NICM: Cryocooler

Presenters:
Joe Mrozinski
Mike DiNicola

NASA Cost Symposium, August 2017

Jet Propulsion Laboratory
California Institute of Technology

NICM Team

- Gary Ball
- Luther Beegle
- Justin Boland
- Bob Cesarone
- Mike DiNicola
- Michael Fong
- Hamid Habib-Agahi
- Dean Johnson
- Joe Mrozinski
- Al Nash
- Chris Paine
- Michael Saing
- Marc Walch
- Wayne Zimmerman

What is NICM?

- NASA Instrument Cost Model
  - Probabilistic Cost Estimates for Space Flight Instruments
  - Used by all NASA Centers
    - And any organization proposing instruments for NASA Instruments
    - And proposal evaluators
  - Version I Released in 2007
  - Version VII Rev 2 Released 2016

What is NICM?

- NICM also:
  - Estimates schedule
  - Supports JCL
  - Contains an normalized instrument database (for civil servants)

Yes – you can get a copy of NICM

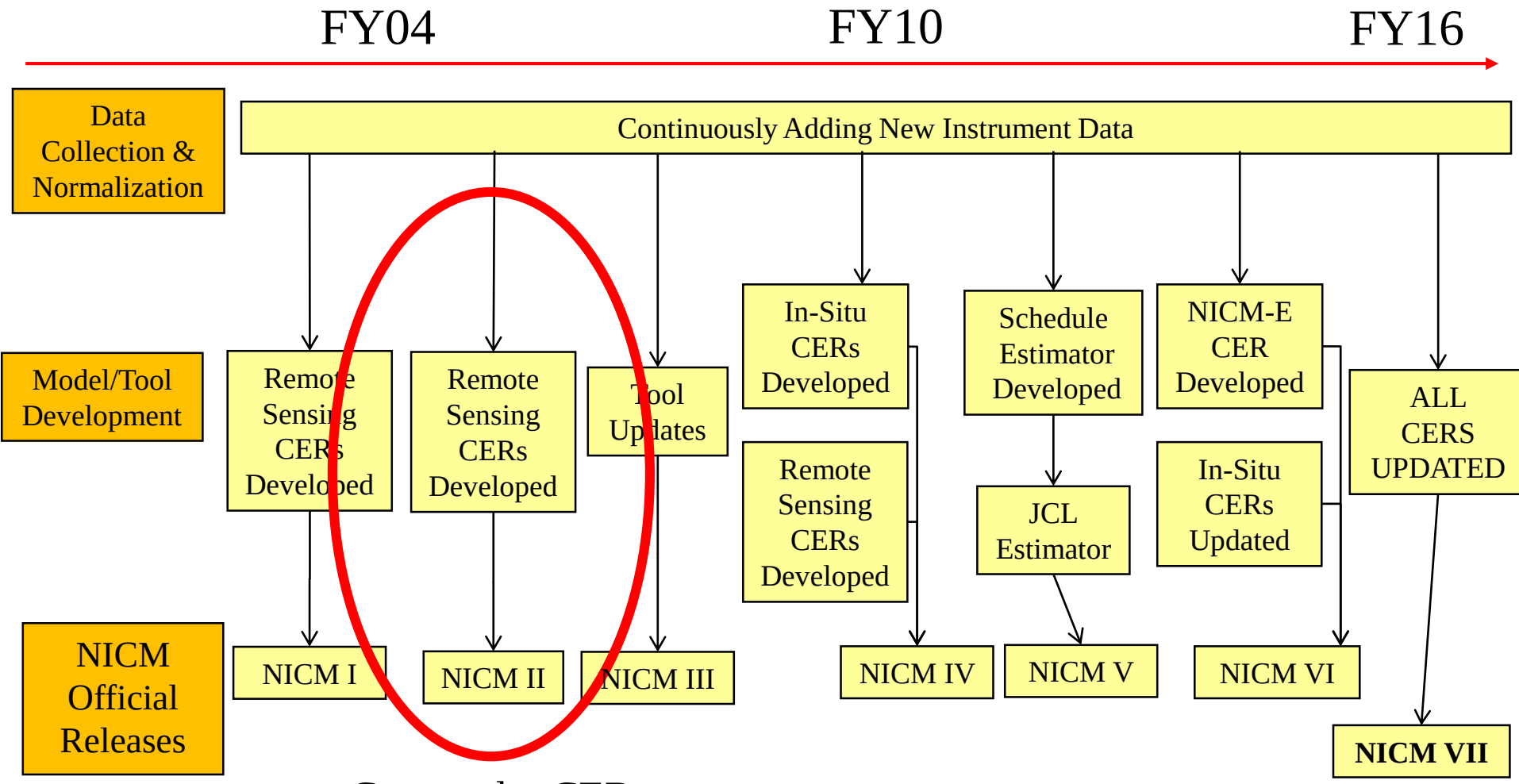
- RSVP for only training at:

Joseph.J.Mrozinski@jpl.nasa.gov

Just kidding, you'll never remember that

NICM@jpl.nasa.gov

Today's Story: Cryocooler Cost Estimation



Background

- NICM VII applies the following equation to estimate the cost of a New Cryocooler Development:

$$\text{Cryocooler Cost (FY04 \$K)} = \mathbf{40{,}099} \times \text{LowTemp}^{-0.15}$$

where "LowTemp" is the lowest temperature (in Kelvin) that the instrument needs to be cooled to by the cryocooler.

- **Note that large coefficient in front of the equation!**

Background

- NICM VII applies the following equation to estimate the cost of a New Cryocooler Development:

$$\text{Cryocooler Cost (FY04 \$K)} = \mathbf{40{,}099} \times \text{LowTemp}^{-0.15}$$

where "LowTemp" is the lowest temperature (in Kelvin) that the instrument needs to be cooled to by the cryocooler.

- **This equation was built off of data from new and unique cooler designs requiring significant development.**

Background

- NICM VII applies the following equation to estimate the cost of a New Cryocooler Development:

$$\text{Cryocooler Cost (FY04 \$K)} = \mathbf{40{,}099} \times \text{LowTemp}^{-0.15}$$

where "LowTemp" is the lowest temperature (in Kelvin) that the instrument needs to be cooled to by the cryocooler.

- **However, many present applications are utilizing commercially available cyrocooler solutions, which present significant cost savings.**

Background

- NICM VII applies the following equation to estimate the cost of a New Cryocooler Development:

$$\text{Cryocooler Cost (FY04 \$K)} = \mathbf{40{,}099} \times \text{LowTemp}^{-0.15}$$

where "LowTemp" is the lowest temperature (in Kelvin) that the instrument needs to be cooled to by the cryocooler.

- **Described here is our work to improve this estimating capability to be able to estimate costs for both new designs and those leveraging commercial solutions.**

Agenda

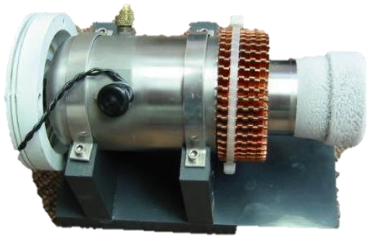
- Cryocooler Terminology for this Presentation
- Data
- Modeling Process
- Analysis & Early Findings
- Future Work

Agenda

- **Cryocooler Terminology for this Presentation**
- Data
- Modeling Process
- Analysis & Early Findings
- Future Work

Cryocooler Technologies

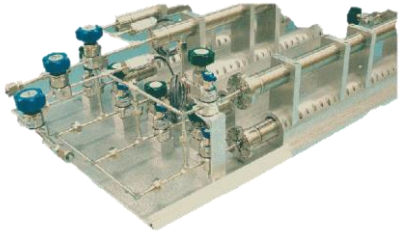
Pulse-tube Cooler



Stirling Cooler

Dewar

Joule-Thomson

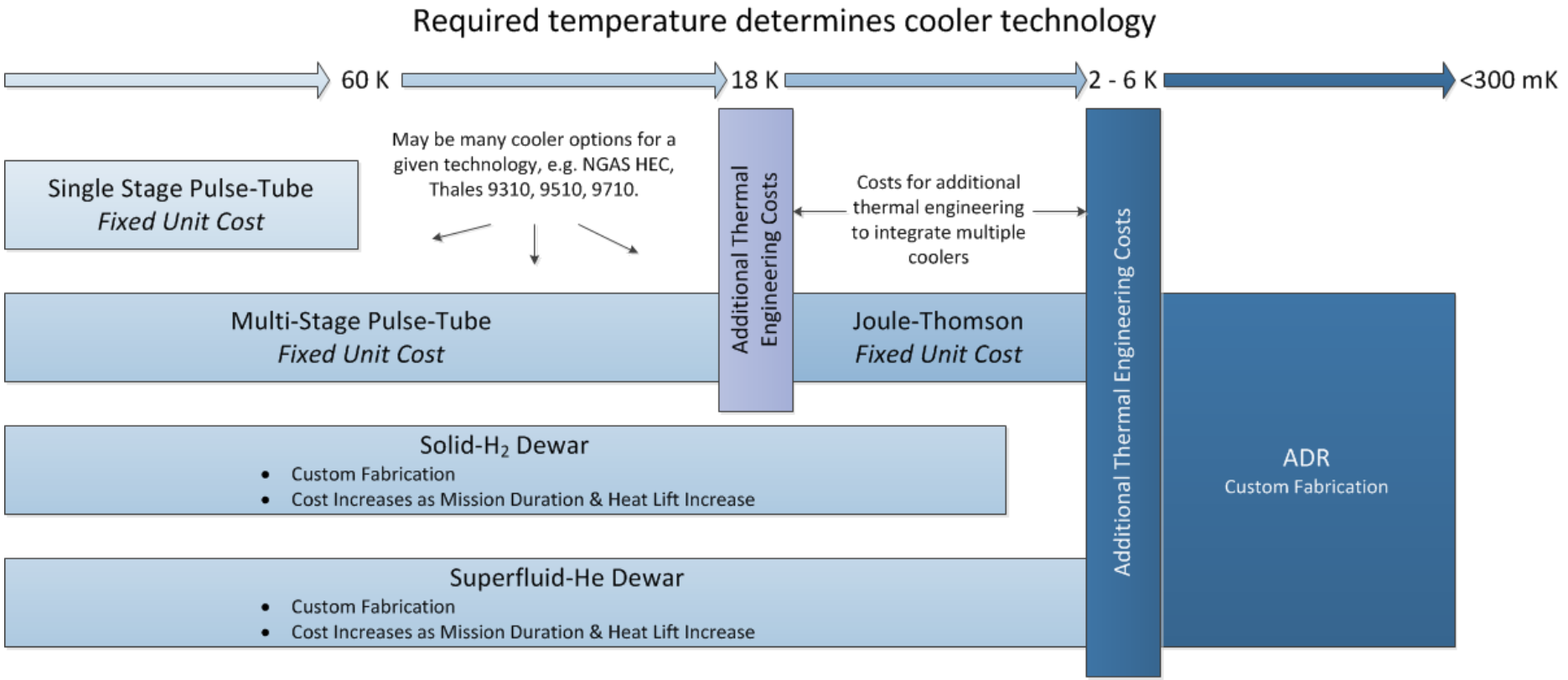


Sorption Cooler

Reverse Turbo Bryton

Adiabatic Demagnetization Refrigeration (ADR)

Cryocooler Cost Modeling



Agenda

- Cryocooler Terminology for this Presentation
- **Data**
- Modeling Process
- Analysis & Early Findings
- Future Work

Data Collection

- Cryocooler cost and technical data being gathered for over 35 different cryocooler systems flown on NASA missions
  - Data go as far back as mid-1980s, but CERs will focus on more current data and technology
  - Database includes 38 attributes, including cryocooler cost, minimum temp required, heat lift, design life, # of stages
- 18 data points are complete and reviewed enough to be used for analysis
  - Includes 7 cryocooler technologies
  - Equal number of commercial (a.k.a. "COTS") and New Development observations

Technology	Commercial*	New Development
ADR		2
Dewar	2	2
Joule-Thomson		1
Pulse-Tube, Stirling	7	2
Reverse-turbo Brayton		1
Sorption		1
Total	**9**	**9**

*Includes one flight spare under "Pulse-Tube" category for OCO-1.

Cryocooler Data Excerpt - Preliminary

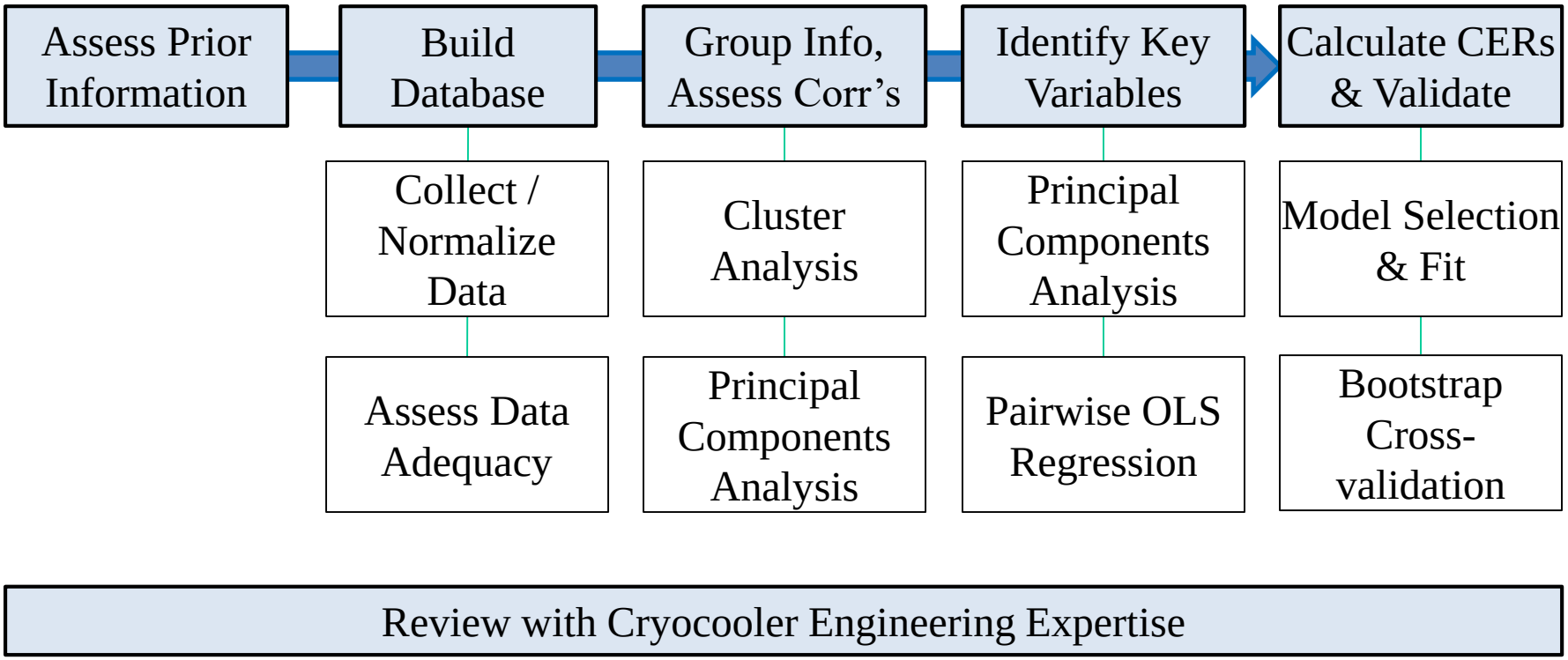
Mission Name	Instrument Name	Cryocooler Technology	Minimum Temperature Required (K)	Design Life (Months)	Implement-ation Type	# of Stages
Suzaku	X-ray Spectrometer (XRS)	ADR and Dewar	0.05	36	New Dev	3
Astro H	Soft X-ray Spectrometer System	ADR, JT, and Stirling	0.05	36	New Dev	3
IRAS	IRAS - Infrared Astronomical Satellite	Dewar	1.8	12	New Dev	1
WIRE	WIRE	Dewar	7	4	Commercial	2
SPITZER	SPITZER's telescope	Dewar	2	60	New Dev	1
WISE	WISE Telescope and detector	Dewar	7.3	18	Commercial	2
JWST	MIRI	Hybrid - JT and Pulse Tube	6	120	New Dev	4
ISS Instrument	Ecostress	Pulse Tube	65	12	Commercial	1
Aqua	AIRS - Atmospheric Infrared Sounder (AIRS)	Pulse Tube	55	170	New Dev	1
EOS-Aura	TES	Pulse Tube	62	60	New Dev	1
OCO-1	OCO-1	Pulse Tube	110	36	Flight Spare	1
OCO-2	OCO-2	Pulse Tube	110	24	Commercial	1
GOES-R	Advanced Baseline Imager (ABI),	Pulse Tube	60	120	Commercial	2
HST	NICMOS	Reverse turbo-Brayton	72	60	New Dev	1
PLANCK	PLANCK	Sorption Cryocooler	20	53	New Dev	1
Shuttle Instrument	AMS - Alpha Magnetic Spectrometer (launched on Discovery STS-91)	Stirling	77	0.3 (10 days)	Commercial	1
MSL	ChemMin	Stirling	173	21	Commercial	1
ISS Instrument	AMS-02 - Alpha Magnetic Spectrometer (Launched on Endeavor 2011)	Stirling	77	120	Commercial	1

- 18 Mission Data Points
- 7 Cryocooler Technologies
- Cooler operating minimum temperature range from 0.05K to 173K

Agenda

- Cryocooler Terminology for this Presentation
- Data
- **Modeling Process**
- Analysis & Early Findings
- Future Work

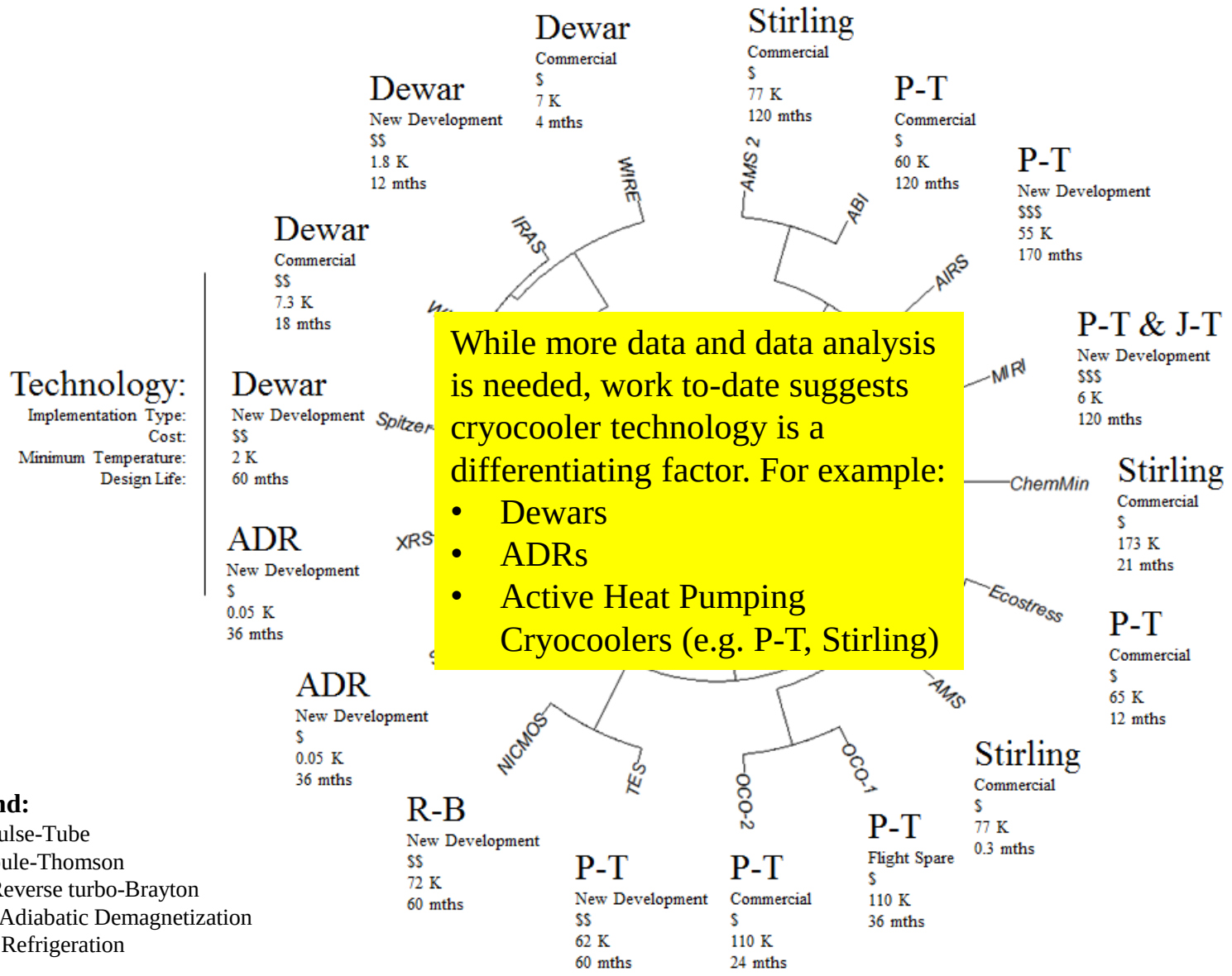
Model Development Process



Agenda

- Cryocooler Terminology for this Presentation
- Data
- Modeling Process
- **Analysis & Early Findings**
- Future Work

Preliminary Cluster Analysis Suggests Grouping by Cryocooler Technology

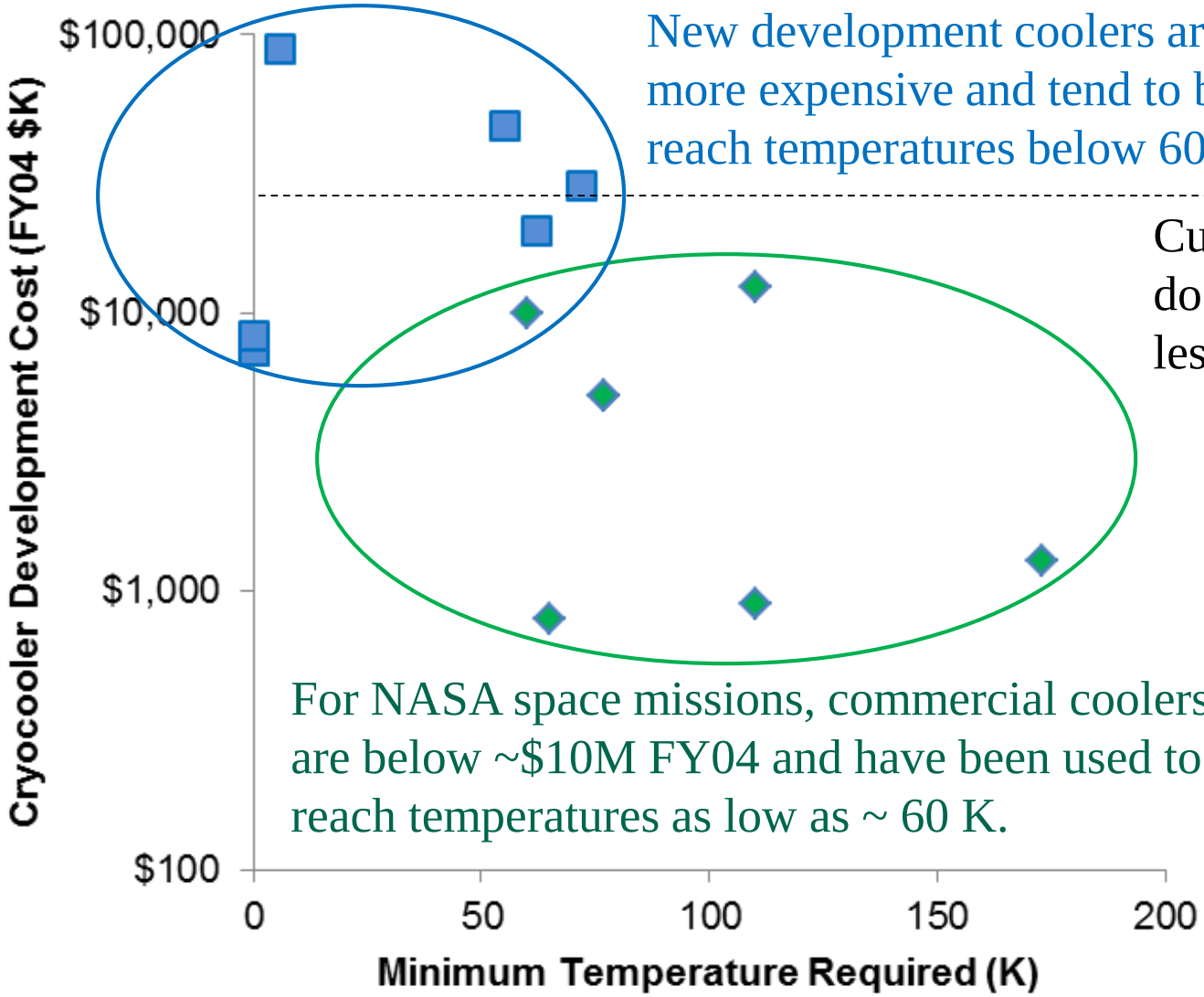


While more data and data analysis is needed, work to-date suggests cryocooler technology is a differentiating factor. For example:

- Dewars
- ADRs
- Active Heat Pumping Cryocoolers (e.g. P-T, Stirling)

Legend:
P-T: Pulse-Tube
J-T: Joule-Thomson
R-B: Reverse turbo-Brayton
ADR: Adiabatic Demagnetization Refrigeration

Commercial vs New Development Cryocoolers



New development coolers are considerably more expensive and tend to be used to reach temperatures below 60 K.

Current NICM VII CER does not let you out for less than $20M FY04.

For NASA space missions, commercial coolers are below ~$10M FY04 and have been used to reach temperatures as low as ~ 60 K.

Note: Dewars not shown on graph.

Principal Components Analysis (PCA)

- What if we could somehow look at all variables at once and determine how they are correlated?
  - Specifically, what is correlated with cryocooler cost?
- What if we could identify combinations of variables that explain the most variation in the data
  - This could help us develop a regression relationship
- What if we saw the data projected onto the primary sources of variation in the data?
  - This is another way to see how our data might be clustering
  - Different than the previous clustering technique because it factors in correlation

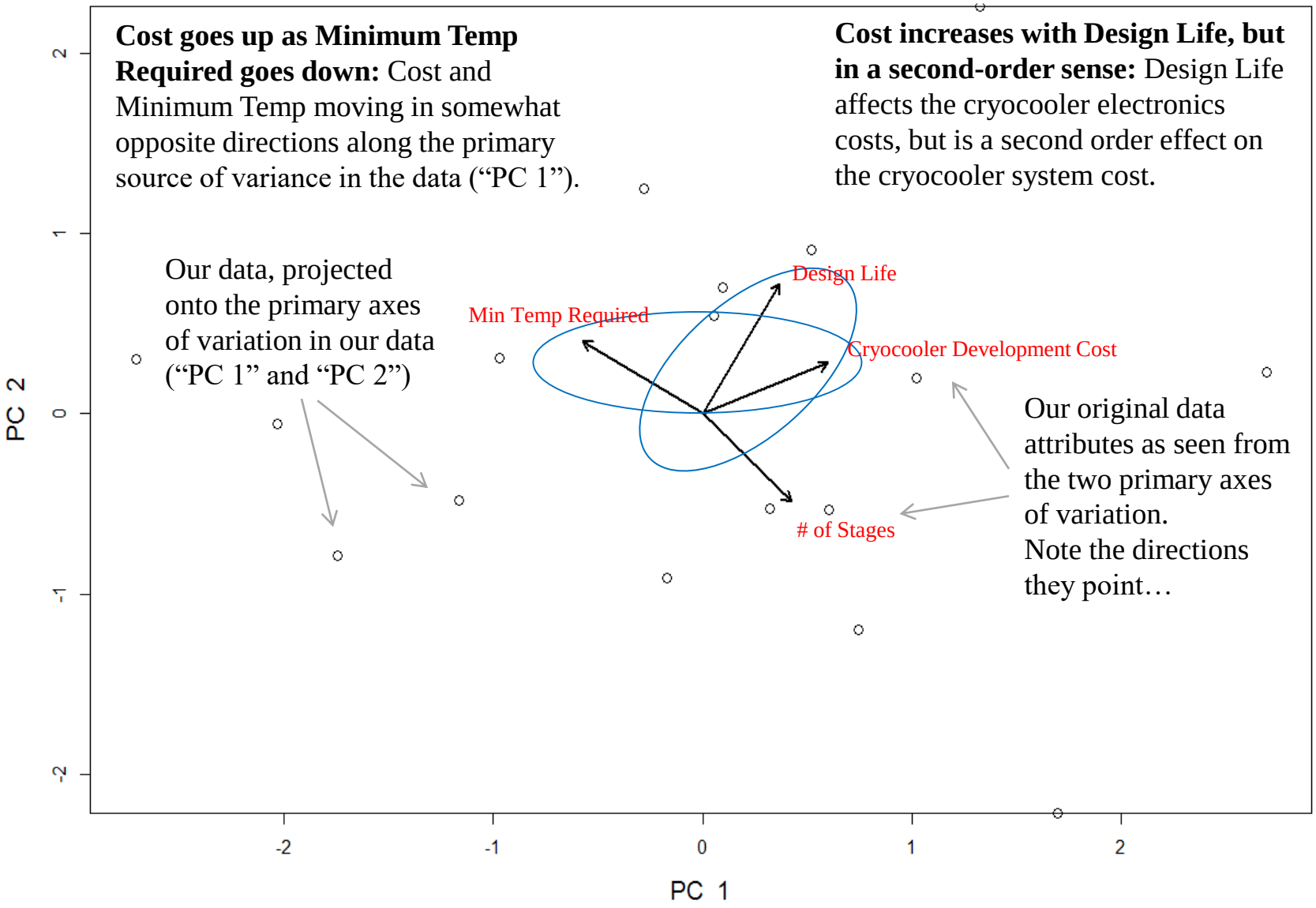
These are some of the many benefits of PCA.

Preliminary Principal Components Analysis

Cost goes up as Minimum Temp Required goes down: Cost and Minimum Temp moving in somewhat opposite directions along the primary source of variance in the data ("PC 1").

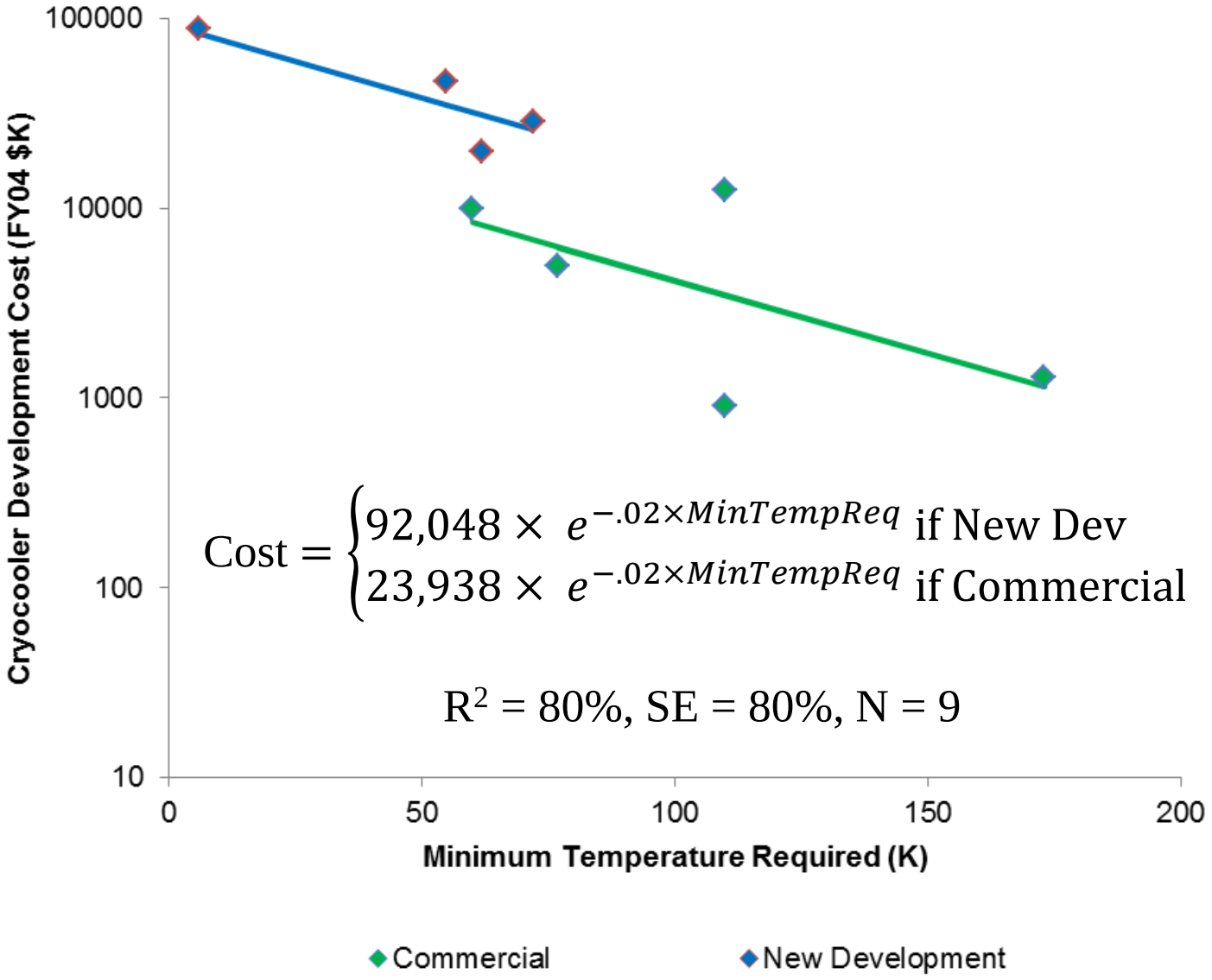
Cost increases with Design Life, but in a second-order sense: Design Life affects the cryocooler electronics costs, but is a second order effect on the cryocooler system cost.

Our data, projected onto the primary axes of variation in our data ("PC 1" and "PC 2")



Our original data attributes as seen from the two primary axes of variation.
Note the directions they point…

Preliminary Cryocooler CER



$$\text{Cost} = \begin{cases} 92{,}048 \times e^{-.02 \times MinTempReq} & \text{if New Dev} \\ 23{,}938 \times e^{-.02 \times MinTempReq} & \text{if Commercial} \end{cases}$$

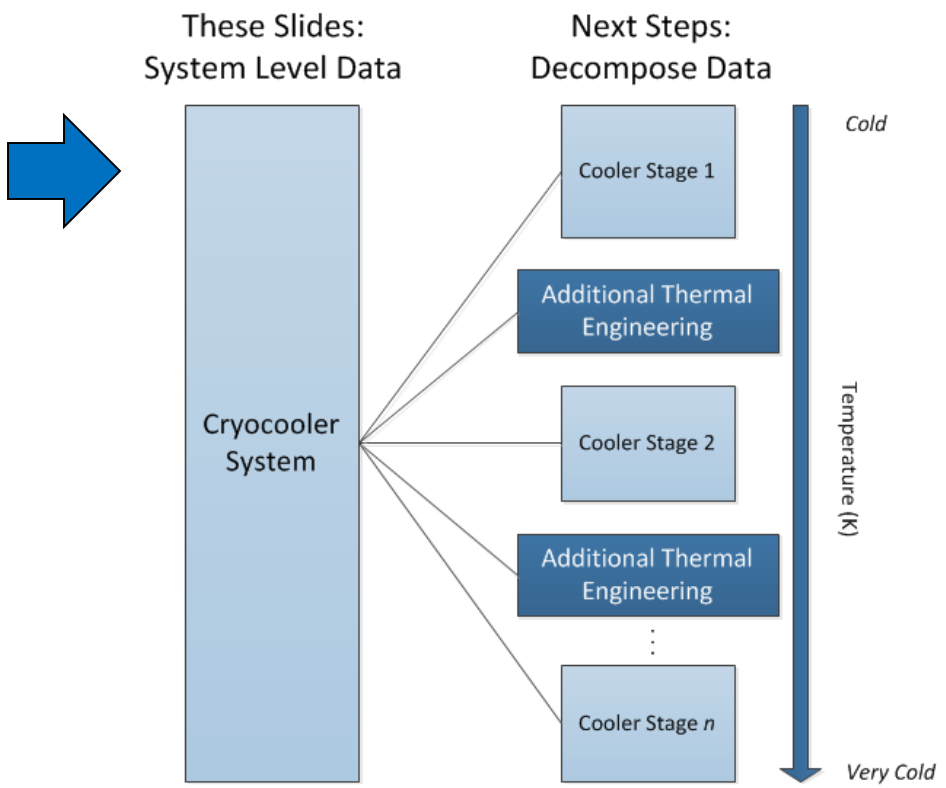
$R^2 = 80\%$, SE = 80%, N = 9

Agenda

- Cryocooler Terminology for this Presentation
- Data
- Modeling Process
- Analysis & Early Findings
- **Future Work**

Concluding Remarks & Future Work

- Top-level relationships in the data at the cryocooler system level have been observed
- Continue collecting and normalizing data
- Explore decomposing cryocooler data into individual cooler technologies and thermal engineering elements.
  - Separates the new development and commercial elements of cryocooler systems



Questions?