National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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ASC Short Course:

Cryogenic Systems Engineering with Cryocoolers

Melora Larson
Jet Propulsion Lab,
California Institute of Technology

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Agenda

8:30-9:15	Introduction to “Systems” and “Systems Engineering
9:15-9:30	Requirements development
9:30-10:00	Requirements exercise and discussion
10:00-10:15	Break
10:15-10:45	Introduction to dry cryogenic systems
10:45-11:15	(Dry) Cryogenic Systems design and case study
11:15-11:45	Cryogenic system design exercise and discussion
11:45-12:00	Final case study and Summary

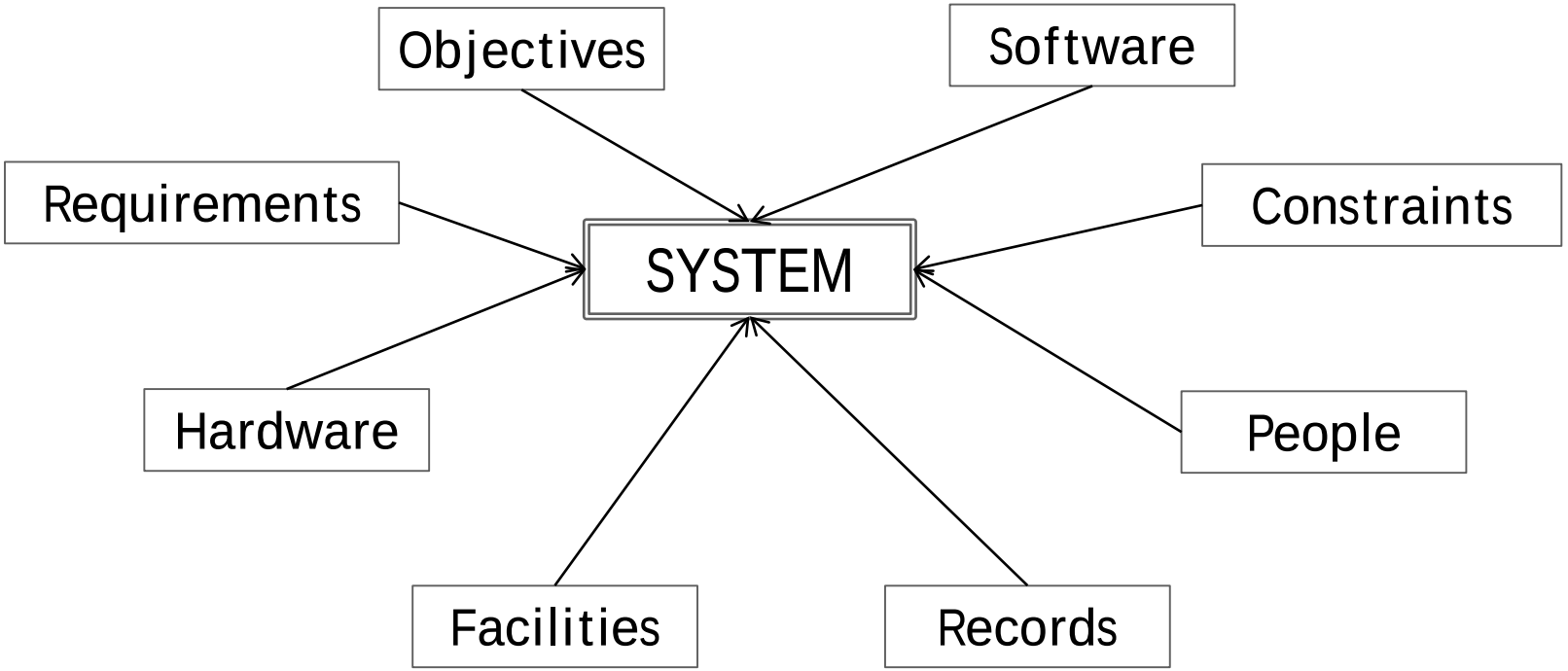
Course Objectives

- Learn how to apply Systems Engineering techniques to the design of a cryogenic system
- Understand the differences between a system that is cooled by a cryogenic cooler (refrigerator) versus one cooled by liquid cryogens
- Understand the constraints and opportunities created when a cryocooler is used to cool a system instead of a liquid cryogen
- Learn how to develop a compete set of requirements for the development of a new cryogenic system
- Learn how to do the trades necessary to design a simple Cryogenic System

Examples will be provided ranging from simple material property measurement systems to space based cryogenic systems.

What is a System?

- A System is the combination of different but interrelated elements that interact to produce a common purpose



Examples of Systems

- Mars Science Laboratory

Objectives

Launch system

Software

Requirements

Operations

Landing system

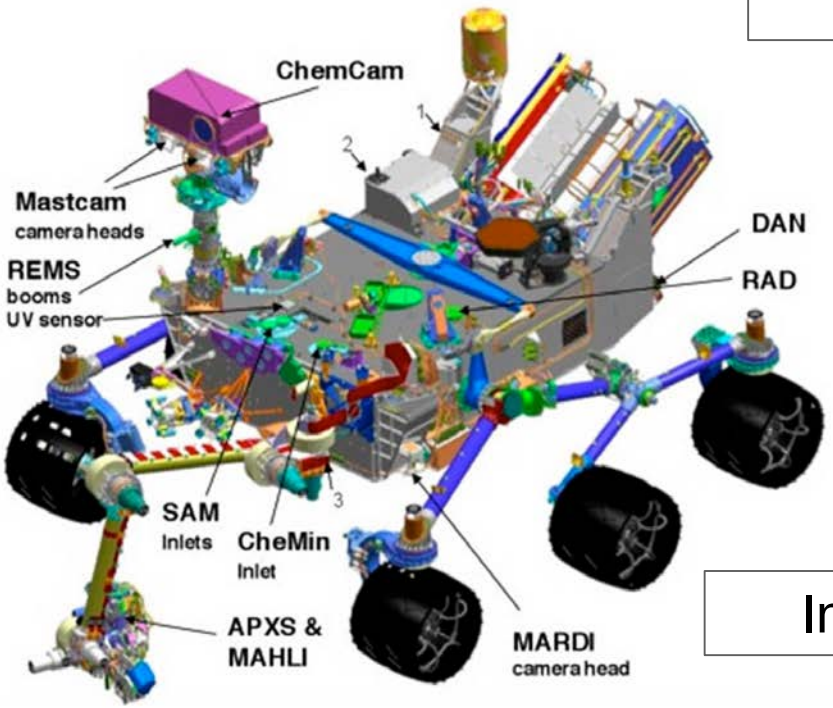
Data

Communication

Constraints

Mobility system

Instruments



Examples of Systems

- Herschel Space Observatory

Launch system

Objectives

Software

Requirements

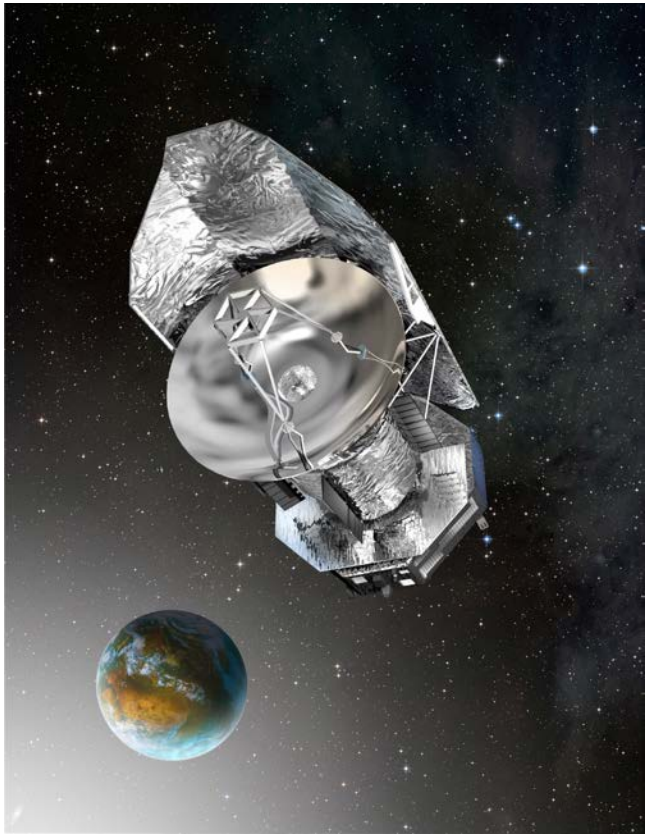
Operations

Instruments

Data

Communication

Constraints



What is a Cryogenic System?

- Any system that includes a volume cooled to below 200K
  - Not exclusively the components that generate cryogenic temperatures
- Goals/objectives of the system can range from:
  - Cryo refrigeration for sample storage
  - Material property measurement
  - Component Functionality testing
  - Detector (light, particles, mineralogy (MSL), gravity waves, etc)
  - Space telescope (Herschel, Spitzer)
  - MRI system
  - Fusion test bed/reactor (ITER)
  - Particle accelerator (LHC)

Systems Engineering

- The process by which a “system” is engineered such that the components and pieces work synergistically together to perform a function or accomplish a purpose
- Robust approach to the design, creation, and operation of a system
- Takes the broad perspective, balancing the objectives with all the constraints and stakeholders
- Is an iterative process that continues from concept development through operation

- The process of applying knowledge in order to translate system requirements into a system design and demonstrate that the final system achieves the desired goal or purpose

Systems Engineering

- Consists of:
  - Identification and quantification of system goals
  - Creation of a set of possible system design solutions
    - Requirements and interface definition
    - Design details
    - Cost and schedule estimates
    - Performance estimates
  - Performance of design trades
  - Selection and implementation of the design that best meets the goals
  - Verification that the design meets the system goals
  - Iterations of the process to finer and finer resolution/breakdown within the System

Systems Engineering Concerns

- Ensure that system definition and design encompasses all system elements (hardware, software, facilities, users, data, etc)
- Use a team of experts with complimentary knowledge to produce an optimally balanced design
- Provide a framework of system requirements for use as performance, design, interface, assembly, and test criteria
- Ensure that life cycle cost considerations and requirements are fully considered in all phases of the design process

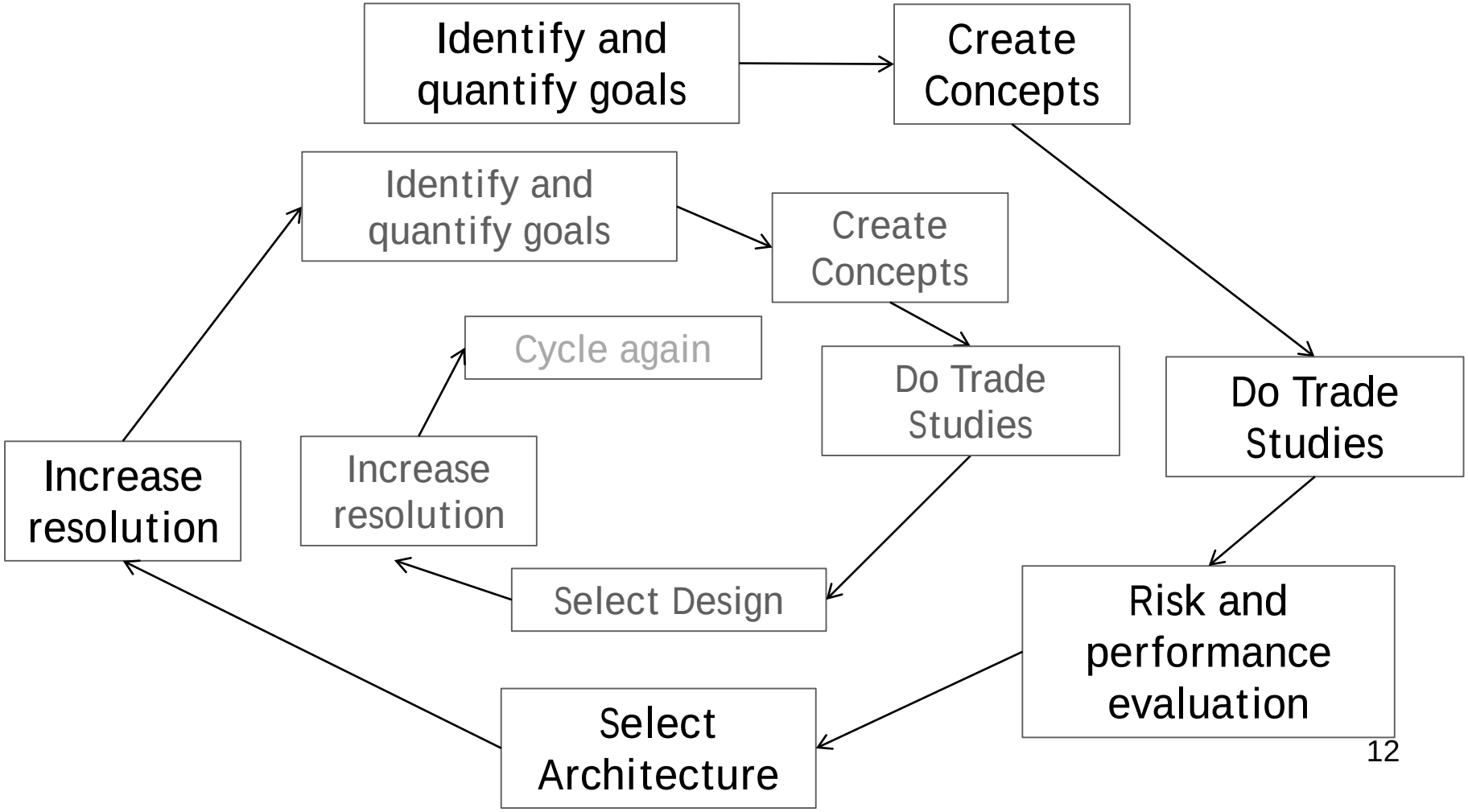
- Important metric is cost versus effectiveness of any given design choice

Systems Engineering Methodology

- The basic methodology can be roughly broken down as:
  - Requirements Analysis
    - Define the problem to be solved
    - Identify the constraints
    - Collect in a set of primary and secondary/implied requirements
  - Technology assessment
    - Compare and tradeoff: performance, complexity, costs, etc.
  - Solution synthesis
    - Find the “best fit” design solution
  - Performance verification

System Engineering Process

- Iterative process that starts with defining the system architecture and then iterates through to the subsystem and component levels



System Engineering processes

1. Requirements
   - What does the system need to do (Goals)
   - How well does it need to do these functions
2. Architecting
   - The overall structure of components, their relationships, and the guidelines
3. Analyze and Characterize the Design
   - Model the system
   - Define scenarios for use
   - Assess performance against requirements
   - Include constraints
4. Technical resource and performance management
   - Identify technical resources that must be watched
   - Define minimal margins for these resources, and allocations

System Engineering processes

5. Interfaces
   - Specify interfaces within the system
   - Determine if there are any unplanned interactions
   - Ensure interface requirements
6. Verify and validate the system performance
   - By Modeling if testing not appropriate
   - Interfaces as well as technical performance
7. Engineering Peer reviews
   - Leverage knowledge of people outside the core team
8. Risk management
   - Identify risks and potential mitigations during all phases
9. Document the effort to ensure configuration control
   - Drawings (interfaces especially)
   - Requirements documentation
   - Hardware and software User manuals

Requirements framework

- Top Level
  - What need(s) shall the system fulfill?
  - How will the system operate?
  - What context will the system operate within?
- Function Requirements (actions)
  - What are the functions of the system?
  - Decompose the functions from top to lower levels
  - Group by common functions
  - Group to simplify interfaces
  - Group by who will implement, especially when purchasing components
- Interface Requirements
- Constraint requirements
  - If not already captured by interface requirements

Requirement prioritization-Refinement

- How can importance be estimated?
  - Impact on System life cycle costs
  - Improvement in system effectiveness
  - Improvement in system availability/reliability
- What are the required resources?
  - Budget, personnel, facilities, technology
- Why is it significant?
  - Improvement over current capability
  - Uniqueness of capability provided

Value= Benefit/Cost

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Requirements Matrix Tool

- Spreadsheets can be used to collect and assess completeness of initial top level requirement set
  - Allows connections and decomposition to be made
  - A method for checking if have complete set of requirements at each level of decomposition

Goals	**Purpose**	**Functions**	**Context and Interfaces**			**Spatial**	**Temporal**	**Other**
			Where	Power	Temp (K)			
What 1	why	Mode 1		max	out	volume	How fast	vacuum
				ave	in	sample	How often	mass
							How long	etc
		Mode 2				motion	etc	
						etc		
What 2	why	Mode x						
		Mode y						

Requirements Exercise

	1. Retro-fit existing facility	2. Add new capability in existing labs	3. Build up new lab in new facility
A. Magnet and magnet wire test facility	a. 1K-10K b. 4K-30K c. 15K-100K	a. 1K-10K b. 4K-30K c. 15K-100K	a. 1K-10K b. 4K-30K c. 15K-100K
B. Physical property measurement system	a. 0.1K-10K b. 4K-30K c. 15K-100K	a. 0.1K-10K b. 4K-30K c. 15K-100K	a. 0.1K-10K b. 4K-30K c. 15K-100K
C. Detector test facility	a. 0.05K-4K b. 4K-30K c. 15K-100K	a. 0.05K-4K b. 4K-30K c. 15K-100K	a. 0.05K-4K b. 4K-30K c. 15K-100K

- Break into 4-5 groups: 4-5 people each
- Pick a system with one main goal, context, and temperature range from the above
  - For example: group 1: A-2-c; group 2: B-3-a; group 3: C-1-b; group 4: A-3-b; group 5: B-2-c

Team exercise: Requirements

Assigned system, constraints, operational (temperature range)

- Top Level: Concept of operations (What will it do, why, and how will it do it)
  -
  -
  -
  -
- Function Requirements (modes, actions)
  -
  -
  -
  -
  -

Team exercise: Requirements

- Context (where: university, national lab, company) and Constraint requirements (Environment (lab, observatory, reactor, accelerator), budget, other)
  -
  -
  -
- Interface Requirements (facility resources: Power, available space, access, external temperatures, other)
  -
  -
  -
  -
  -
- Operational requirements (how fast, how cold, how long, how large volume cooled, etc)
  -
  -
  -

Exercise discussion

Overview of Cryogenic Cooler (dry) systems

- Uses local electrical power to generate cooling
  - Cooling available at a mechanical interface with limited area
    - Can attach high conductive metal plates and metal shields to get large cooled volumes
    - Minimum T throttled by radiative and conductive loads on the cooled volume
  - Some provide multiple stages with cooling available at different temperatures or heat loads
  - Can need external (room temperature) forced cooling
  - Can generate vibrations at cold tip
  - Can be loud
  - Can draw significant wall power
    - At 80K will need about 10W input per W cooling
    - At 4K can need over 10,000W input per W of cooling

  - Cryogens are generated by commercial, large, cryocoolers
  - Lab systems do exist for local cryogen generation and storage

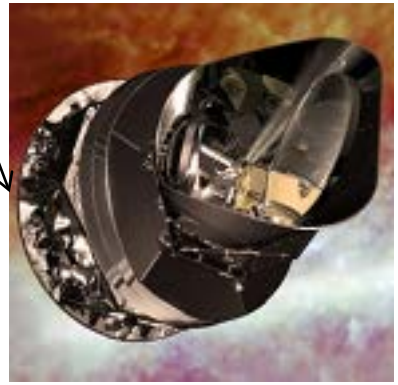
Overview of Cryogenic Cooler (dry) systems

- Variety of thermophysical processes used to generate cooling
  - Turbo-Brayton
  - Gifford-McMahan (GM) (less expensive option, largest vibration)
  - Stirling cycle (mechanical)
  - Acoustic stirling cycle (Pulse Tubes)
  - Joule-Thomson (JT)
  - Adiabatic Demagnetization Refrigerator (ADR)
  - Dilution Refrigerators
- Temperatures below 30K achieved with multiple stages
- Temperatures below 3K achieved by cooling a low T refrigerator (ADR, JT, Dilution) by a 4K or lower cooler

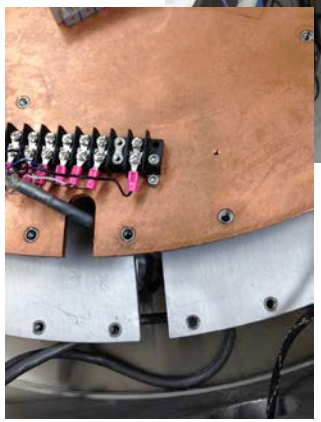
- Resource for researching sources is the Cryogenic Society of America's Buyer's Guide:
  - http://www.cryogenicsociety.org/buyers_guide/

Examples of Dry Cryogenic systems

- Cryogenic lab bell jars
- Plug and play measurement systems (Quantum Design VersaLab shown)
- Spacecraft observatories (Planck shown)



Components of Dry Cryogenic system: 4 or 10K Bell jar



- Bell Jar
- 1st stage thermal plate and shroud
- 2nd stage thermal plate and shroud
- Bell jar hoist
- Chamber vacuum pump, plumbing, and valves
- Chamber thermal readout and control system
- Cooler unit
- Cooler compressor
- Compressor cooling (water) system
- Experiment specific wiring
- Experiment specific plumbing
- Experiment specific readout electronics
- Experiment- including any additional mechanical and/or thermal isolation needed
- etc

Wet versus dry Cryogenic Systems (1/4)

Property	Wet system design	Dry system design
Initial price	Relatively low	Depends on base temperature- Will be 10's of K$ more
Operational costs	Adds up with use and time as liquid helium costs rise	Relatively low, especially if electricity provided
Vibration	Low	If cool from 300K, typically microns of coldtip motion. Might need to add vibration isolation
Cycle time	Can be fast (exchange gas, direct dipping)	Typically longer: large system thermal mass, exchange gas warm up only.
Base Temperature	<2K with external pumping. Additional coolers needed for <1.8K	Typical ~4K lowest with single multi-stage cooler. Additional coolers needed for <4K.

Wet versus dry Cryogenic Systems (2/4)

Property	Wet system design	Dry system design
Unregulated Thermal stability	Good (few mK)- unregulated, large thermal mass	Good (~10mK)- cooler does drift, and base temperature function of heat load (room T)
Operational limitations	Periodic refilling of cryogens required	Few if any
Maintenance	Minimal	Periodic, after 8,000 to 60,000 hours of run time depending on cooler type
Facility requirements	Oxygen monitors and/or dedicated venting.	High current and voltage power feeds; cooling water supply for larger coolers
Safety considerations	Can build up pressure if ice forms, relief valve fails	Limited electrical concerns

Wet versus dry Cryogenic Systems (3/4)

Property	Wet system design	Dry system design
Cooling interface	Typically cooled isothermal top plate, full diameter of working space	Typically single, few square cm cold tip, with large plate attached-thermal gradients from rad loads on plate
Cold volume	Usually few liters max, limited by dewar geometry	Can be large- limited by facility room, budget, and temperature requirements
Temperature uniformity	Full can at bath temperature, minimal temperature gradients	Cold plate and shroud cooled conductively- gradients set by heat loads, material KA/L- can be large if do not blanket and heat sink with care
Optical access	Need specialized dewars or optical fibers	Easy to include windows, but care must be used to ensure heat loads not excessive

Wet versus dry Cryogenic Systems (4/4)

Property	Wet system design	Dry system design
Wiring and heat sinking	Can heat sink using bath and vapor cooling (does require cryogenic, vacuum feedthrough)	Can heat sink at warmer stage and colder stage. Care must be taken to ensure wire actually heat sunk.
Magnet accommodation	Can sit in the cryogen bath, excellent thermal stability, easy magnet lead cooling/design, large thermal mass in case of a quench	Sits in vacuum mechanically linked to cooler (not great for thermal stability). Heat sink at warmer stage can allow for partial HTC-SC leads. Quenching must be designed for carefully
Flexibility	Limited volume, but otherwise one dewar can accommodate many inserts	May need to mitigate noise for high precision measurements, otherwise, large volume allows for testing complex subsystems

(Dry) Cryogenic system design driving requirements

- Base temperature, heat lift at base temperature
  - These requirements limit what coolers technology you should focus on
    - T > 30K GM coolers (cheapest options usually)
    - 30K > T >10K 2 stage either GM or stirling (pulse tube or mechanical)
    - 10K > T > 3K multiple stage pulse tube or cooling chain (multiple linked coolers)
    - 3K > T > 0.05K Cooling chain of various types (Pulse Tube, ADR, Dilution, etc)
    - Heat lift should be minimized to achieve the desired base temperature easily
      - Size of shrouds and number of wires and other experimental inputs should be optimized between flexibility and impact
- Volume of experimental measurement subsystem, number of inputs into experiment (electrical, fluid, other)
  - These requirements feed into the vacuum bell jar design
    - Number of ports
    - Size of cold plates
    - Thermal shrouds design

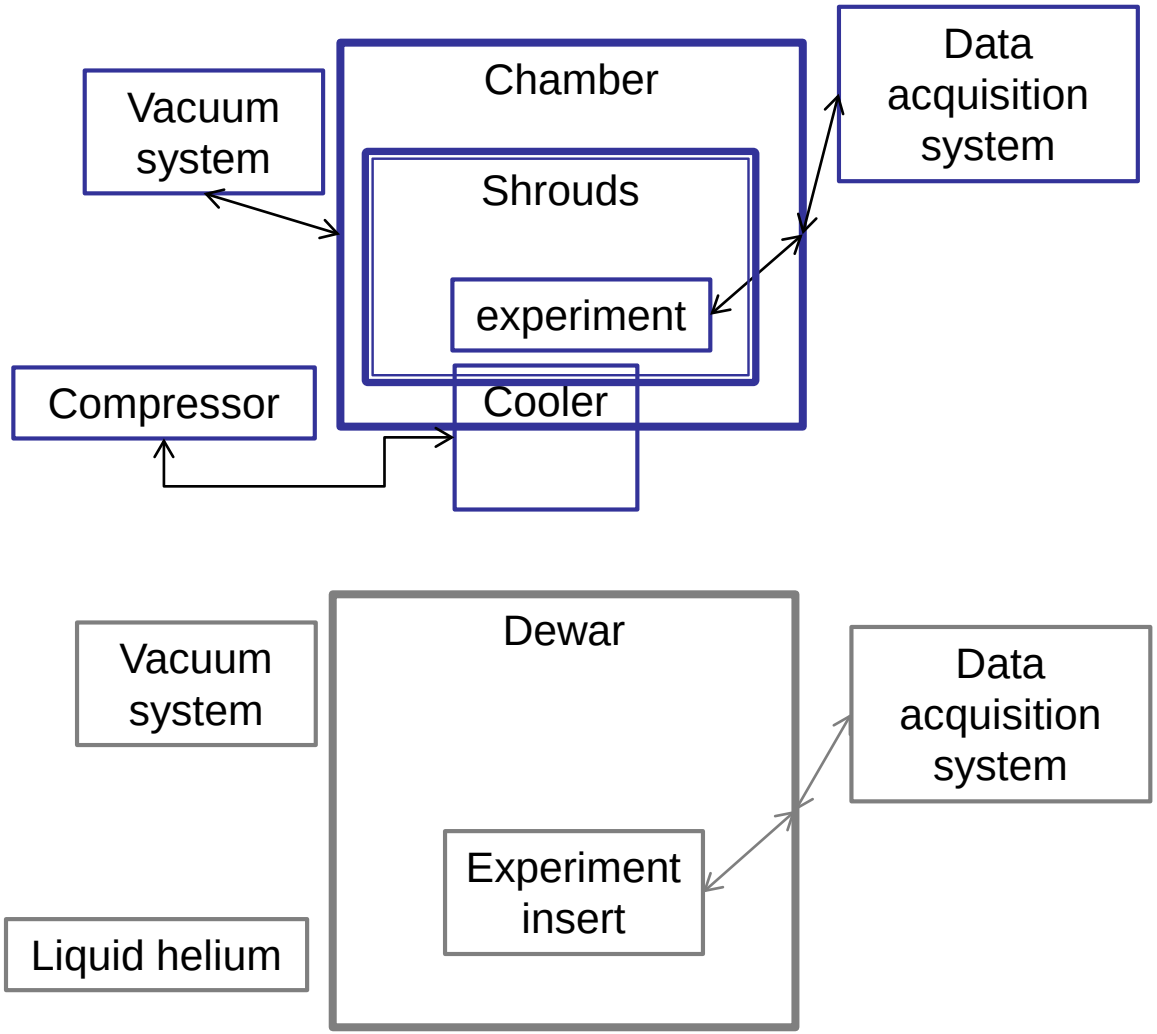
Architecting a design solution

- Once you have an objective and a set of characteristics, functions, and must haves (i.e. requirements), the next step is to develop possible top level solutions (the architecture)
  - Consider how the architecture is affected by interfaces
  - Consider what portion of the system will be designed in house versus contracted out
  - Consider how much of the system will be built in house versus bought
  - Consider the testability of the architecture
    - Can you prove it meets the requirements?
  - Do you want to use any new technologies?

- Using existing hardware, minimal changes to the infrastructure, commercial product lines, and existing architecture or designs will often save money and time

Architecture Trade Study

- To help focus the effort, often useful to make block diagrams or draw sketches to show components
- Identify what resources the components require
  - Power, cooling, etc
- Identify the impacts between pieces of hardware
  - Heat loads on cooler from shrouds, experiment operation, experiment wiring, etc



Choosing the Architecture

- Thermal block diagrams also very useful
  - As simple as possible, but with enough information to understand the approach
  - Identify temperature zones required (or created by the architecture) and define the hardware associated with each zone
  - Can start with the hardware block diagram and annotate
  - Iterate to lower levels of detail as move further into the design
- Identify the thermal drivers
  - Large volume?
  - Long operation time
  - Base temperature
  - Many feed-throughs, wires, other experimental inputs
- Evaluate the performance of the design
  - Can it be made to meet the system requirements?
  - Use back of the envelope calculations for initial evaluation
  - Apply stacked worst case conditions for your evaluation to bring some margin into the evaluation

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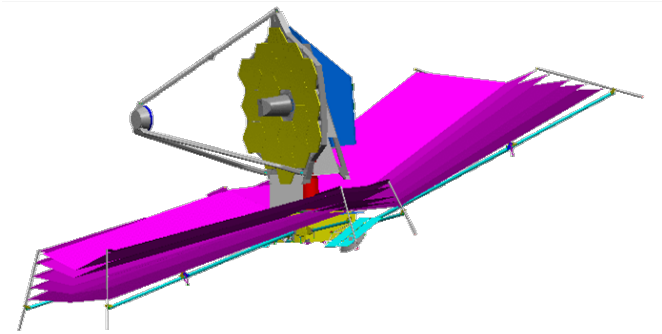
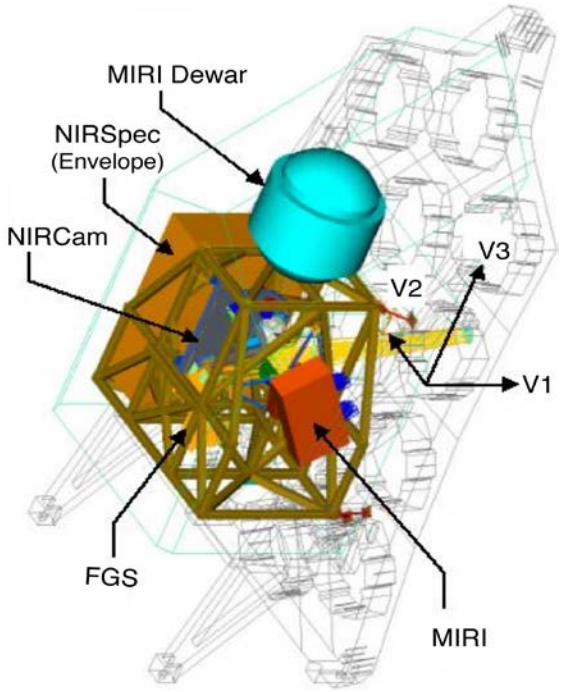
Trade study:
JWST MIRI: Cooler versus Dewar

see Banks, et al, "James Webb Space Telescope Mid-Infrared Instrument Cooler Systems Engineering", Proceedings of the SPIE 7017, 70170A (2008).

- James Webb Space Telescope (JWST) has 4 instruments
  - 3 (NIRSpec, NIRCam, and the Fine Guidance Sensor/NIRISS) radiatively cooled to near 40K
  - The 4th instrument (Mid-Infrared Instrument-MIRI) uses detectors that need to be cooled to ~7K (not possible radiatively)
- JWST cooling architecture for MIRI changed several times
  - Prior to 1999, initial concept had MIRI cooled by turbo-brayton cooler
  - After 1999, MIRI designed assuming cooled by an external solid hydrogen dewar- Coolers technology judged not mature enough
  - 2002 conceptual design shown





MIRI Cooling system driving requirements

- Objective:
  - Cooling system shall provide <7K to cool detectors and <15K to cool the optics
- Top Level: Concept of Operation
  - Cooling source shall be external to the MIRI Optical bench
  - MIRI Optical Bench will be launched at 300K: Cooling shall begin once JWST is in space
  - Cooling shall be provided for the 5 year science mission
- Functional Requirements
  - Cooling system shall provide cooling to the MIRI Optical bench during ground testing without using hydrogen
  - Cooling system shall be filled at the launch site from ambient
- Interface Requirements
  - Cooling system shall have a simple, mechanical connection to the MIRI
  - Cooling system shall not disturb the Observatory (mechanical)
- Constraints (resources)
  - Cooling system shall have a mass less than 250kg

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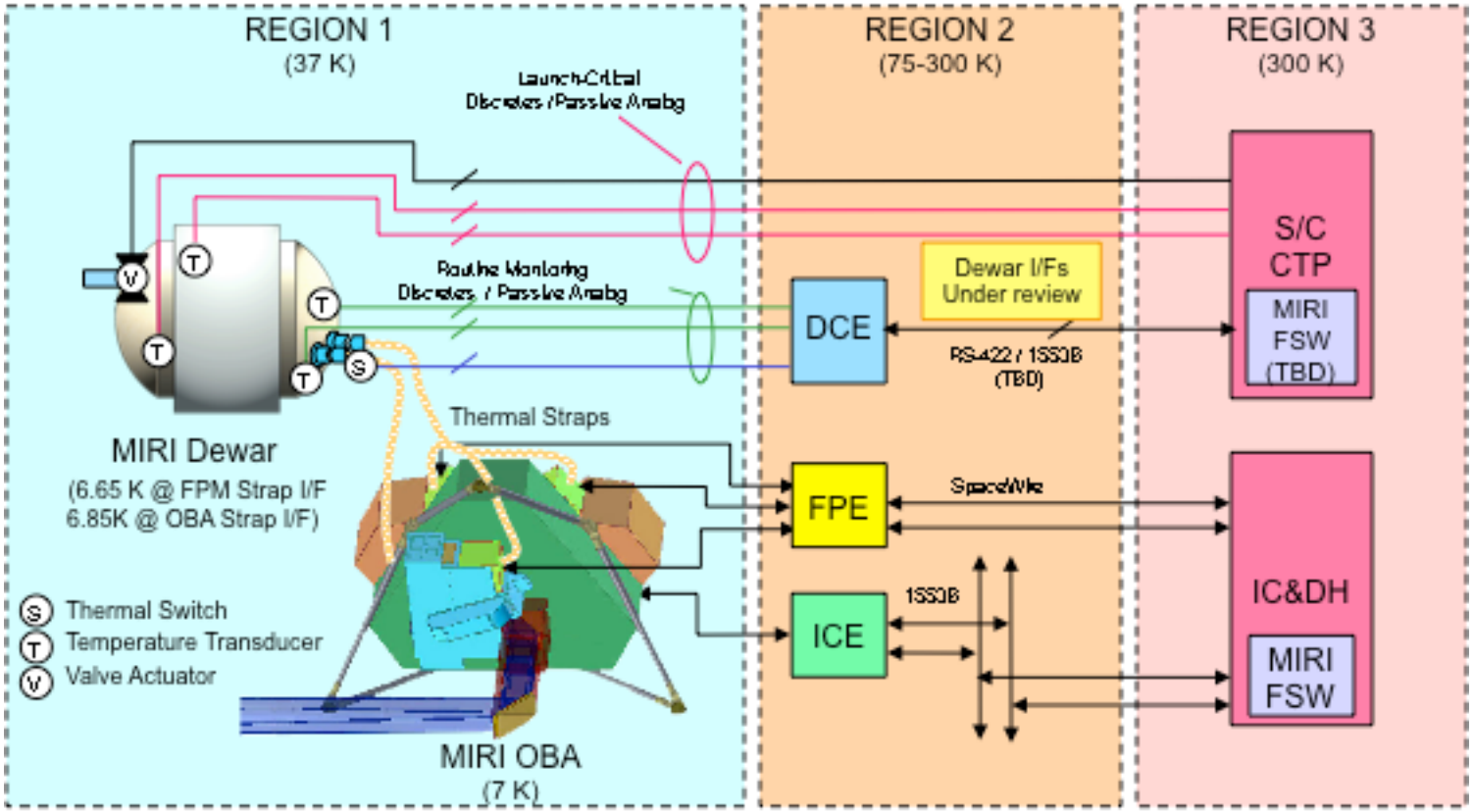
MIRI with Dewar block diagram



MIRI Cooler-Dewar trade

- In 2005, JWST mass needed to shrink to regain margin on launch vehicle capability
  - MIRI Dewar larger mass driver than just its (large) mass
  - Other (safety, lifetime, etc) issues strong negatives for Dewar
  - Cooler technology judged ready for incorporation

- JWST Project decided to perform a trade to see if reasonable to switch from MIRI Dewar to MIRI Cooler
  - Result of trade study was a change in the cooling architecture-MIRI Cooler
- Change enabled by the original, modular design of MIRI and its cooling system
- All top level requirements still applicable and met
  - Only mass and other resources that were implementation specific (power, volume, telemetry) needed to be changed with the architecture change

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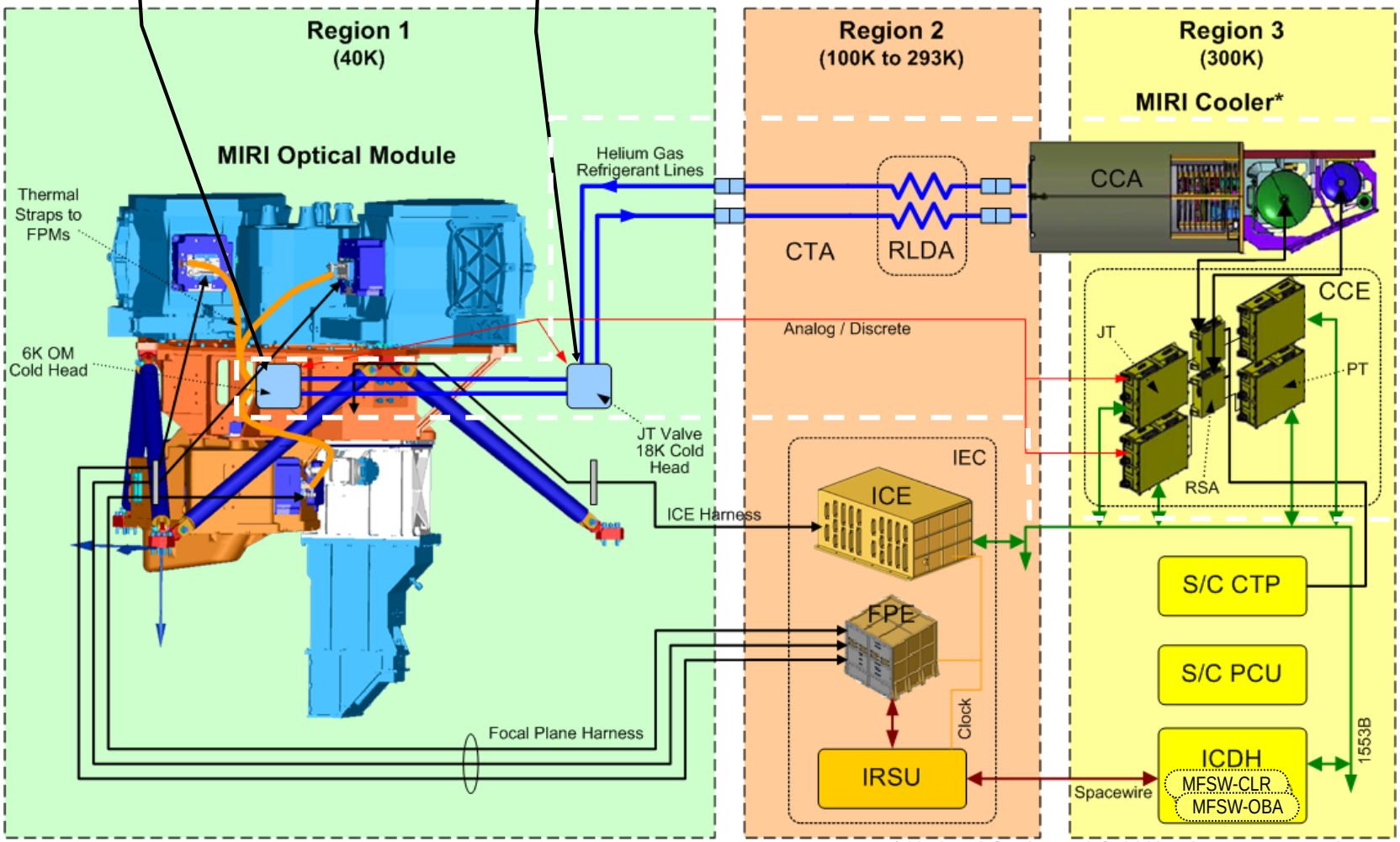
MIRI System Block Diagram

- **6K CHA to MIRI OM Deck**
- **18K HSA support off ISIM**



* Notional Cooler and Cold Head arrangement shown

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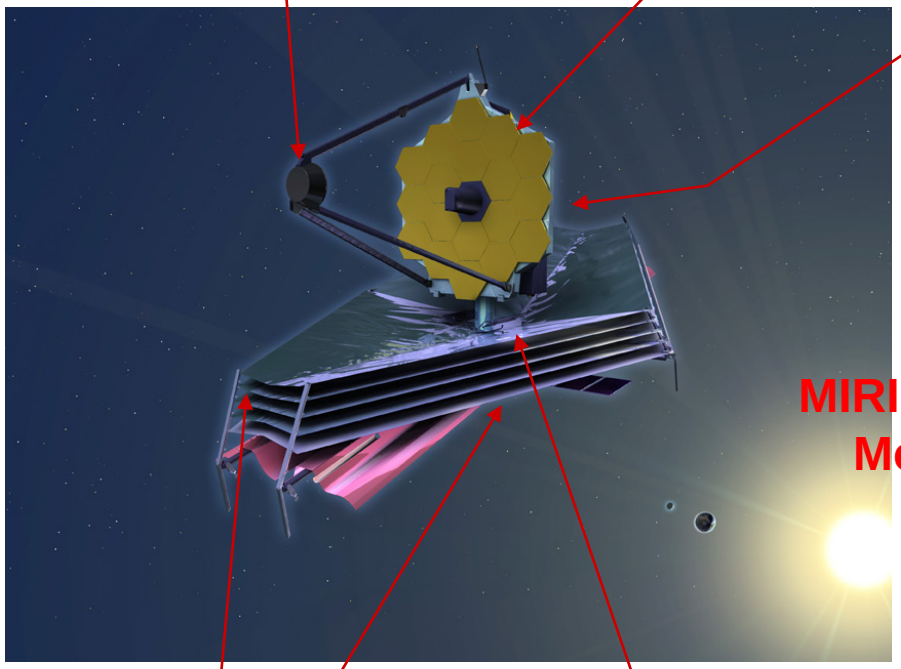
James Webb Space Telescope
(more photos at http://jwst.nasa.gov/images.html)

Secondary

6 m Primary (25 m^2)

ISIM



HSA

MIRI Optical Module

MIRI Cooler CCA

Sun Shield

Spacecraft

6 m Primary (25 m^2)

Cryogenic system design exercise

- Return to the system selected for the previous exercise
- Start from the requirements set your team generated
- Define at least 2 possible design solutions
- Perform design trades between these possible solutions
  - Rough out design details
  - Develop performance estimates
  - Focus on performance or resource requirement differences

- Remember that cost versus effectiveness of the designs can be traded against non-critical performance

Rough rules of thumb for exercise

Disclaimer: while values below are about the right order of magnitude, these are not actual quotes, nor specific property values. When you repeat these steps for your Systems, use current, researched values for costs and properties.

- Cost of helium $10/liter,
- Cost of helium dewar $5K
  - Dewar empty boiloff rate 5 liters/day
  - Boil off increase 1 liter/hour per Watt heat load into 4K
- GM Cooler,
  - 10K base Temperature cost $40K, can take out 1W at 15K
- Pulse tube
  - 3K base temperature cost $80K, can take out 1W at 4K
- Heat load from cold shroud on to 4K (radiative heat load)
  - Watt = Area in sq meters *(0.2)
- Heat load from wires in to 4K (assumes heat sinking)
  - Q Watt/wire =1e-4W **each**
- Heat load in to 4K for any other experiment resource
  - (cooling, light input, gas flow, magnet leads) Q = 0.2W each

Exercise

- System top level description/Objective

- Solution 1

- Solution 2

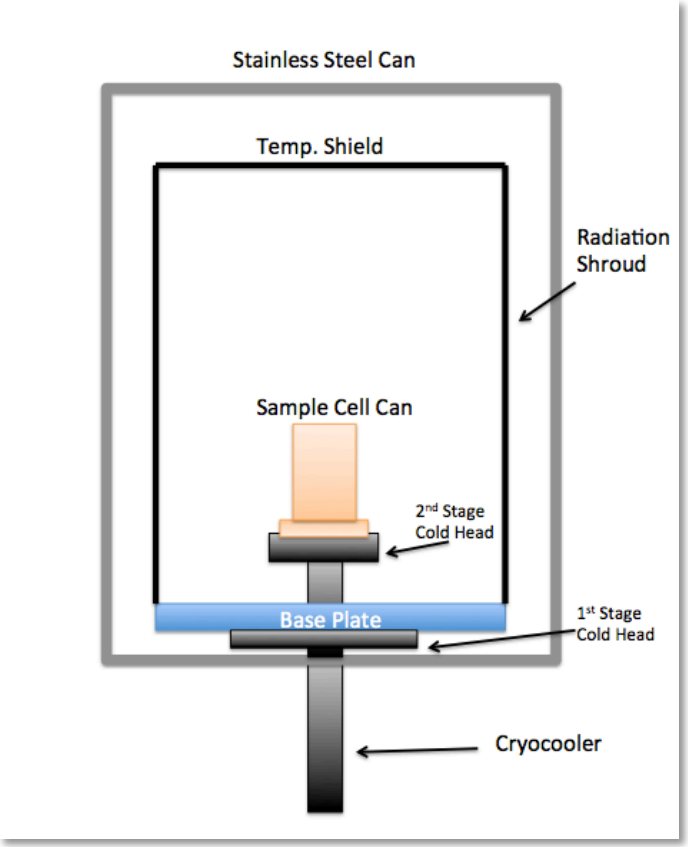
Exercise

Requirement	Solution 1 compliance	Solution 2 compliance

Exercise discussion

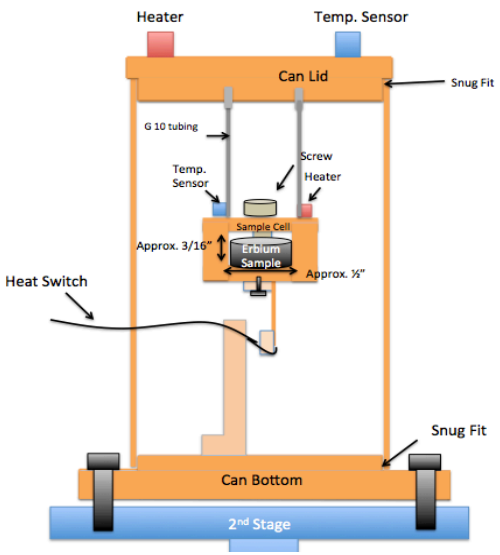
Case study: Design without requirements

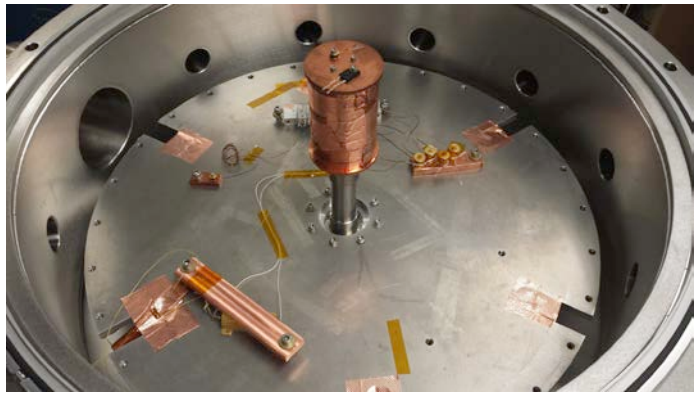
- Thermal properties measurement system
  - Common design for Heat capacity and thermal conductivity
- Had Bell jar with 2 stage cooler
  - 10K cooler with effective base temperature ~15K
- Had rough idea requirements- not written down
  - Requirements actually in more then one head
  - Could not check if design of assembled system met the requirements
  - Did not do any analysis to see what performance requirements needed to be to make the desired measurements
- Figured if use a system that can cool to where we needed, we use thermometers with high (mK) resolution, good current source and voltmeter, we should be fine…



Impact of lack of requirements

- Did not achieve the desired temperatures initially because:
  - Did not control heat leaks into sample cell
    - Wires not heat sunk
    - Heat switch pull string not heat sunk
    - Thermal shroud not bolted to 1 stage cold plate
  - Iteratively improved performance by adding more and more heat sinking
- Did not get the desired stability
  - Long thermal time constants in design due to pressed contacts and large masses (heat capacities)
  - Design better optimized for thermal conductivity, not heat capacity
- Hard to improve performance when one does not know what is good enough
- Resulted in no useful data taken in limited time we had to run experiment





Conclusions

- Systems Engineering should be done up front, and continue through the life of a System
- Upfront time to define the system, the system's requirements, and seeing if the proposed system will meet the requirements will save time and rework costs later
- There are multiple valid approaches for most objectives
  - Trades between cost, performance, etc may provide optimum design approach

- Cooler based (dry) cryogenic systems have more upfront costs, but can be cost effective over time

- Acknowledgements: Some material derived from JPL Thermal Systems Engineering course: Art Avila, Glenn Tsuyuki, Virgil Mireles, Jose Rodriguez, Gary Kinsella
- References:
  - NASA Systems Engineering Handbook (SP-6105, 1995)
  - Readings in System Engineering (SP-6102, 1993)