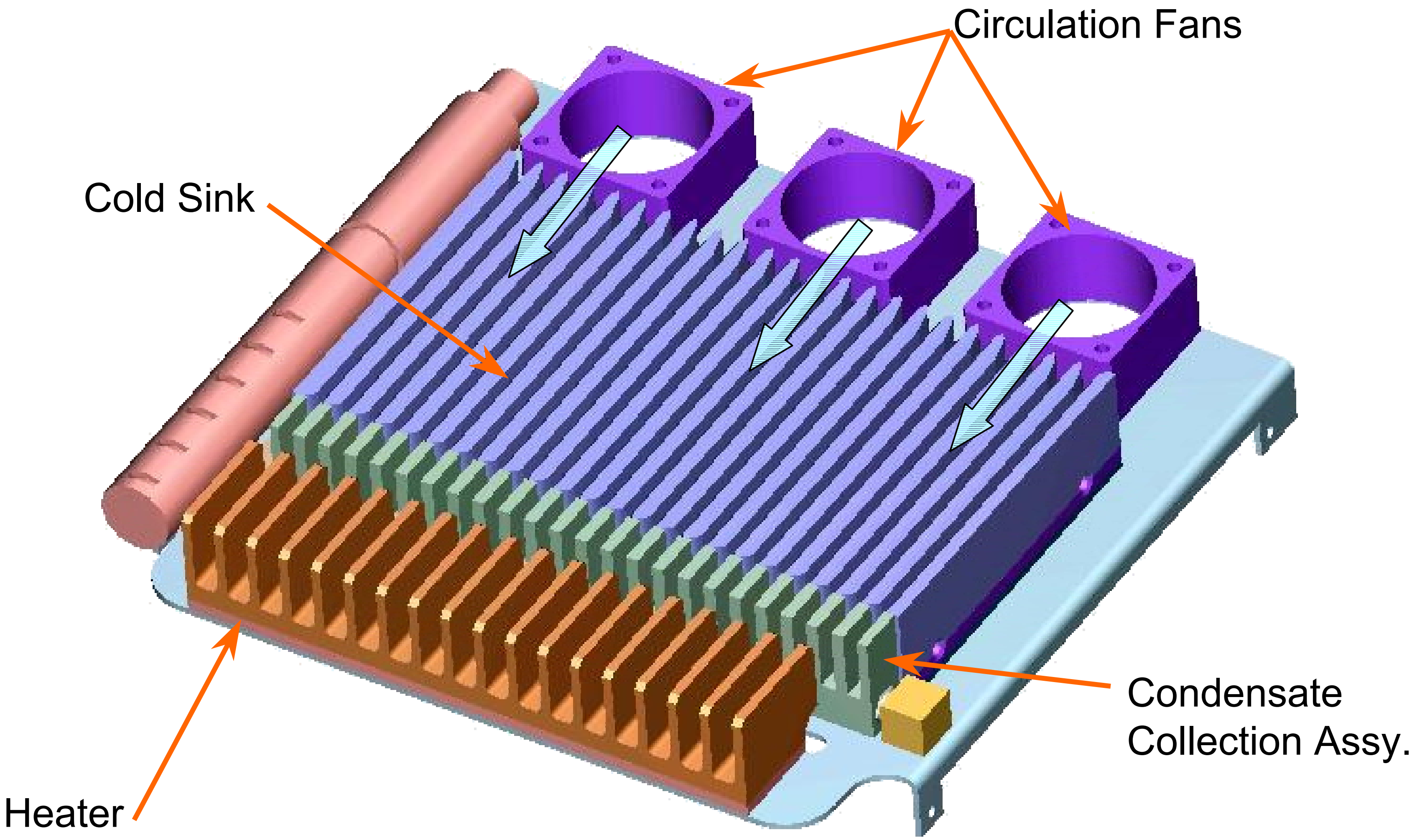
Humidity Control

- Humidity control achieved by controlling air flow over the PGC Cold Sink and by warming the air with the heater
- Heater only required for some cases when humidity set point is low and heat into PGC from locker air LLM is low
- Control is open loop based on ground characterizations of PGC thermal characteristics
  - Fan settings are lookup values based on setpoint
  - Heater power is based on light power, Inlet air temperature and PGC temperature

Humidity Control Concept

- Cold Sink acts as condenser
  - When cold sink temperature is below dew point condensation begins
  - Cold sink temperature dependent on TEC heat removal and volume air flow over Cold Sink
  - Reducing air flow by shutting off one or more fans promotes condensation
  - Heater used to increase air temperature when dehumidification results in excessive air cooling

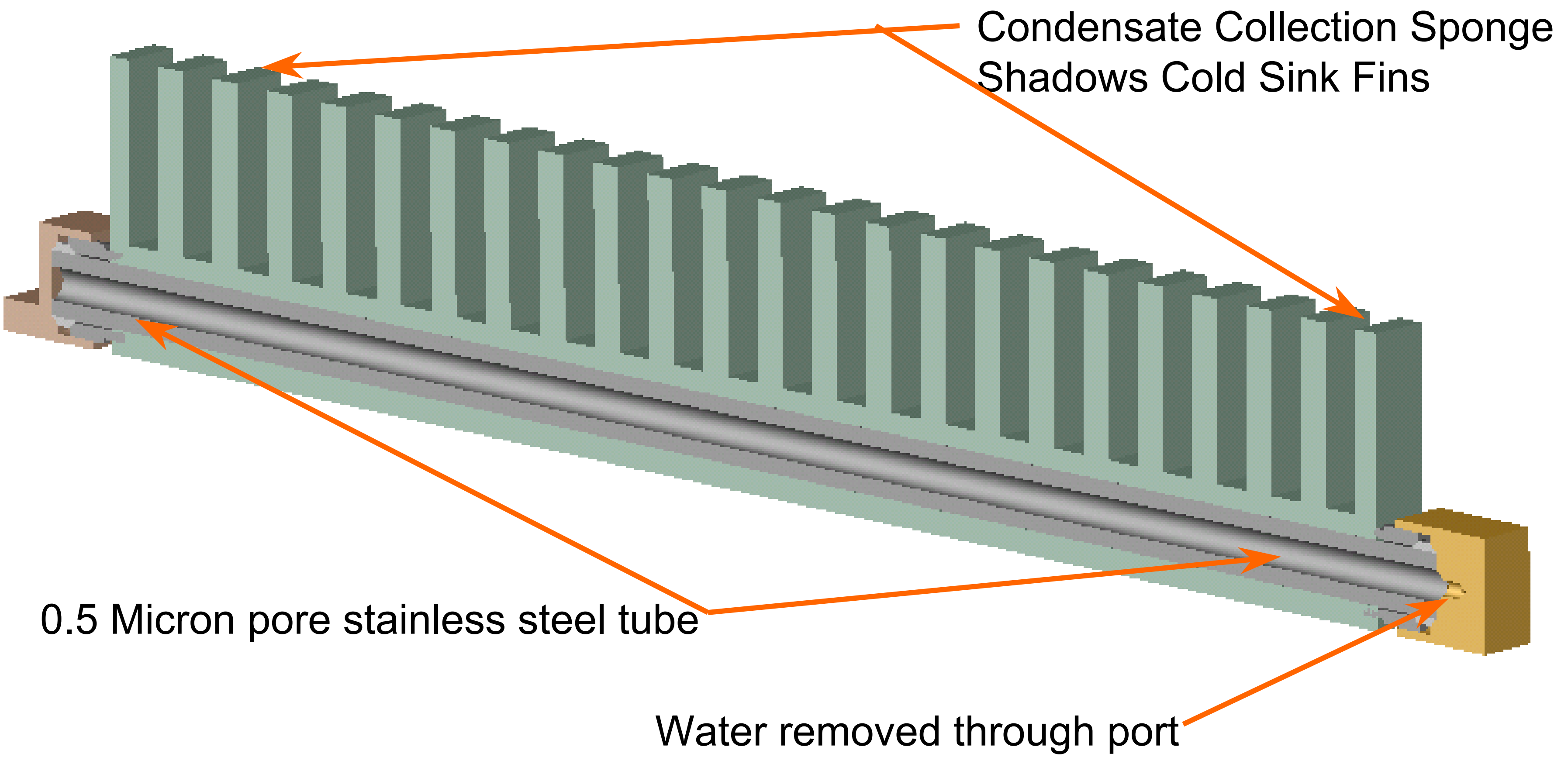
Humidity Control Concept



Condensate Removal

- Condensate on Cold Sink is removed by cooling air flow
  - With all fans on the air velocity through the cold sink will exceed 1250 ft/sec
  - Hydrophobic coating on Cold Sink surface promotes water shedding
  - All fans are cycled on once every 10 minutes for 30 seconds to remove water
  - Water is captured by condensate collection assembly

Condensate Collection



Cross-section of Condensate Collection Assembly

Condensate Collection

- Similar concept as prototype PGF-SP
  - Porous plate to remove condensate
- Peristaltic pump maintains slight negative pressure in porous tube to remove water from sponge
- Sponge captures and holds water more readily allowing for repriming and reducing loss of prime due to evaporation
  - Saturated sponge takes hours to dry
  - Sponge can accept many times the volume required to prime the porous tube
  - Sponge decreases probability of loosing prime by holding water on the surface of the porous tube

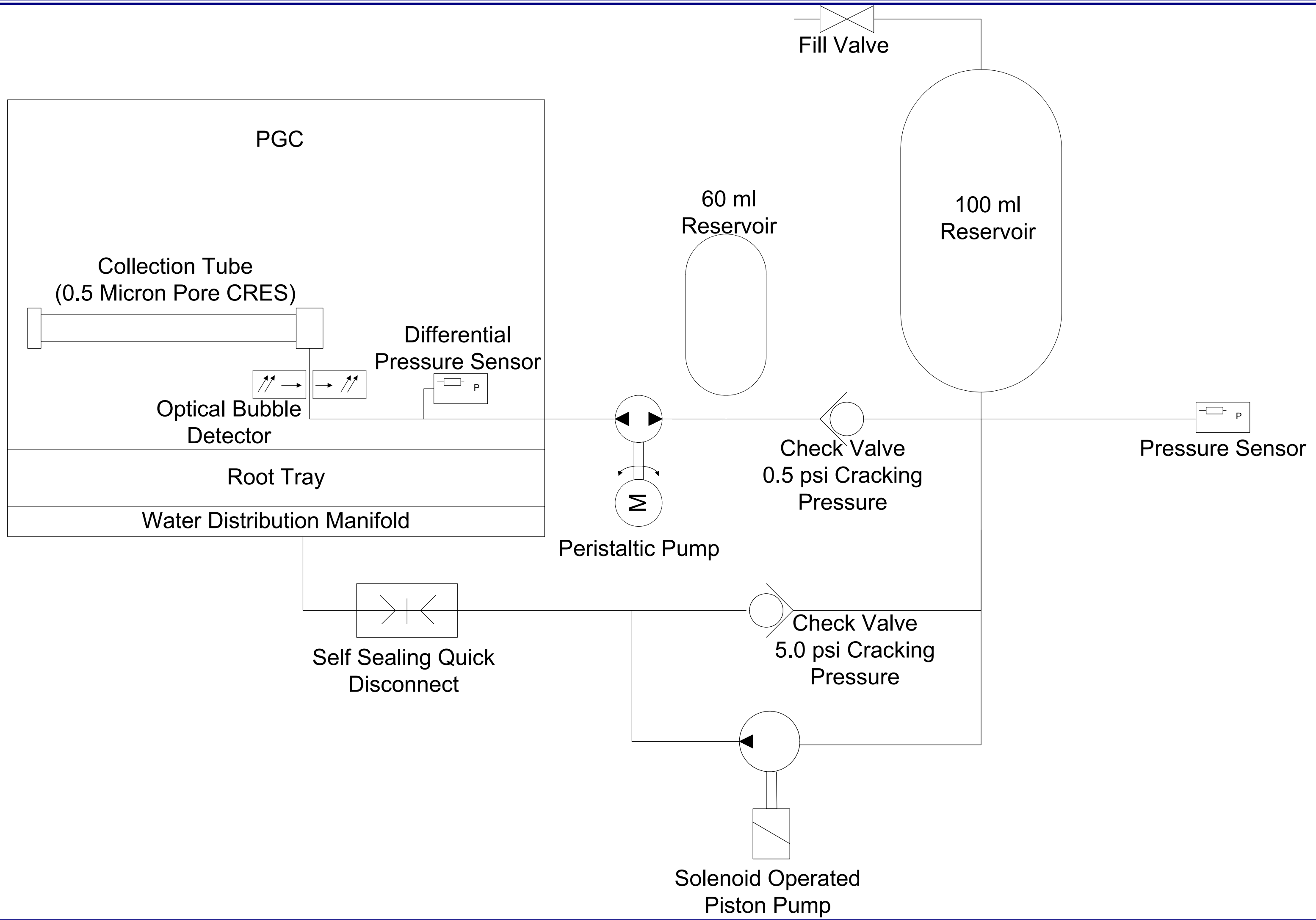
Condensate Collection

- **Porous tube demonstrates easy priming in 1g in any orientation**
  - **Back filling with water produces a reliable prime**
- **Porous tube maintains good performance despite some air intrusion**
- **Sponge has excellent capacity to store water making remainder of system less sensitive to changes in humidity, temperature and pressure**
- **Pressure of -0.9 psid produces a flow of approximately 0.12in^3/min (2 ml/min) from a saturated sponge**

Condensate Collection

- Humidity control, condensate removal and collection were evaluated in 1g
  - Initial results indicate all systems work well
  - Chamber humidity is effected by fan speed
  - Cold sink treated with hydrophobic coating sheds water with all fans on
  - Sponge catches >75% of condensate
  - Porous tube will remove excess water from sponge
- More 1g and zero g testing required

Condensate Collection and Watering Diagram



Condensate Recovery and Watering System

- Condensate captured by sponge removed by porous tube
- Peristaltic pump maintains negative pressure using pressure sensor and closed loop control
  - Peristaltic pump - Instech P625/66
    - Used on PTIM module
  - Pressures sensor located in PGC to reduce head pressure effects
  - Pressure Sensor - Omega PX26-005DV
    - +/-5 psi range differential sensor
    - Same family as prototype sensor used with good results

Condensate Recovery and Watering System

- **Optical bubble detector prevents introduction of air into system**
  - **Peristaltic reverses and drives 10 ml back into porous tube to clear bubble**
  - **Bubble detector located near porous tube to catch bubbles quickly**
  - **Optical interrupter module - DigiKey part H21A1-ND**
  - **Breadboard standalone bubble detector worked well**

Condensate Recovery and Watering System

- Priming reservoir (60 ml) acts as buffer to ensure that porous tube can reprime with pure water if required
  - Enough volume to fill porous tube and sponge to 25% saturation twice
- Check valve maintains separation between nutrient reservoir and priming reservoir
  - Smart products .25” cartridge check valve
- Nutrient reservoir (100 ml) collects excess condensate and stores water or nutrient solution
- Pressure sensor used to indicate reservoir full to crew

Condensate Recovery and Watering System

- Solenoid pump sends water from nutrient reservoir to root tray
  - LEE LPLA1210550 solenoid pump
    - Used on prototype with good results
- Check valve allows excess water to flow into root tray to prevent overfilling of bag
- Quick disconnect on root tray allows water to be disconnected when root trays are removed
- Water distribution system is experiment specific

Water Conservation

- Water reservoir size and refilling are dependent on systems ability to conserve/contain water and water vapor and plant growth
- Generally the priming reservoir will remain full under normal operations
- The growth media will be maintained at roughly the same saturation throughout the experiment by the watering schedule
- Most water will remain within a "water cycle"
  - Evaporation/transpiration
  - Condensation
  - Collection
  - Watering

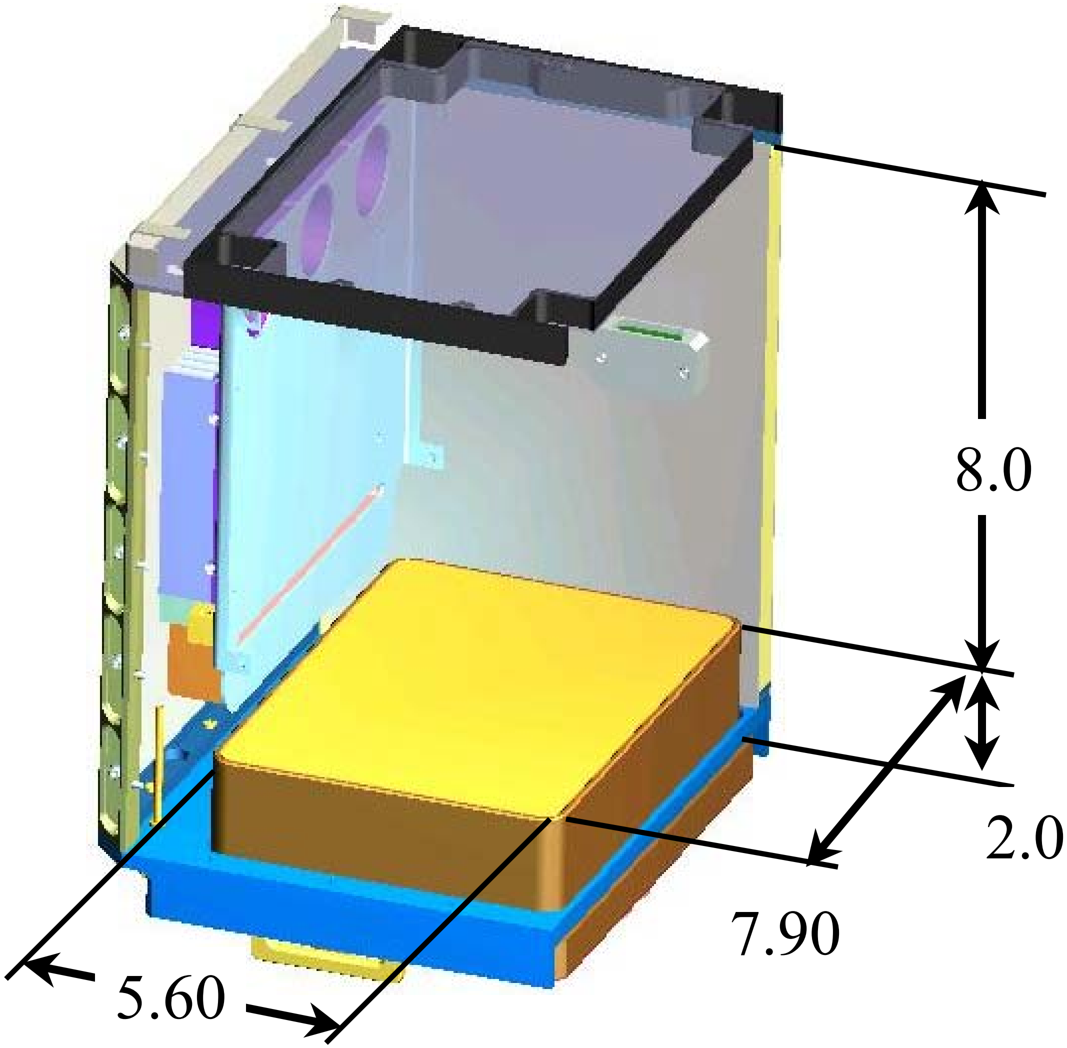
Water Conservation

- **Water is lost from this cycle by**
  - Plant Growth - assume plants are almost completely water
  - Air leakage
  - Water trapped in LiOH cartridges, assumed low since cartridges are only changed once a week
- **Air loss due to leakage is approximately**
  - 1.34E-5 ml liquid water/ml of air
  - Multiplied by air leak rate of 10 ml/min
  - .19 ml per day - negligible
  - Based on exchange of 20% RH air for 80% RH air at 70F

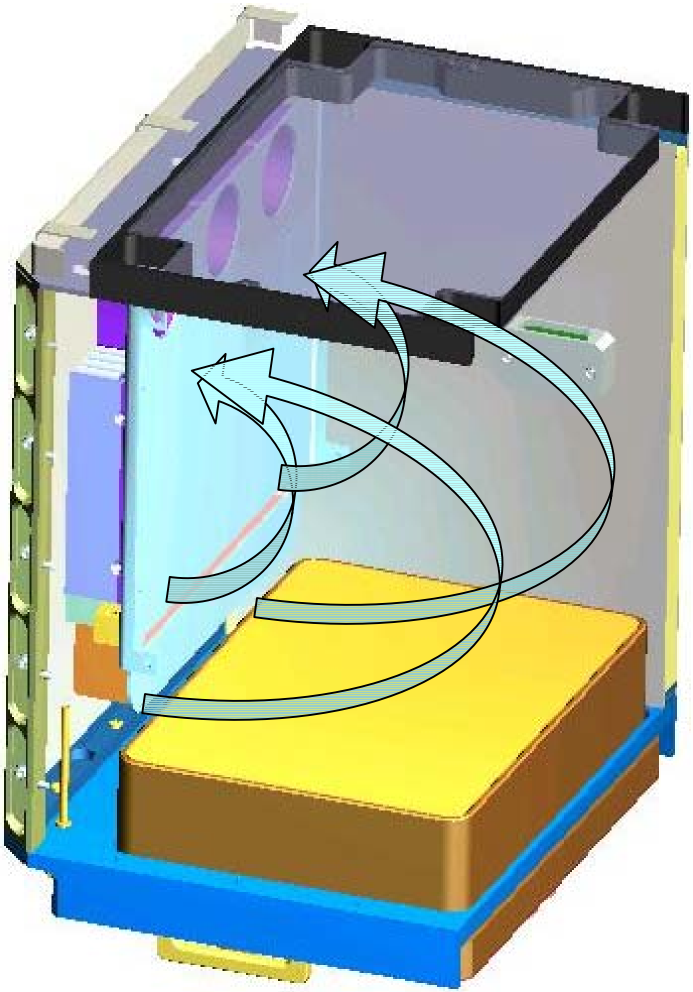
Water Conservation

- Estimated plant volume for RASTA experiment is roughly 600 ml per chamber
  - Based on 1.5” diameter radish as bulk of volume
  - 15 radishes per chamber
  - 21 days worth of growth
- Reservoir will require filling every 3.5 days on average
- Estimates from ground experiments indicate that nearly 500 ml/day of evaporation or transpiration was experienced at end of experiment
- This is within the 2 ml/min capacity of system

Growth Volume

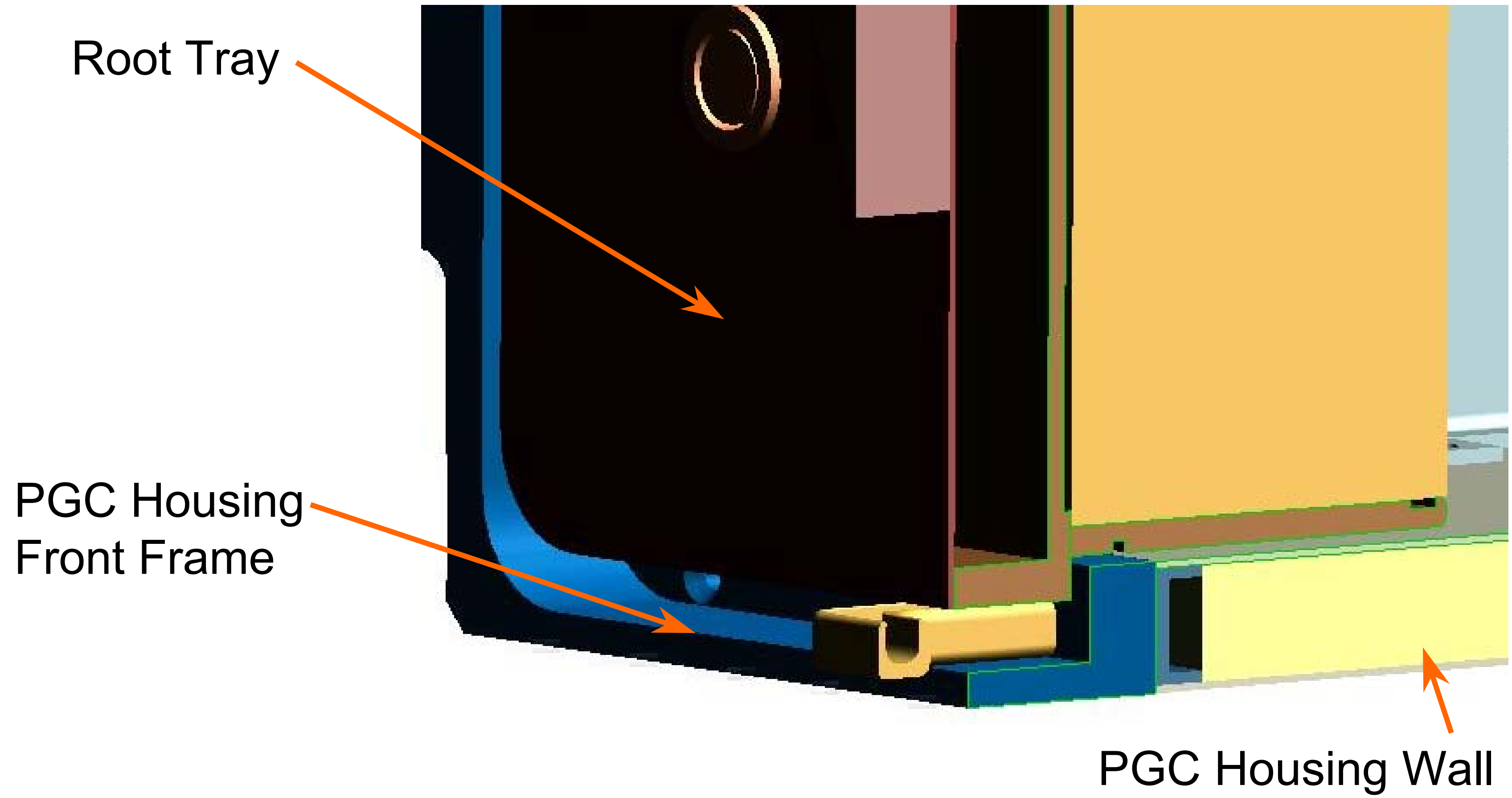


PGC Air Flow



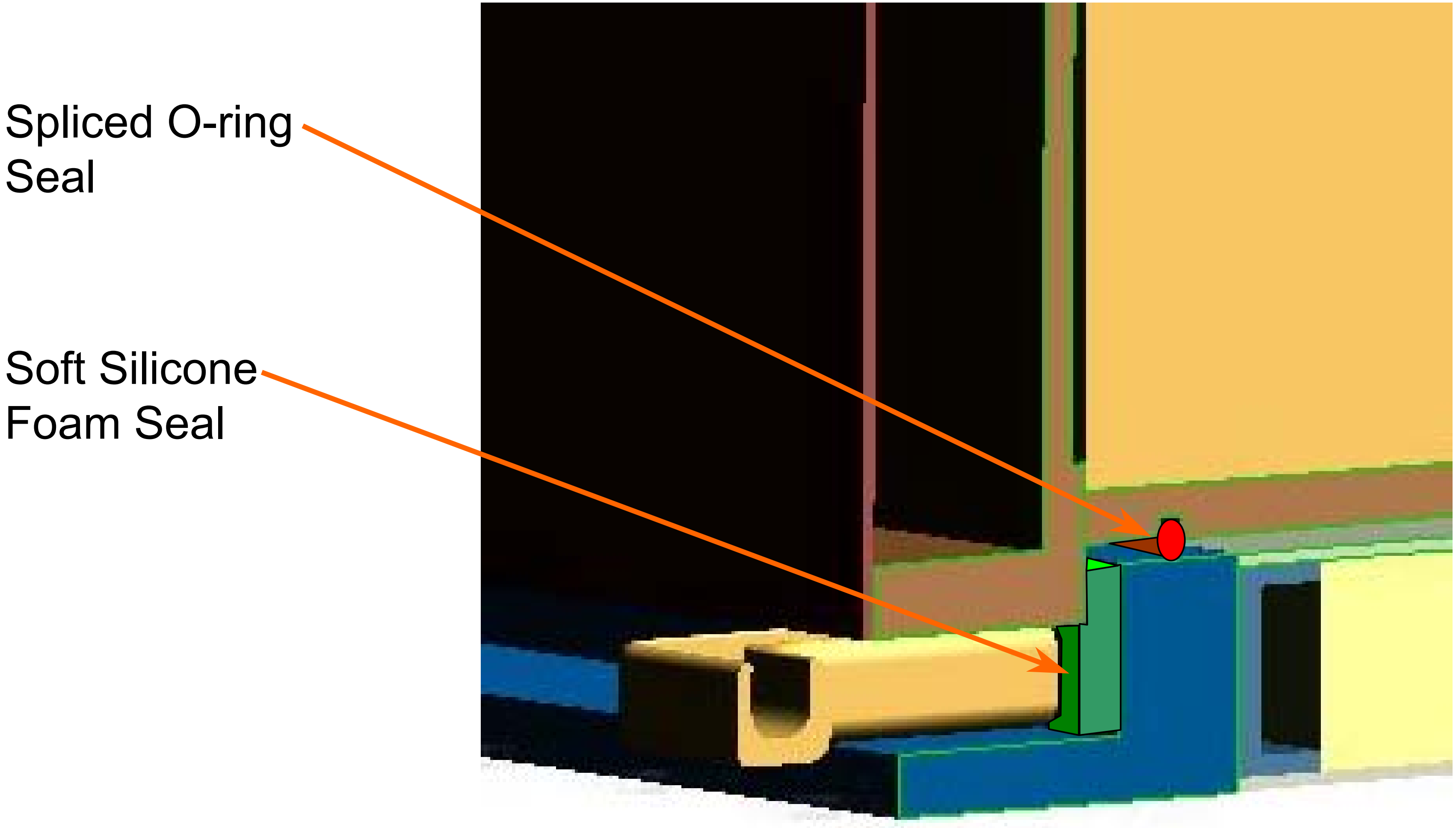
- Nominal Volume Flow Rate dependent on Humidity set point
  - 6 cfm for 60% RH
  - 15 cfm for 80% RH
  - 17 cfm during condensate removal
  - 295 ft/min (1.5 m/s) Air velocity at entrance to growth area during condensate removal

PGC Sealing

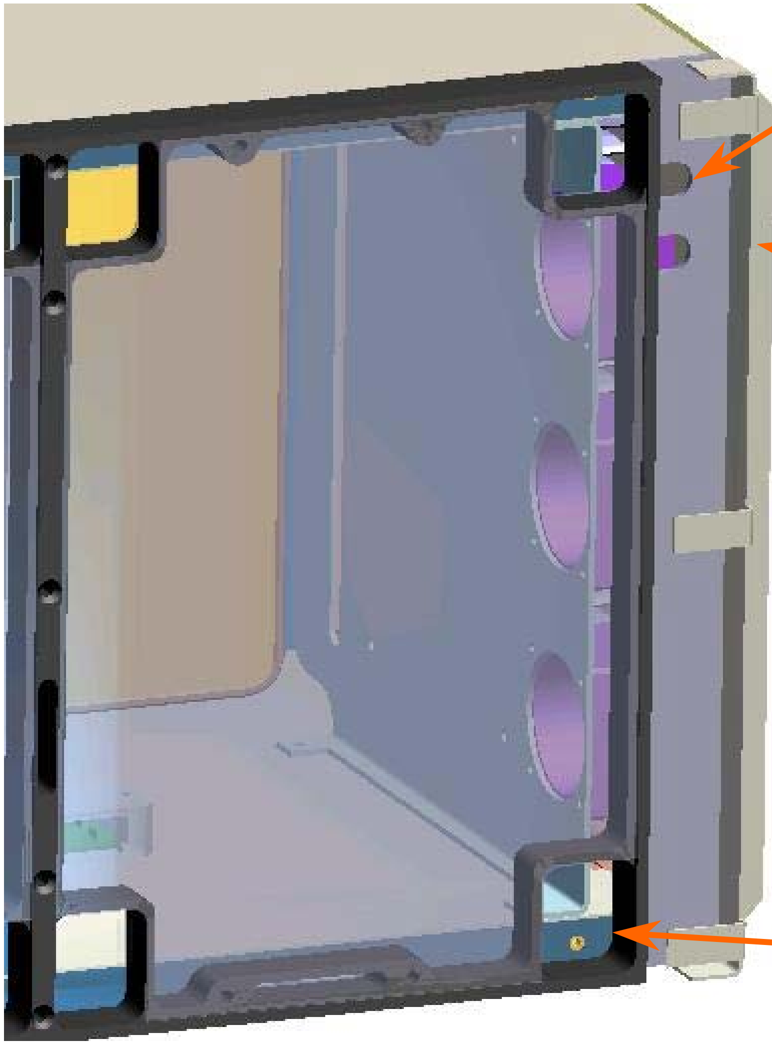


Cross-section view of Root Tray and PGC Housing Seal

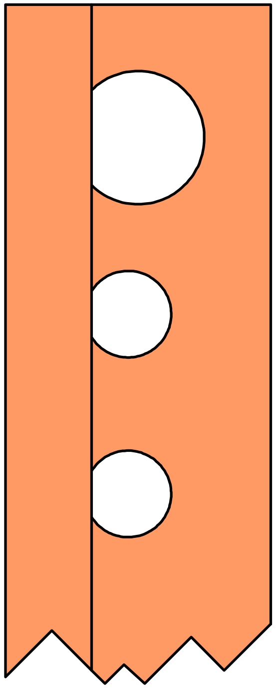
PGC Sealing



PGC Sealing

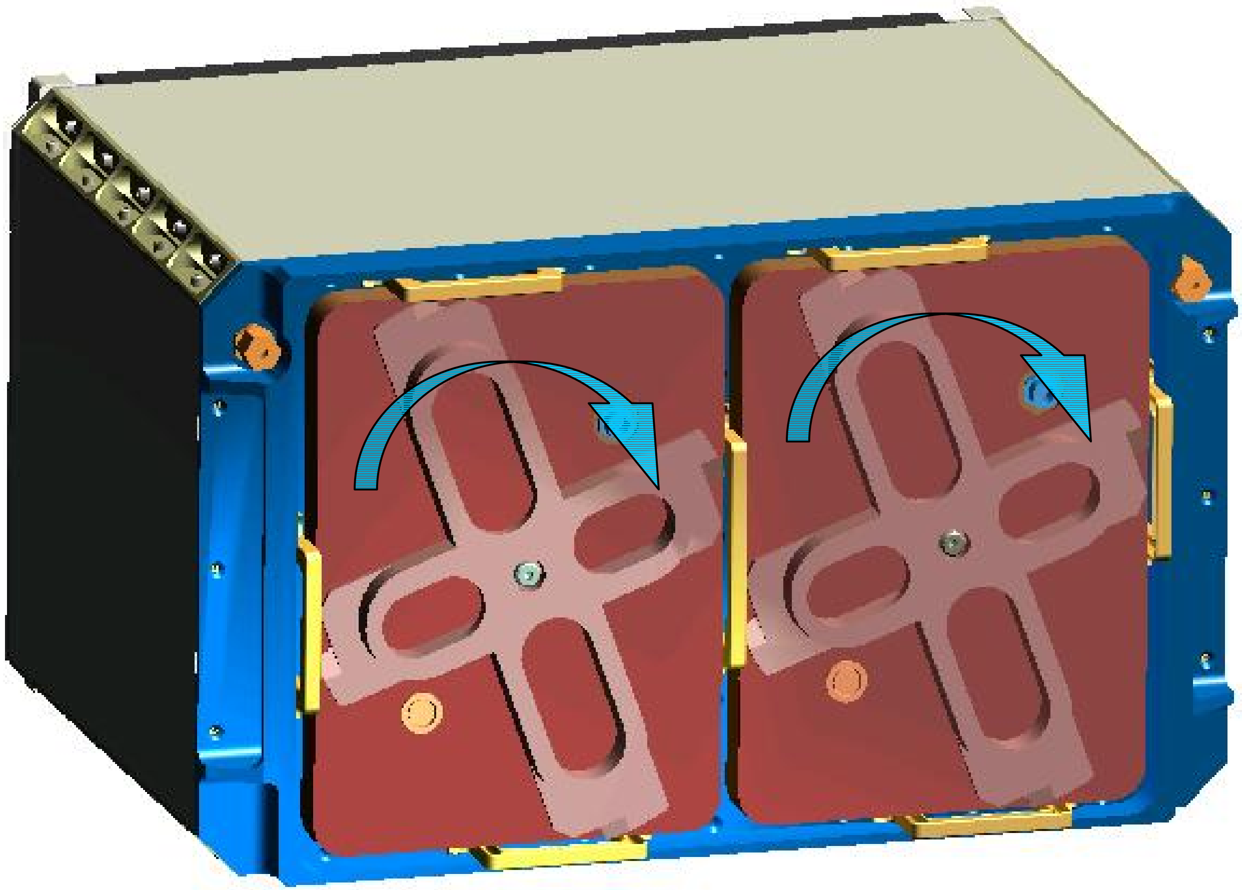


Two Piece seal with undersized holes to seal to hoses and cables



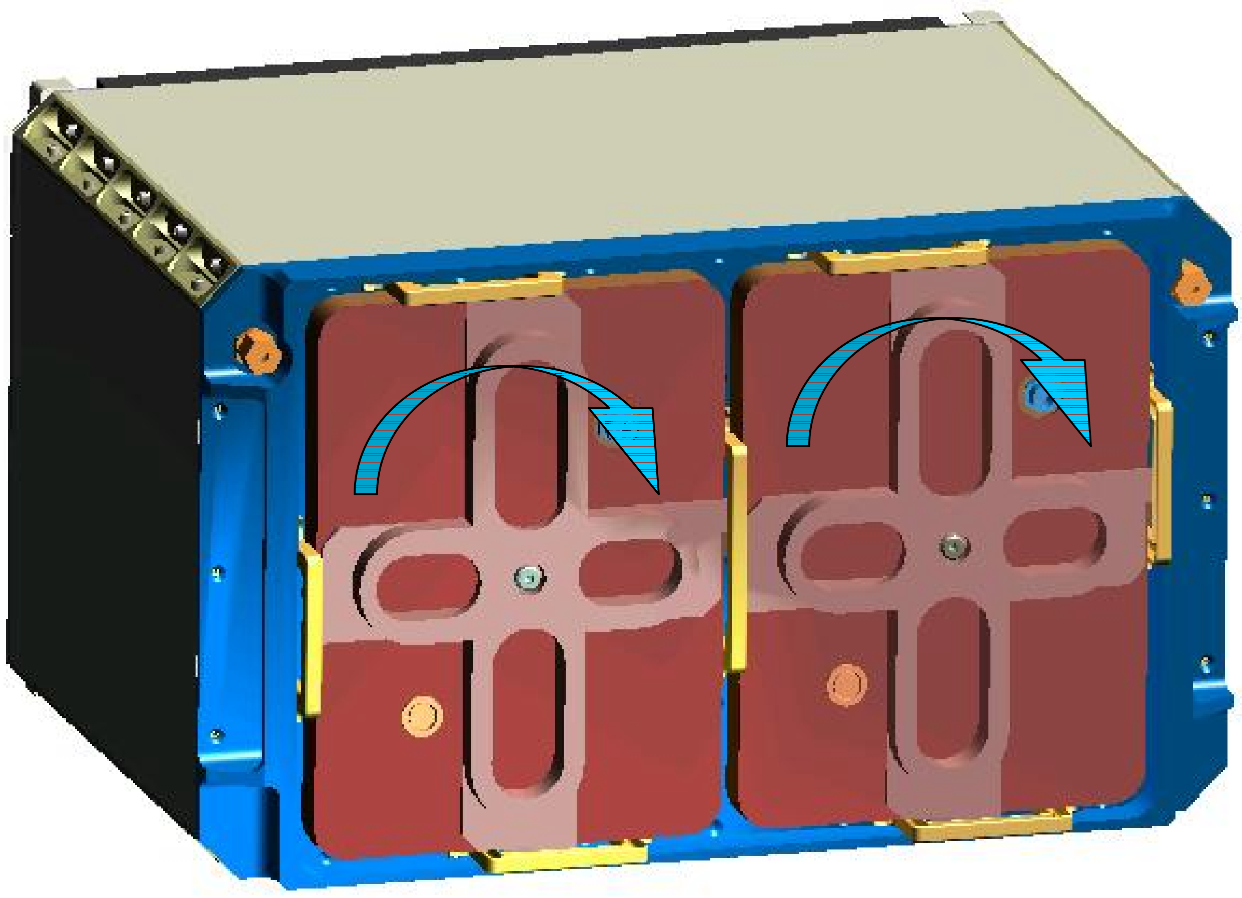
Root Tray Latch

- **One-handed rotate to lock Root Tray latch**



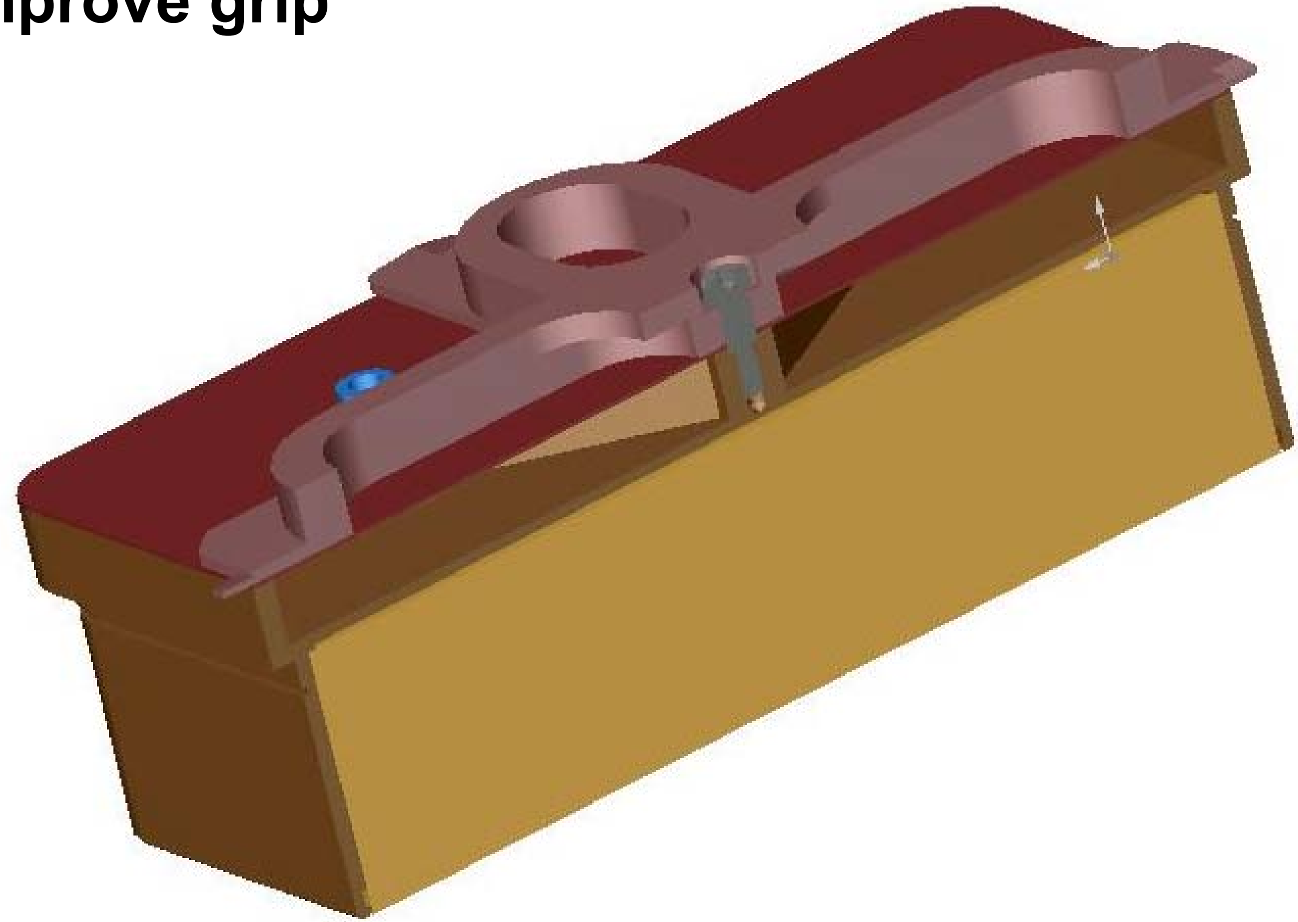
Root Tray Latch

- One-handed rotate to lock Root Tray latch

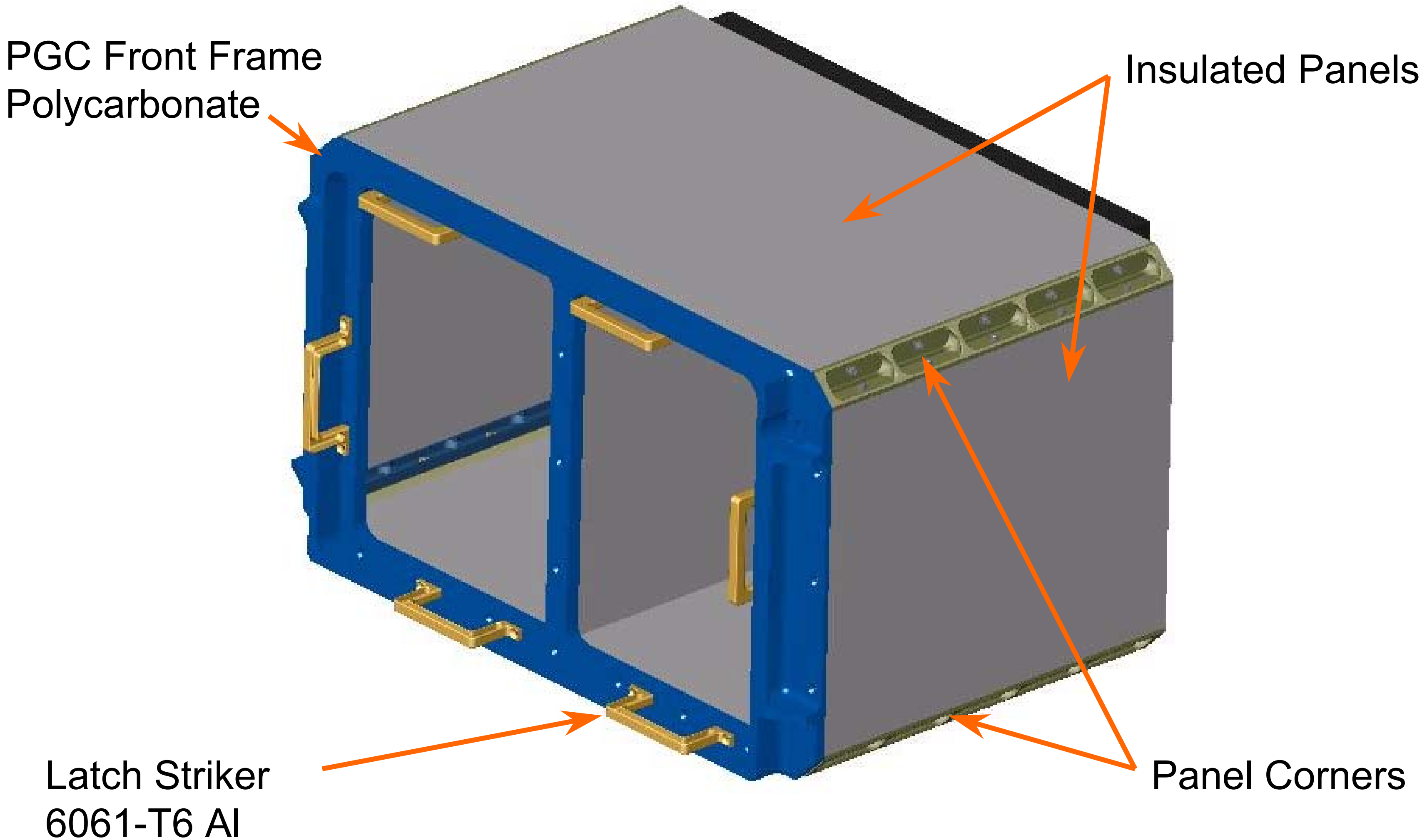


Root Tray Latch

- Large finger holes in handle with undercut to improve grip

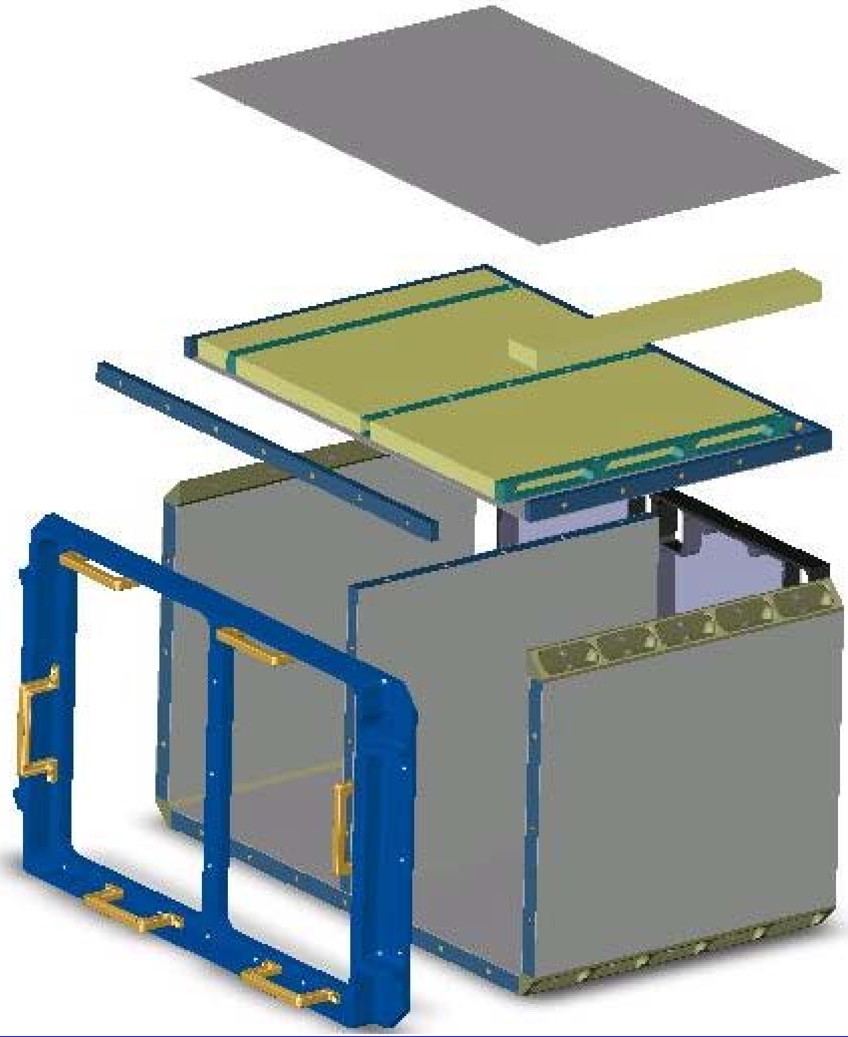


PGC Housing Construction



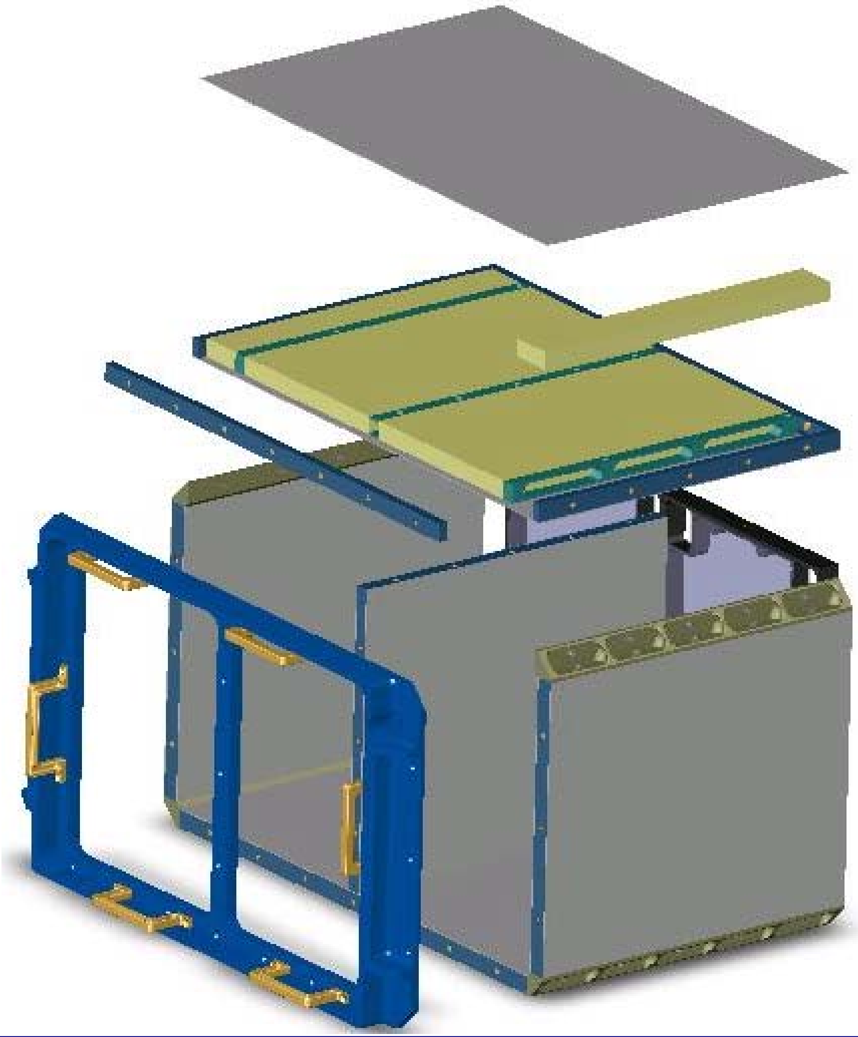
PGC Housing Construction

- **Insulated Sandwich Panel Construction**
  - .030" FR-60 Polycarbonate facesheets
  - Machined Polycarbonate Edge supports
  - Last-A-Foam FR6703 Urethane Foam
  - Threaded #2 inserts in edge supports for assembly



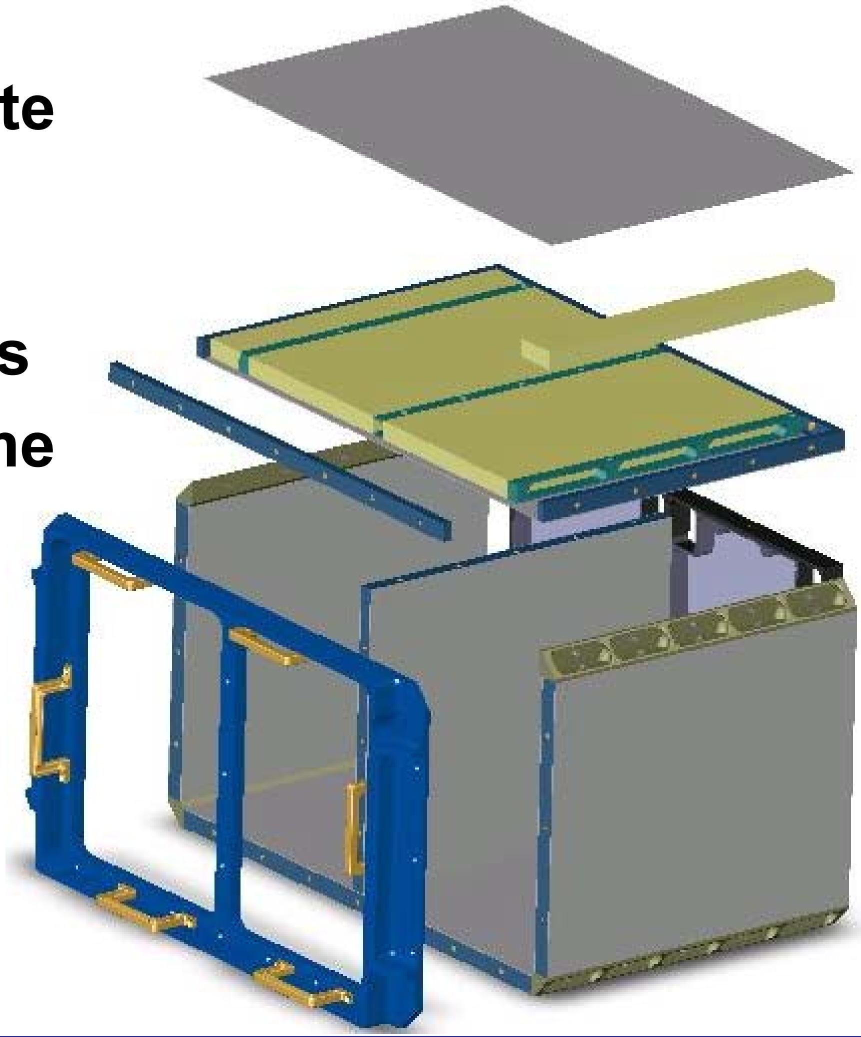
PGC Housing Construction

- **Insulated Sandwich Panel Construction**
  - Solvent bonded rails
  - Low out gassing acrylic 966 film adhesive bonded facesheets
  - Painted interior surfaces with MIL-PRF-85285C white polyurethane paint



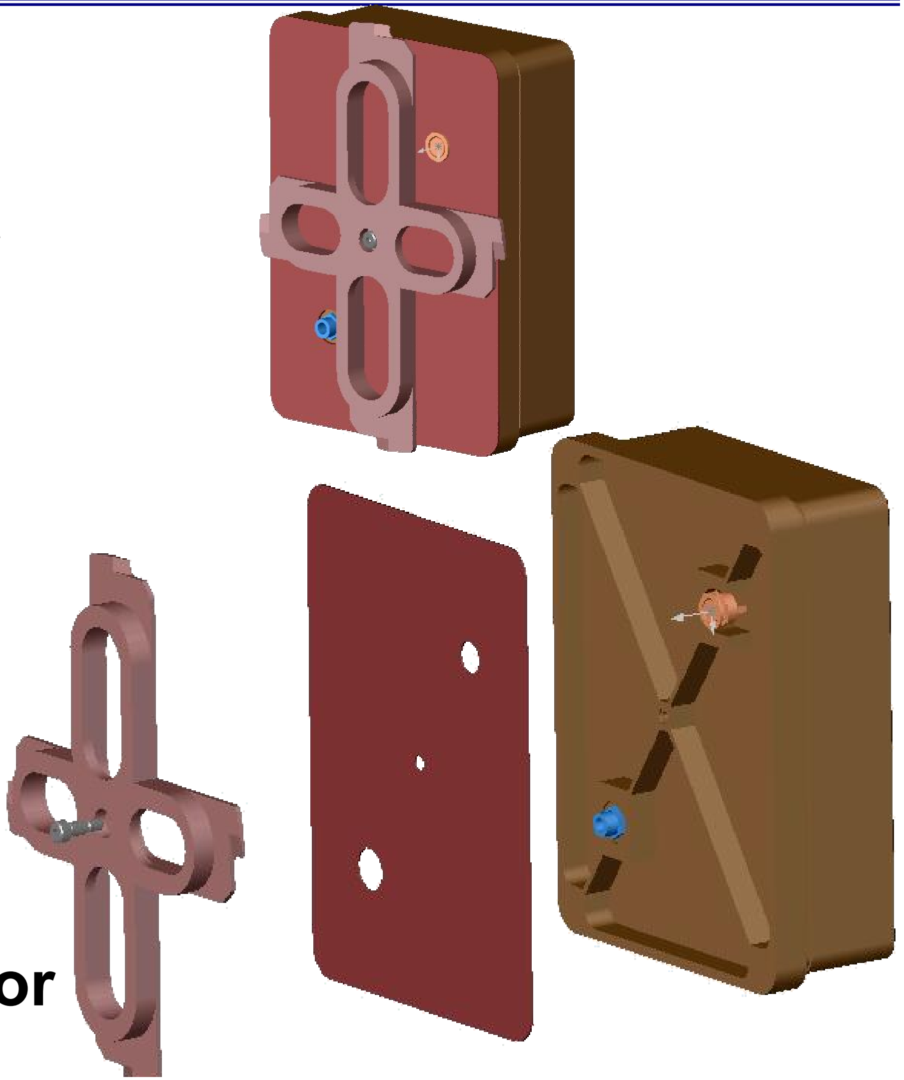
PGC Housing Construction

- LED double pane window
  - Machined polycarbonate frame
  - .063” thick FR-60 polycarbonate windows
  - Solvent bonded to frame
  - Small vent holes in frame

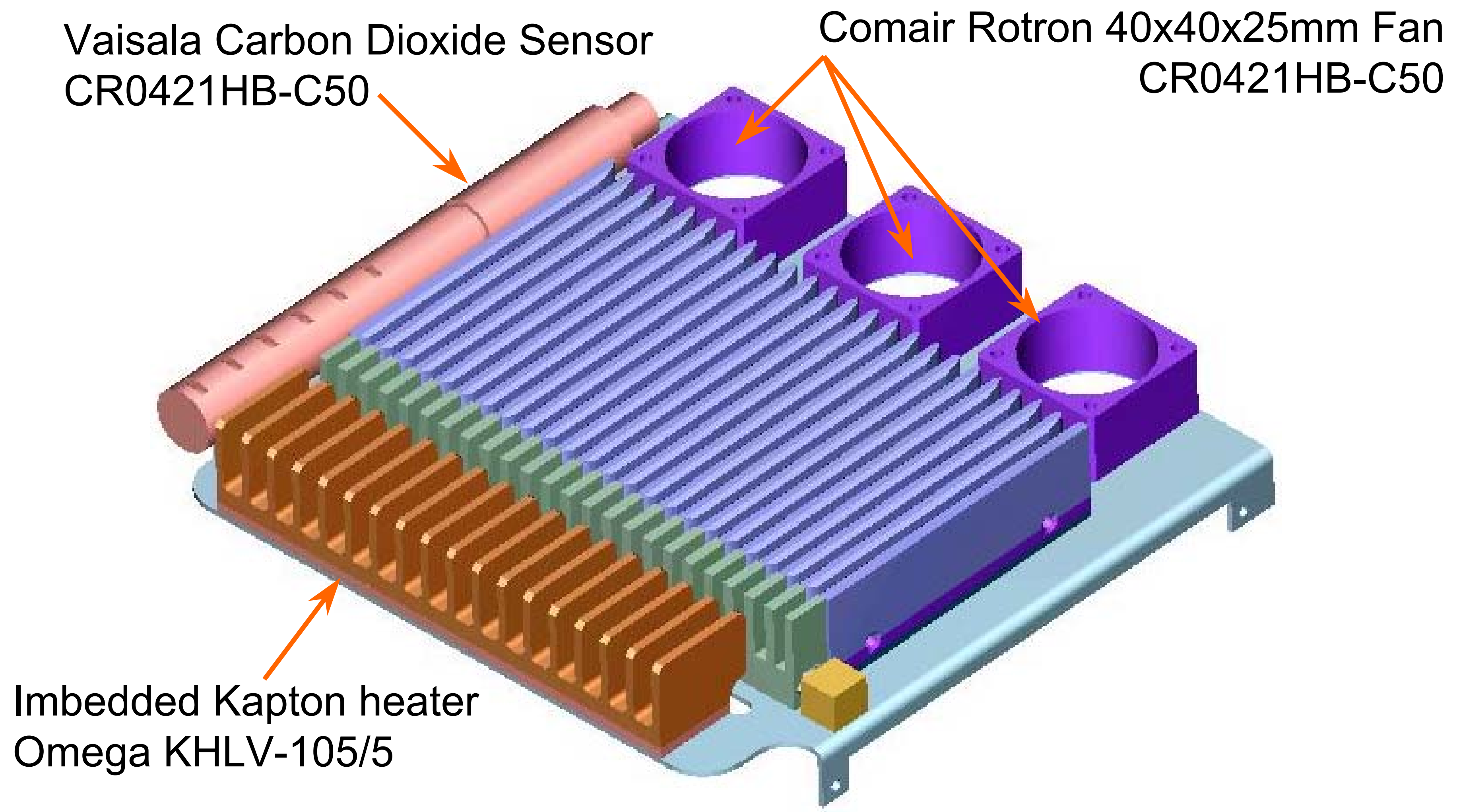


Root Tray Construction

- Machined/solvent bonded polycarbonate body
- Last-A-Foam Insulation (not shown)
- 966 adhesive bonded facesheet
- Shoulder bolt pivot point
- Machined polycarbonate handle
- Water quick-disconnect
- Mini-circular connector for root zone temperature sensor



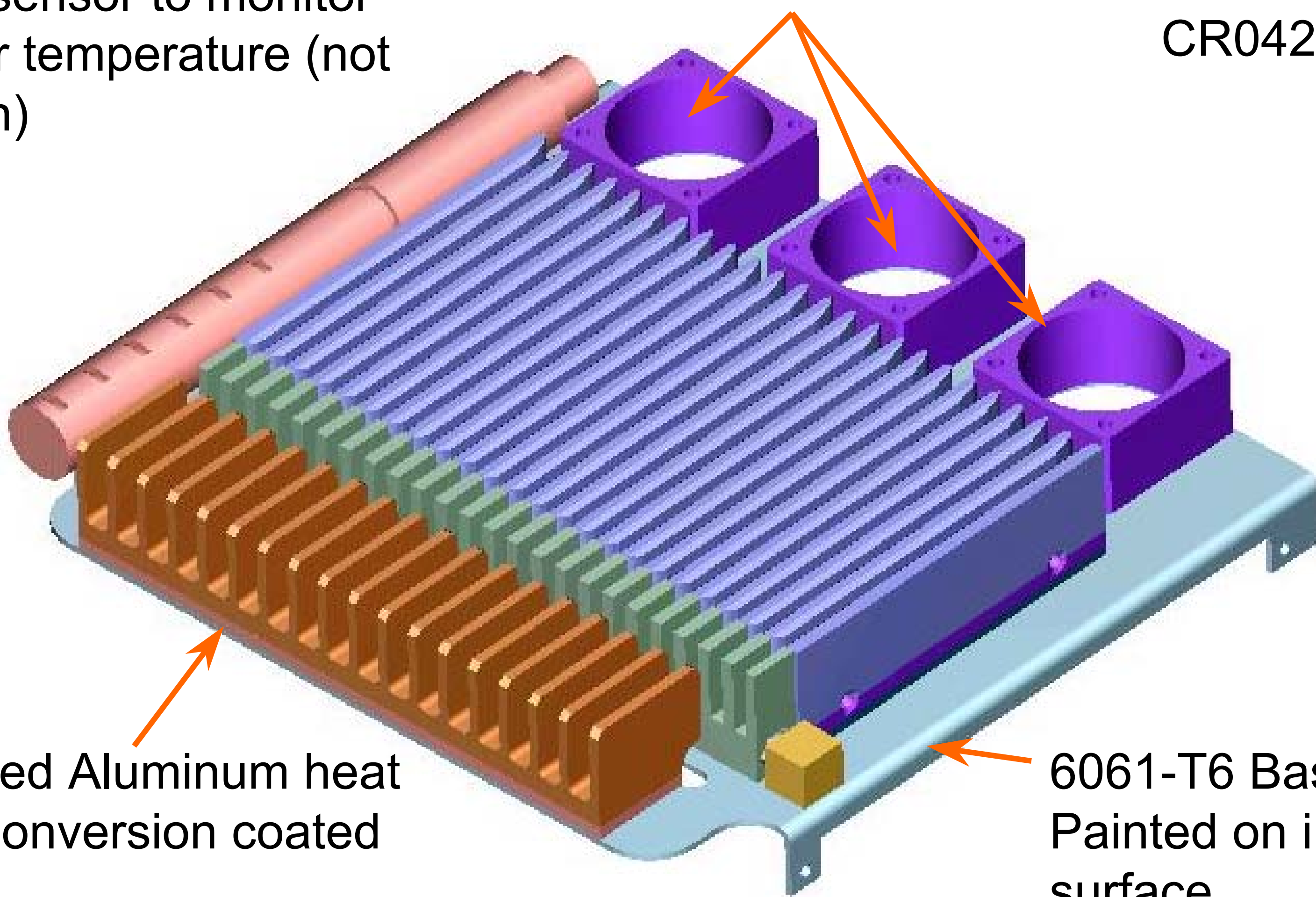
Environmental Control Panel Construction



Environmental Control Panel Construction

Heat sensor to monitor heater temperature (not shown)

Comair Rotron 40x40x25mm Fan CR0421HB-C50

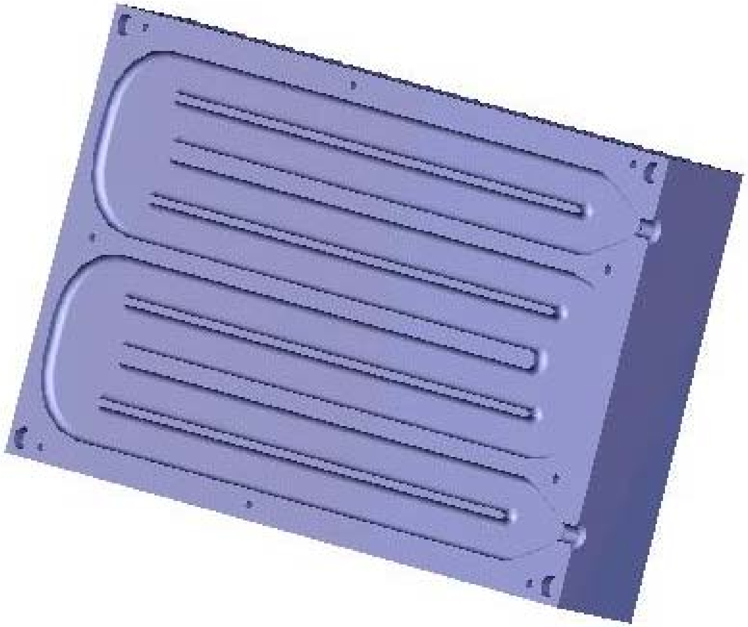


Machined Aluminum heat sinks Conversion coated

6061-T6 Base Plate Painted on inside surface

Cold Sink Construction

- Two piece machined aluminum
- Sealed with RTV 3140
- Bolted
- Coated with Hydrophobic coating

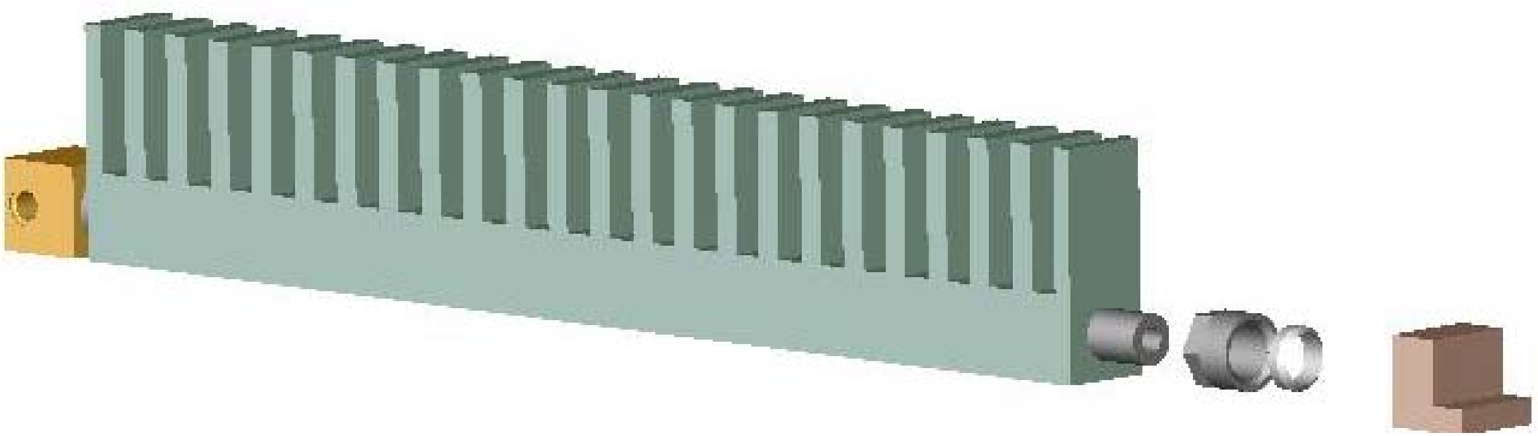


Hydrophobic Coating

- Baseline material is Tulanox
  - Fumed silica product
  - Acrylic binder
  - Solvent deposited
  - Excellent anti-wetting properties
  - Fair adhesion
  - Additional testing required
- Alternate materials include
  - Teflon
  - Nickel Teflon
  - Alternate silica based product

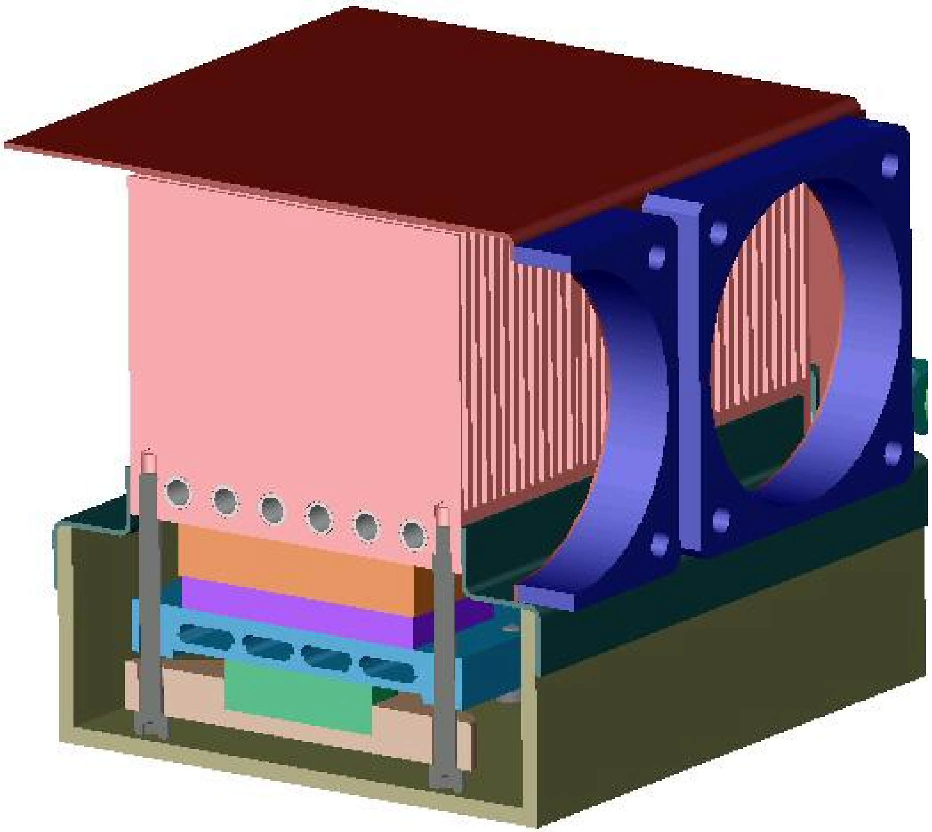
Condensate Collector Construction

- Polyvinylalcohol sponge - clean room/surgical sponge material with excellent absorption and resistance to fungus
- Mott 0.5 micron 0.25”OD stainless steel tube
- Delrin end caps
- HDPE compression seals
- Stainless low profile compression nuts



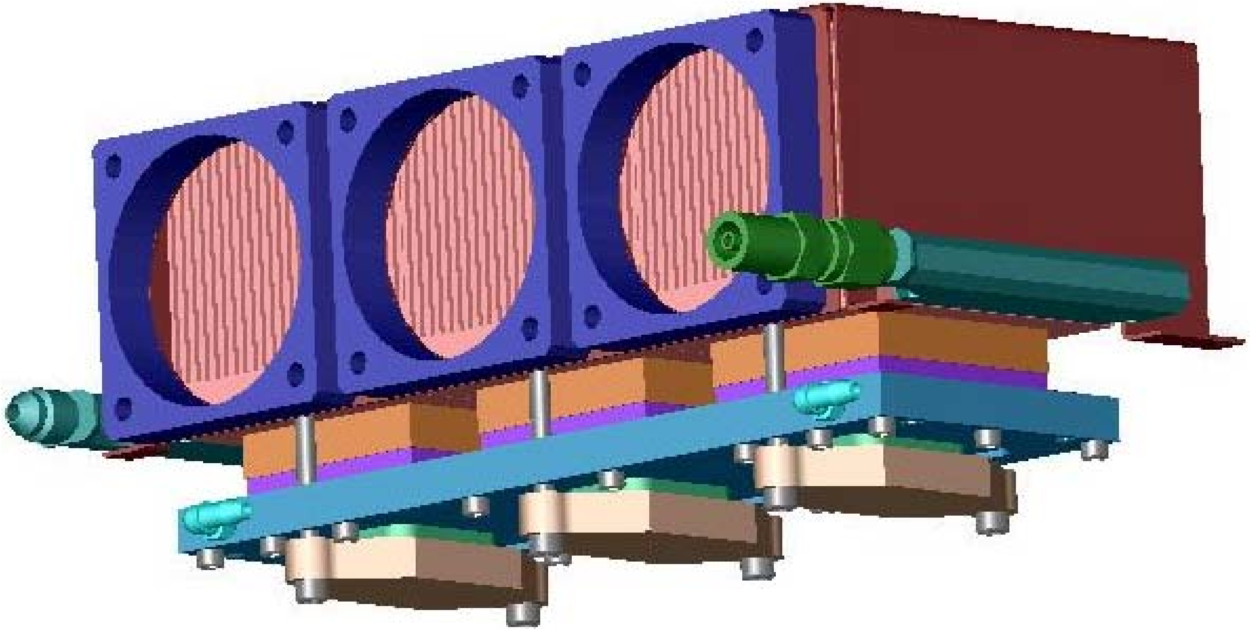
Cooling Unit Construction

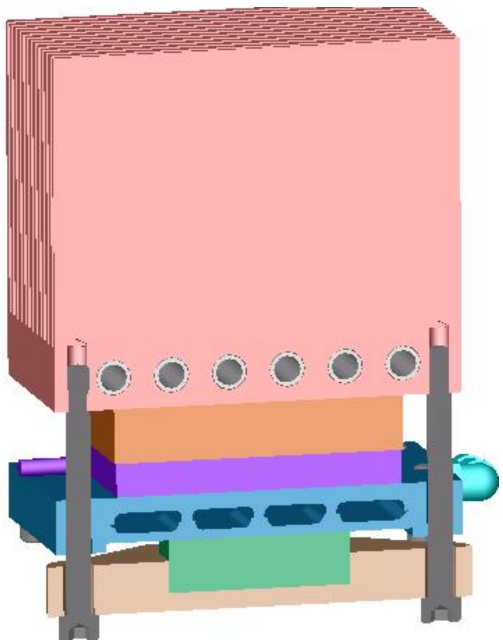
- Machined Aluminum Heat Rejection fins
- Two Piece cold side heat exchanger
- Stainless steel tubes for MTL water
- Insulation on cold side to prevent thermal short-circuits
-



Cooling Unit Construction

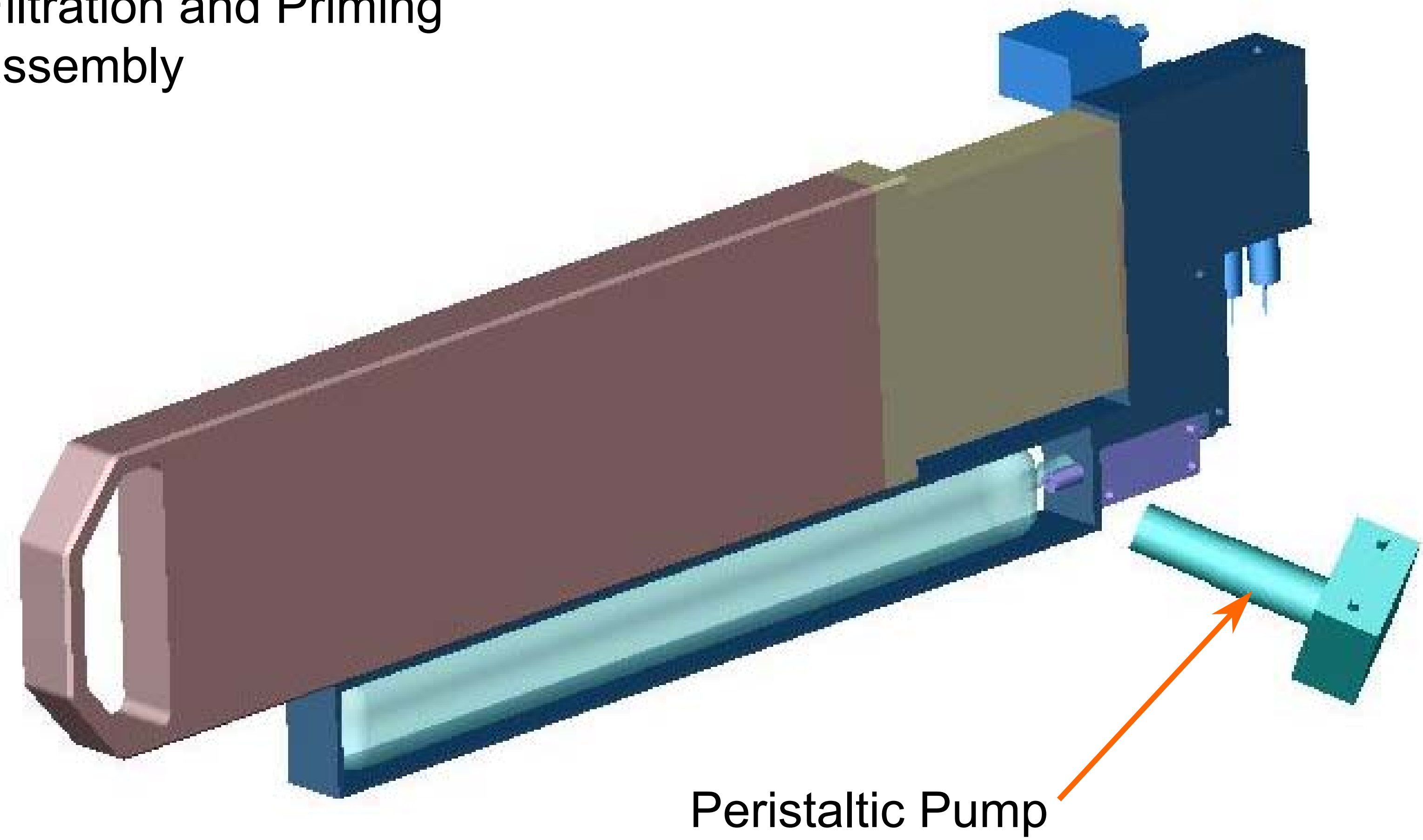
- TECs centrally loaded through Cold Side Heat Exchanger to promote good contact with heat sinks
- Thermal grease used to optimize heat transfer
- Insulation added to eliminate thermal Shots





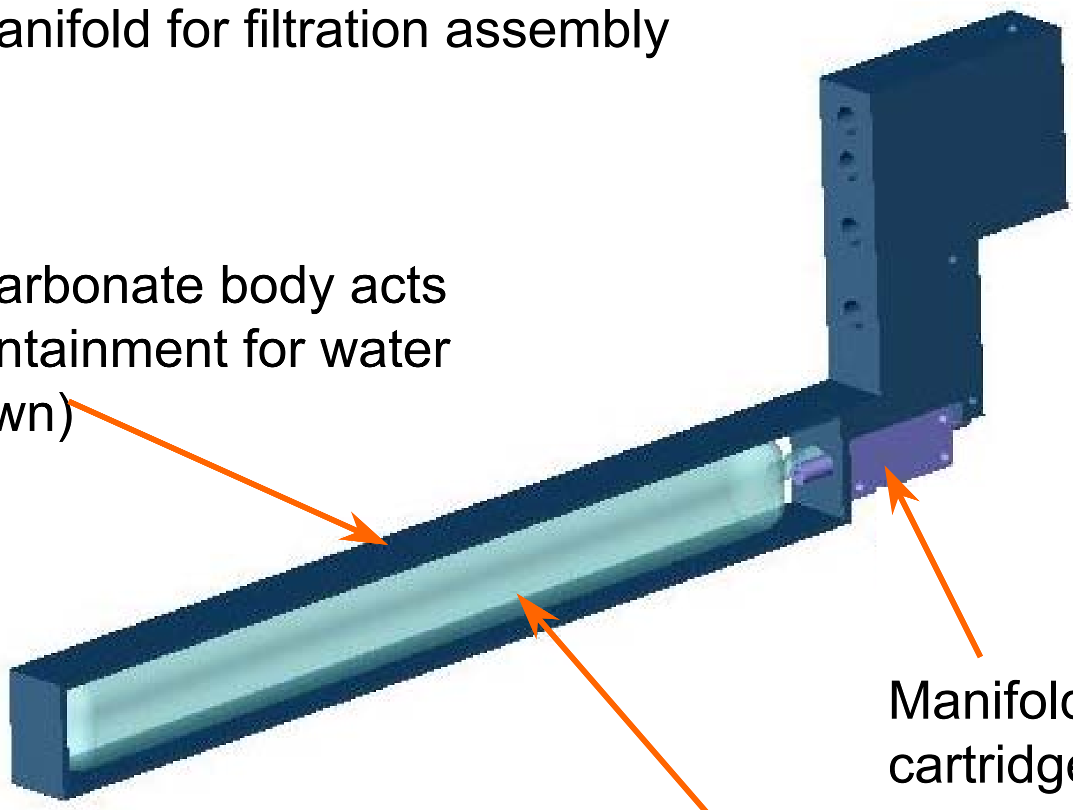
Priming Reservoir and Manifold

Filtration and Priming assembly



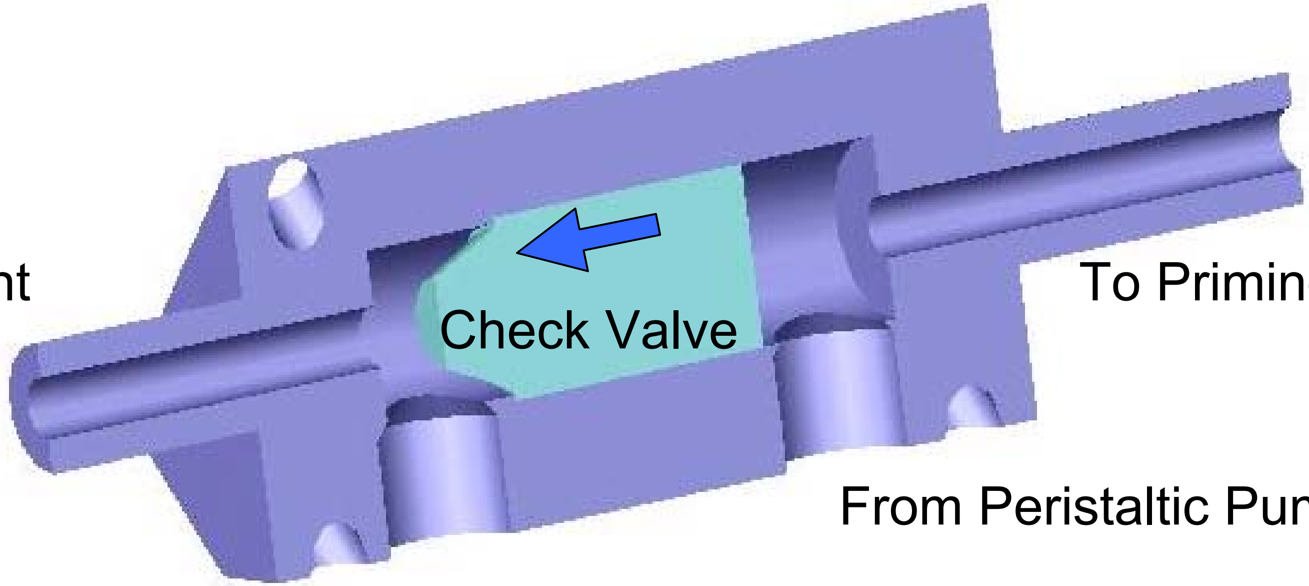
Priming Reservoir and Manifold

Priming Reservoir Body includes mounting features and manifold for filtration assembly



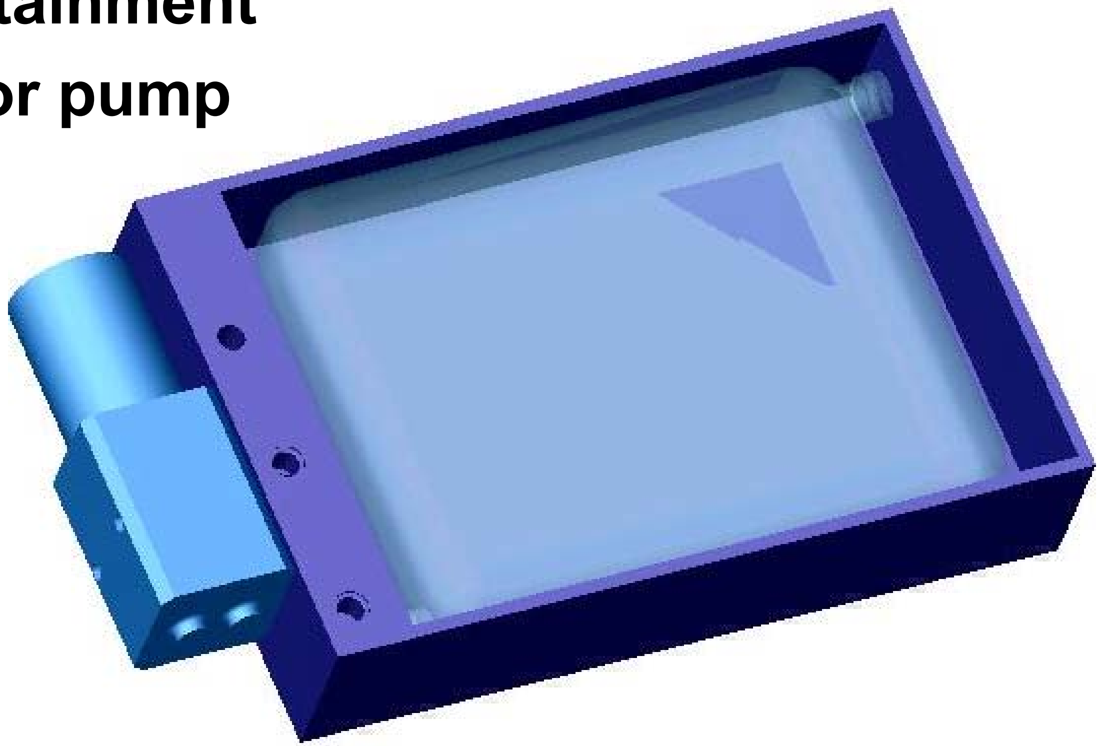
Priming Manifold

- **Machined polycarbonate housing with pressed in check valve and hose barb**
- **Ports from water pump and to Nutrient Reservoir**
- **Threaded holes for hose barbs**

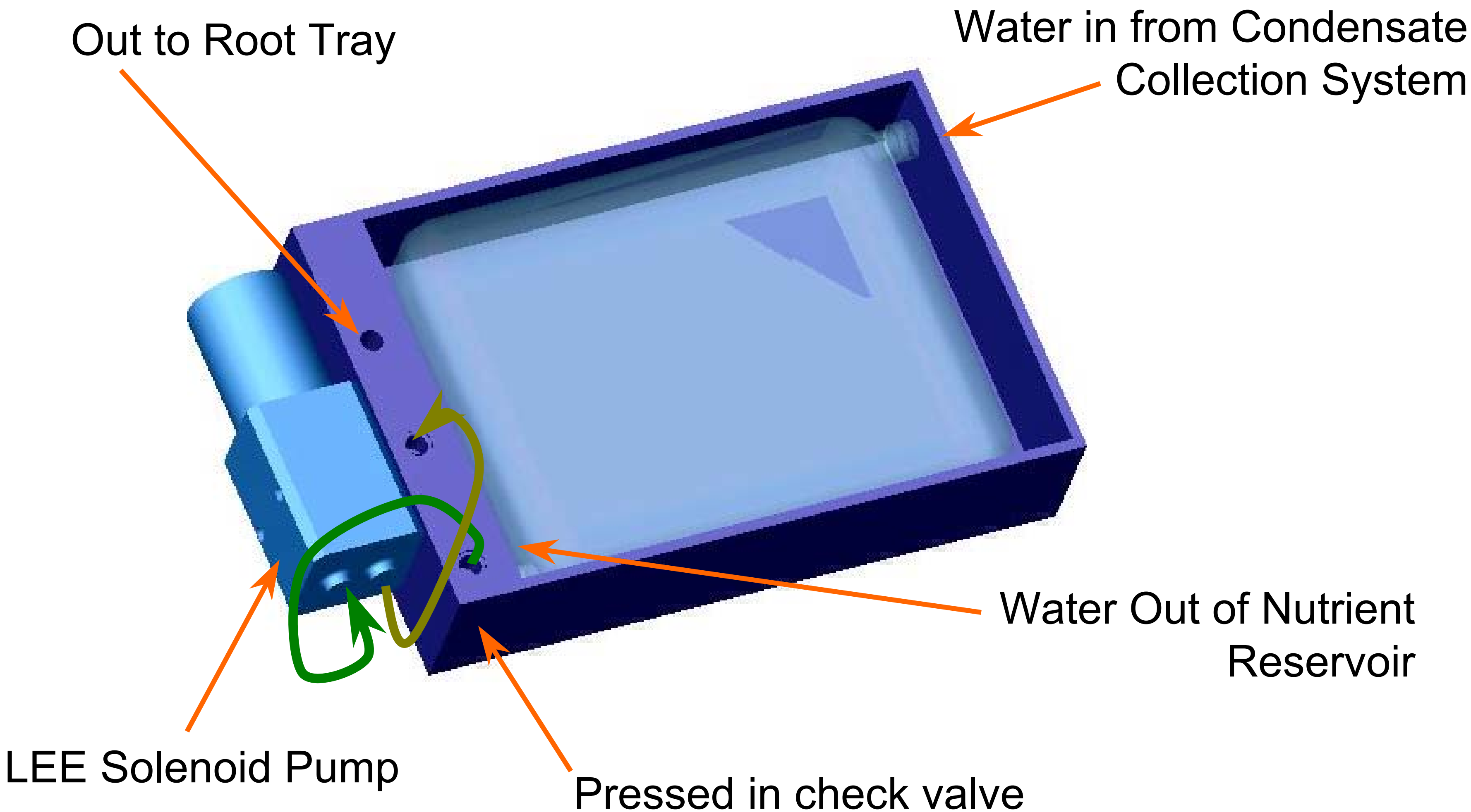


Nutrient Reservoir

- Mounted to front door for easy access and refilling
- 100 ml flexible bag in polycarbonate housing for two levels of containment
- Mounting point for pump
- Cover not shown

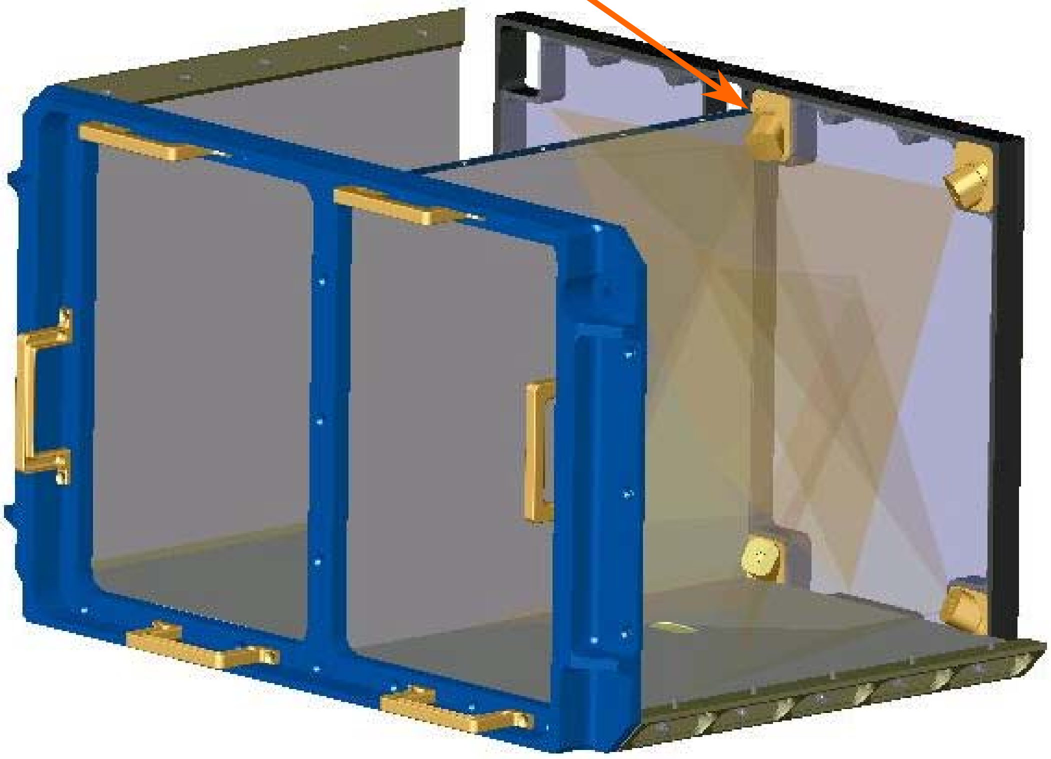


Nutrient Reservoir

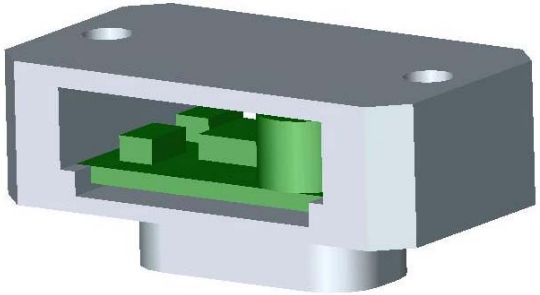


Analog Camera

- **For general imaging requirements**
- **Angled overhead views provides excellent plan views at all time**
- **Four per chamber cameras provide complete coverage from multiple angles**
- **O-ring seals to LED Window**
- **Additional design required**



PGC Sensors



- **Temperature and Humidity Sensor in digital module**
- **Temperature sensor**
  - Dallas Semiconductor - DS 1621
  - Base accuracy of +/-0.5°C
  - Software improved accuracy <+/-0.062°C
  - Being evaluated in thermal control breadboard
- **Humidity sensor**
  - Same as prototype
  - Micro Switch - HIH-3602-C
  - Accuracy of +/-2% RH at 25°C
  - Used in prototype

PGC Assembly Risks

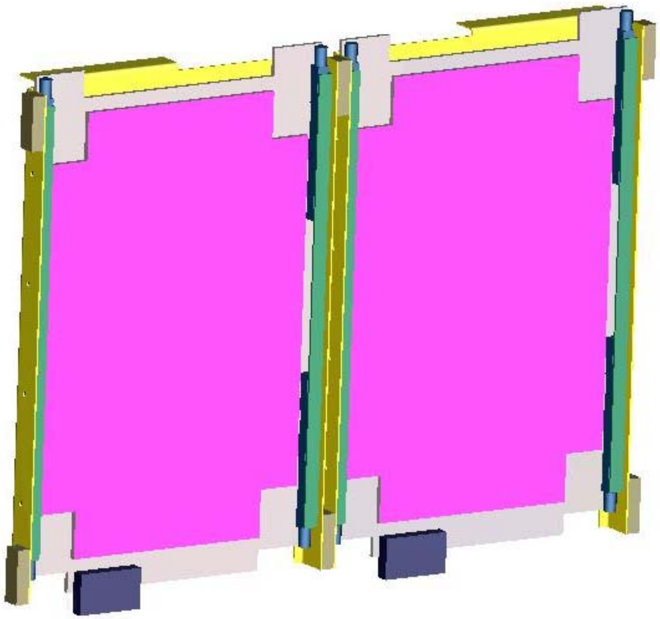
- Fluid leakage
  - All lines will be pressure tested
  - Reservoirs are double contained
- Inadequate temperature control
  - Significant analysis and testing conducted
- Condensate collection system fails to trap water
  - Initial tests indicate good performance
  - Zero G tests planned
- Inadequate plant volume
  - Design represents largest volume available in single locker system

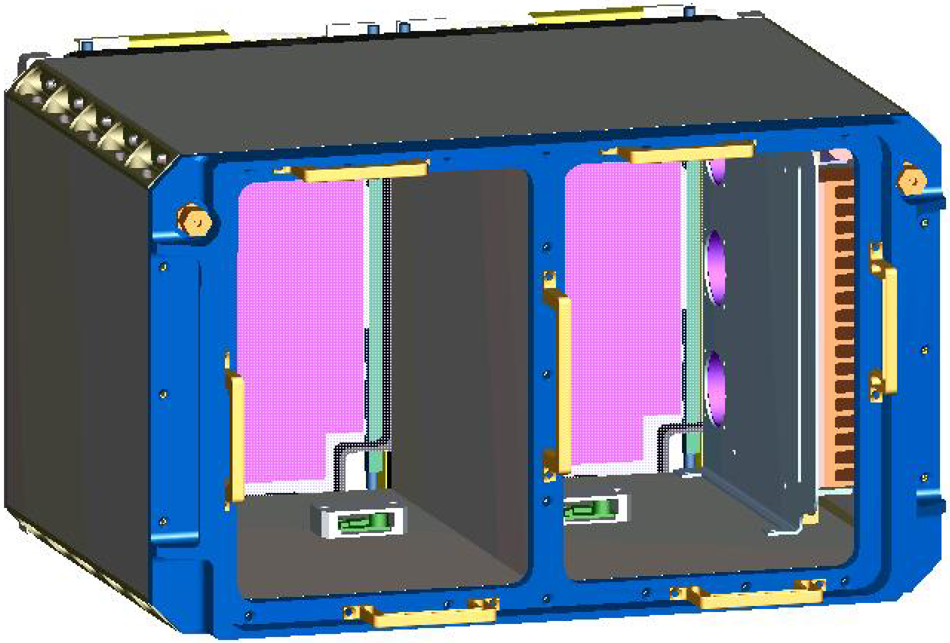
PGC Assembly Summary

- **Multiple systems providing Temperature and Humidity control**
- **Light weight sandwich panel construction**
- **Efficient high capacity cooling system**
- **Easy access to assemblies for maintenance**
- **Weight - total weight of all subassemblies**
  - **25.8 lbs.**
  - **Some hardware, small brackets, and hoses omitted**

LED Lighting Module

- **Independent Light Banks**
- **LED growth lighting for improved efficiency**
- **Red Blue and White LED's for full spectrum coverage**
- **Electrical Design presented separately**





LLM Requirements

- Produce good quality light for plant development
- Produce up to 300 µmoles/m^2/sec of photosyntheticly active radiation
  - Measured 8" from LED window (surface of growth media)
  - Average value of growth area
- Record light levels
- Maintain light levels to within +/- 5% of set point
  - Will result in less than 10% variation between chambers when set points are same
- Allow different lighting set points for each chamber

LLM Requirements

- Provide light intensity distribution less than +/-10% of set point
  - Rasta requirement is variation less than 15% (+/-7.5%)
  - System may not meet this requirement
- Provide timed control of Day/Night cycle

Interfaces

- **Structural interface to PGC housing**
- **Structural interface to Cooling Unit**
- **Electrical interfaces to ECU**
- **Optical interface to LED window**
- **Plants**
  - **Quality of light**
  - **Intensity of light**
  - **Day/Night cycle**

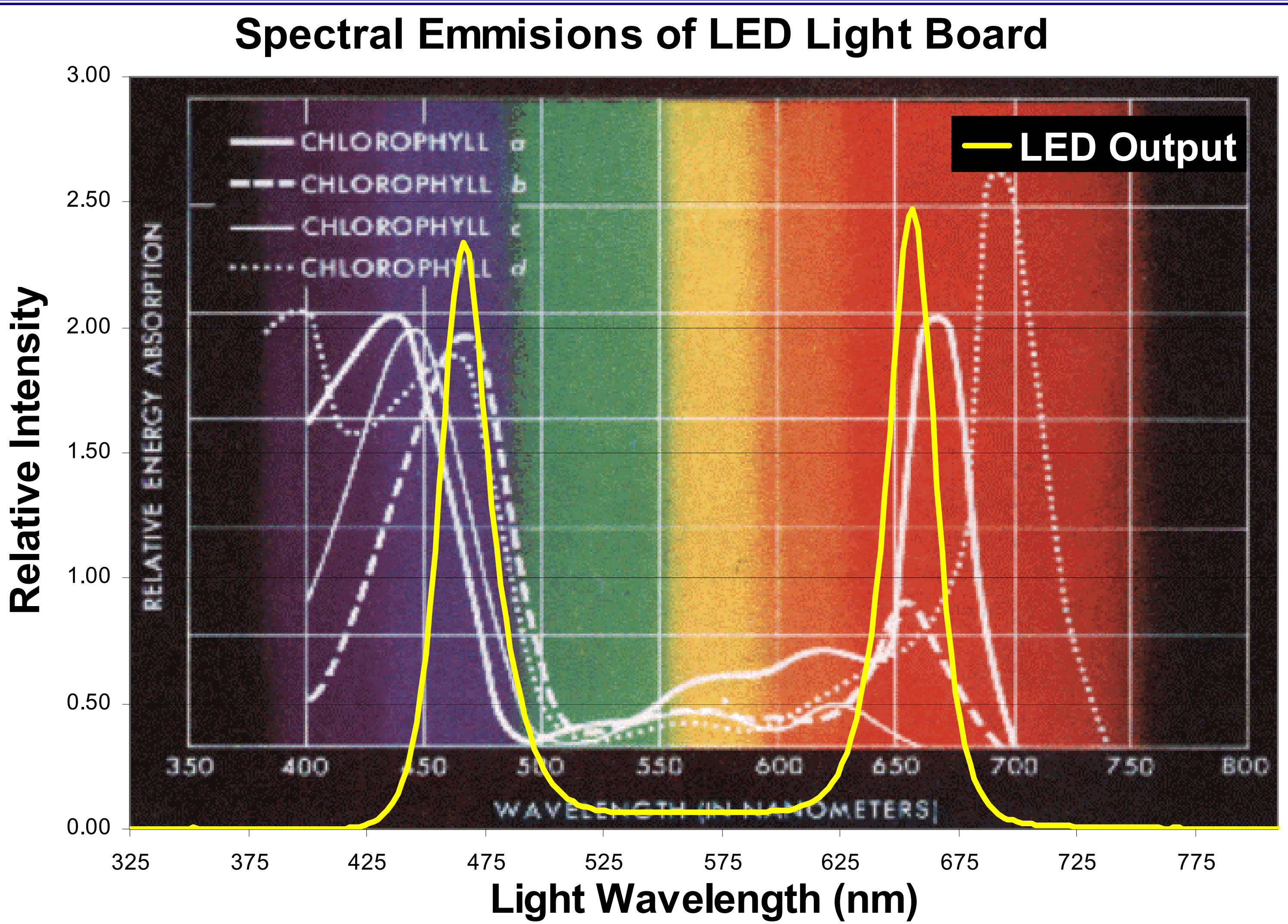
Goals

- Maximize efficiency
- Minimize heat generation
- Provide broad range of capabilities for light levels
- Provide modular board design for different spectrums
- Provide easy removal for potential on-orbit maintenance
- Provide white light only illumination for general imaging

LLM Features

- Tested on prototype PGF-SP with excellent results
- LED lighting system for high efficiency and flexibility
- Multiple banks in each board to adjust light distribution
- Pulse Width Modulation for efficient dimming
- Onboard control for reduced wire routing
- Onboard light intensity sensors
- Highly reliable and fault tolerant design

LLM Light Quality



LLM Efficiency

- Radiant energy output efficiency
  - Approximately 14%
  - Radiated power/power in
- Photosynthetic Active Radiation output efficiency
  - Approximately 11%
  - PAR power/power in
- 80% of radiant energy is useful light
- Based on measurements with a single pane acrylic window
- Heat transfer measurements used to determine total radiant power transmitted through window

Expected Output in PGCs

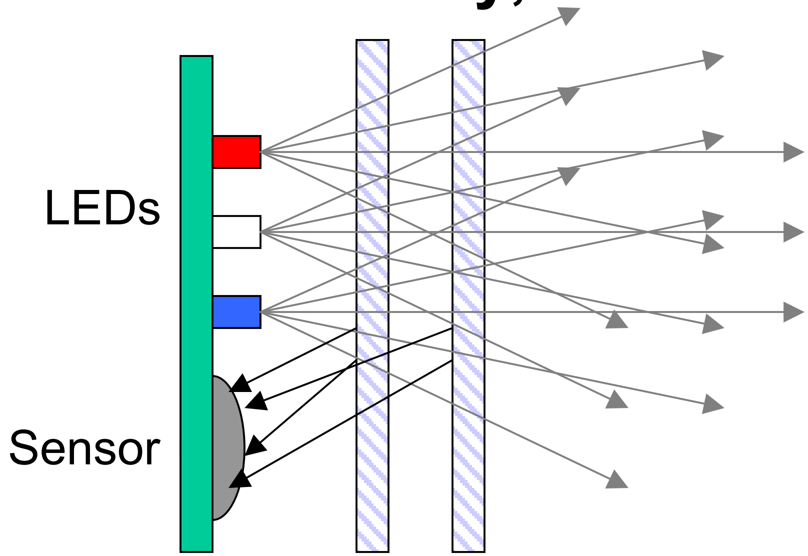
- Estimated losses in double pane window
  - 18% based on breadboard measurements
- Light intensity reduction due to distance from lights
  - 35% based on calculations and measurements
- Overall relationship between power to light bank and PAR at root tray interface
  - PAR = LED power (watts) x .11 x .82 x .65 x 183 µmoles/m^2/sec/watt
  - 27 watts to achieve 300 µmoles/m^2/sec per light bank

Light Intensity Control

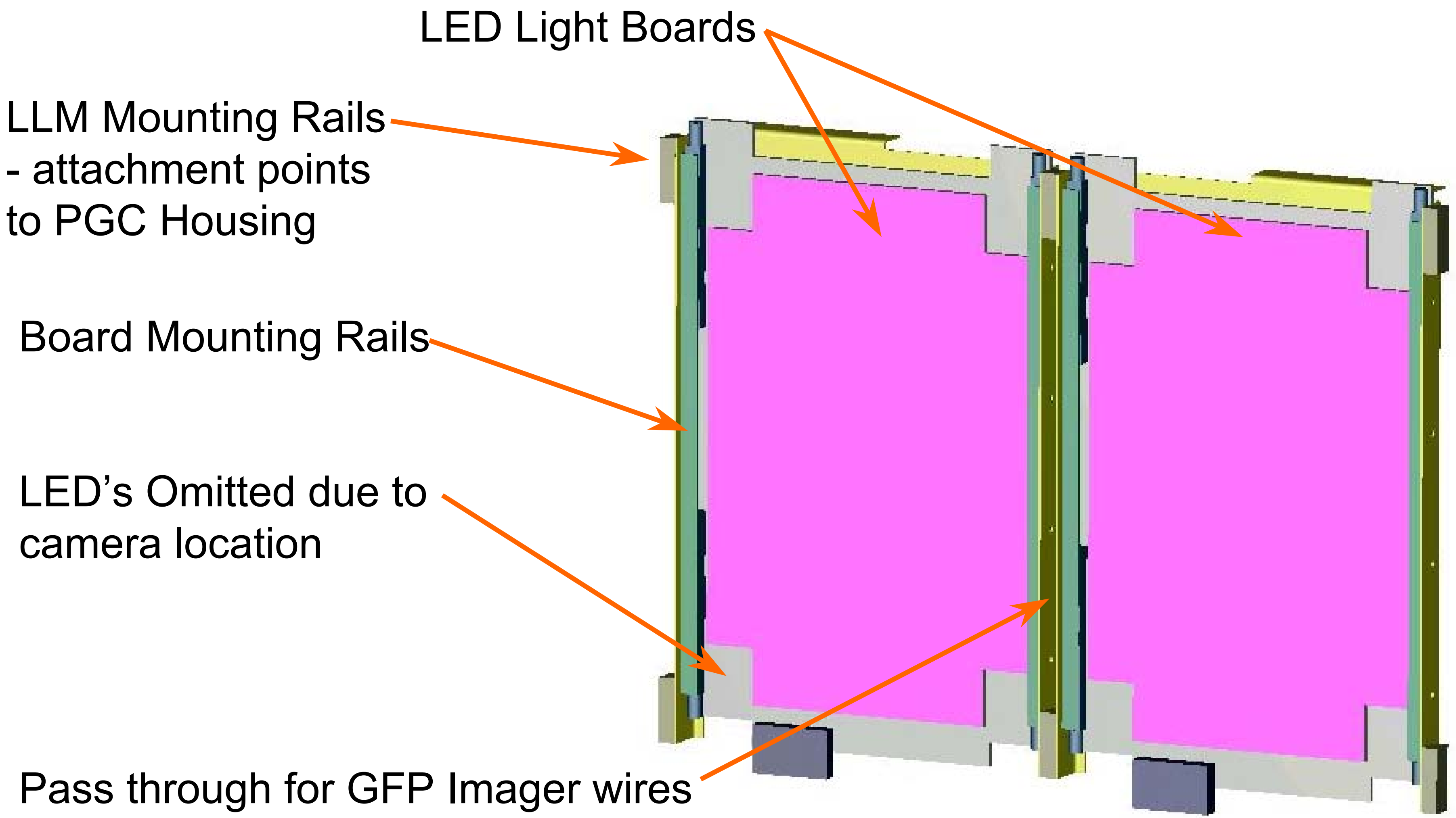
- LEDs are evenly distributed by color
- LEDs arranged in banks to alter brightness by zones
- LLM performance characterized and optimized during ground studies
- Open loop control on orbit
- Light sensors used to record light levels and alert crew in case of failure

Light Intensity Sensors

- Four Light Intensity sensors mounted on LLM board
- Measure light intensity reflected by LED window
- No shadows from plants
- Calibrated to measurements taken at Root Tray top surface
- Used as monitors only, not for control



LLM Housing Construction

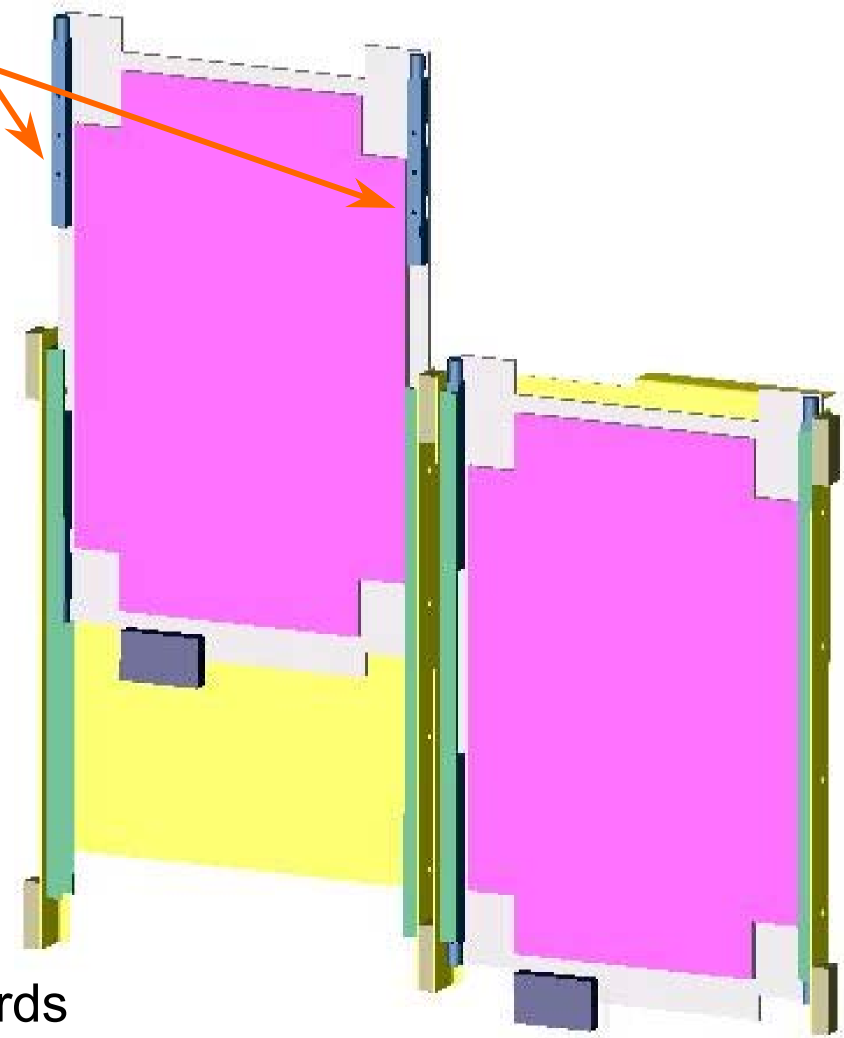


LLM Housing Construction

Wedge lock card retainers allow for easy removal
Calmark - V265-2.80-E-T2LK

Sheet Metal Aluminum Housings and card mounting rails
6061-T6

Card mounting rails riveted to housings



Same concept used for most control cards

LLM Risks

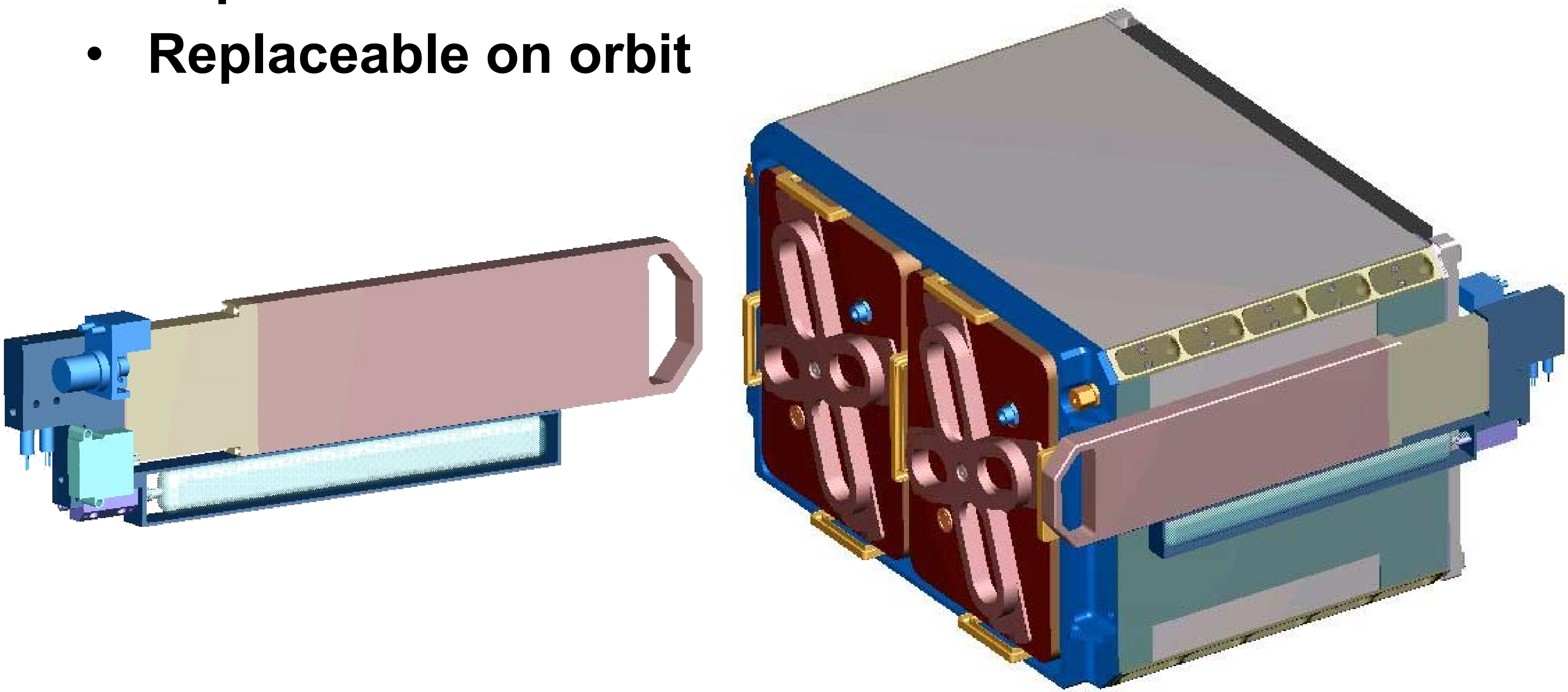
- Light Level Control
  – Prototype design indicated that the LED design has sufficient excess capability to allow for a wide range of settings and control options
- Eye injury
  – Safety interlocks will be added to put system in stand-by mode (lights off) when the door is opened

LLM Summary

- **Weight: Estimated weight based on solid models**
  - **2.2 lbs**
- **Power Consumption/Heat Generation**
  - **27 watts at 300 μmoles output per side**
  - **7.5 watts at 80 μmoles output per side**
- **Materials**
  - **6061-T6 aluminum housing and rails**
  - **Polycarbonate mounting rails**
  - **Silicone foam insulation**

Air Filtration System

- Controls Carbon Dioxide level in PGCs
- Removes VOCs and Ethylene
- Expendable filtration modules
- Replaceable on orbit



Air Filtration Requirements

- Control Carbon Dioxide in Growth Chambers to a set point between 700 - 3000 ppm
- Allow for different set points in each chamber
- Control Carbon Dioxide to within +/-75 ppm of set point
  – Based on sensor measurement
- Limit Ethylene in Growth Chambers to 50 ppb
- Reduce VOCs in Growth Chambers to 25% of cabin atmosphere
- Allow for option to remove or not remove Ethylene and VOCs in each chamber independently

Interfaces

- Priming Reservoir Body
- PGCs
  - Air exchange and leak rate
- Crew
  - Removal and replacement
- ECU
  - Closed loop control of carbon dioxide
  - Open loop control of ethylene and VOCs

Goals

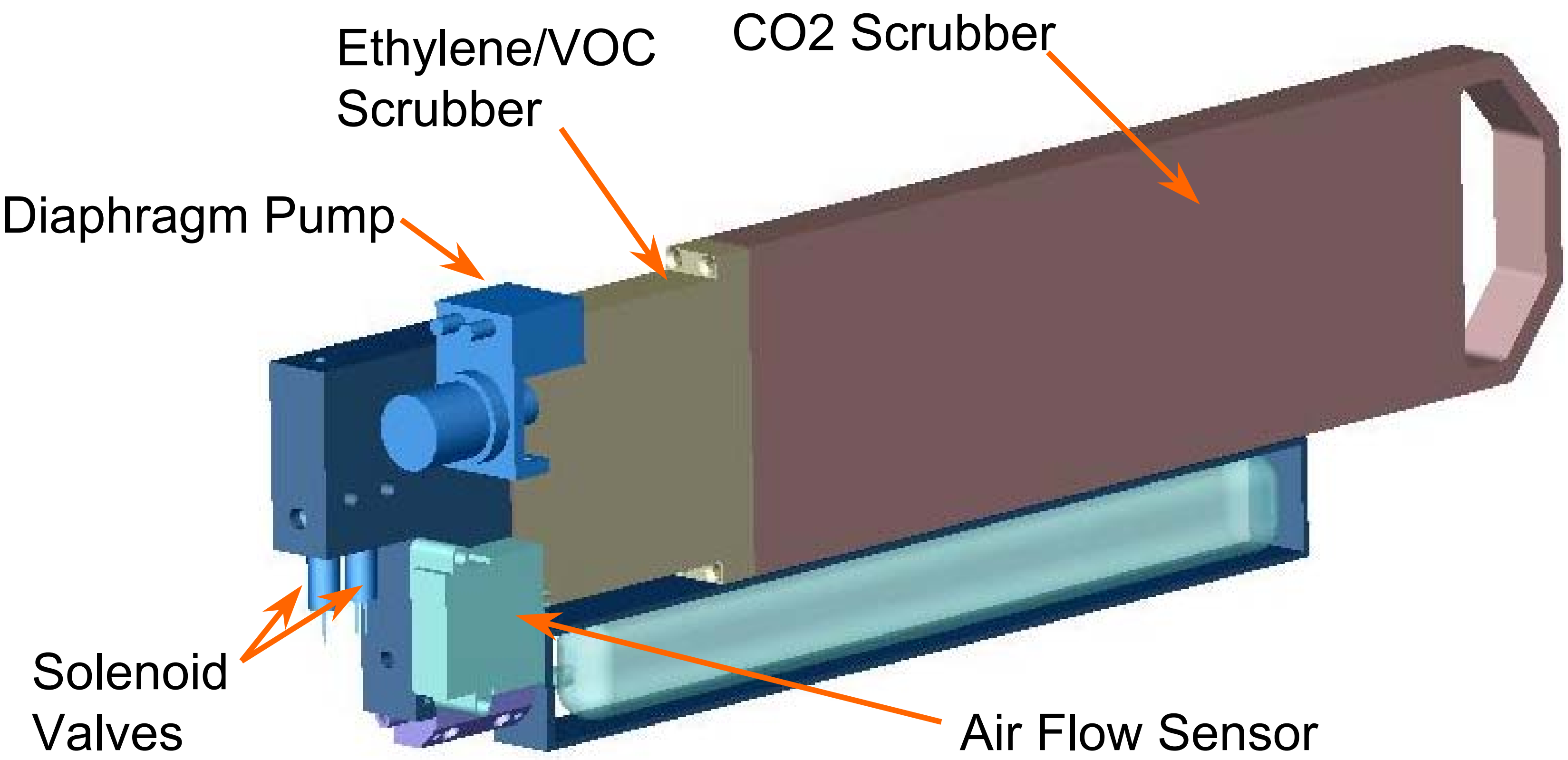
- **Minimize frequency of filter replacements**

Concept of Operation

- **Carbon Dioxide levels are monitored by sensors in each growth chamber**
- **Carbon Dioxide is reduced in growth chambers by passing air through Lithium Hydroxide scrubber**
- **Carbon Dioxide is increased by pulling in avionics air (cabin air in front breather configuration)**
- **Ethylene and VOCs are reduced by passing air through Potassium Permanganate (Purafil) scrubber**
- **Ethylene and VOC levels monitored by gas sampling and ground based analysis**

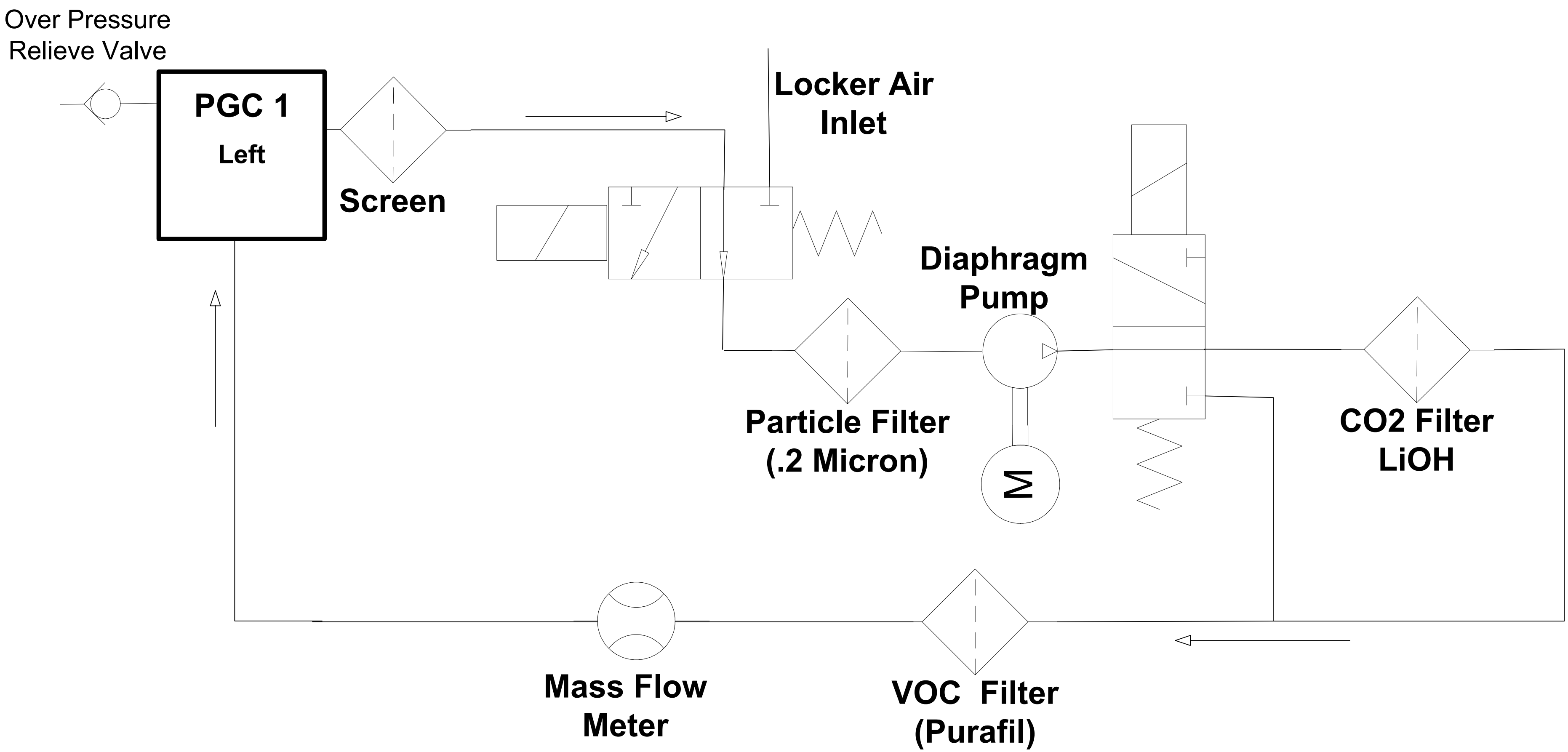
Filtration System Design

- Left and Right Assembly
- Integrated with Priming Reservoir Housing



Air Filtration Flow Diagram

- Repeated for right side



Air Filtration Flow Diagram

- First Solenoid valve controls source of air
  - LEE - LHDA12 11111H
  - Air may be drawn from either the locker or the PGC
  - Air from PGC for CO_2/VOC removal
  - Air from Locker for CO_2 addition
- Diaphragm pump circulates air
  - Thomas - 3003-3012
  - 0.85 liters/min. max flow rate
- Second Solenoid valve routes air to CO_2 scrubber or bypasses scrubber

Air Filtration Flow Diagram

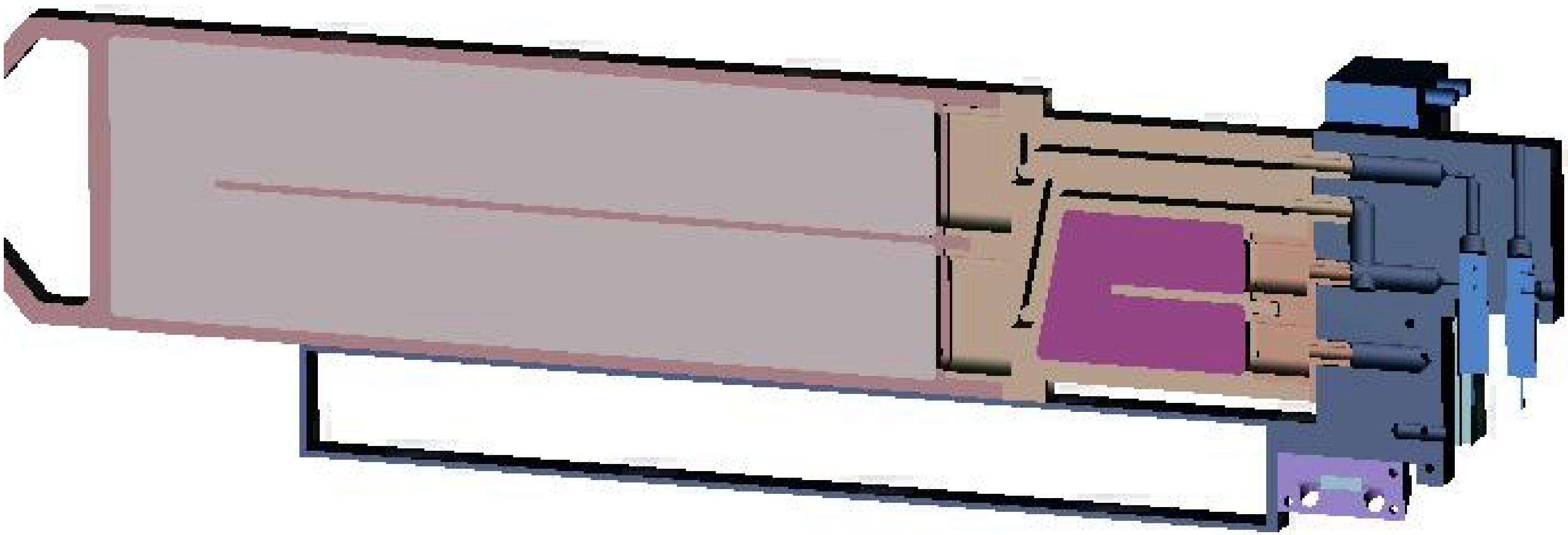
- **All air is routed through Ethylene/VOC scrubber body**
  - **When Ethylene/VOC reduction is not desired an empty cartridge is installed**
- **Air mass flow meter monitors system for clogging**
  - **Used to alert crew and troubleshoot problems**
- **Air is returned to growth chamber**

Filtration System Performance

- CO_2 scrubbers hold 60 grams of Lithium Hydroxide (LiOH)
- Ethylene/VOC scrubbers hold 4 grams of Purafil
- Prototype testing indicated that this was adequate volume for approximately 5 days when PGC leak rates were reasonable
  - Very sensitive to PGC leak rate
- System could control CO_2 to within 100 ppm when operating properly
  - Software improvements should reduce error
- No testing performed on Ethylene/VOC performance

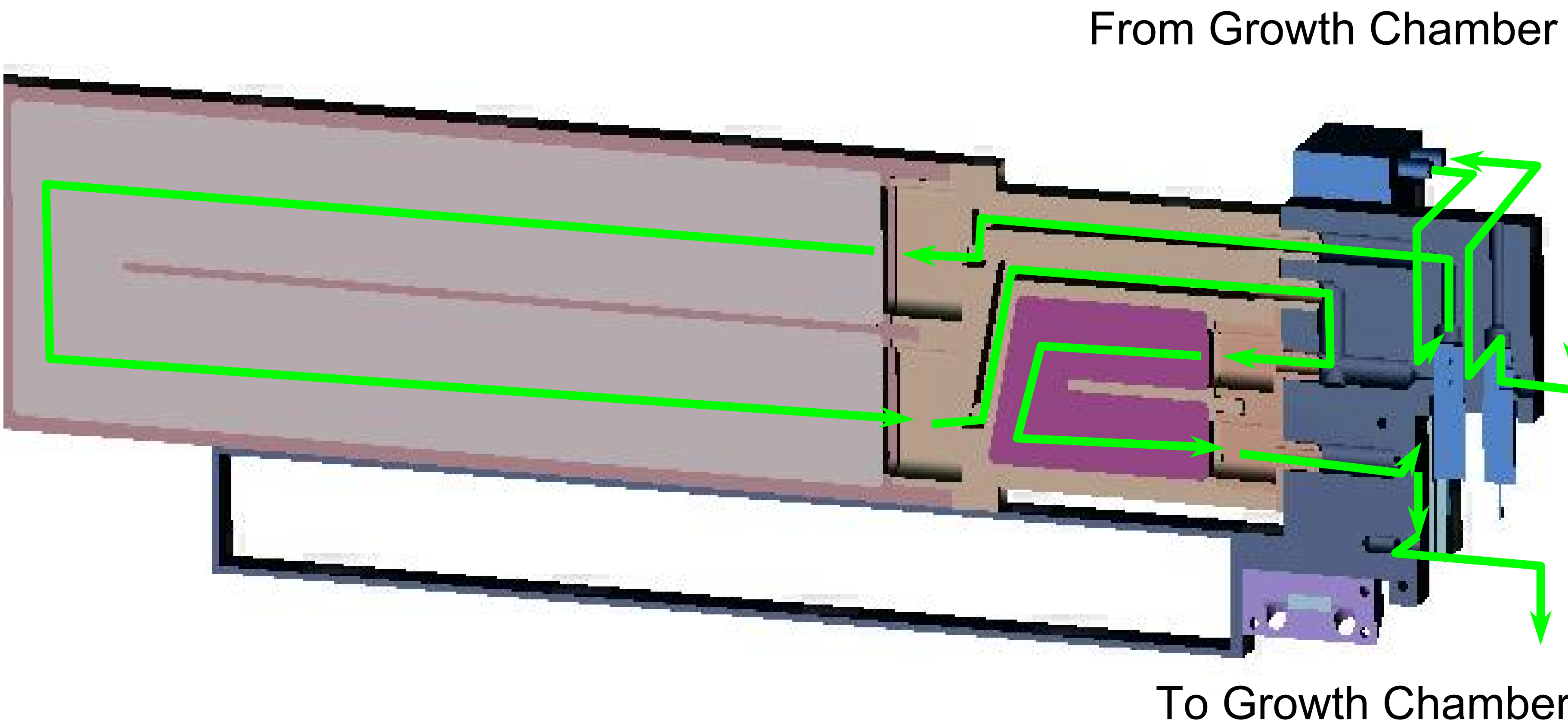
Scrubber and Manifold Design

- **Internal passages in Priming Reservoir body act as manifold for Air Filtration System**



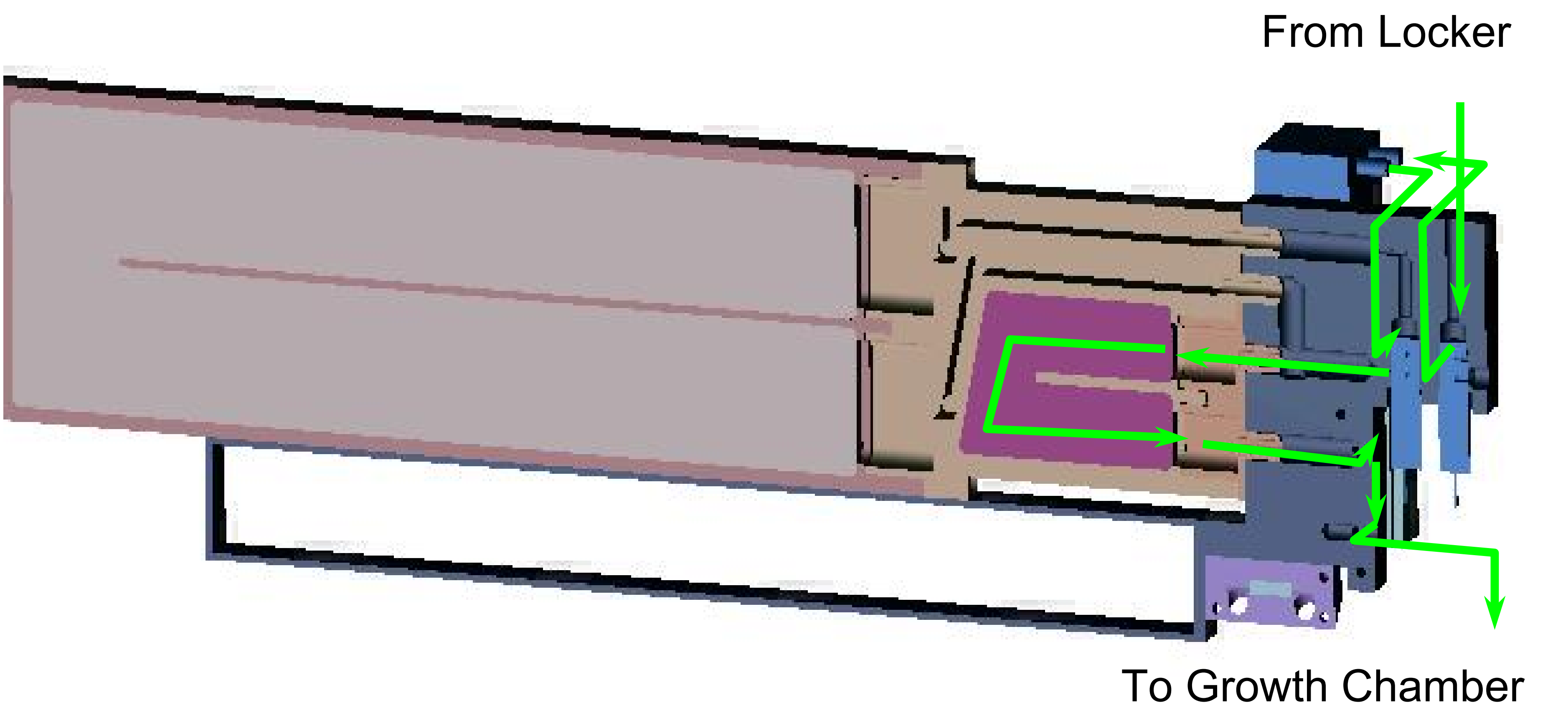
Scrubber and Manifold Design

- **Showing air flow during CO_2 removal**



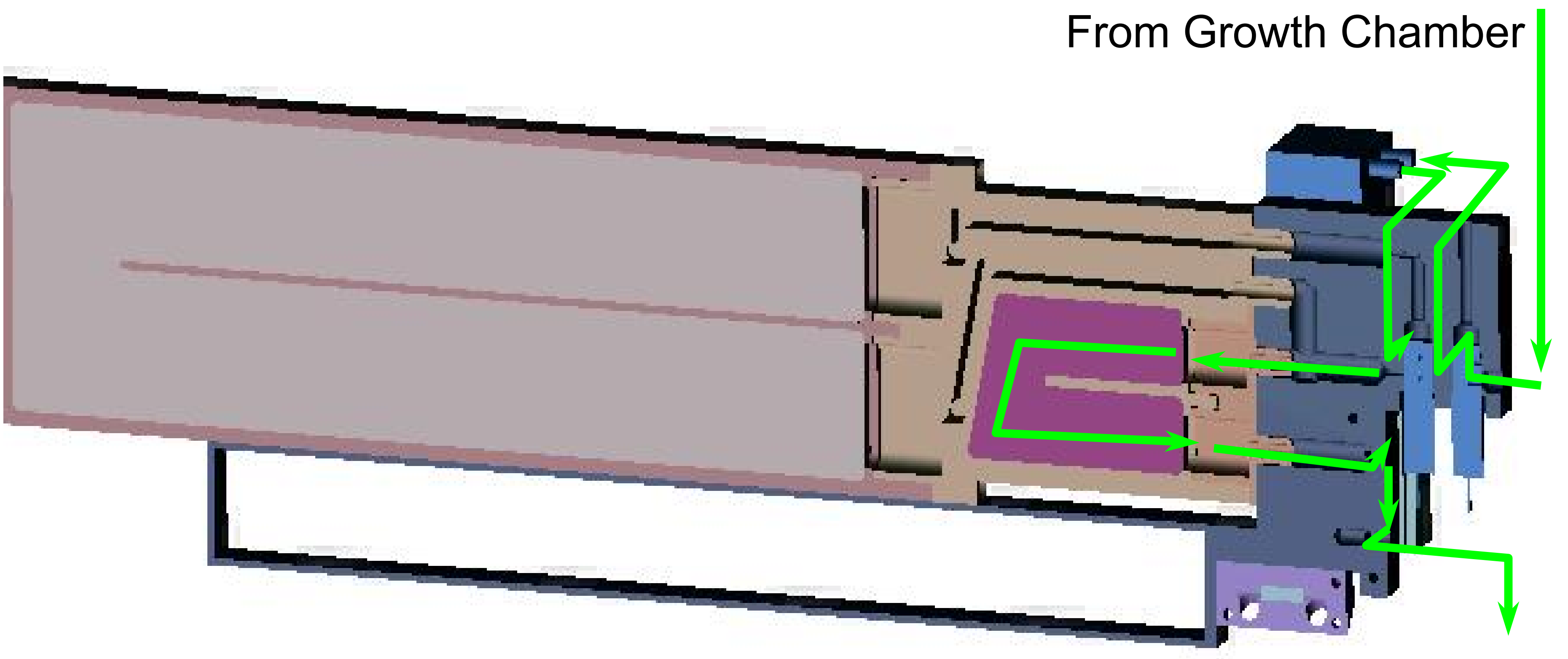
Scrubber and Manifold Design

- **Showing air flow during Cabin Air Injection**

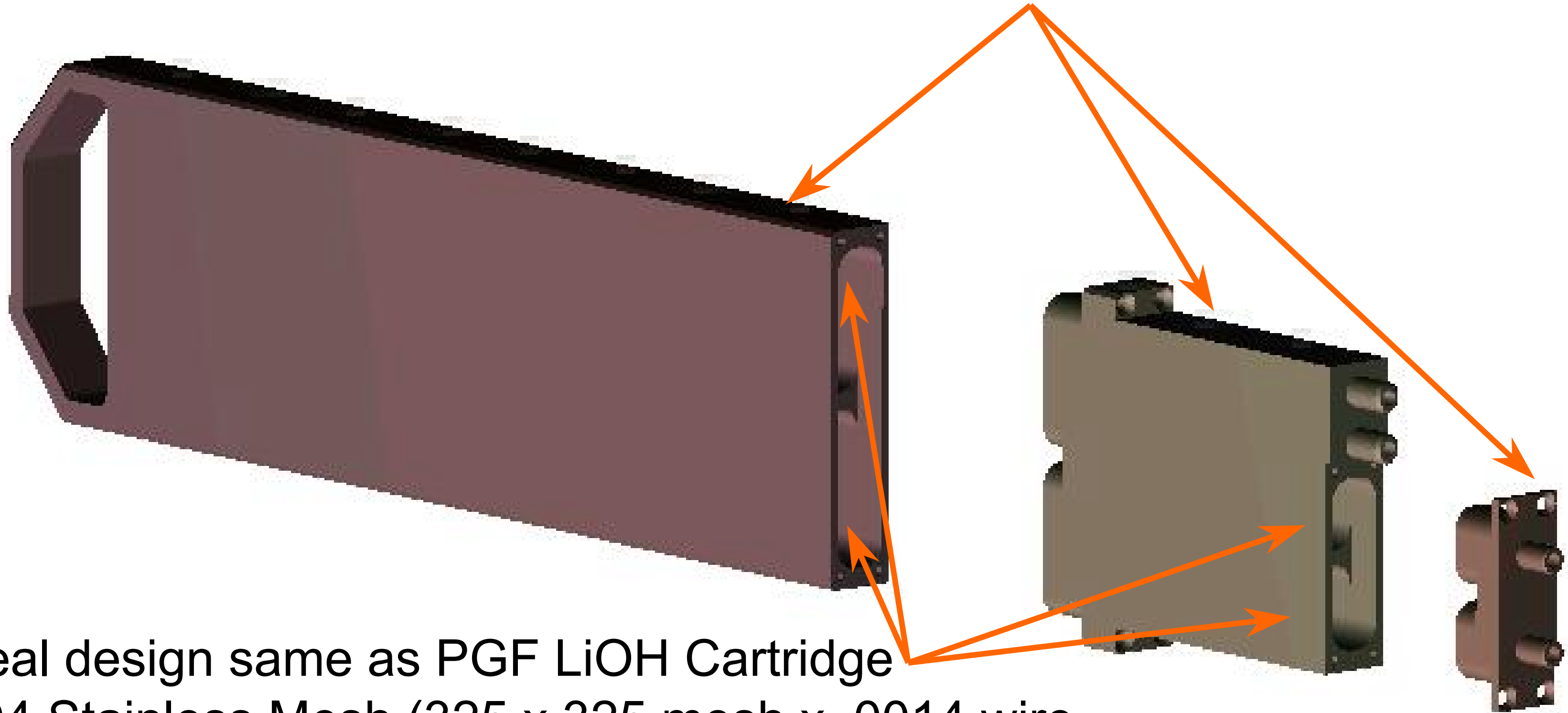


Scrubber and Manifold Design

- **Showing air flow during Ethylene/VOC removal without changing CO_2**



CO2/VOC Scrubber Construction



Seal design same as PGF LiOH Cartridge
304 Stainless Mesh (325 x 325 mesh x .0014 wire diameter) and Nylon filter cloth (390 x 390 mesh x .0014 thread dia) not shown
O-ring seals around plugs

Scrubber Performance

- Initial tests indicate that LiOH volume is sufficient to control carbon dioxide for up to seven days
- LiOH performance sensitive to PGC leak rates
- LiOH performance sensitive to build up of water in cartridge
- No evaluations on potassium permanganate
- More ground testing required with new system

Filtration System Risks

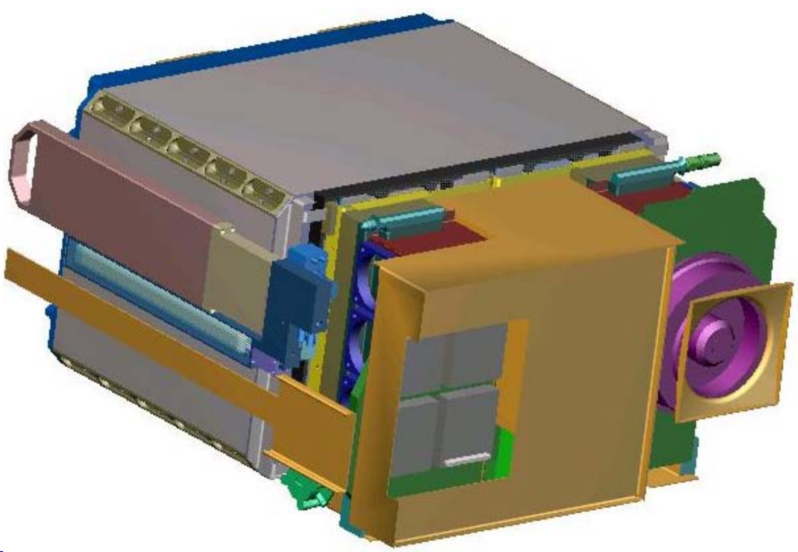
- Risks
  - Inadequate control of air quality
    - Performance to be verified in ground testing
    - Design based on PGF filtration system
    - Some ground tests indicate adequate performance
  - Release of hazardous substances
    - Design based on PGF design for double containment

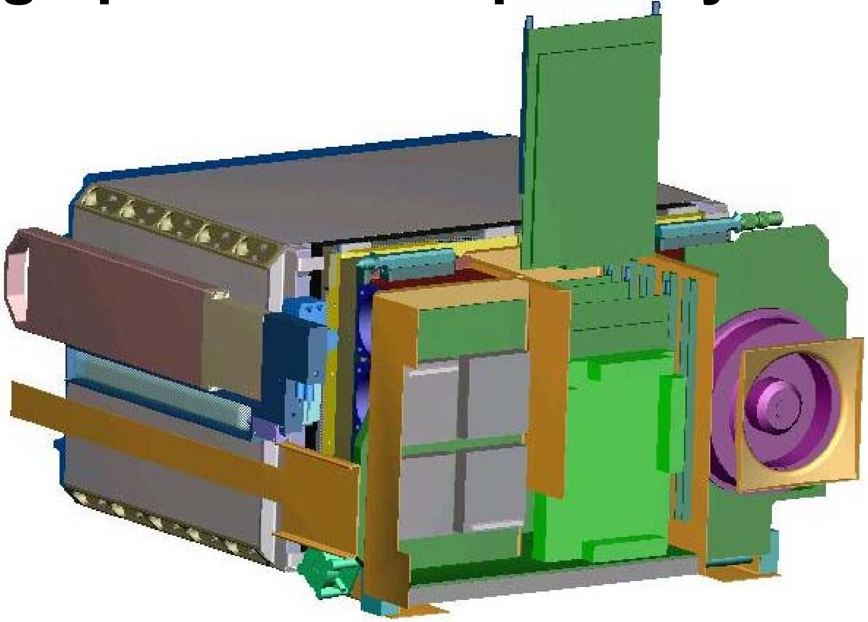
Filtration System Summary

- Lithium Hydroxide and Potassium Permanganate sacrificial scrubbers used to control air quality
- Removable on orbit
- Power Consumption
  - 2.8 watts max
- Weight
  - 1.0 lbs
  - 0.36 lbs per CO2/VOC scrubber assembly

Electronic Control Unit

- Automated control system
- Power distribution and monitoring
- Distributed control system with independent PGC control
- Data Storage
- Electrical and Software design presented separately





ECU Mechanical Requirements

- Contain and Support electronics
- Provide air flow path

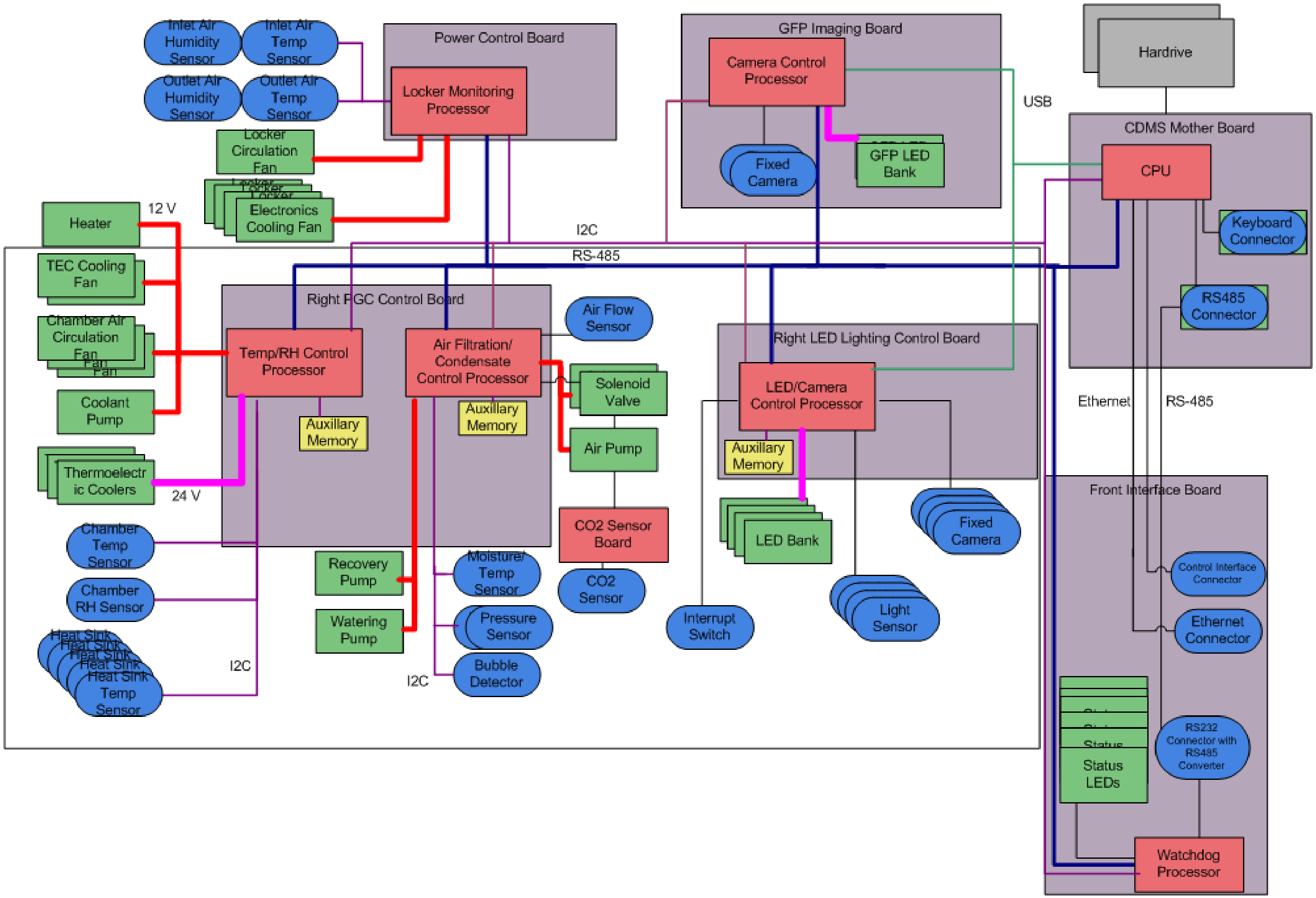
ECU Mechanical Interfaces

- ECU cards
- TIA
- Locker air flow
- APML/CCDL

ECU Goals

- **Minimize weight**
- **Maximize access to electronics for maintenance**

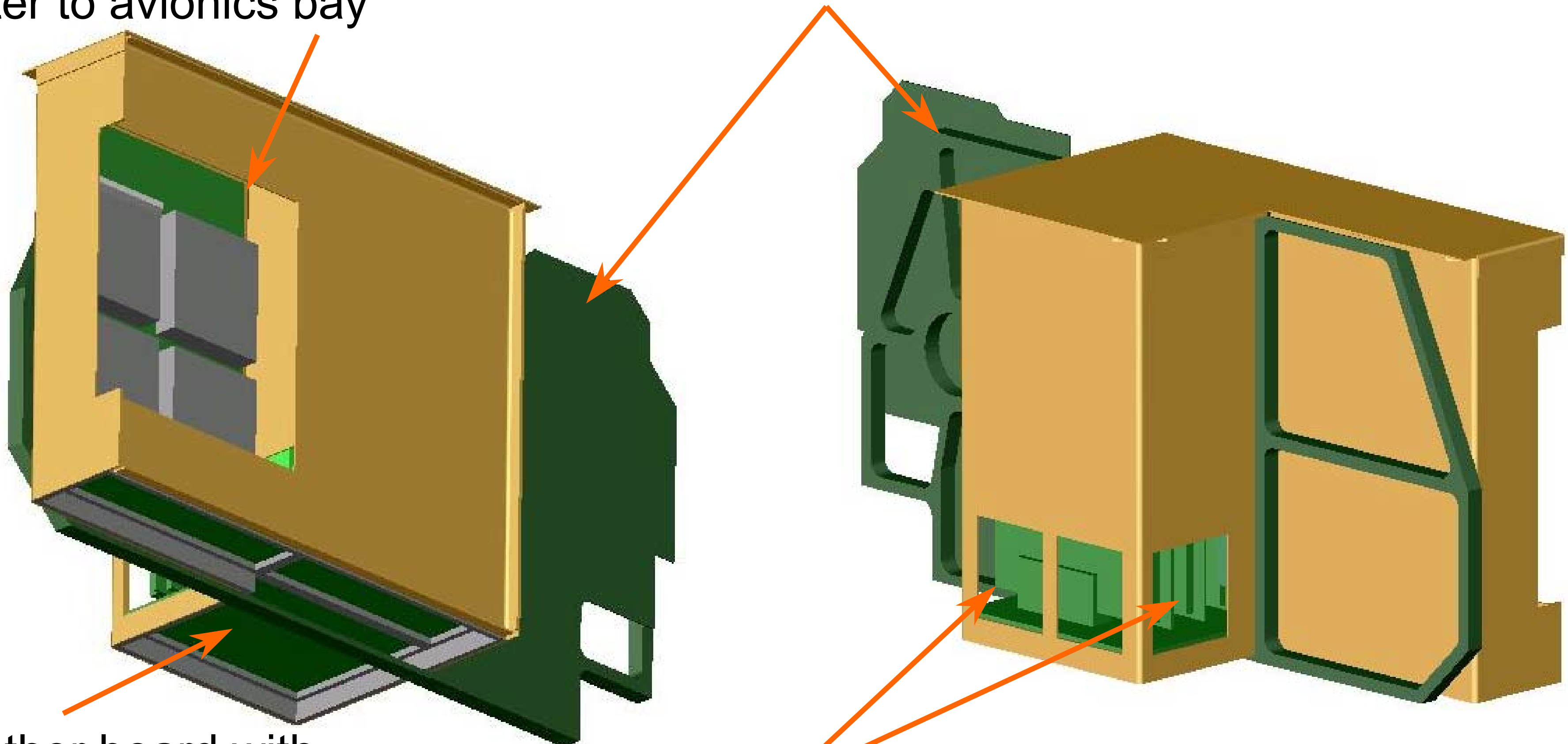
Controller Functional Block Diagram



ECU Housing

Air Outlet through EMI/Dust Filter to avionics bay

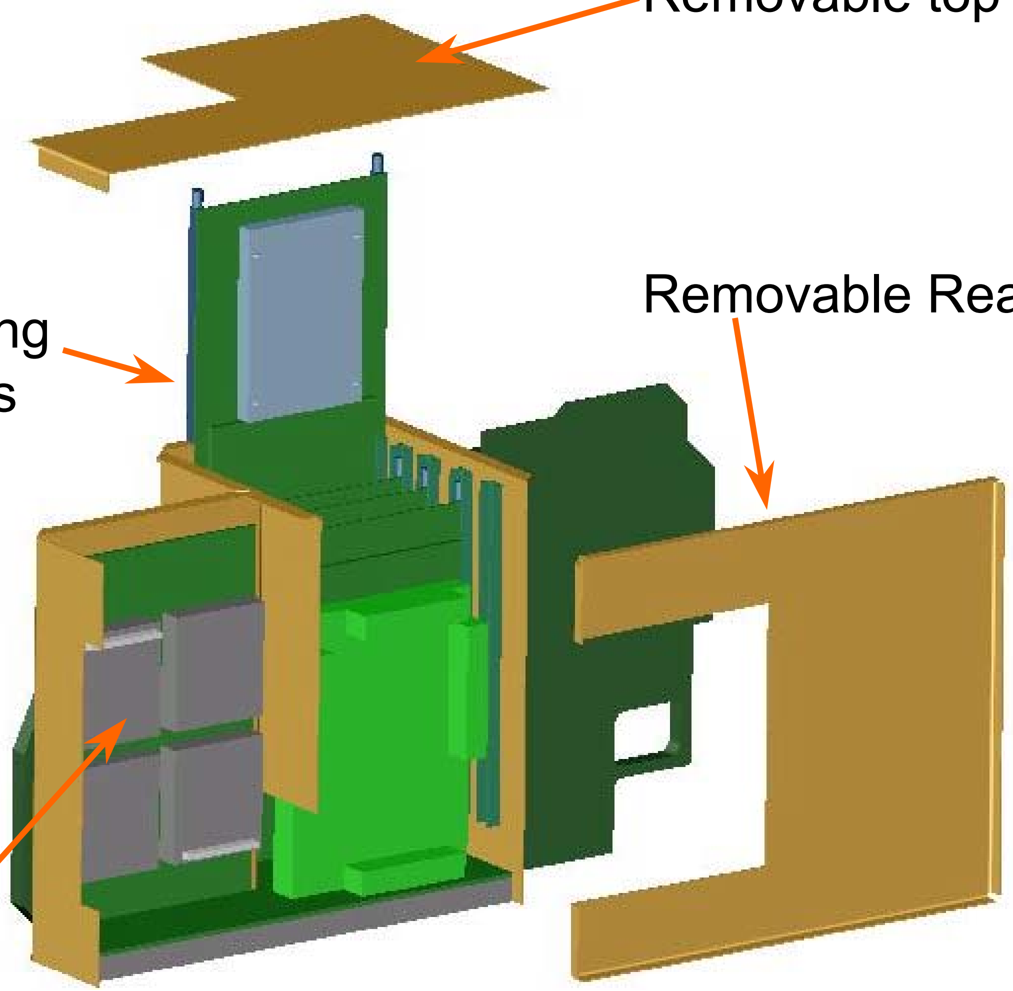
Support Bracket



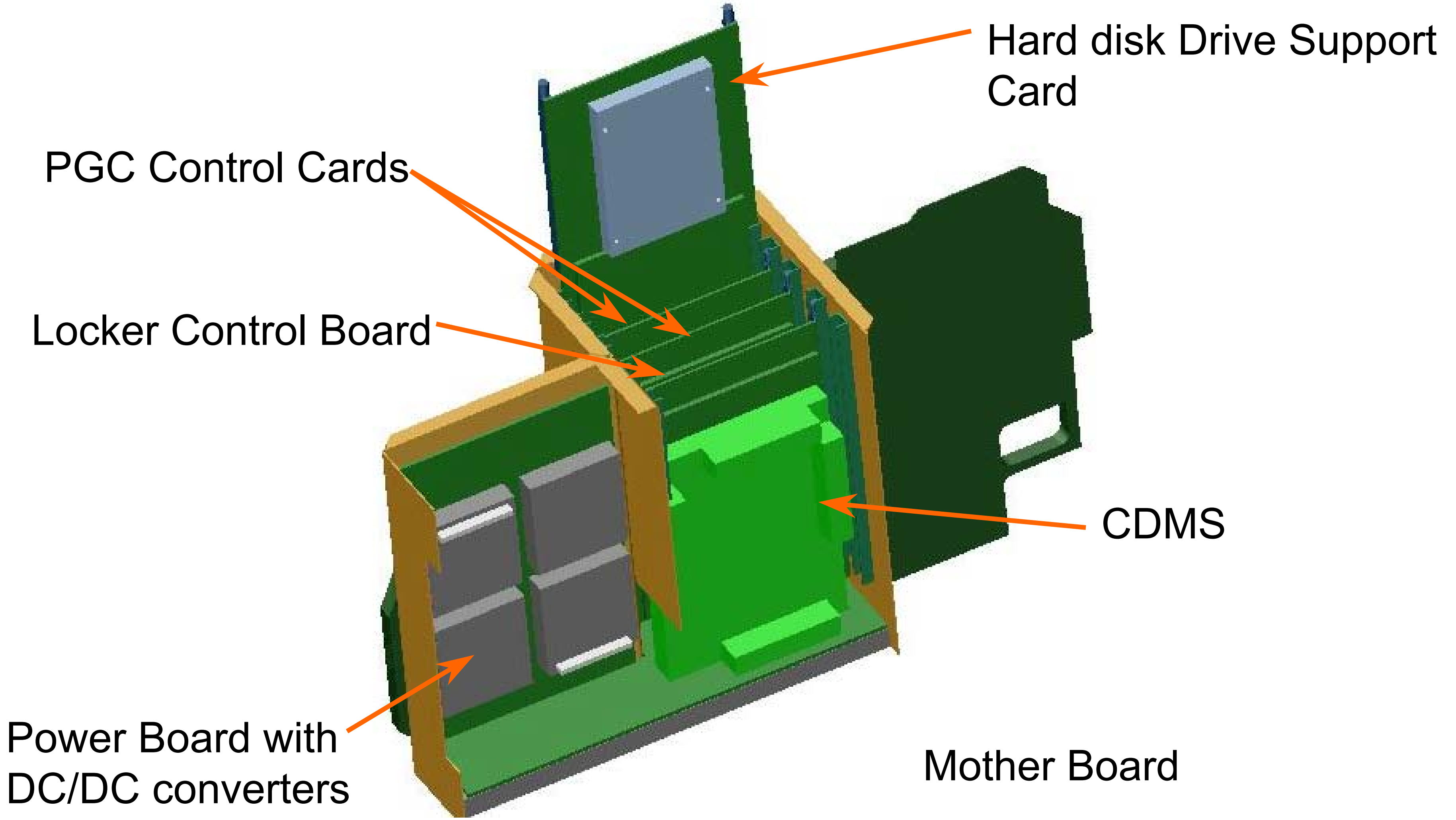
Mother board with connectors to remote devices

Air Inlet from LLM and Cooling Units

ECU Construction



ECU Construction



ECU Construction

- **Aluminum Housing - .040” thick 6061-T6 sheet metal construction with threaded inserts**
- **Fiberglass mounting bracket - machined .375” G-10 board**
- **Removable top and back for access to electronics**
- **Cards slide in and blind mate to connectors on mother board**
- **Screens over inlet protect electronics from dust or large amounts of water in case of water leakage**
- **Housing covered in cut to fit silicone foam to prevent thermal short-circuits (not shown)**

ECU Mechanical Risks

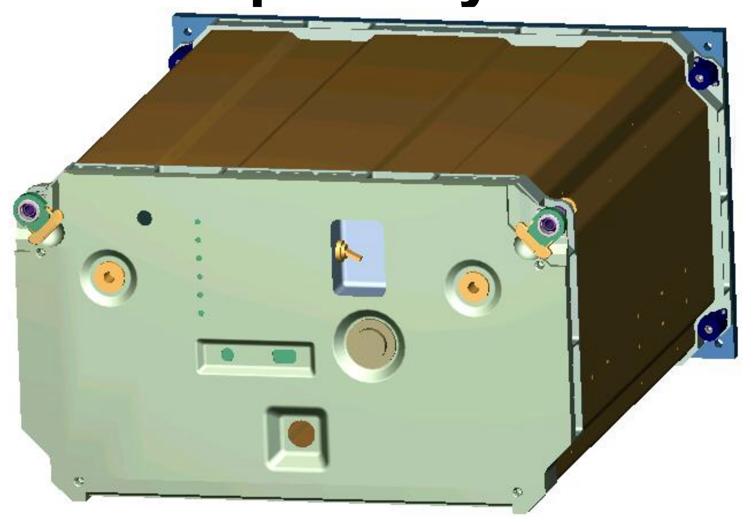
- Poor air circulation
  - Air baffles will be added as required to prevent hot spots
- Crew hazards, shock or touch temperature
  - Screens will be added to prevent access to dangerous surfaces

ECU Mechanical Summary

- Housing and assembly for primary processing and power conversion equipment
- Controls air flow and prevents thermal short-circuits
- Weight
  - 6.53 lbs
  - Does not include wires, insulation and fasteners
- Power Consumption
  - Approximately 57 watts

Front Interface Panel Mechanical Design

- **Door Mounted Interface**
  - Direct interface with crew
  - LED status indicators
  - Data ports
- **Remote handheld graphical interface with touch screen, stowed separately for launch and landing**
- **Electrical an Software presented separately**



Front Interface Panel Requirements

- Meet ISS human interfaces requirements
- Supply state of health data to crew and ISS computers
- Allow for download of images and telemetry on orbit
- Notify crew of required operations
- Control power and operational functions of PGF-SP

Front Interface Panel Interfaces

- Crew
- CDMS - RS485, I2C
- Orbiter Laptop - RS232
- EXPRESS Rack LAN - Ethernet

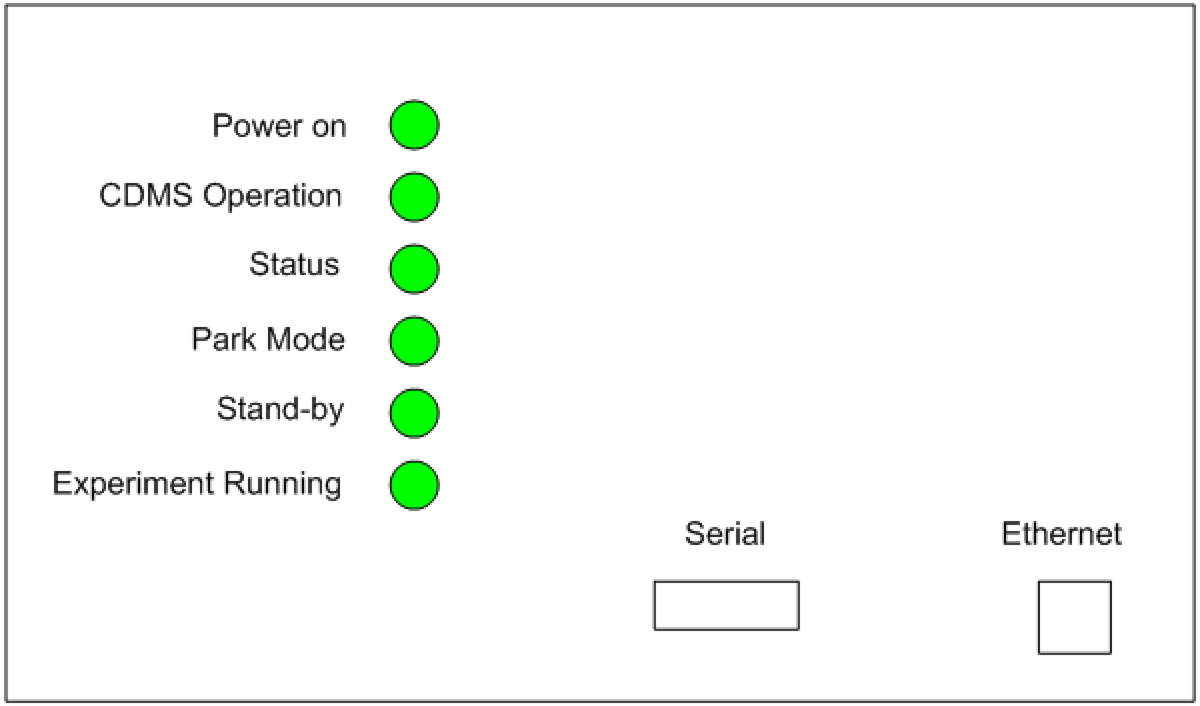
Front Interface Panel Goals

- Minimize weight
- Maximize crew ease of use
- Minimize data access time
- Provide remote access to control of internal PGF-SP systems
  - Camera control
  - Control Set points
  - Telemetry

Front Interface Panel Design

- **Door mounted front interface processor communicates with CDMS via**
  - **RS485 - primary**
  - **LAN - for high speed data transfer of images**
  - **I2C - as backup**
- **Front interface processor converts RS485 to**
  - **RS232 for orbiter laptop operations**
  - **LAN for communications with EXPRESS Rack**
- **Front interface process acts as watchdog and general controller in case of CDMS failure**

Front Panel Display



Notes:

Power on LED is green and on steady
CDMS Operation LED is green and blinks (1 /sec.)
Status LED is green or amber depending on condition and on steady
Park Mode LED is green and steady when on
Stand-by LED is green and steady when on
Experiment LED is green and steady when on

Front Interface Panel Design

- **Recessed Power Switch**
- **Recessed Data Connectors**

Hand Held User Interface

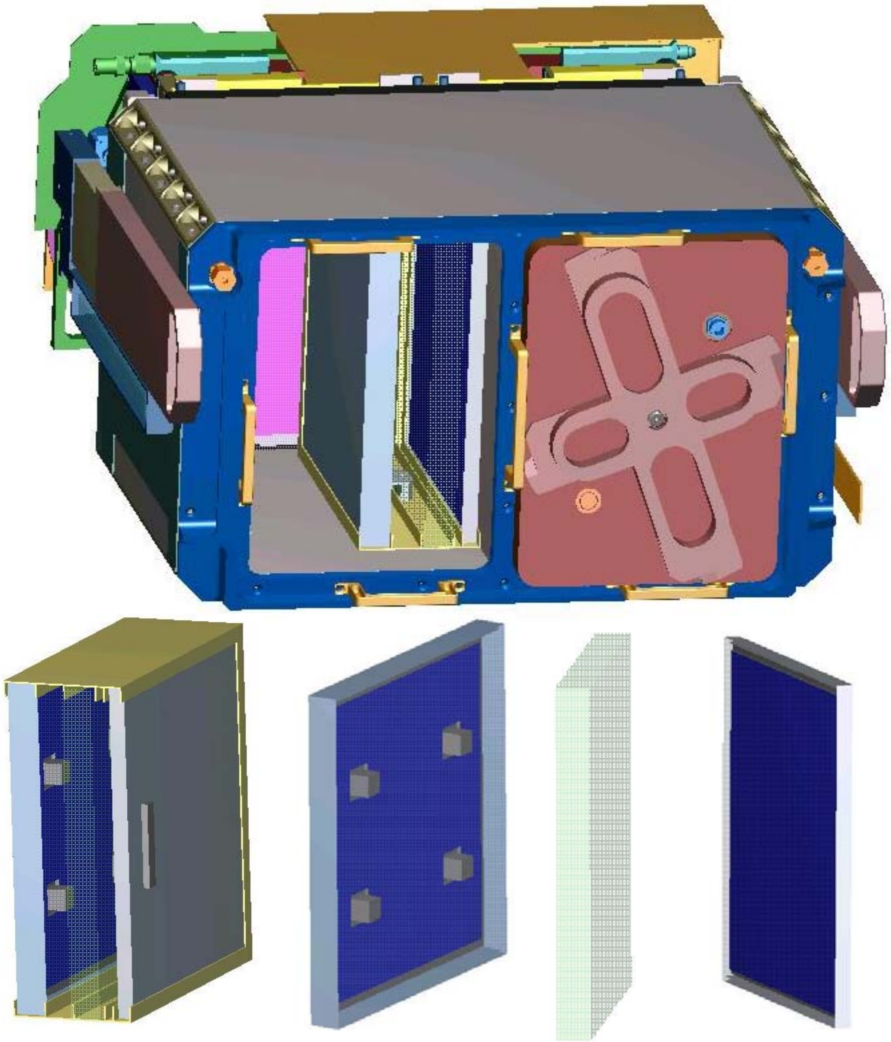
- Handheld user interface
  - COTS
  - Programmable
  - Built in buttons
  - Touch screen control
  - Full color screen
  - Removable and storable
- Allows access to higher functions
- Allows for real time viewing of plants
- Stowed for launch and landing
- Used to switch experiment modes

Front Interface Summary

- Provides status to crew
- Provides command and data connections to crew laptop or EXPRESS Rack
- Weight
  – Hand Held Unit 1.92 lbs
  – Built in equipment 0.76 lbs
  – Excluding wires, two miniature connectors, and cover
- Power Usage
  – Hand held system 12 watts
  – Built in panel 3 watts

Green Fluorescent Protein Imager Overview

- **Modular insert into PGCs**
- **Special Illumination and Imaging for TAGES-2SD Experiment**
- **One in each PGC as backup**
- **Custom sample tray to allow for flexible experiment design**



GFP Imager Requirements

- Perform special imaging for TAGES-2SD experiment
- Captured in separate EIS

GFP Imager Interfaces

- PGC housings
  - Structural support
  - Data connector
  - Growth Chamber Environment
- CDMS
  - Command via RS485
  - Image capture via USB
- Front Interface Processor
  - Command via RS485 (remotely commanded imaging

GFP Imager Goals

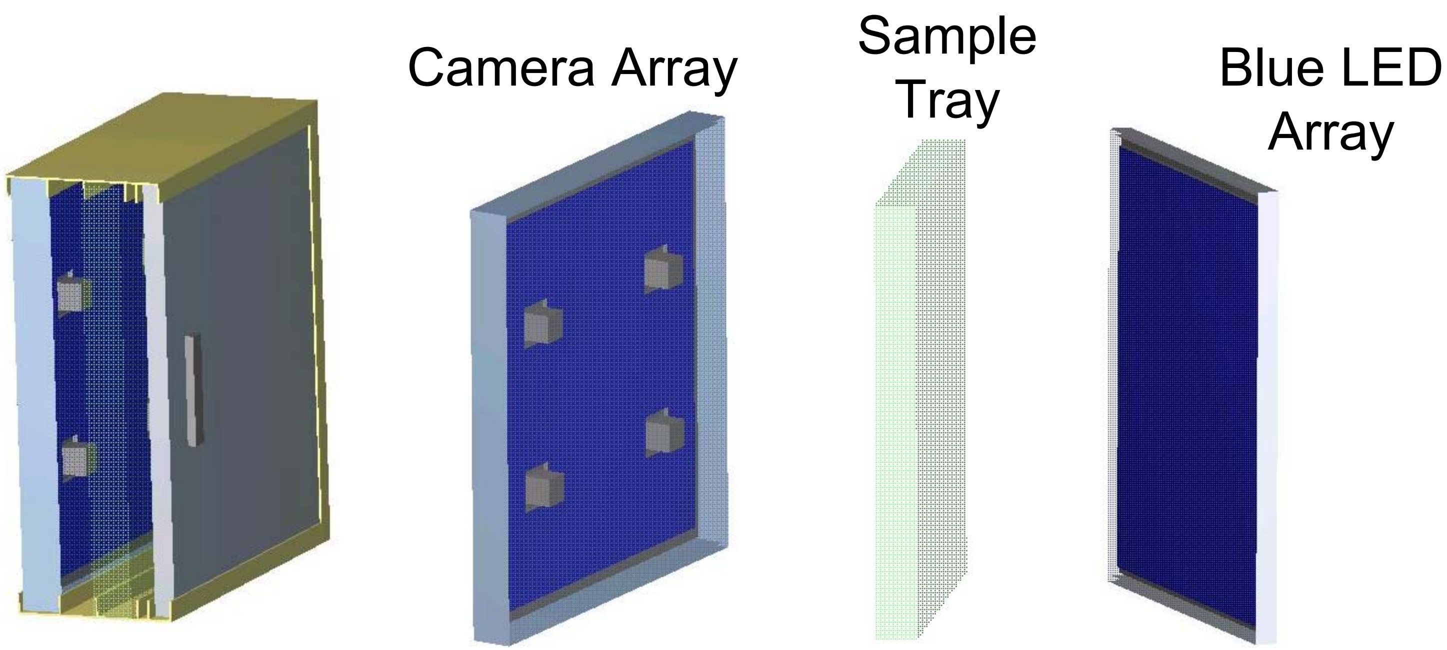
- Occupy less than half each growth chamber
- One in each chamber for redundant operation
- Provide flexible sample tray design

GFP Imager Concept of Operation

- GFP Imager installed inside growth chamber
- Receives power and command from CDMS via connector
- Holds plant samples on custom sample tray
- Back illuminates plants with filtered blue light to stimulate fluorescent response
- Captures filtered images using array of cameras to view entire sample area
- Provides unfiltered white light for comparison images

GFP Imager Design

- **4 x 4 camera array**
- **7.5” x 7.7” x 0.75” sample tray**
- **LED array for backlighting**



GFP Imager Summary

- TAGES-2SD Unique equipment
- Separate design effort
- One in each PGC
- Expected weight
  - >3.0 lbs
- Expected power consumption
  - 20 watts, short duration