ISS-CREAM Thermal and Fluid System Design and Analysis

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Topics

- Introduction
- ISS-CREAM Overview
- Analysis and Design Overview
- Active Thermal Control System (ATCS) Analysis and Design
  - Coldplates
  - SCD
  - System Level
- Midsection, Structure, and Instrument Level Model
- Planned Verification / Testing

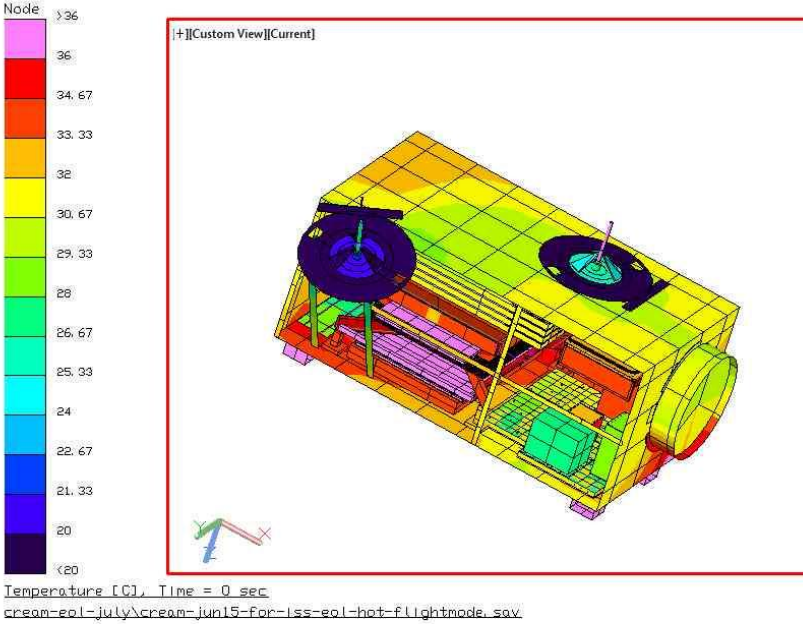
- Primary focus for TFAWS is thermal fluid analysis and design, not ISS-CREAM description

ISS-CREAM Payload

ISS-CREAM (Cosmic Ray Energetics And Mass for the International Space Station)

Physical Characteristics

- Payload total mass: 1392 kg
- Payload Dimensions: 1.85 m x 0.95 m x 1 m (size of a refrigerator)
- Launch scheduled in 2016
- Nominal data collection of 3 years on International Space Station (ISS) Kibo/Japanese Experiment Module (JEM) Exposed Facility (EF)



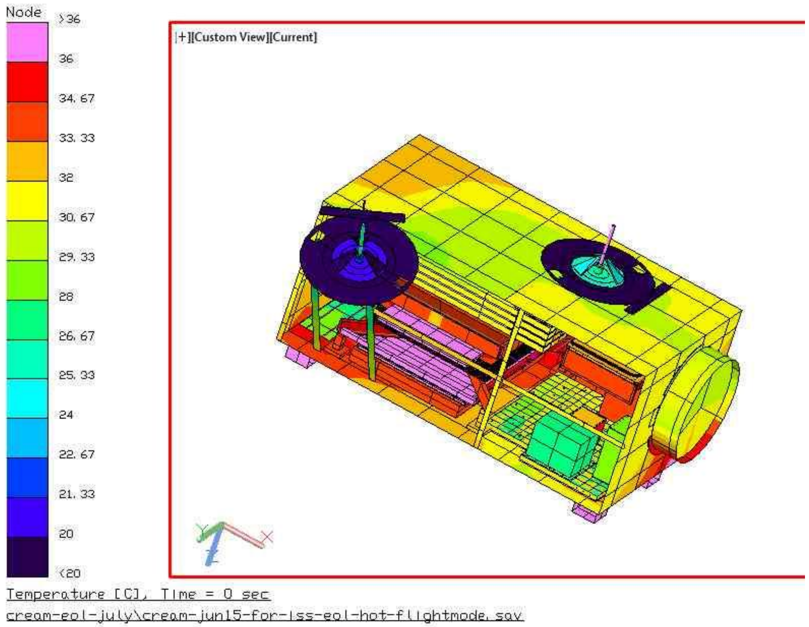
ISS JEM EF Provided Services

- 580 W operational power
- 120 W survival heater power
- 200 kg/hr Fluorinert supply at 16-24C
- Data

ISS-CREAM Payload

- Primarily cooled by JEM EF fluid
- ISS payload on JEM EF location
  - Complex ISS models and ISS I/F
- Complex payload in small package
  - 5 Instruments (Calorimeter System , SCD, TCD, BCD, BSD)
  - 7 electronics boxes
- Previously flown balloon hardware + enhanced sensor suite
- Detectors and electronics built by variety of organizations: University of Maryland, NASA Goddard, South Korean universities (see final slide)
- Low cost project ($20M)
- NPR 7120.8 / Do No Harm payload = Technical risk is high
- Only Calorimeter and HPDs and SCD are considered primary instruments

- Intent is to provide years of cosmic ray science



Acronyms on final slide

ISS-CREAM Description / Schedule

- ISS-CREAM, science objectives, and ISS JEM EF are documented on several websites available on the Internet including:
  - http://cosmicray.umd.edu/iss-cream/
  - https://directory.eoportal.org/web/eoportal/satellite-missions/i/iss-cream
  - https://directory.eoportal.org/web/eoportal/satellite-missions/i/iss-jemef

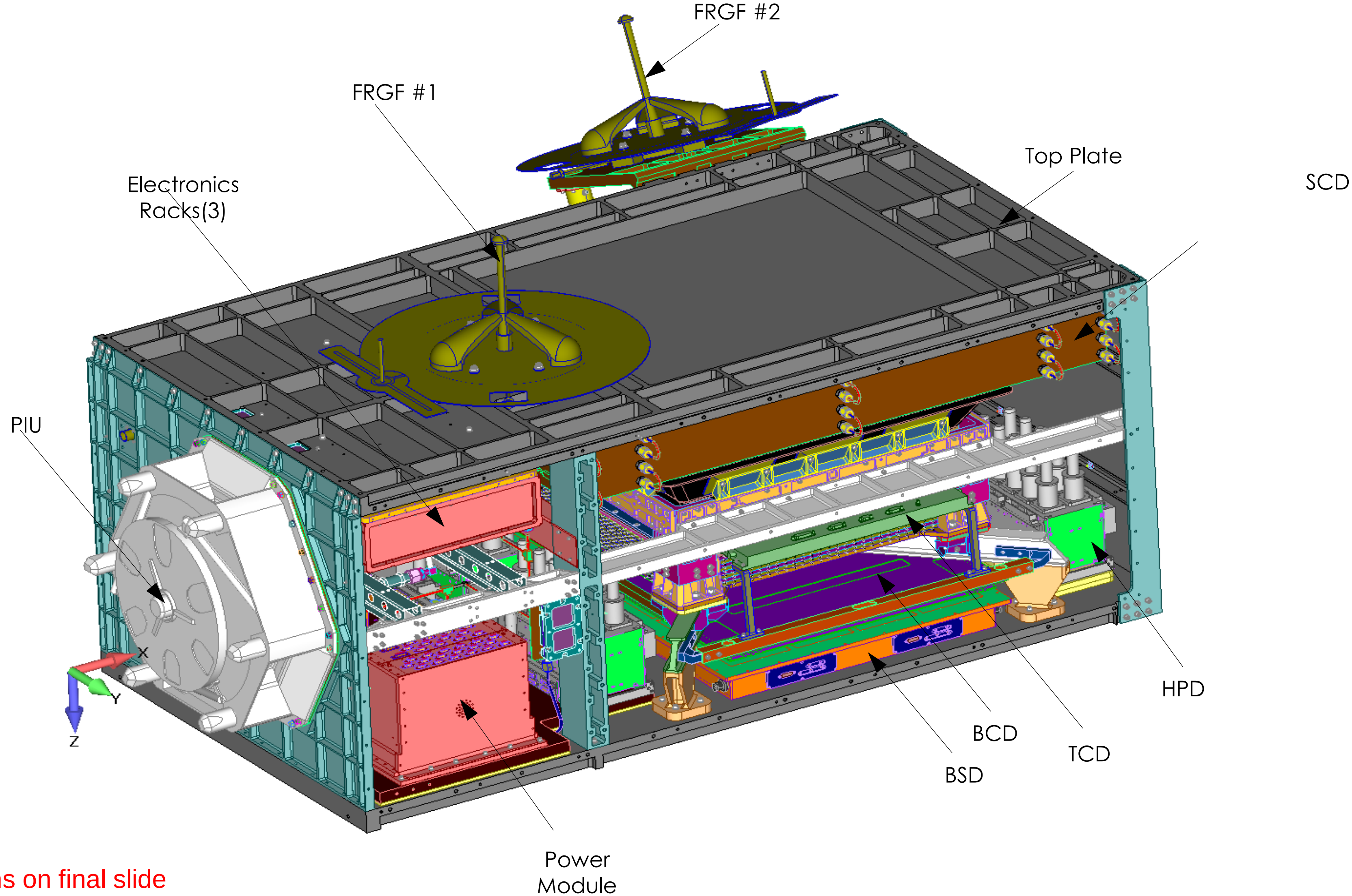
as well as many papers on both ISS-CREAM and prior CREAM balloon flights

(Many graphics and ISS-CREAM descriptions were taken from these sites)

Current Schedule:

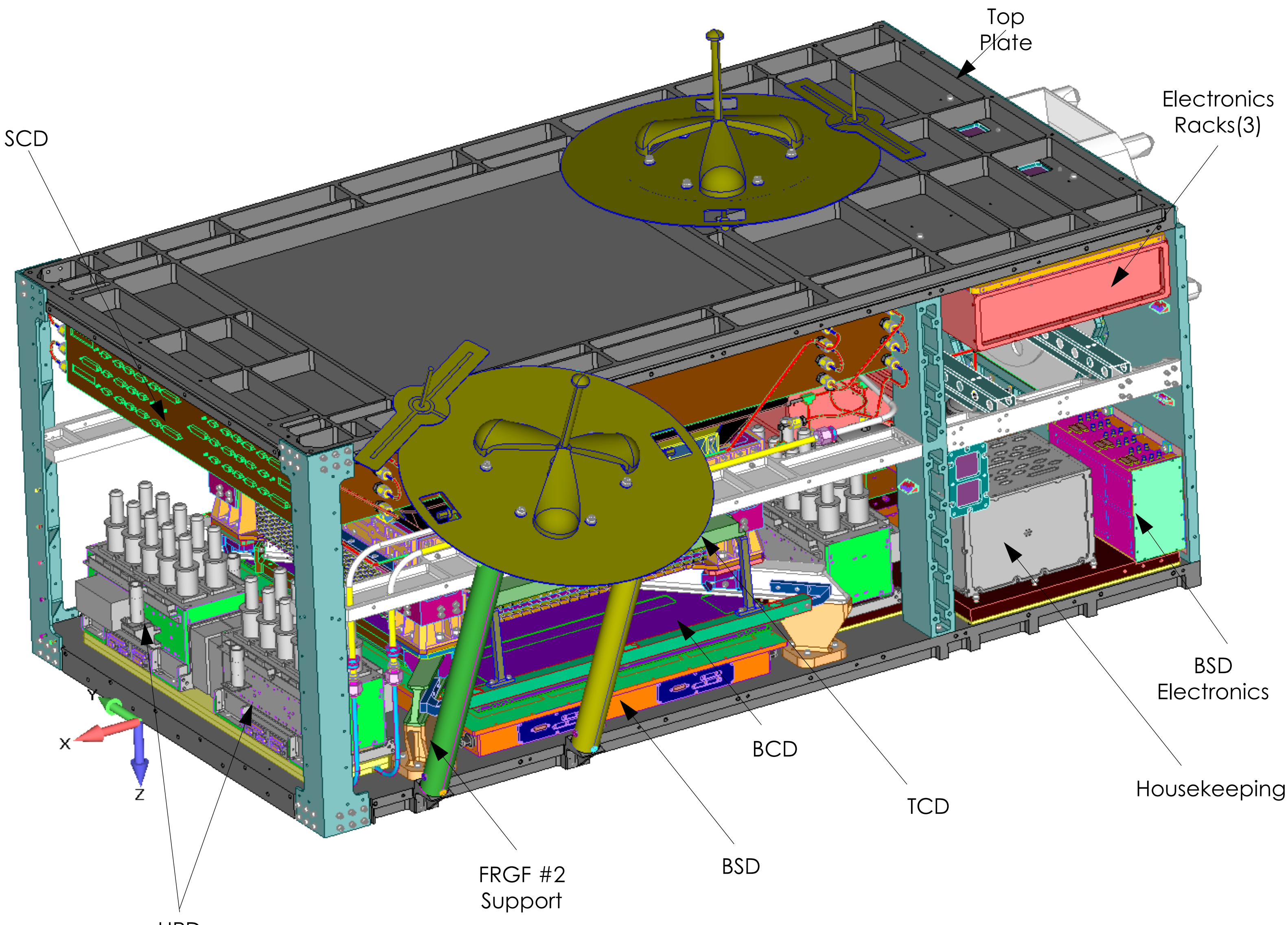
- ISS-CREAM was selected in response to a ROSES-10 proposal to repackage a balloon-borne instrument for accommodation on the ISS/JEMEF around 2012.
- CDR September 2013
- Extensive thermal redesign by SGT / Bastion team under GSFC MSES contract
- Delta-CDR for thermal design in June 2014
- Flow testing and ambient testing of payload from January 2015 to June 2015
- Tvac scheduled for July 2015
- Launch in 2016

ISS-CREAM Payload (+Y view)



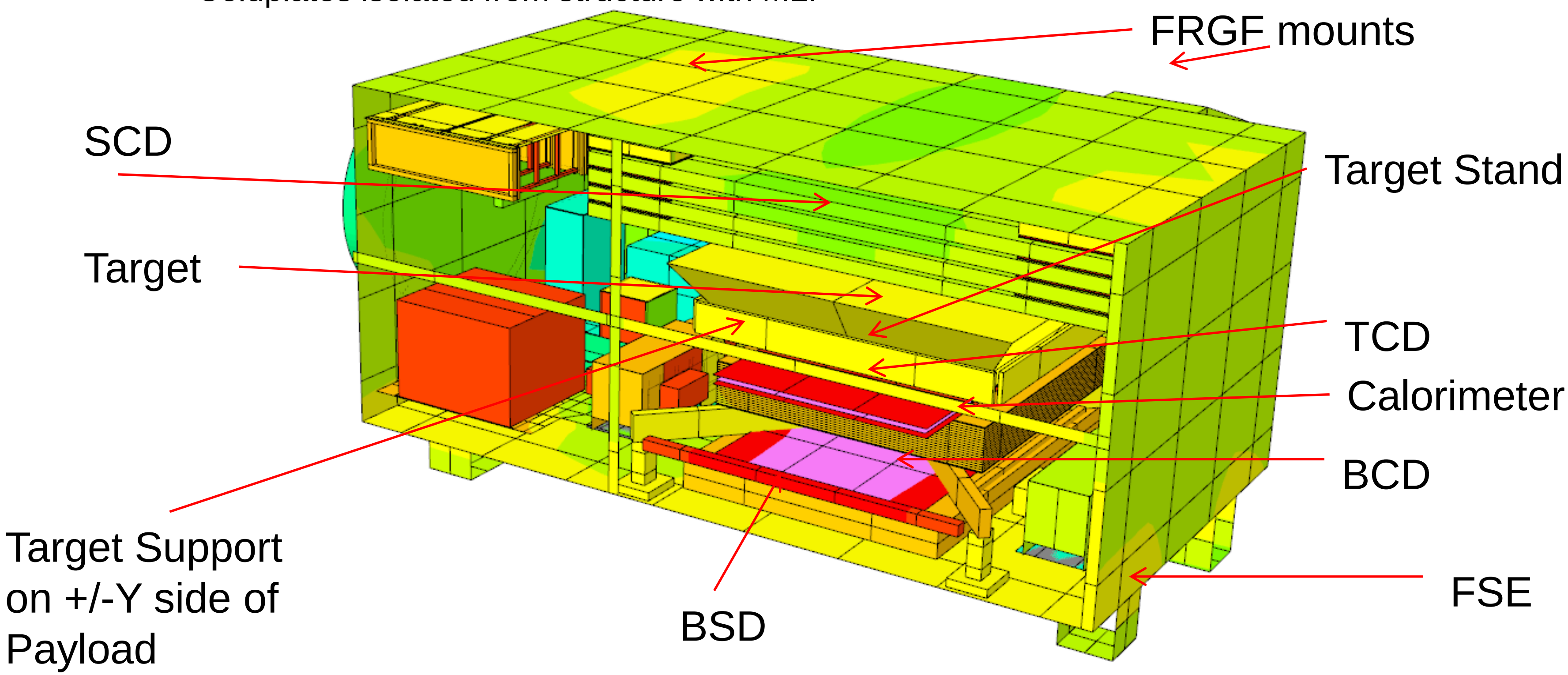
Acronyms on final slide

ISS-CREAM Payload (-Y view)

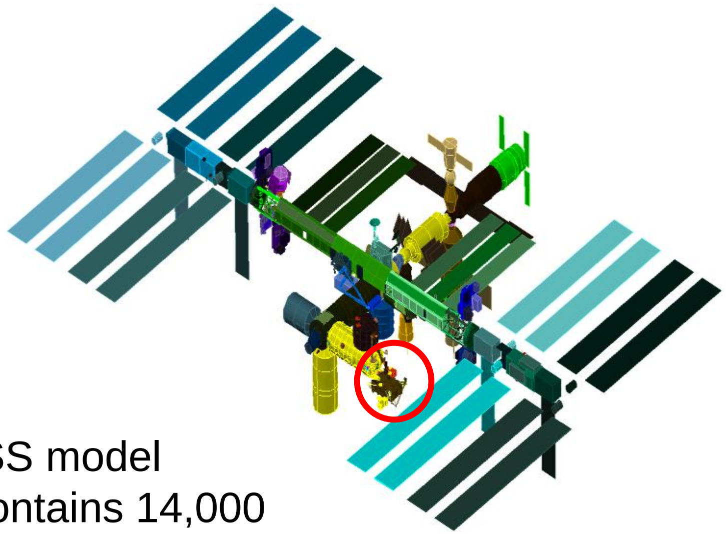


Passive Thermal Design

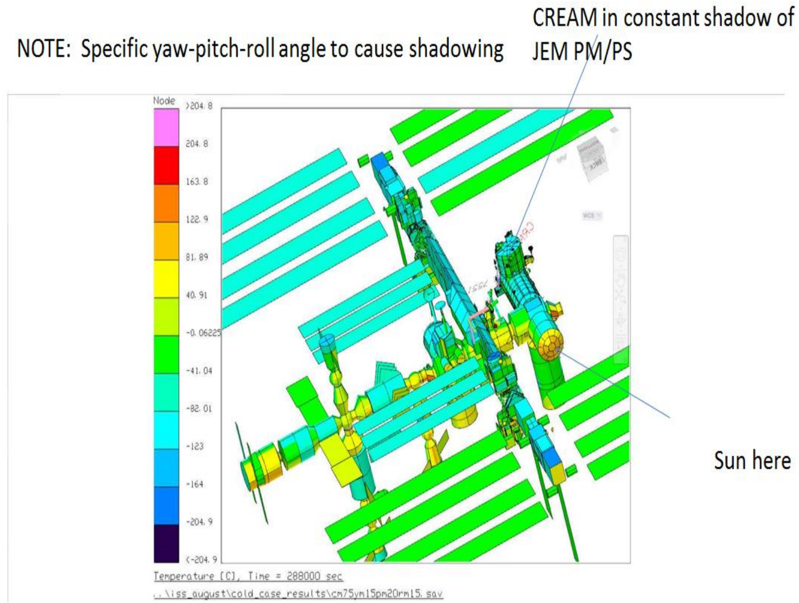
- ISS-CREAM exists in ISS JEM EF environment, so despite full blanketing, environment does impact both hot and cold cases
  - 1392 kg mass limits orbital swings
  - PIU connects CREAM to JEM EF, some conduction losses
  - FSEs (SpaceX feet) have high a/e coating, some heat input/output
  - FRGFs (grapple fixtures, one on diving board structure) provide another heat leak
  - Midsection is passively cooled through connection to bottom plate
  - SCD has 8 large bolt connections to top plate
  - Coldplates isolated from structure with MLI



ISS Thermal Model with CREAM Connected to JEM EF Module



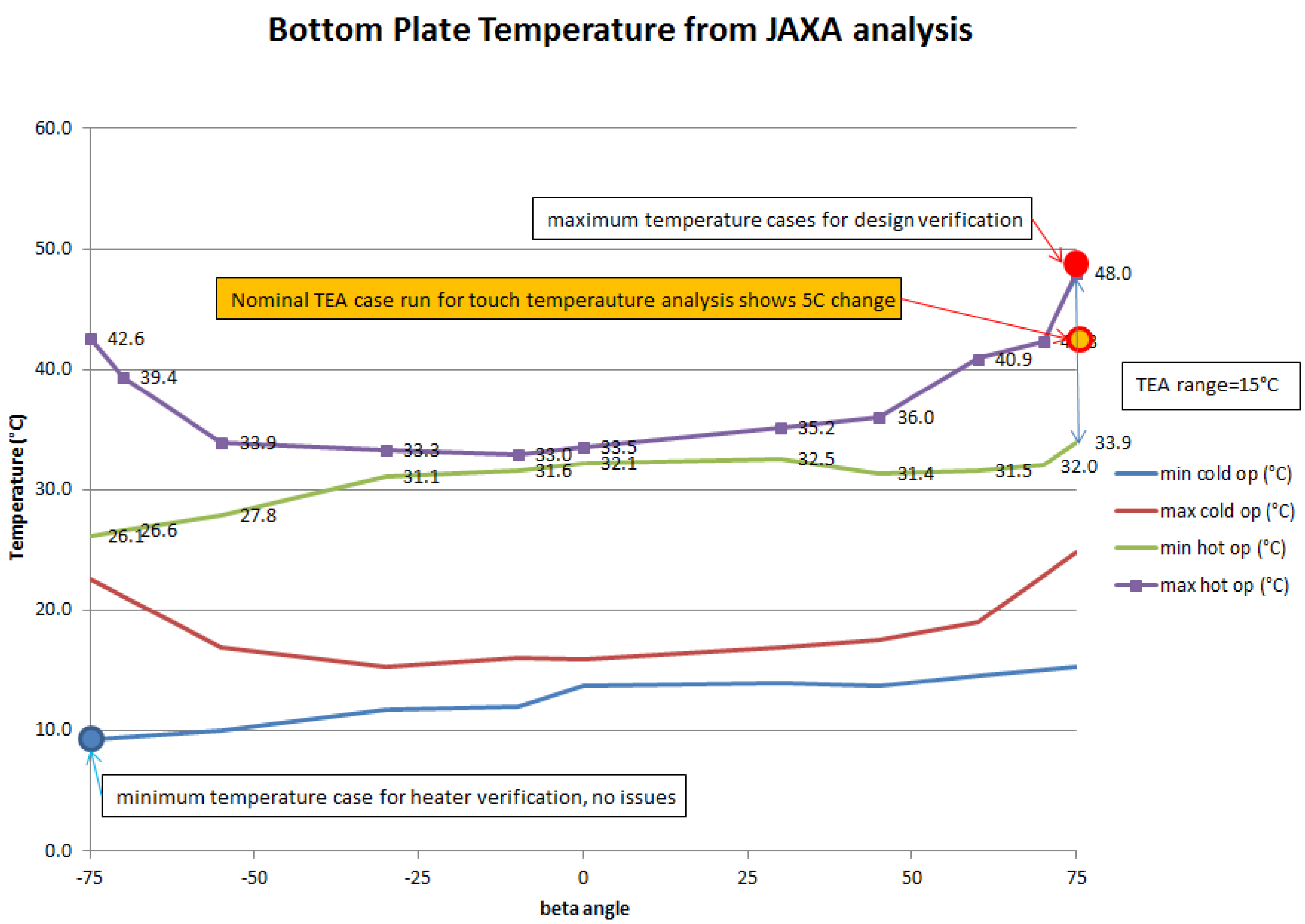
ISS model contains 14,000 nodes and 10,000 surfaces and a 9 MB SINDA model.



Coldest environments have shadowing by JAXA PM/PS module

Hottest environments are due to direct solar for extended periods

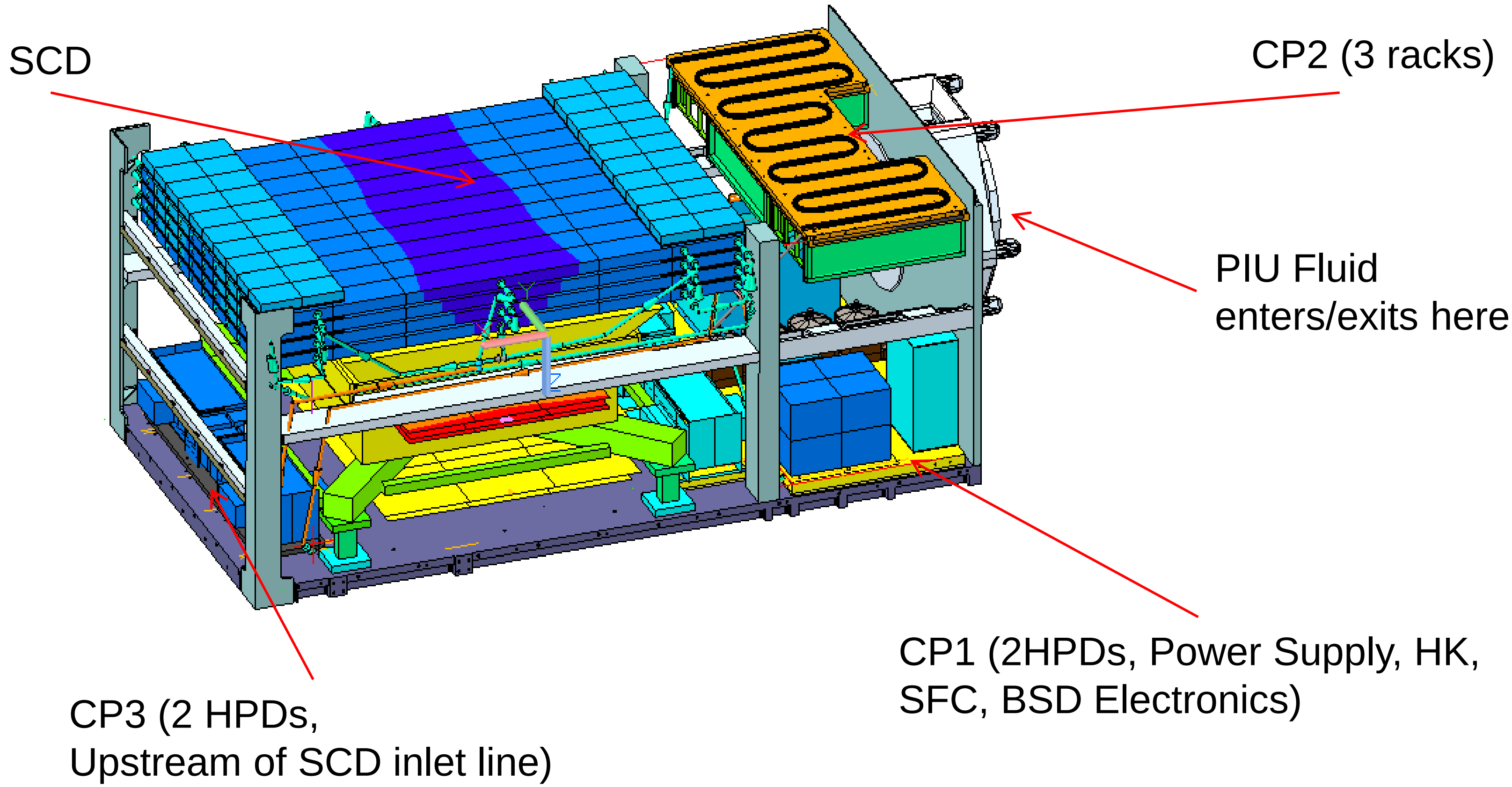
Beta / TEA Effect on Bottom Plate



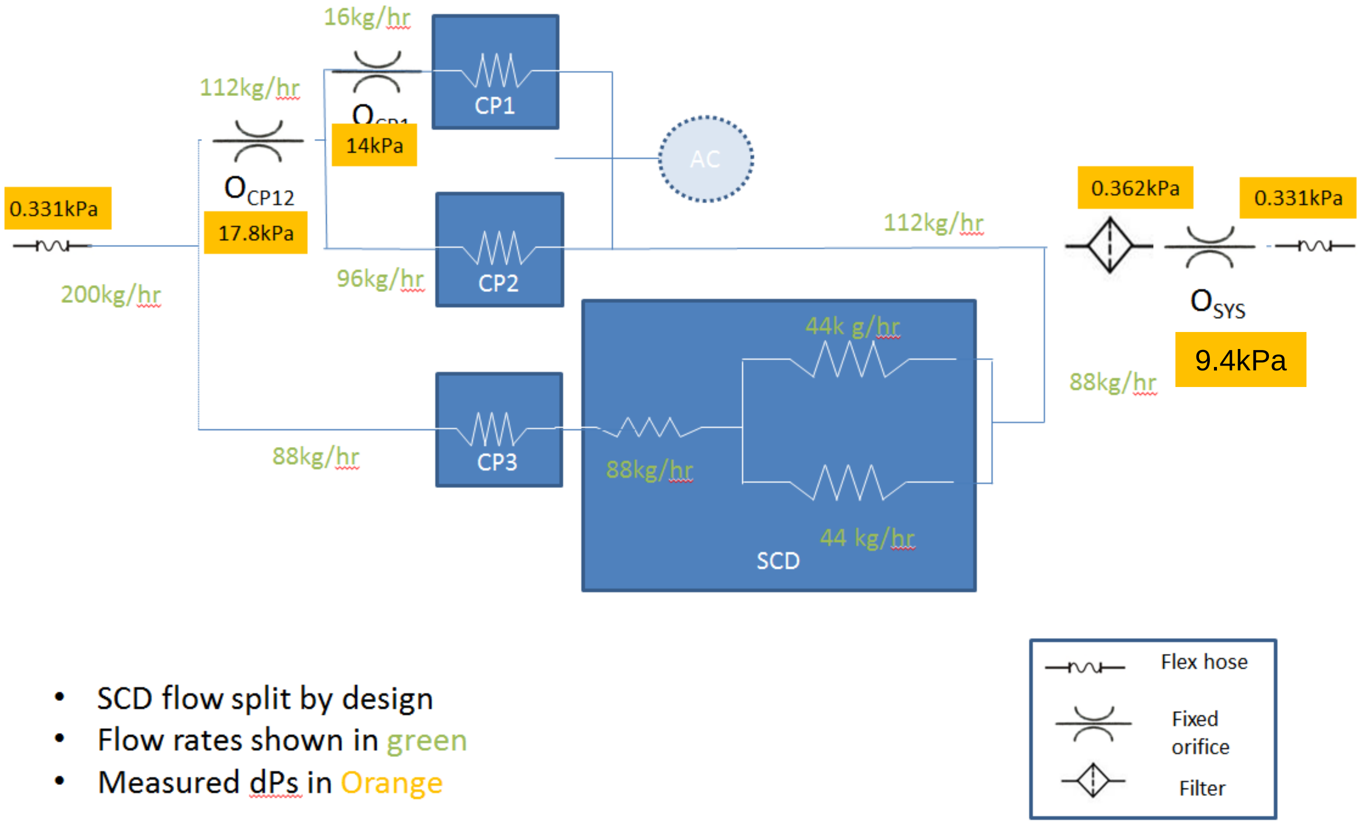
Surveyed 100s of Beta and Torque Equilibrium Attitude (TEA) combinations to determine worst cases

Active Thermal Design

- ATCS provides cooling for most CREAM components and mitigation of some extreme hot and cold environments
- ATCS contains 3 coldplates in parallel. Coldplate 3 outlet flows into SCD assembly (20 bores in SCD plates). Orifices are used to distribute flow as required thermally.
- SCD was most critical component during ATCS design, complete redesign with optimum plumbing layout allowed flow distribution to be changed to maximize flow in CP1



ATCS Schematic



- SCD flow split by design
- Flow rates shown in green
- Measured dPs in Orange

- ATCS Requirements include overall pressure drop (52-58 kPa), volume and some thermal isolation (fluid not to be used as a heater)
- Thermal requirement to keep all cooled elements in operational range
- Flow split adjustment through orifices is required to get adequate cooling on all three paths
- Packaging

CREAM ATCS Modelling

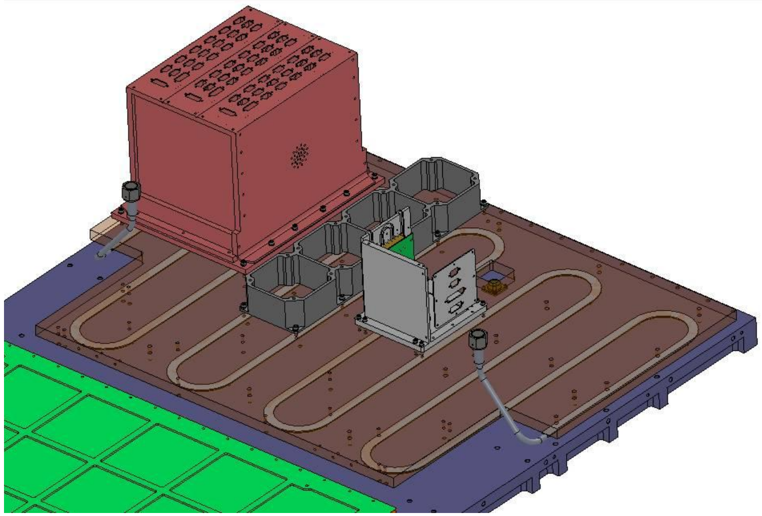
- FLUINT representation of entire CREAM fluid system / ATCS

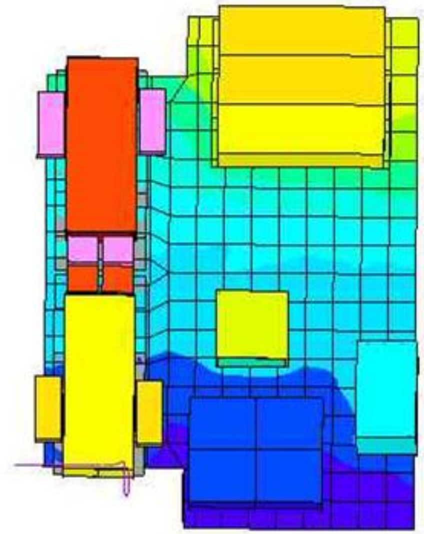
- Coldplate 1 model with 6 reduced electronics box models
- Coldplate 2 models with 3 reduced electronics box models
- Coldplate 3 model with 2 reduced electronics box models
- Reduced SCD model

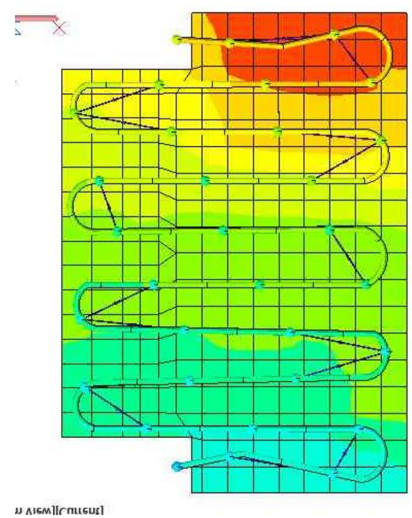
- FloCAD used to create a FLUINT model on full CREAM CAD model including pipe runs
  - Pipe runs designed with mechanical designer in CAD, pressure drop, volume constraints considered along with packaging and mounting options
- All plumbing runs include filter, flex hose, Gamah fittings, bends modeled using loss coefficient (FK) method
- Flow split
  - design optimized with MFRSET,
  - replace with orifice FKs based on sensitivity analysis,
  - replaced with as-built tested FKs

Coldplate 1

Traditional cold plate
Several mounted electronics boxes
High power ~190W



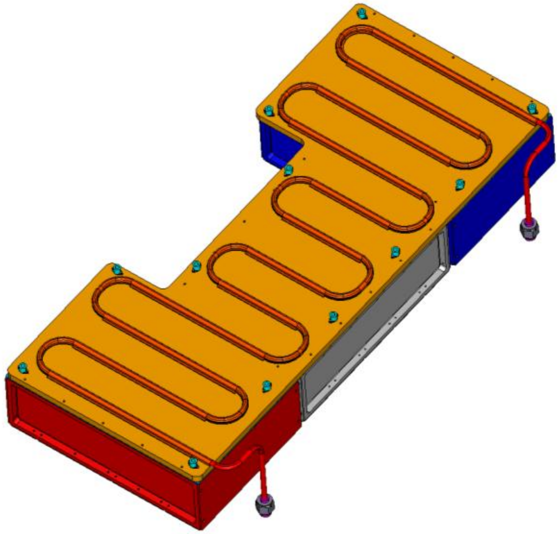


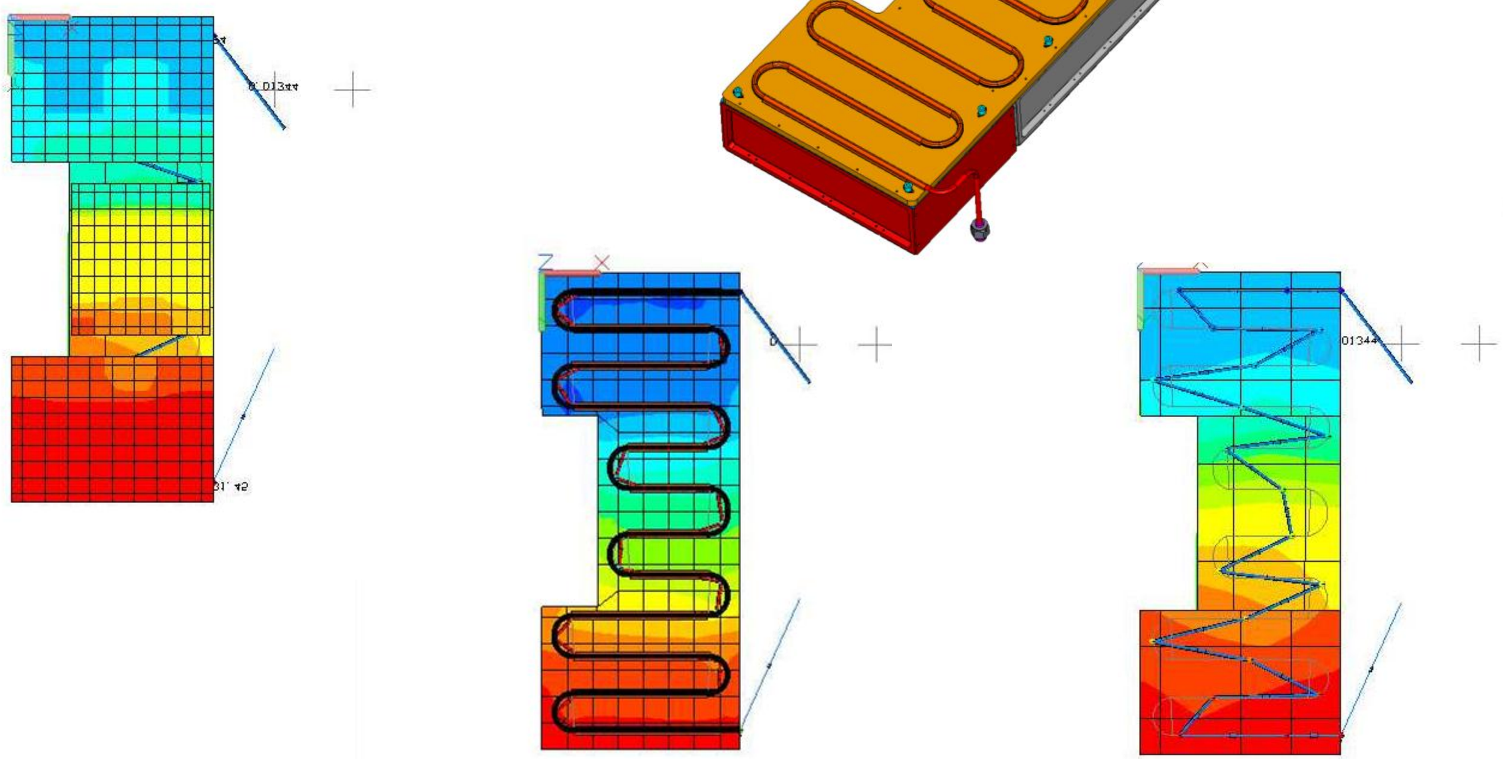


Meshed plate
FloCAD pipe along fluid pipe
- Tubes
- Tanks
- Ties

Coldplate 2

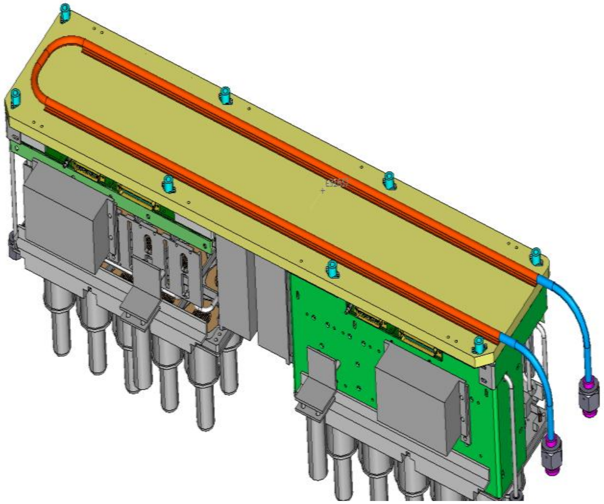
Traditional cold plate
3 electronic racks
Low power ~20W
Similar FloCAD model to CP1

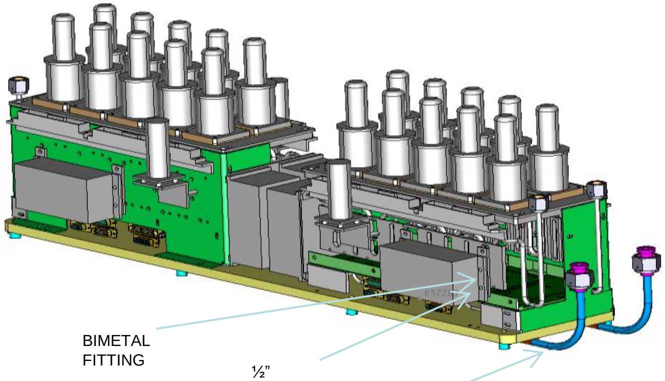


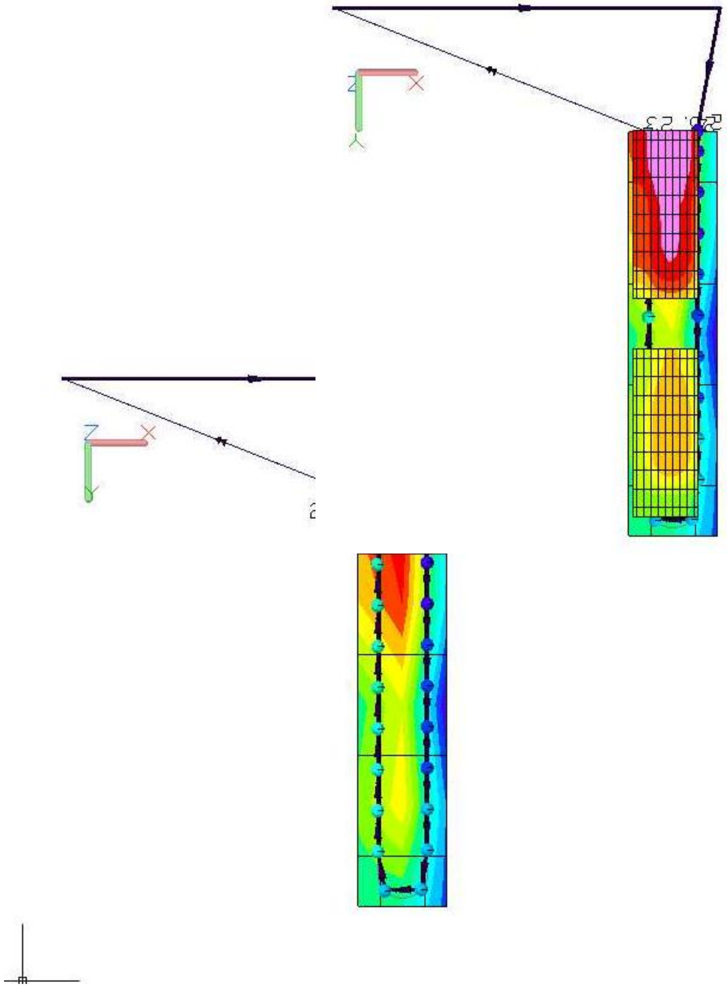


Coldplate 3

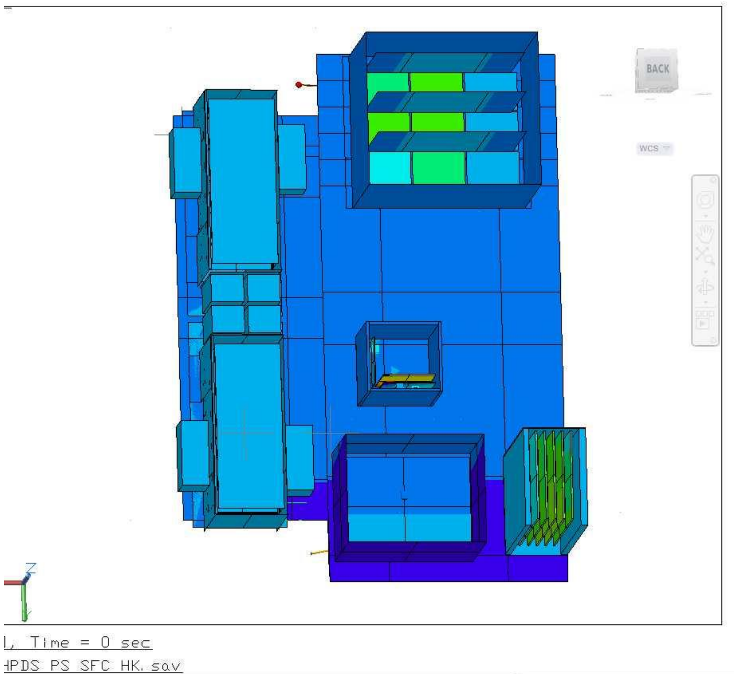
- Traditional cold plate
- 3 electronic racks
- Moderate power ~30W
- Similar FloCAD model to CP1



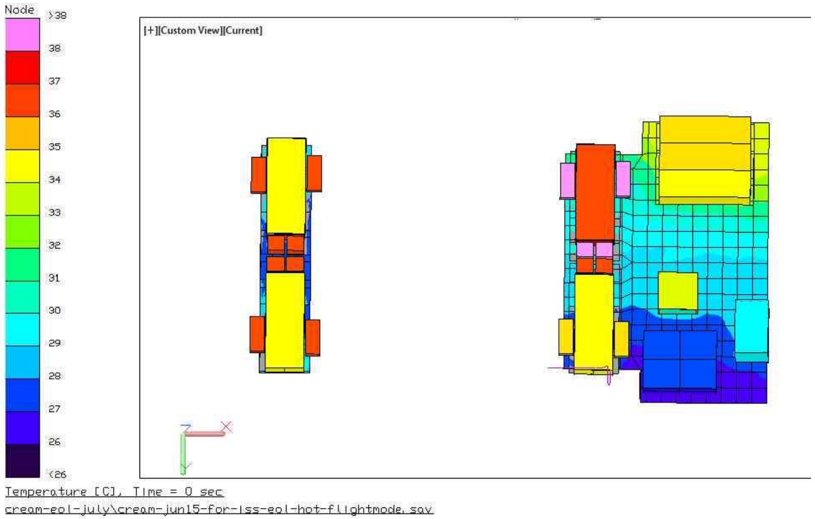




CP models with integrated box models



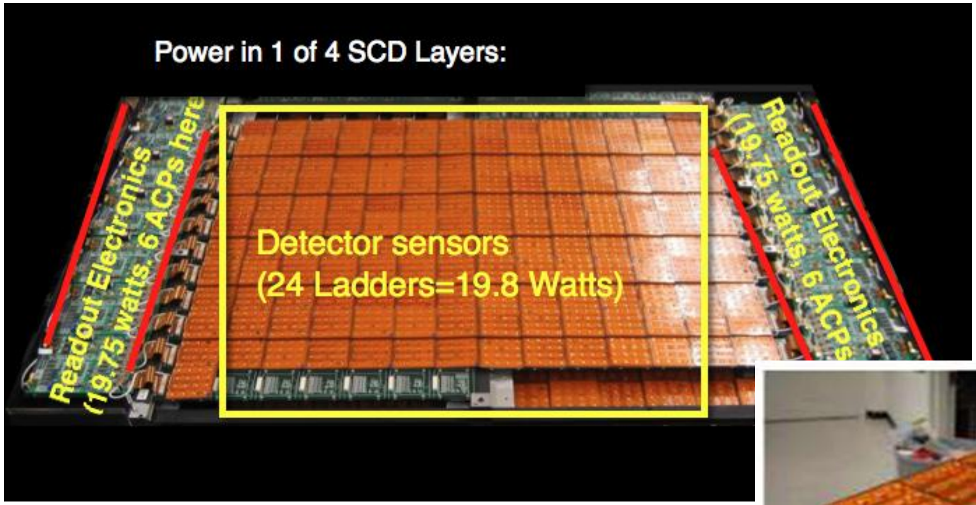
Coldplate 1 with Covers Removed



Coldplate 1 and 3

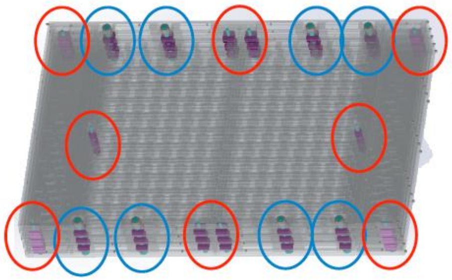
SCD Assembly

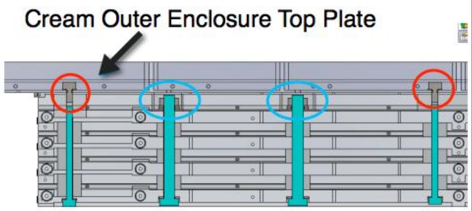
- Four major plate assemblies and cover
- Extensively 3-D machined aluminum plates
- 672 silicon sensors, low power, complex attachment, <40C for noise
- 48 electronics cards
- Instrument bolts tie plates together
- Fluid system has 20 bores, 5 on each major plate assembly

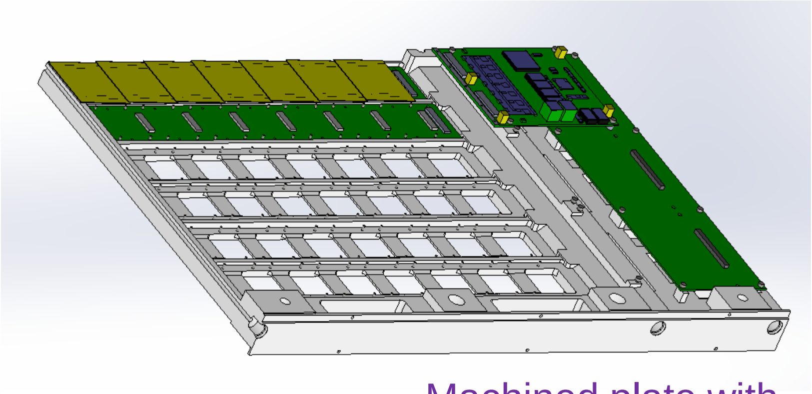


Ladder with 7 detectors

Attachment to CREAM top plate





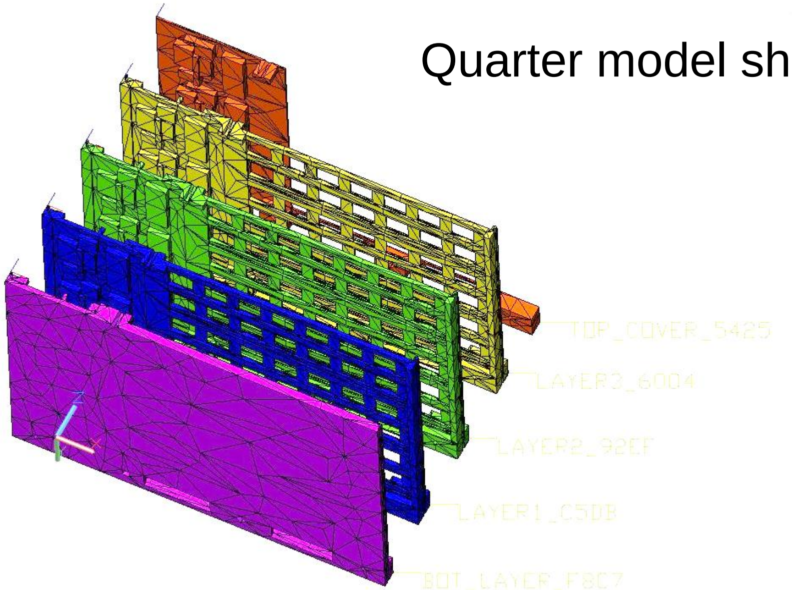


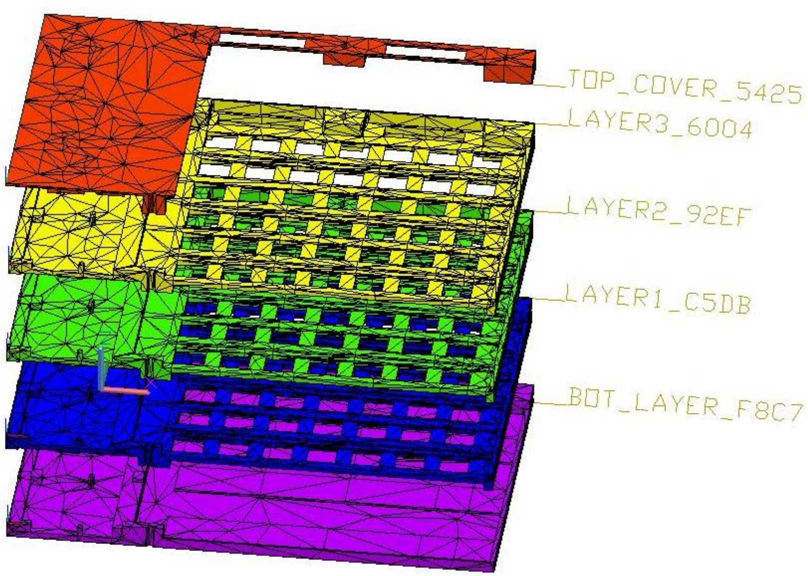
Machined plate with ladders and cards

SCD Plate and Cover Thermal Models

- Unusual thermal design, hard predict heat flows
  - Light-weighting in prior design
- Finite Elements based on CAD solid
  - CAD model greatly simplified in Inventor
  - TDmesher used for meshing
  - eliminate details (reduce material= conservative) until mesh works
- 3000+ nodes per plate and cover

Quarter model shown





<u>Resulting Model Includes:</u>

Complex conduction in plate due to ladder details

Complex conduction in ACP area due to the pads to pick up heat from lower layers

Bolt contact areas

Cover details

Bore locations

SCD Sensor / Ladders Thermal Model

chips
supports
analog board

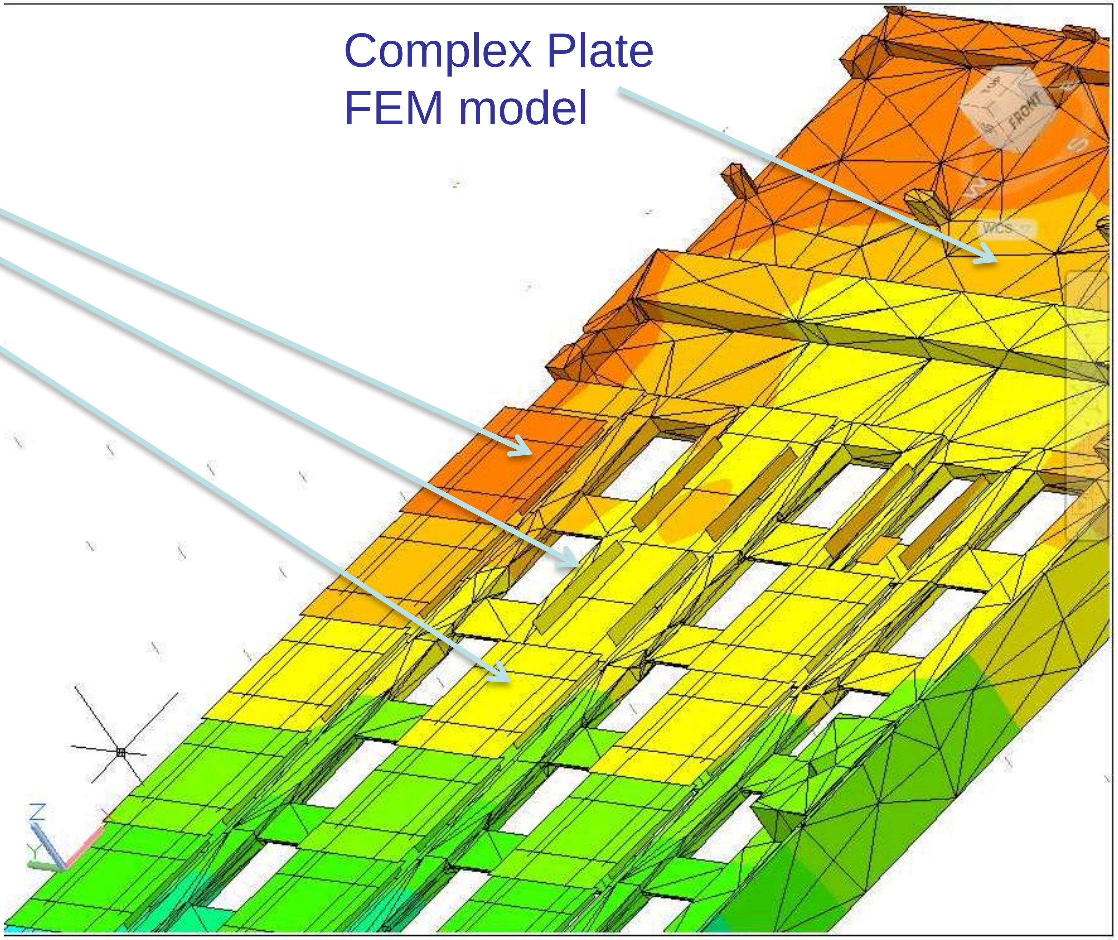
Created modular model

Duplicated as needed with submodel or numbering changes

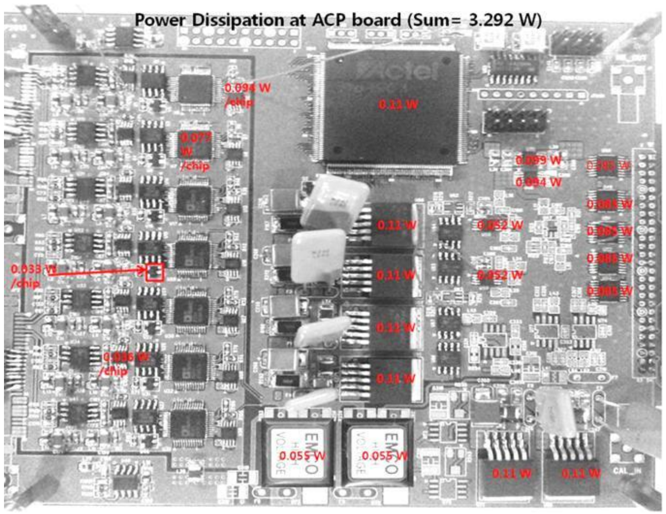
Use AutoCAD External References (Xref) to bring in various layers

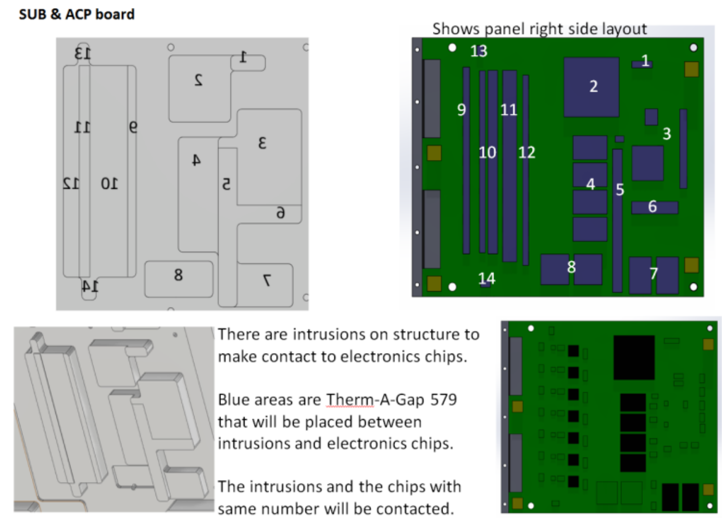
Xref-ed files are equivalent to INSERT files, but contain full TD models that can be setup to run independently

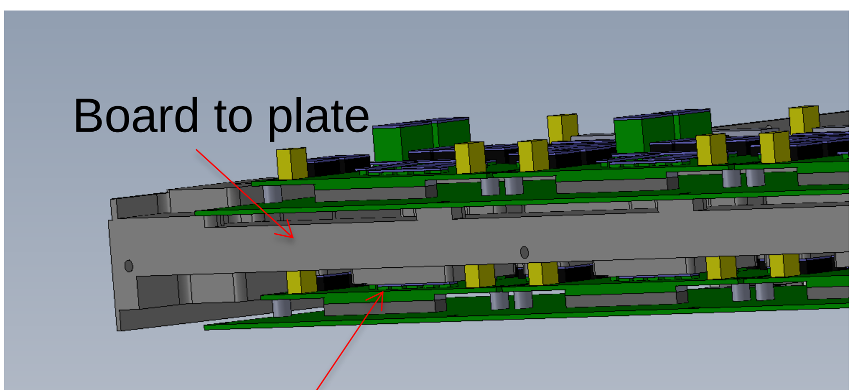
Complex Plate FEM model

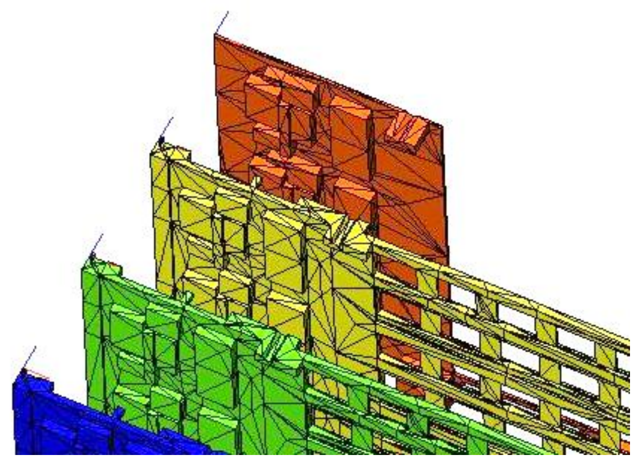


SCD Electronics





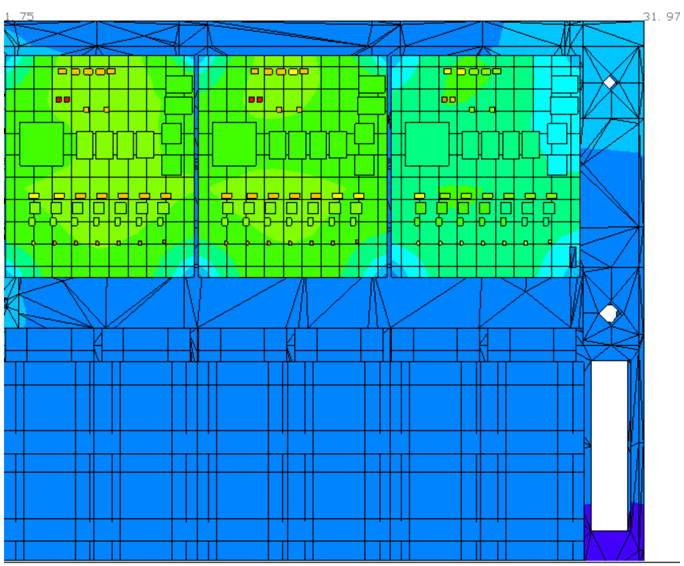




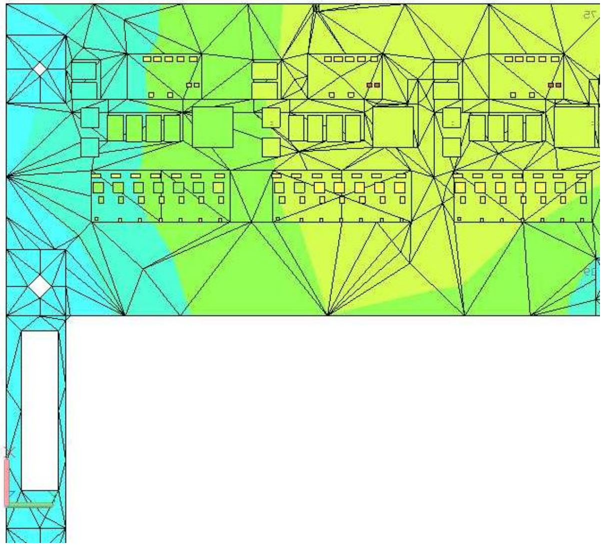
Components to Plate highs

SCD ACP Thermal Model

- Each chip is represented by a TD rectangle with applied heat load (size from photo or CAD)
- Chip is tied to card either dry or with solder
- Chip is tied to highs on cover (or plate above) with Therm-a-gap (chip area) – 50% of published interface conductance = 1.4W/in2-C
- Cards tied to plate with 4 screws into solid at corners



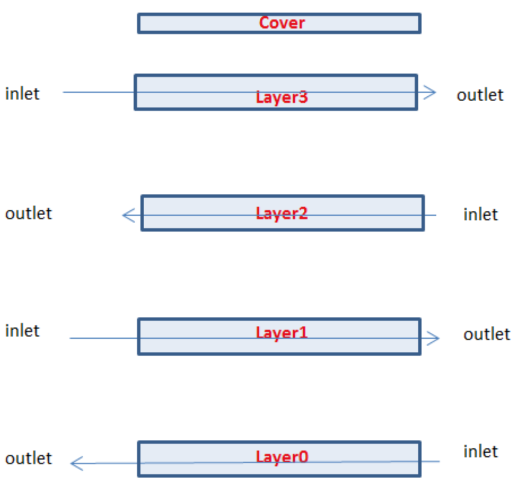
Top View
ACP chips on L3 cards and plate



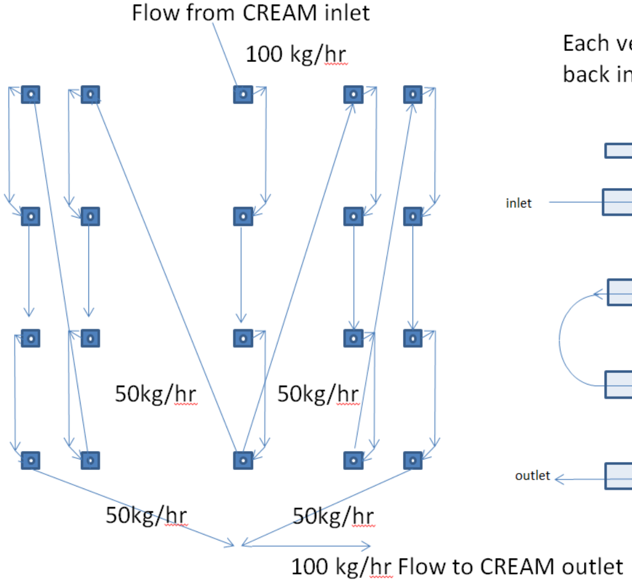
Bottom View
ACP chips on cover highs (card removed for visibility)

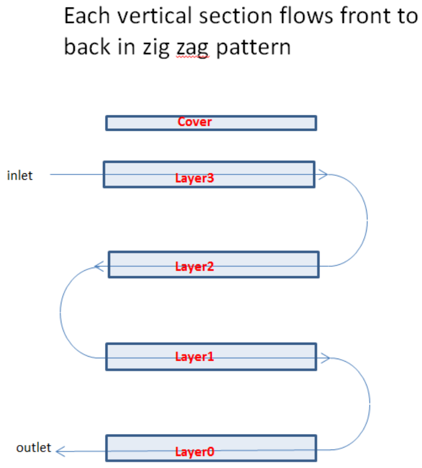
Fluid Cooling of SCD

Original design had 20 parallel paths in 5 stacks like this



Final design uses 2 parallel paths





<u>Laminar Flow</u>

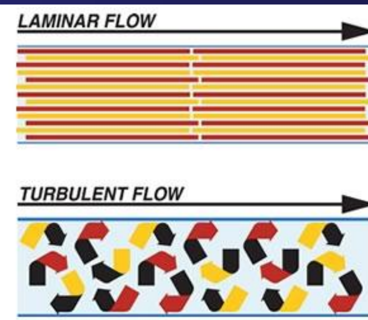
- Reynolds number < 500
- H = 54 W/m2-K
- Manifolds on both sides
- Flow balancing of 20 legs near impossible, backflow
- Very low pressure drop (use orifices to meet dP spec)

<u>Turbulent Flow</u>

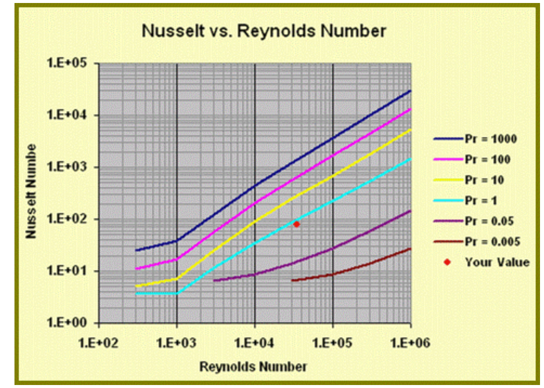
- Center Channel Re≈12,000
- H > 1000 W/m2-K
- Side Channel Re ≈ 6,000
- H> 600 W/m2-K
- Flow balance 2 legs (not critical)
- Pressure drop within range of requirement (35kPa vs.. 50kPa for system)

Temperature of hottest sensors dropped 10C and met specification

Fluorinert Cooling and flow regime



- Laminar flow (CDR design) for 0.18” ID pipe
  - Fluorinert low conductivity (k) yields low laminar convection coefficient
  - H=3.66 k/D (Nu=3.66)
  - H(Fluorinert) = 54 W/m2-K (k=0.057 W/m-K)
  - H(Water) = 550 W/m2-K (k=0.58 W/m-K)
  - H(liquid ammonia) = 450 W/m2-K (k=0.48 W/m-K)
- Turbulent flow (dCDR design)
  - Re = 6000 (side channels), 12000 (center channel)
  - Pr=12.35 (water=7, liquid ammonia=1.24)
  - Cooling n=0.3
  - Nu (Re=6000) = 51.5
  - H(Fluorinert) = 690 W/m2-K
  - H(Water) = 5900 W/m2-K
  - H(liquid ammonia) =2900 W/m2-K



Dittus-Boelter equation [edit]

The Dittus-Boelter equation (for turbulent flow) is an explicit function for calculating
commercial applications) is cautioned. The Dittus-Boelter equation is:

$$\mathrm{Nu}_D = 0.023\,\mathrm{Re}_D^{4/5}\,\mathrm{Pr}^n$$

where:

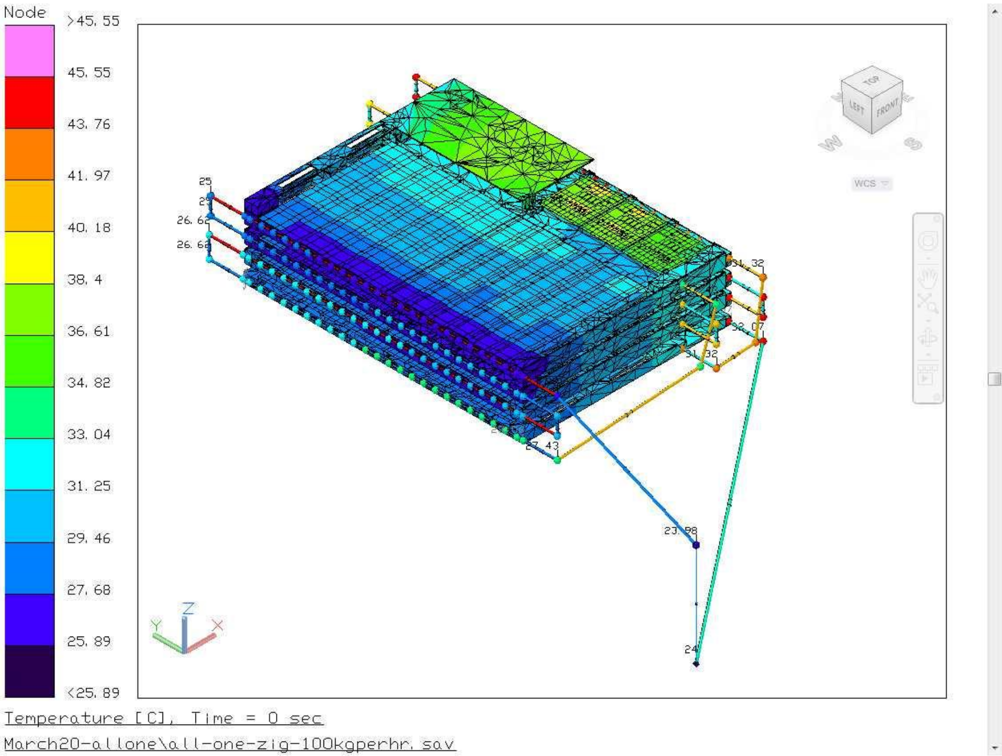
D is the inside diameter of the circular duct
Pr is the Prandtl number
$n = 0.4$ for heating of the fluid, and $n = 0.3$ for cooling of the fluid.[1]

The Dittus-Boelter equation is valid for [3]

$$0.6 \le \mathrm{Pr} \le 160$$
$$\mathrm{Re}_D \gtrsim 10\,000$$
$$\frac{L}{D} \gtrsim 10$$

SCD Detailed Thermal Model Buildup

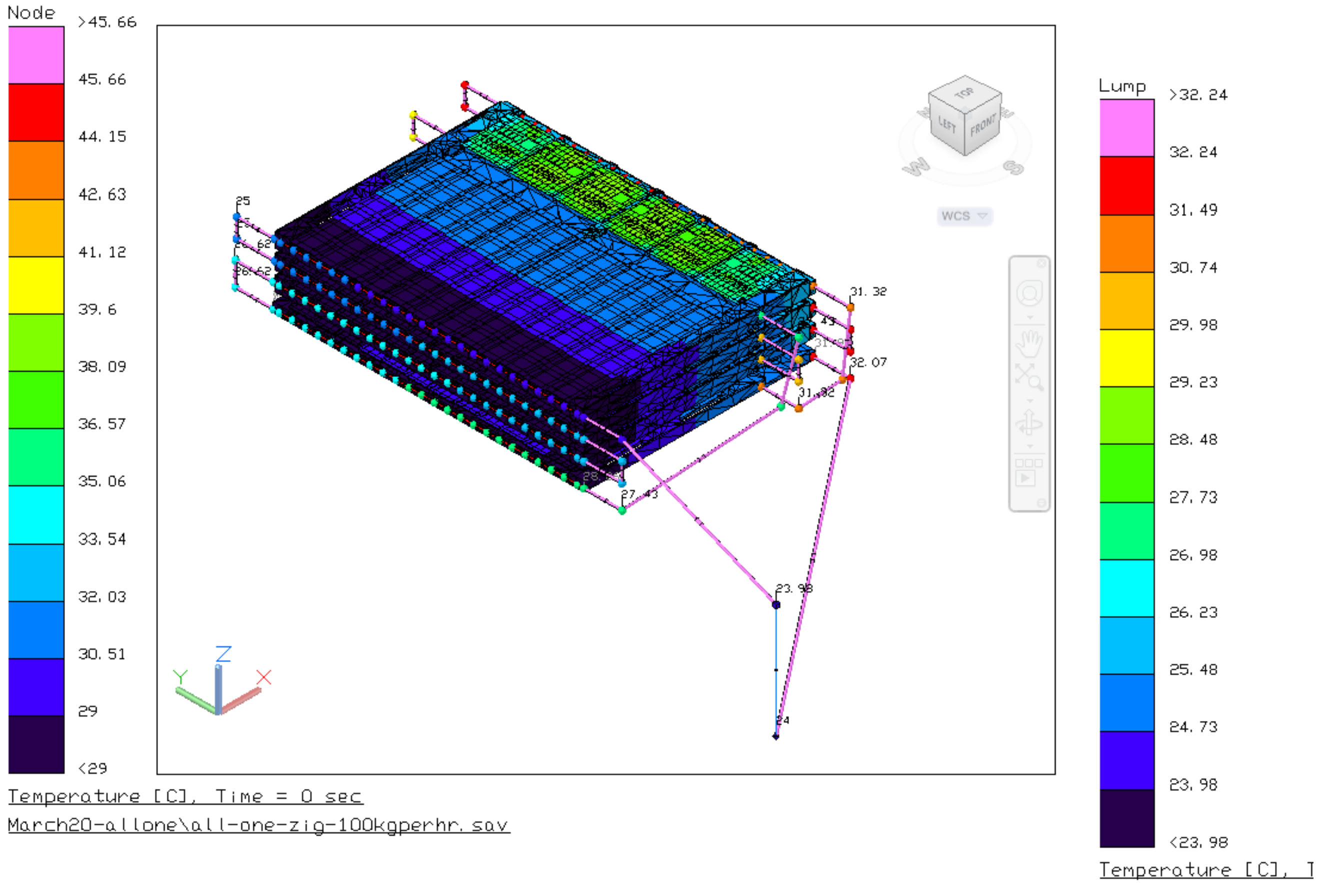
- Build up each layer quarter model with plate solid, ACP model, sensor ladder model. Add interface features for bolts, cards, fluid bore internal area (Tagsets).
- Top cover is included in Layer3 model
- Make clone of each layer quarter model
- Xref used to bring in these 8 models.
- FloCAD used to create fluid loop to plenum



SCD Fluid Modeling

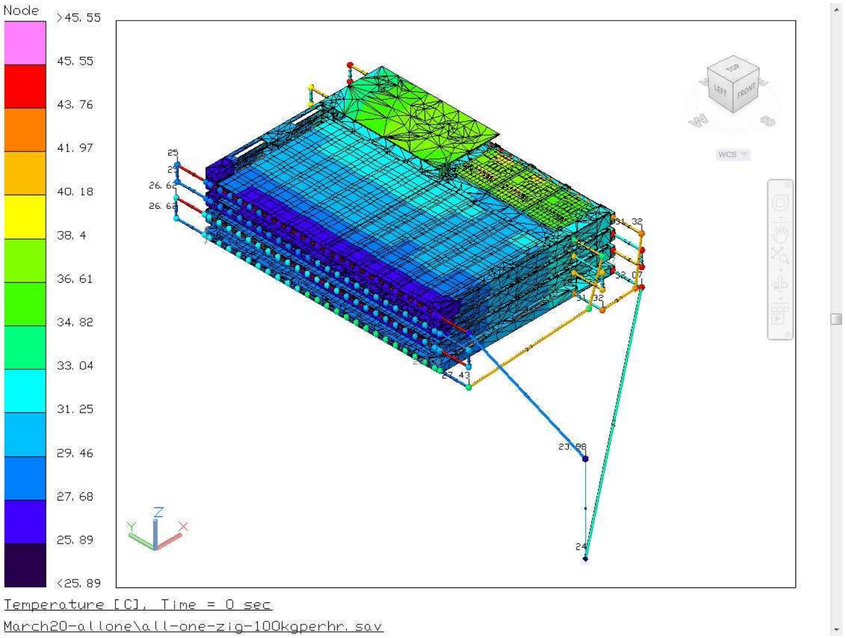
- FloCAD used to depict fluid network in Thermal Desktop model
- FLUINT Used for all flow calculations
- Use pipe representation inside each bore
- Model pipe bends with appropriate FKs
- Use MFRSET to determine flow imbalance pressure drop, design two legs to get good distribution

- Since this is a half model, use duplication factors



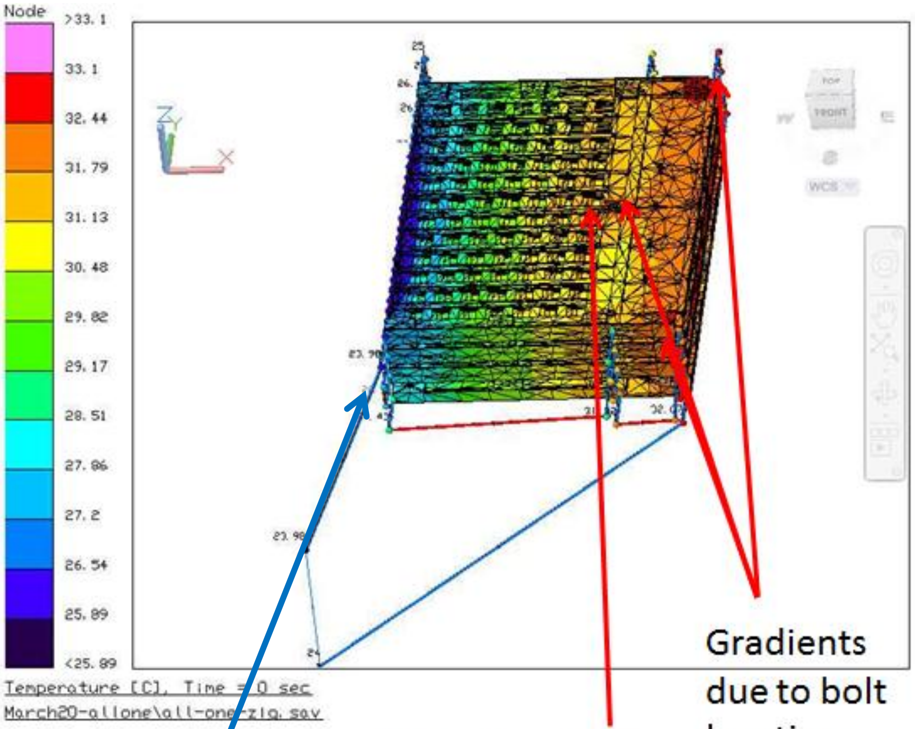
SCD Thermal Characteristics (1/2)

- Majority (67%) of power in ACP sections
  - Majority of power transferred through Therm-a-gap to highs of plate above or cover
  - Heat transfer to card, on card and to circuit board screws is tortuous
  - Majority of heat in this section transferred to fluid in two bores in each side
- Sensor power (33%) distributed on large section of plate through ladder and plate details, fairly low heat flux
  - Plate conduction and analog boards limit hot spots
  - Fluid transfers heat along fluid path
  - Majority of heat in this section transferred to center bore fluid
  - High flow rate, cold fluid (inlet supply) preferentially cools the sensor section



SCD Thermal Characteristics (2/2)

- Fluid flow provides heat transfer along width of plate
- Fluid direction and higher flow in center provides additional cooling and isothermalization of the plate in vertical dimension
- Bolts provide good vertical heat transfer
  - Some limitations on ACP section due to only one bolt in center
  - Sensor region only has bolts on two edges, OK for fluid cooled design
- Cover has gradients due to bolt locations and heat from ACPs on Layer3

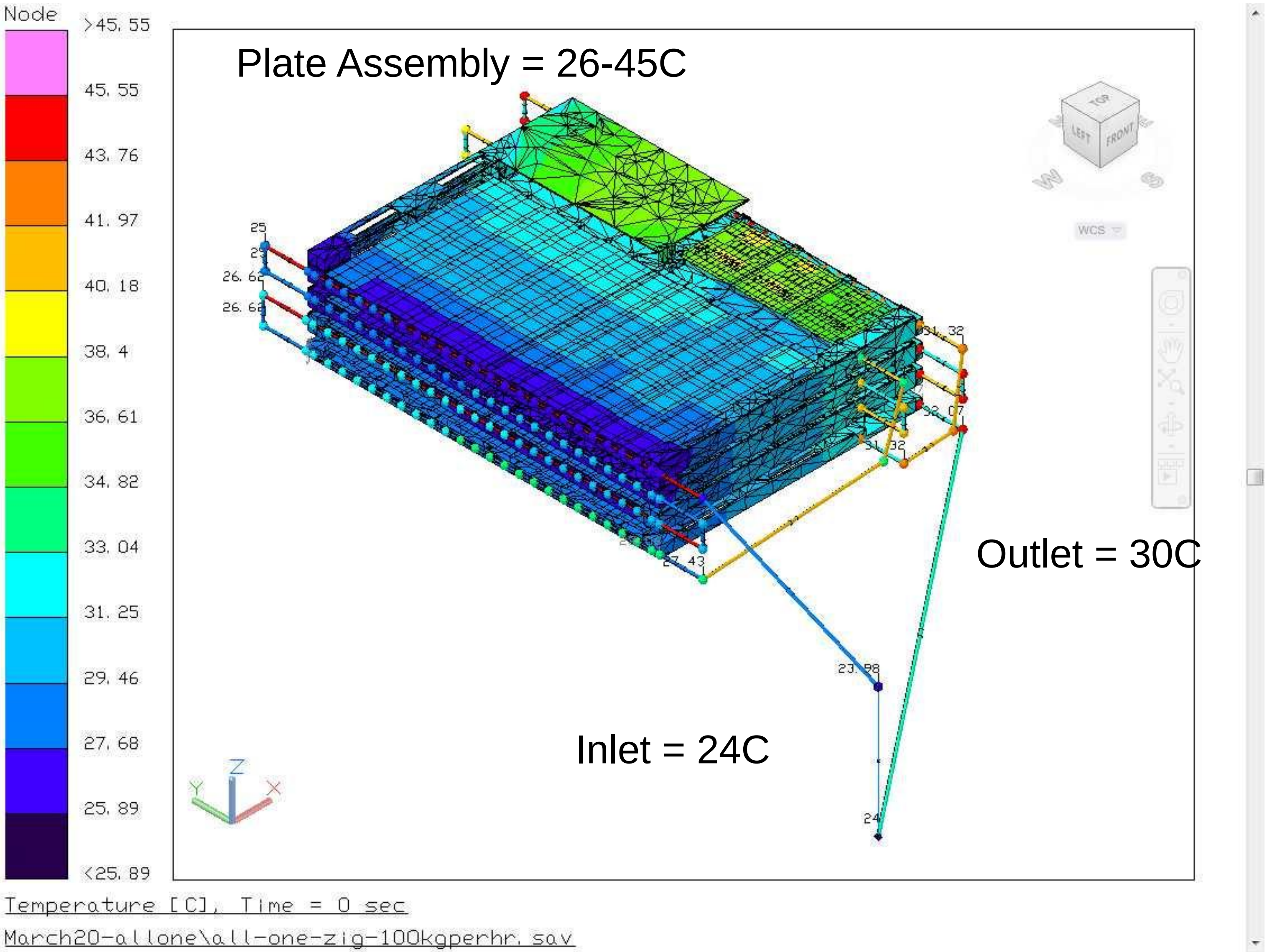


Gradients due to bolt locations and cover effects

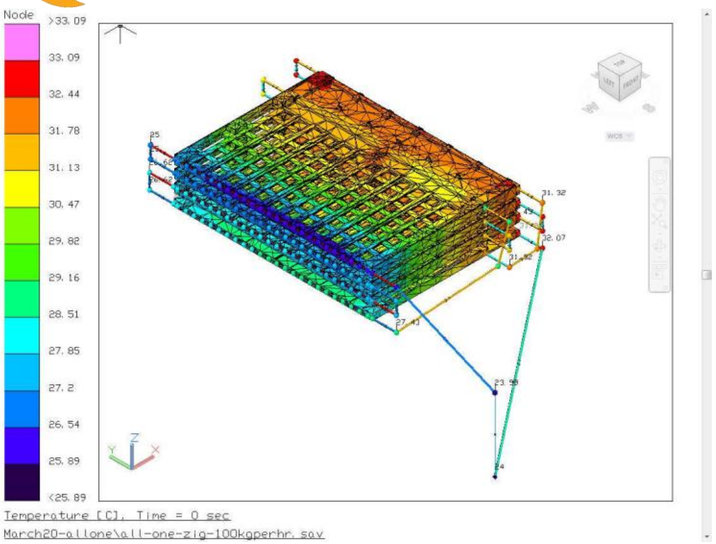
Hottest sensors

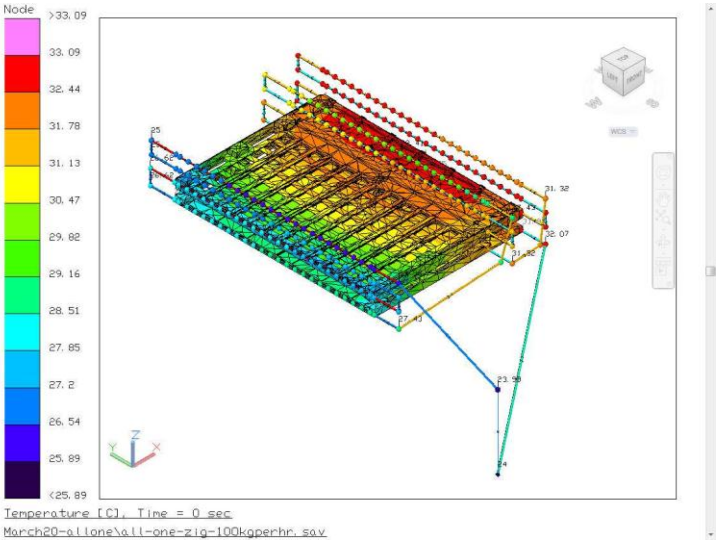
Coldest fluid, highest flow rate in center to cool sensor area

SCD Temperatures

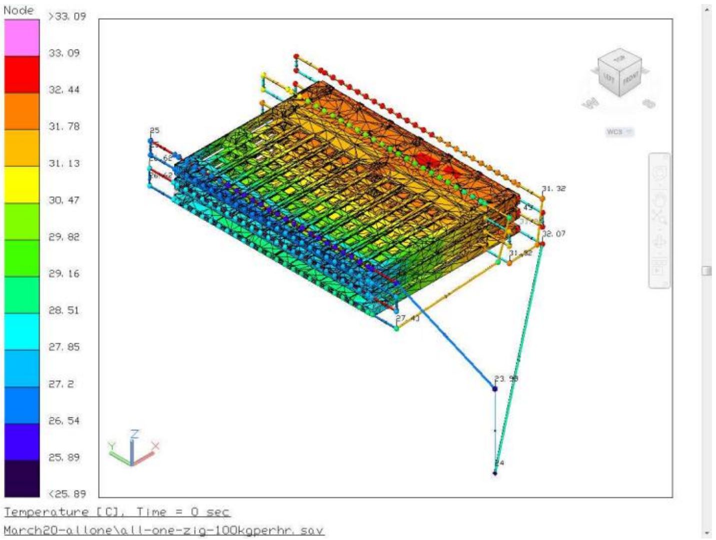


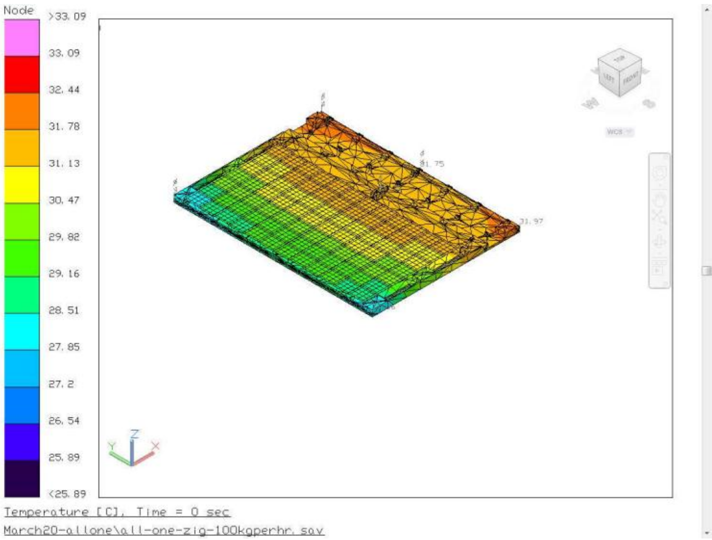
SCD Plate Temperatures



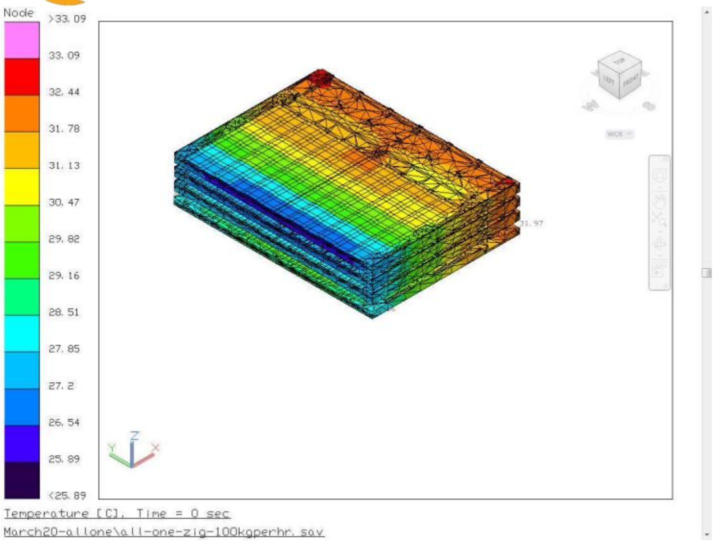


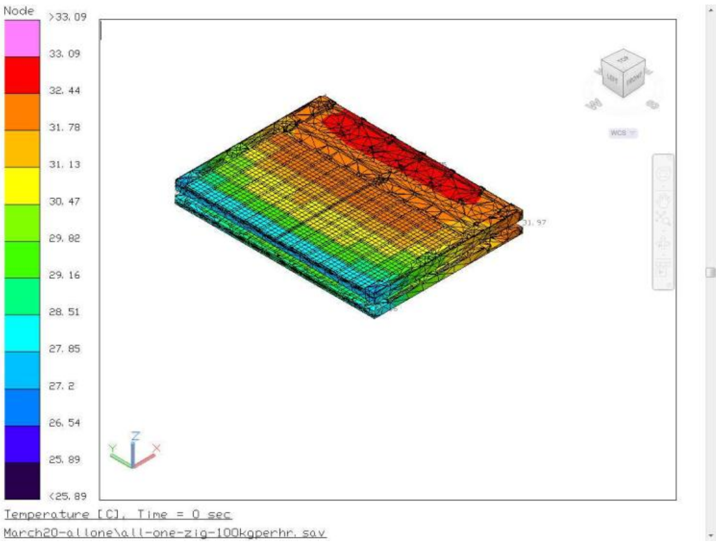
Very isothermal due to fluid flow design



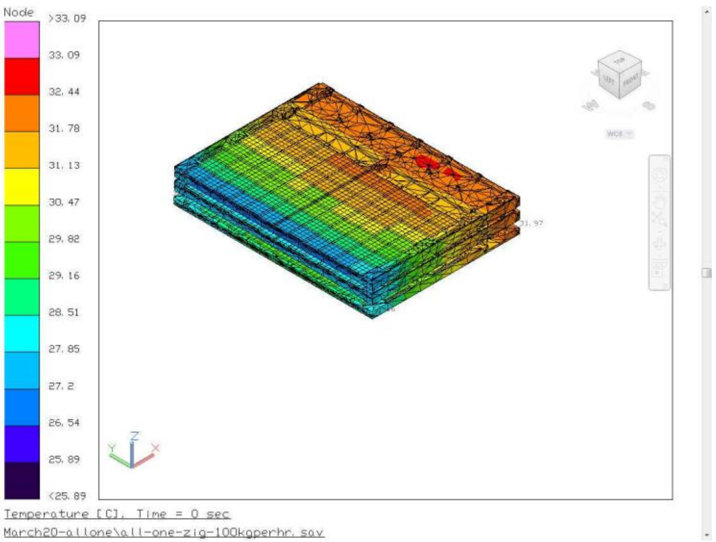


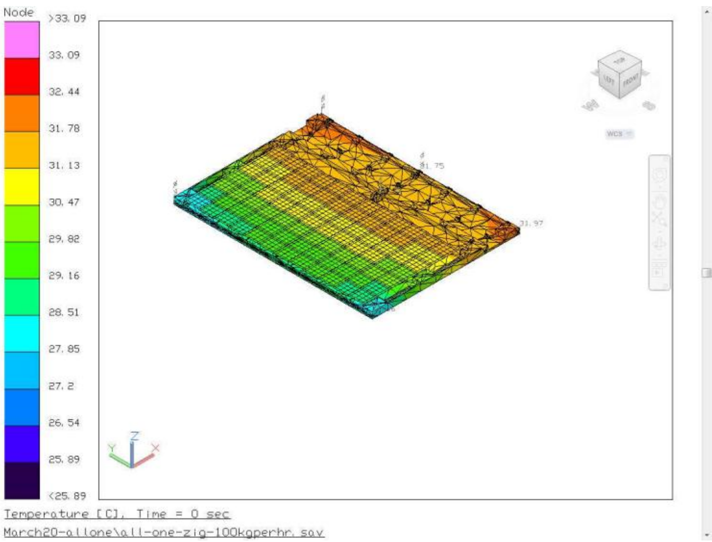
SCD Plate and Sensor Temperatures



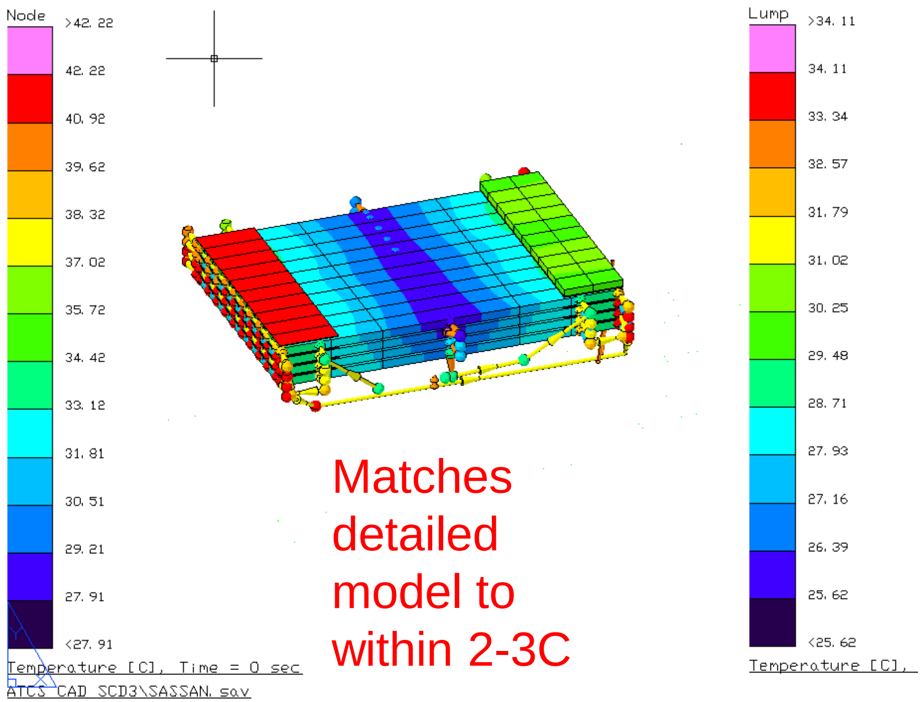


Very isothermal due to fluid flow design





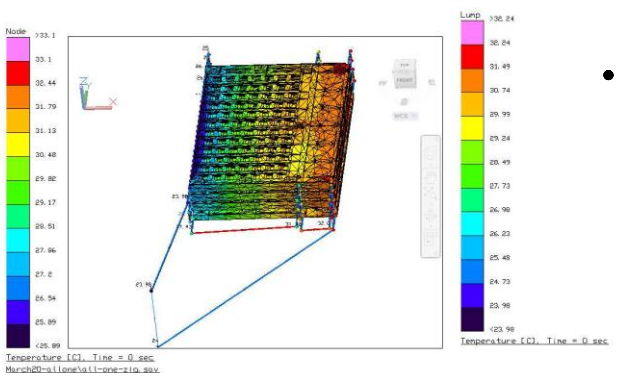
SCD Reduced Model



Matches detailed model to within 2-3C

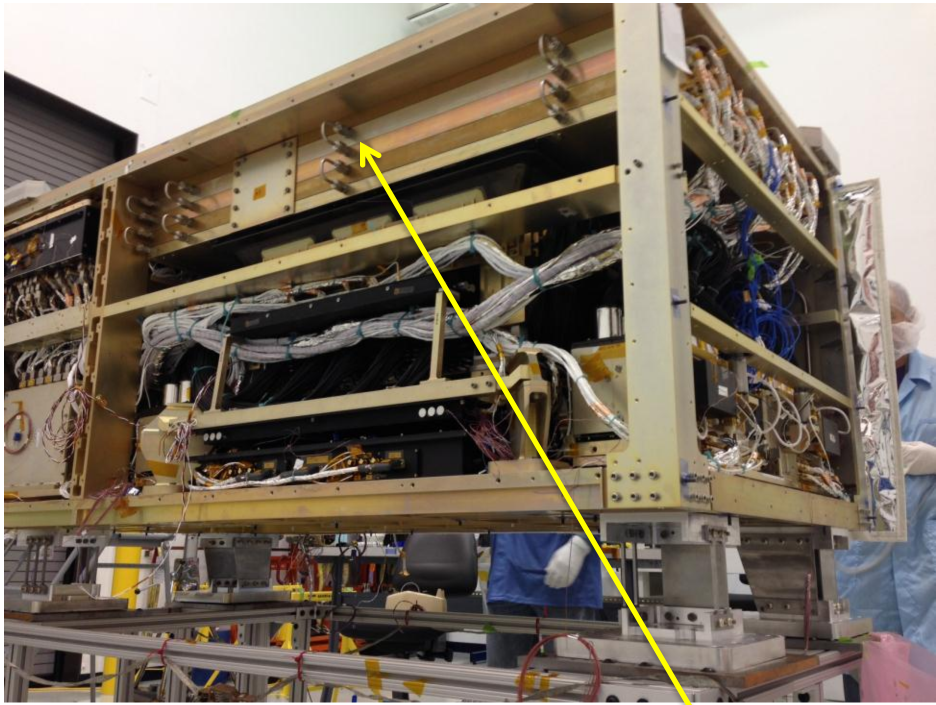
- Reduced Model
  - 408 TD/RC Nodes
  - 48 surfaces
  - 10 fdsolids
  - 240 FLUINT lumps
  - 20 pipes
  - 35 contactors
- Pipe lateral conductance ~ 10mm Aluminum pipe thickness
- Other conductances considered by contactors (tie each node to neighbor node on another pipe with equal conductance)
- Bolts conductances used to connect nodes
  - (total 60W/K layer to layer, 16 bolts)
- Plate conductances set to match detailed model

<u>Half SCD Detailed model</u>
30000 nodes total
14000 plate mesh nodes
550 cover mesh nodes
4000 ACP nodes
12000 sensor nodes
4000 other
340 FLUINT lumps



SCD Pictures

- Shows final configuration of plumbing to SCD
- Tight packaging, but it works

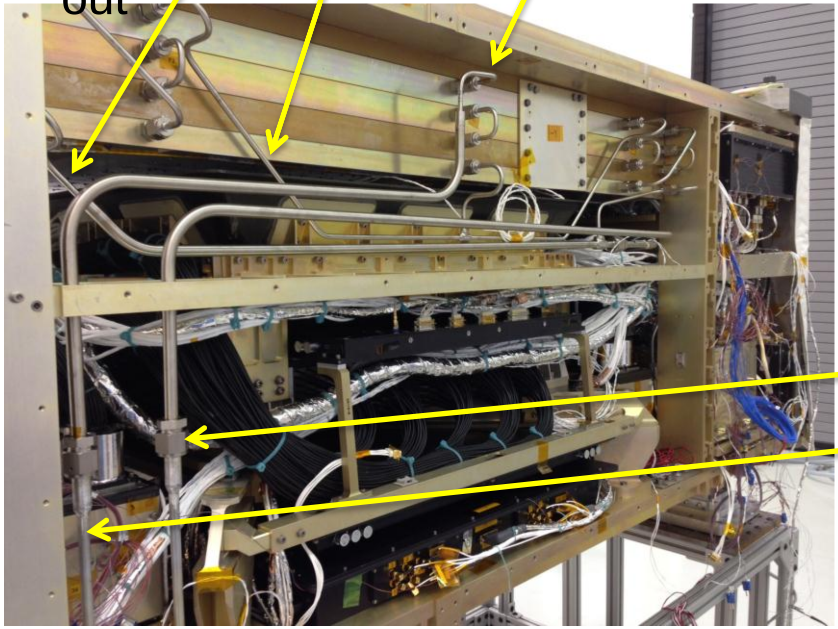


Layer 1 to 2 loop

Center Bores

Left side in

Left side out

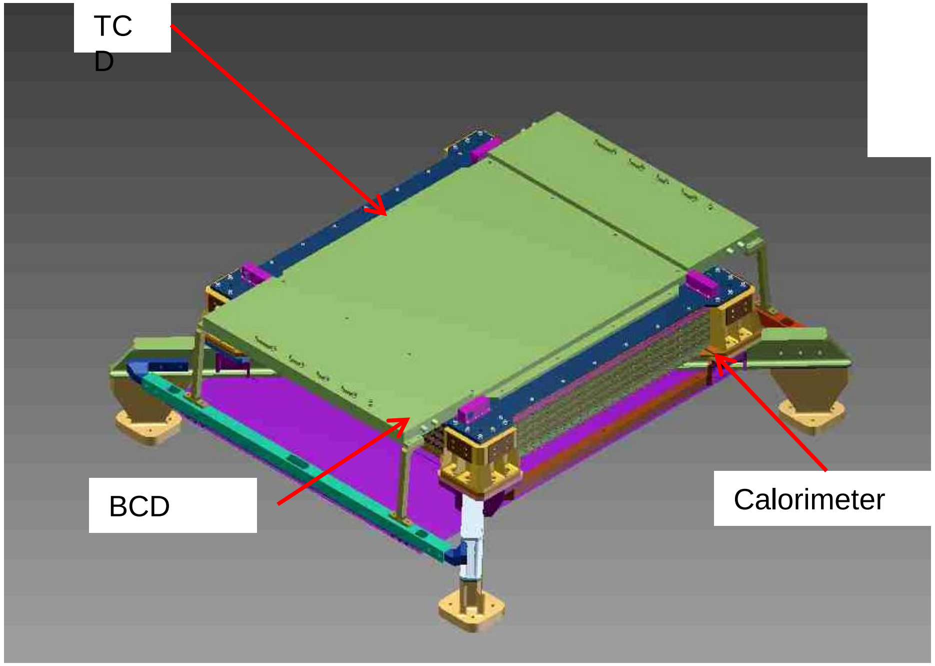


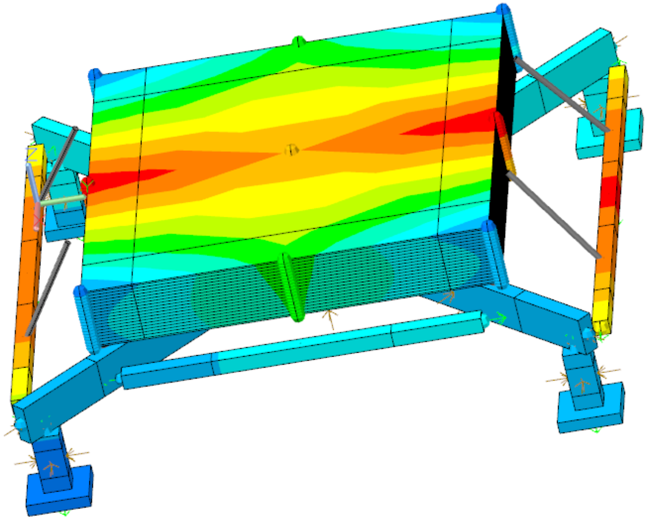
Line to CP3 (from inlet)

Lines from CP3 (supply)

Stand with TCD, BCD, Calorimeter

Calorimeter stand provides structural support and heat paths from 400 kg calorimeter (tungsten plates layered with epoxy) to CREAM baseplate
Also supports TCD and BCD, passively cooled instruments



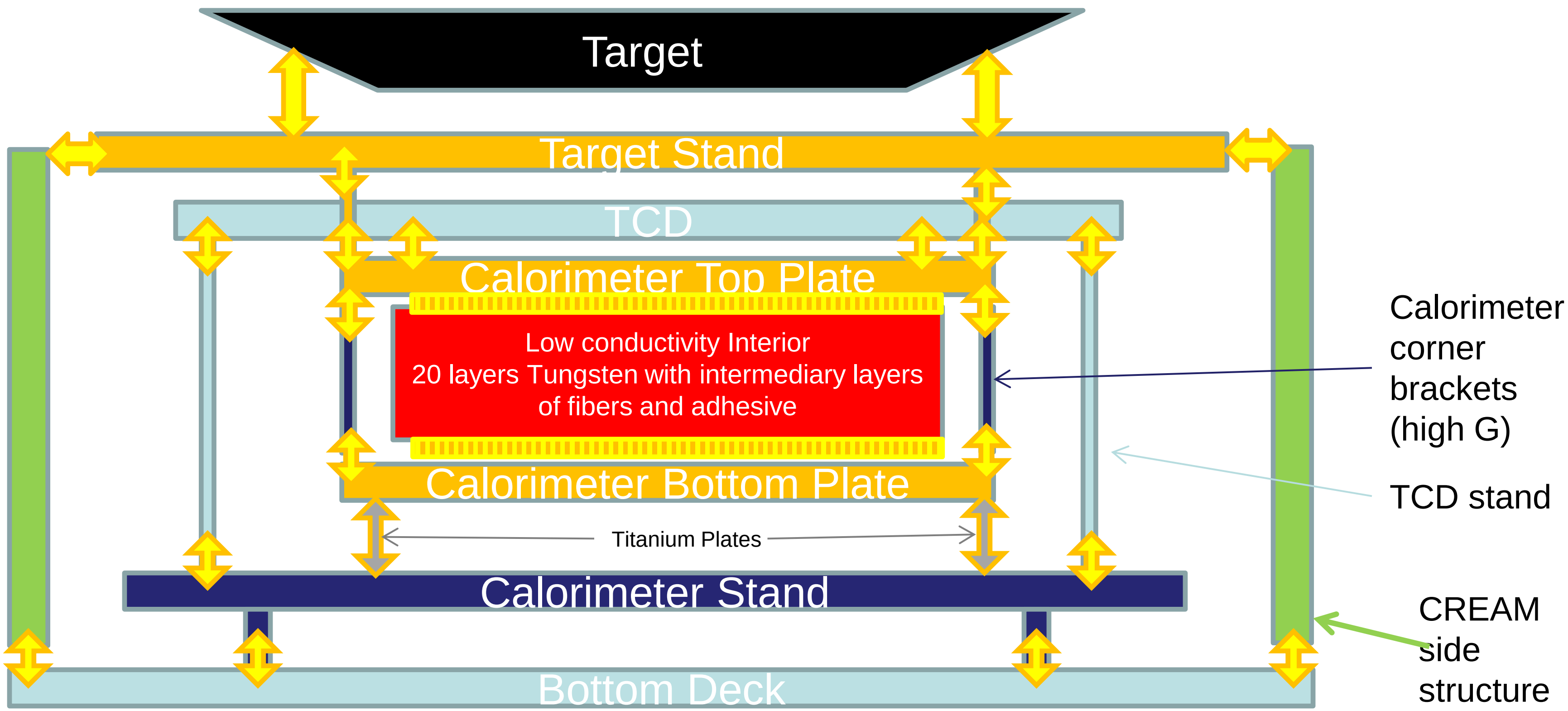


On-orbit, some temperature rise expected due to power in TCD and BCD

In ground testing, major factor in ability to cool instrument to hot and cold plateaus

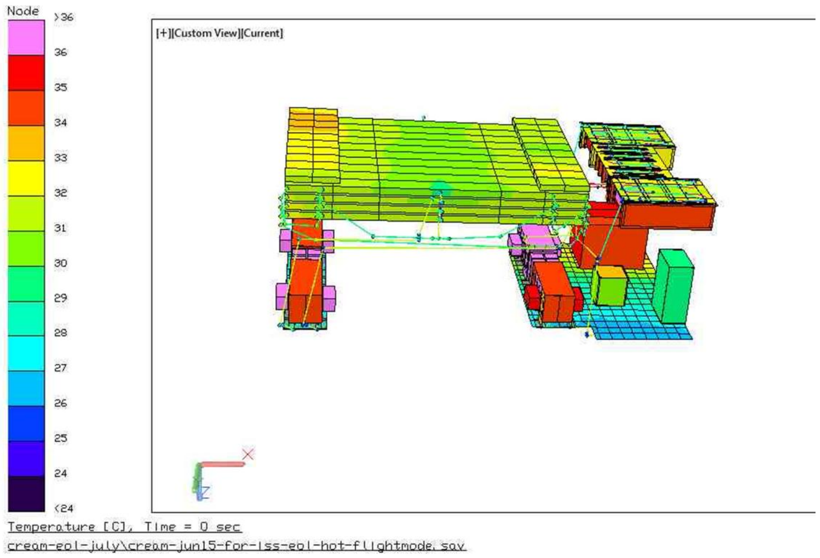
Calorimeter Heat Paths

Target = 175 kg of graphite
Calorimeter = 400 kg of Tungsten, fibers and adhesive

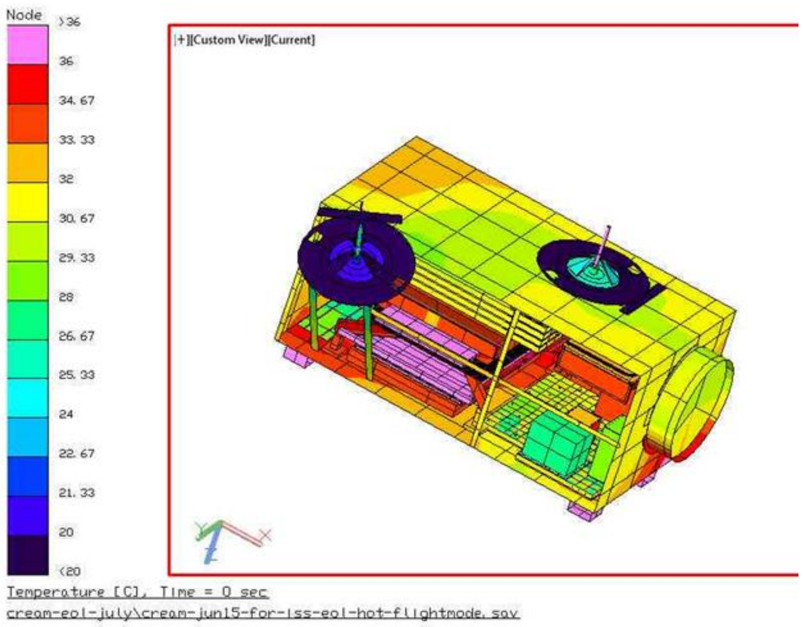


ISS-CREAM Integrated Model

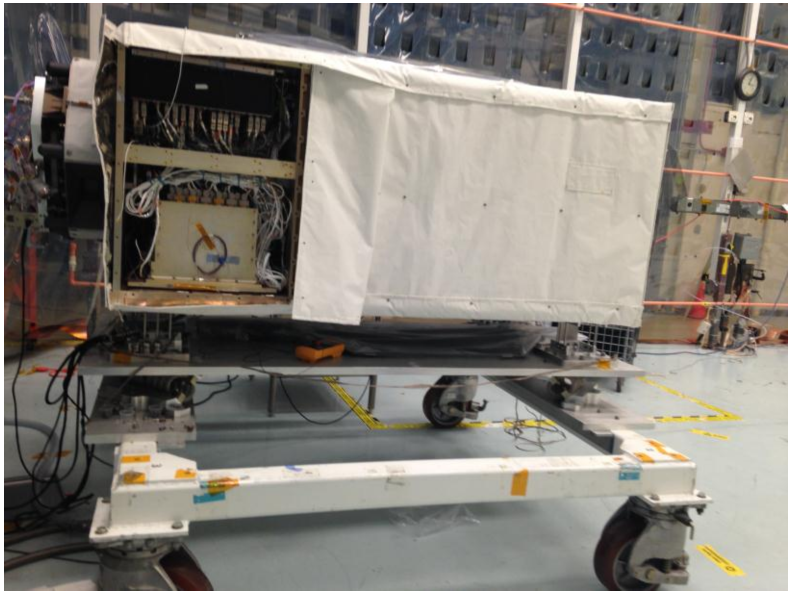
ATCS Components

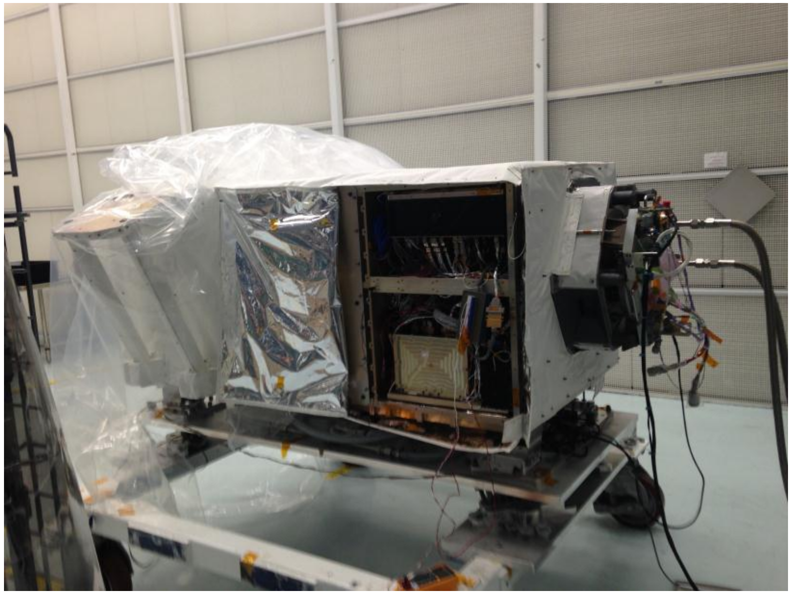


Full ISS-CREAM model



ISS-CREAM Pictures

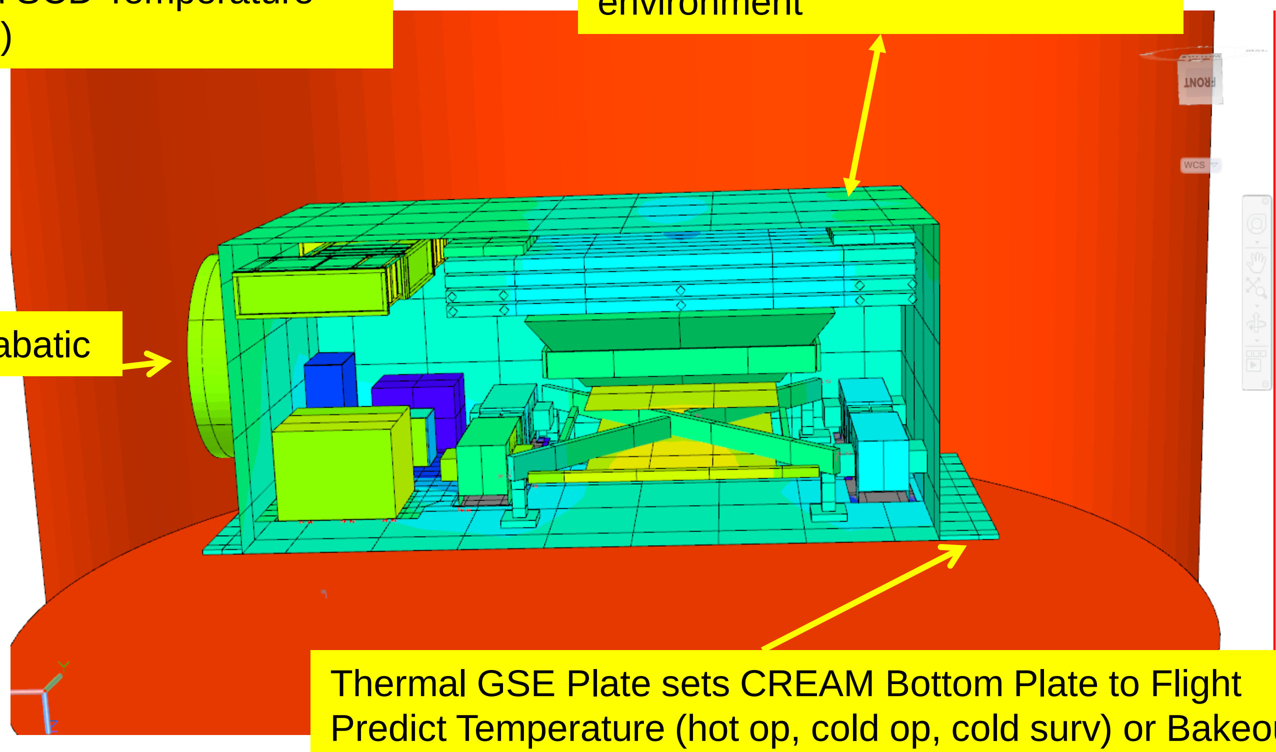




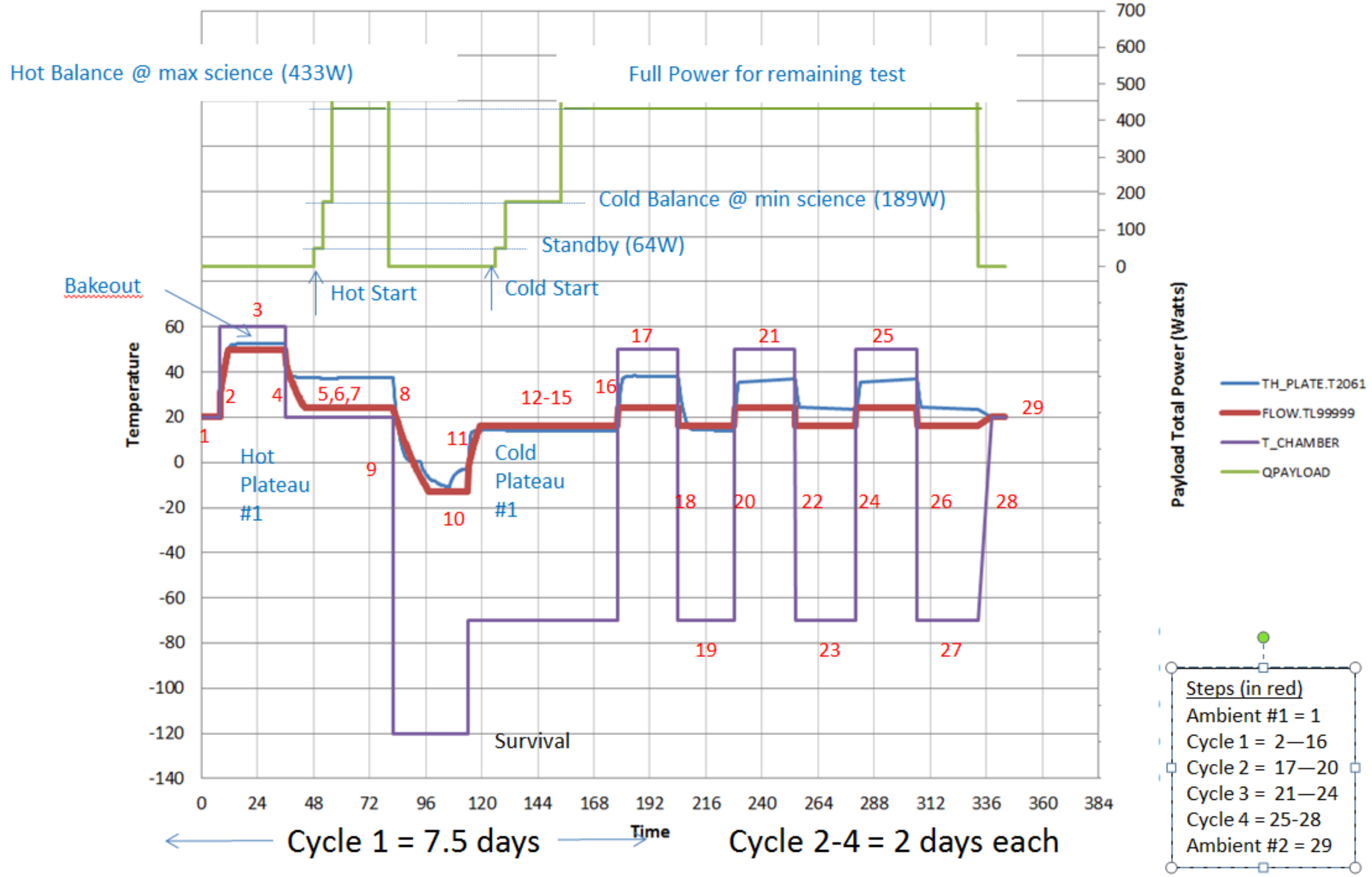
TESTING AND VERIFICATION

Tvac Test Concept

Fluid cooling and conductive cooling of bottom plate
Allows transitioning of 1300kg instrument within 1 day



Tvac Profile



Thanks to the ISS-CREAM Team

- Collaborating Institutions
  - University of Maryland, USA
  - Penn State University, USA
  - Northern Kentucky University, USA
  - NASA Goddard Space Flight Center, USA
  - National Autonomous University of Mexico, Mexico
  - KyungPook National University, Korea
  - Sung Kyun Kwan University, Korea
  - LPSC Grenoble and CESR Toulouse, France
  - NASA GSFC WFF (incl. CSC/Vantage, SGT, and NMSU PSL) - project management and engineering support
  - NASA JSC ISS Program Office - launch support and ISS accommodation.
  - NASA MSFC - flight operations

Author would especially like to thank:

- Project
  - Linda Thompson (Project Manager, Wallops)
  - Peter Patterson (Systems, SSRI)
  - Chris Rose (I&T, Wallops contractor)
- Thermal
  - Sassan Yerushalmi / SGT
  - Dharmendra Patel / SGT
- ATCS – Build, Review, Test
  - Caitlin Bacha / GSFC 549
  - Stephen McKim / GSFC 549
- GSFC
  - David Steinfeld / GSFC 545
  - Dan Butler / GSFC 545
  - Kirk Rhee / GSFC 381

Acronyms / Detectors

- Cosmic Ray Energetics And Mass for the International Space Station payload (ISS-CREAM)
- ISS JEM EF International Space Station (ISS) Kibo/Japanese Experiment Module (JEM) Exposed Facility (EF)
- Active Thermal Control System (ATCS)
- Silicon Charge Detector (SCD) – 4 layers of 2x2 cm silicon pixels used to determine incident particle charge Carbon Targets
- (C-targets) – Layers of carbon plates to induce hadronic interactions for measurement in the calorimeter
- Top/Bottom Counting Detector (TCD/BCD) – Plastic scintillator for electron/proton distinction
- Calorimeter (CAL) – 20 layers of alternating tungsten plates and scintillating fibers used to measure incident particle energy and trajectory within the instrument. Four Hybrid Photodiode (HPD) boxes detect scintillation within the Calorimeter.
- Boronated Scintillator Detector (BSD) – Boron-doped scintillator to capture thermal neutrons from hadronic interactions in the calorimeter providing additional e/p distinction
- Science Flight Computer (SFC) – The onboard computer used to control detectors, assemble events and store science data
- FRGF – Flight-Releasable Grapple Fixture
- Payload Interface Unit (PIU) - Power, data, fluid interface to ISS JEM EF
- FSE – Flight Support Interface - SpaceX interface

- Detector info from http://cosmicray.umd.edu/iss-cream/files/ISSCREAM_FactSheet.pdf