NICM: Cryocooler

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NASA Cost Symposium, August 2017

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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
  - Estimates cost and schedule phase breakdowns
  - 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

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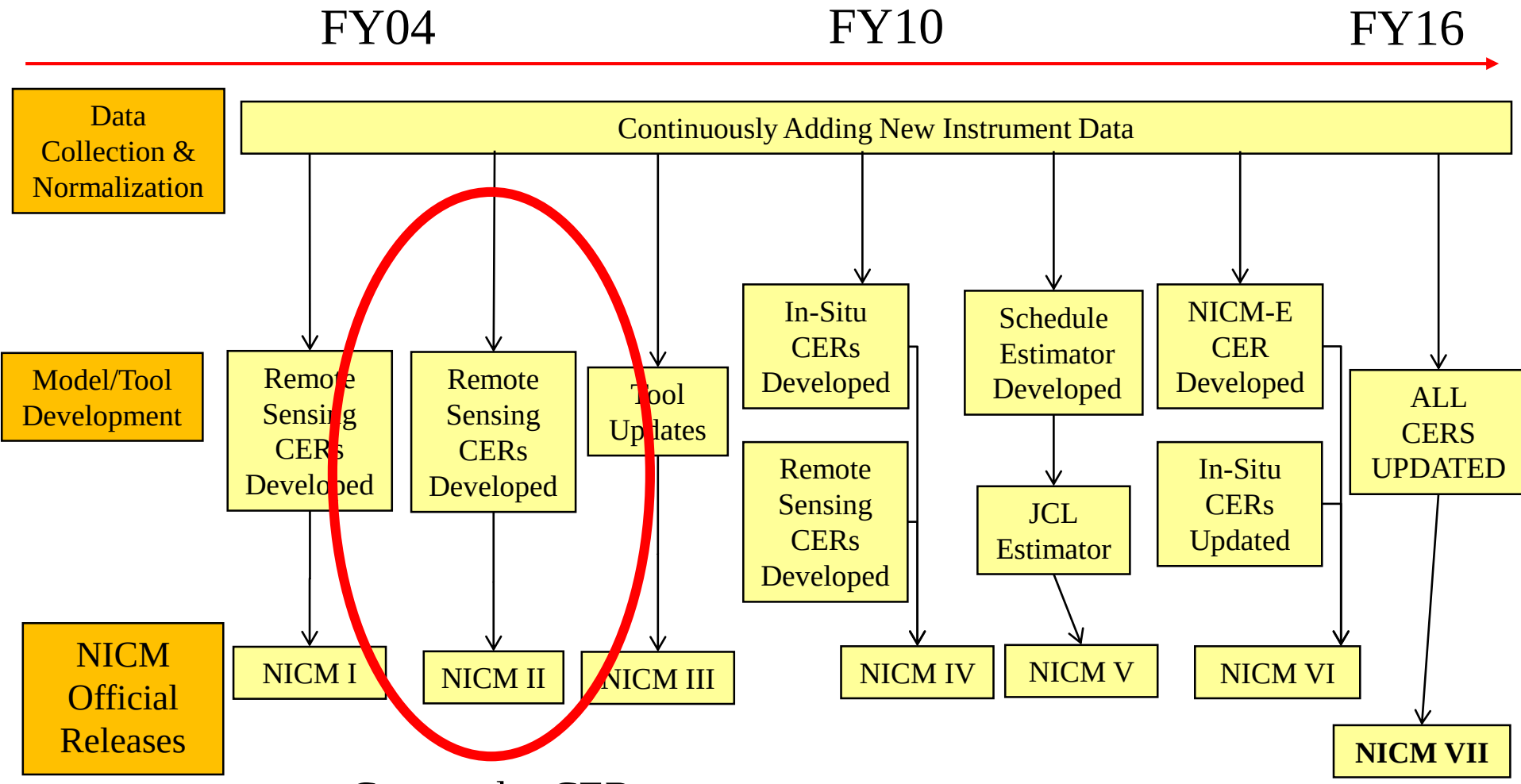
Today's Story: Cryocooler Cost Estimation



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!**

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

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

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- **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.**

NICM: Cryocooler Cost Analysis To-date

Mike DiNicola

NASA Cost Symposium, August 2017

Agenda

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

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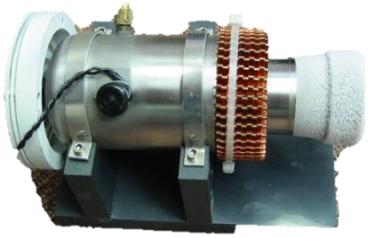
Cryocooler Technologies

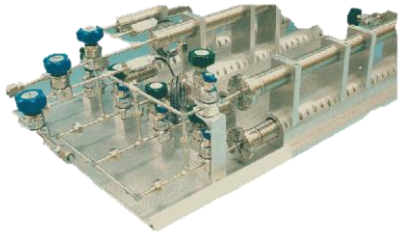
Pulse-tube Cooler
(Thales LPT6510)



Stirling Cooler
(Global Cooling
M100B)

Dewar

Reverse Turbo Bryton



Sorption Cooler

Adiabatic
Demagnetization
Refrigeration (ADR)

Joule-Thomson
(Orca Mixed Gas JT)

Cryocooler technologies used for an instrument depend on how much heat needs to be removed ("lifted"), power draw, mission duration and other environmental conditions

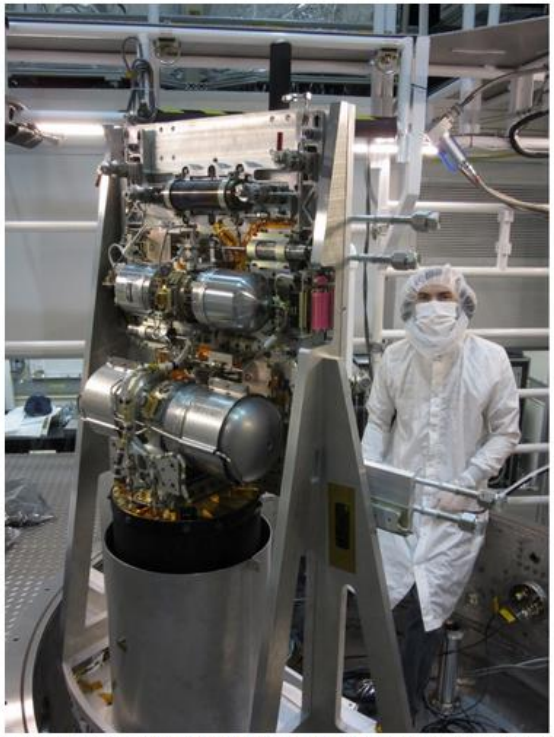
Stages & Minimum Temperature Required

- *Example*: The MIRI Cryocooler being developed for JWST has four "**stages**" to get the MIRI instrument Si:As detector to its necessary operating temperature

"Precoolers"
- Stages 1&2: Pulse-Tube technology, gets from ambient to 35 K
- Stage 3: Pulse-Tube technology, takes from 35 K to 18 K

"Cold Head"
- Stage 4: Joule-Thomson technology, gets from 18 K to 6 K

- MIRI **Minimum Temperature Required** = 6 K at the Si:As detector



The Cryocooler Compressor Assembly. This photo shows the flight one installed "upside-down" in a vacuum chamber for testing, before the chamber was closed. Credit: NASA/JPL-Caltech

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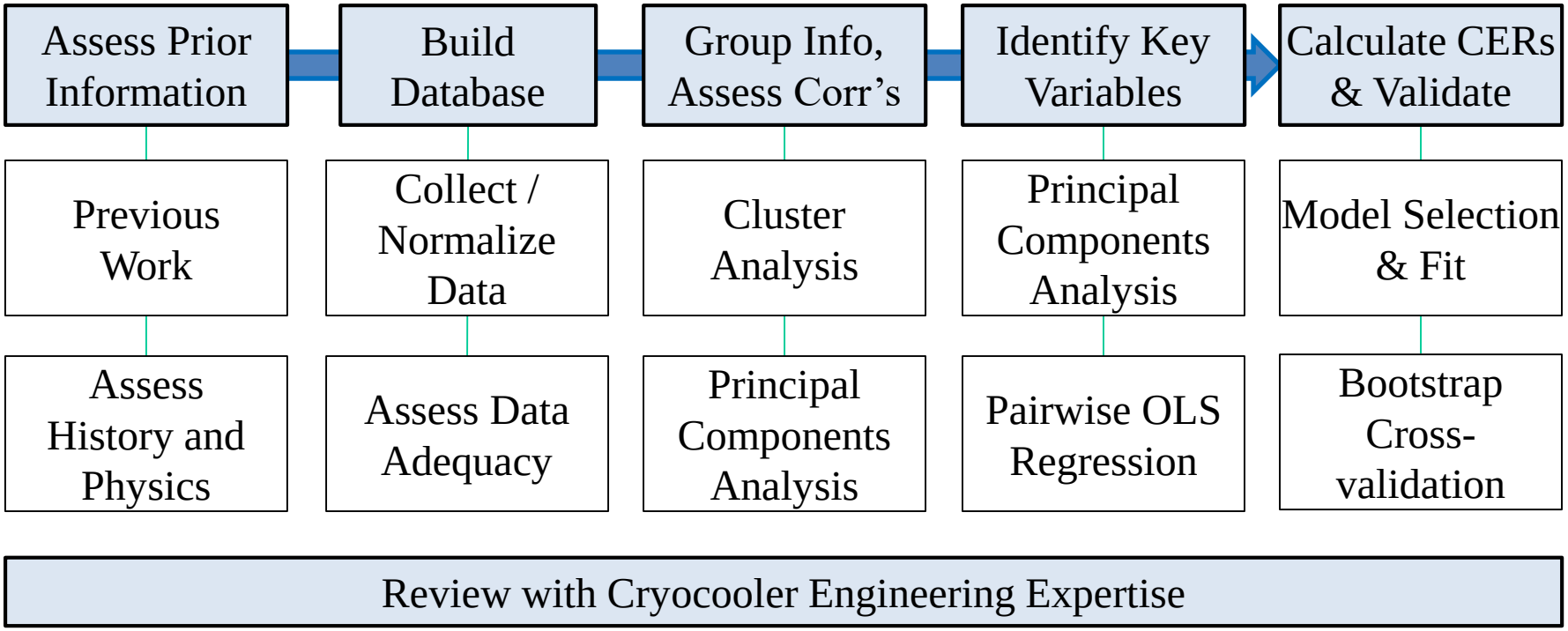
Model Development Process



- Cryocooler SMEs are a critical component to understanding the data and building the cryocooler model.
- Process allows us to approach this model development from both Classical and Bayesian perspectives.

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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 6 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
- Cost data not shown due to proprietary nature of data

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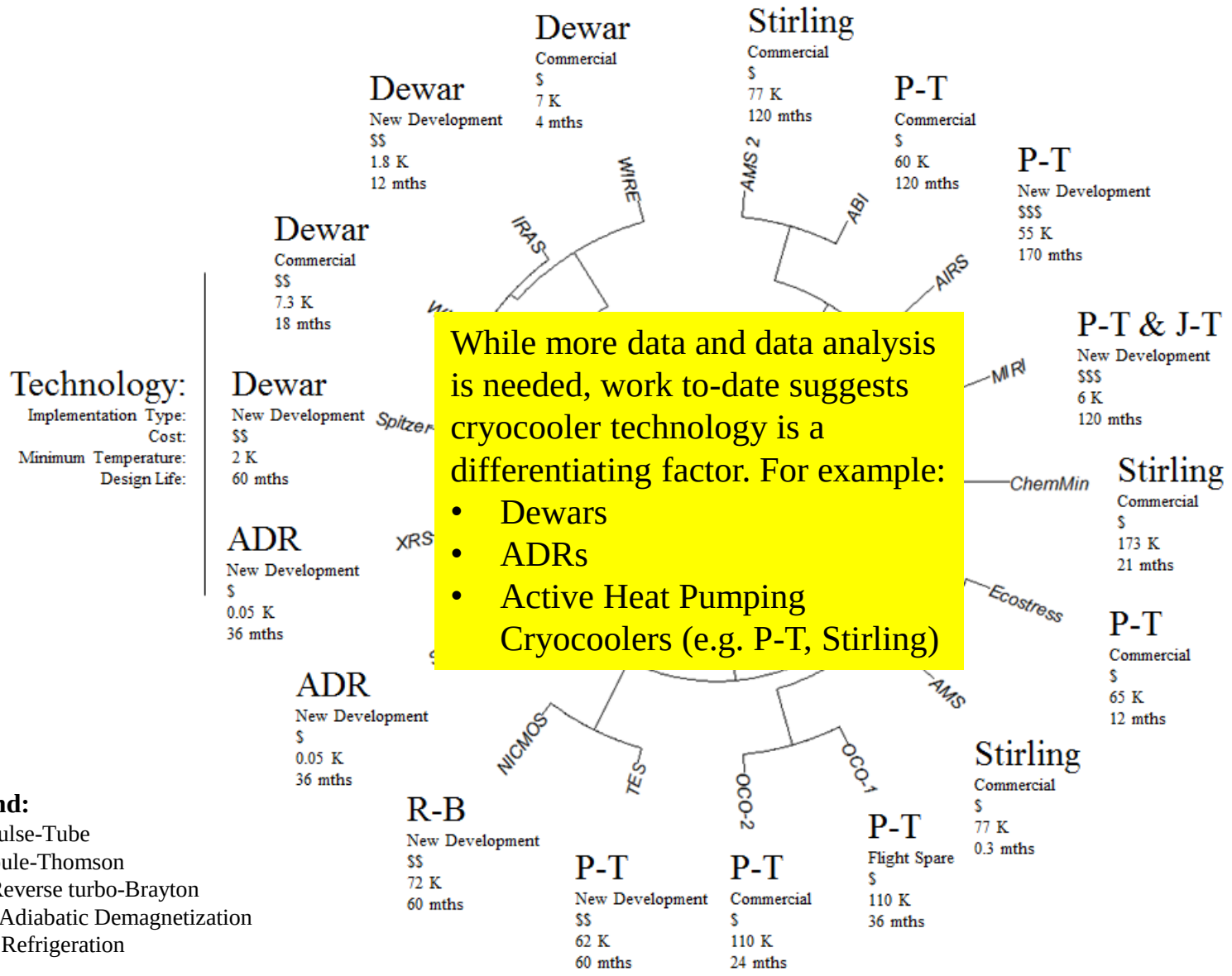
Preliminary Cluster Analysis Suggests Grouping by Cryocooler Technology



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)

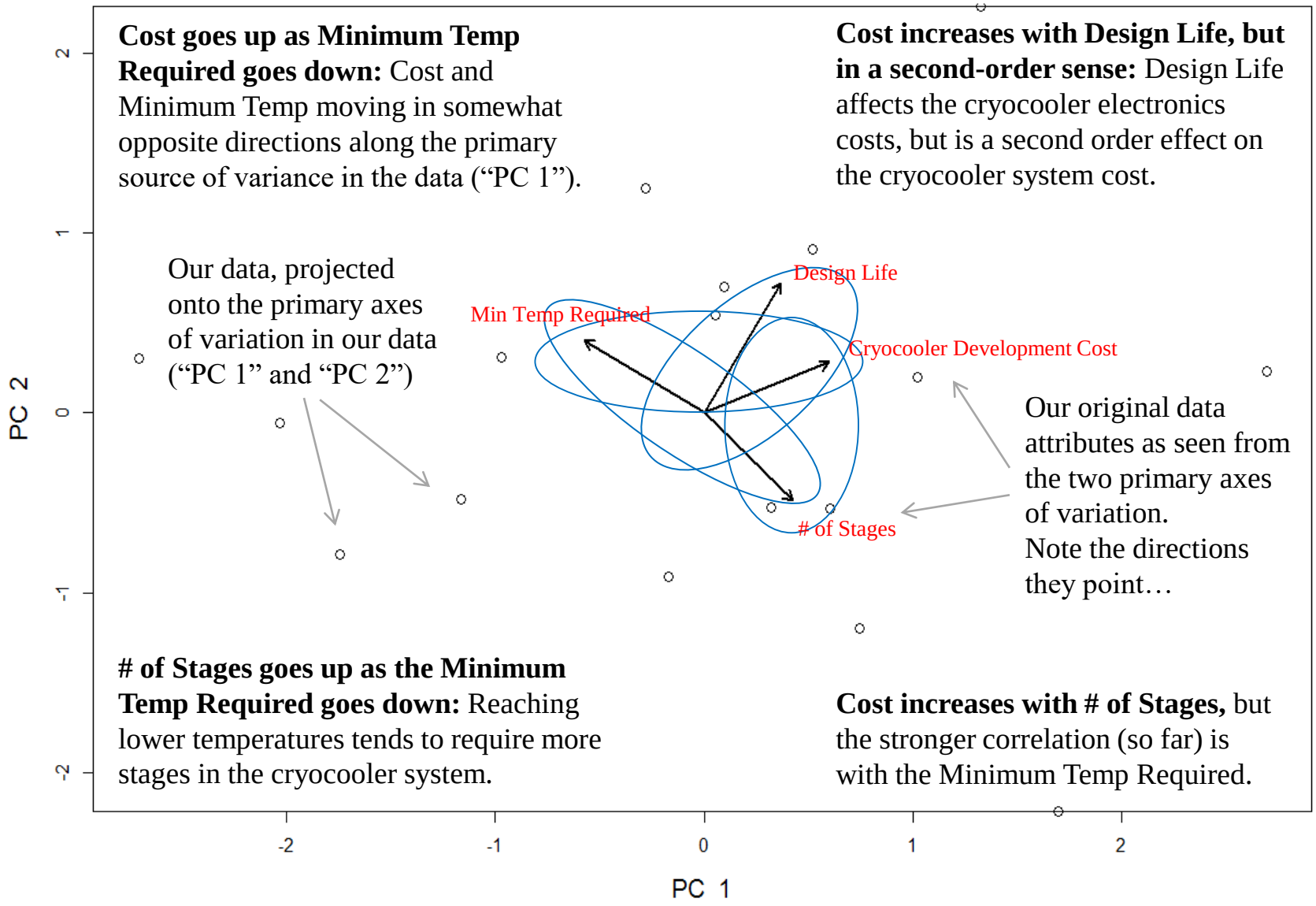
Legend:
P-T: Pulse-Tube
J-T: Joule-Thomson
R-B: Reverse turbo-Brayton
ADR: Adiabatic Demagnetization Refrigeration

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")

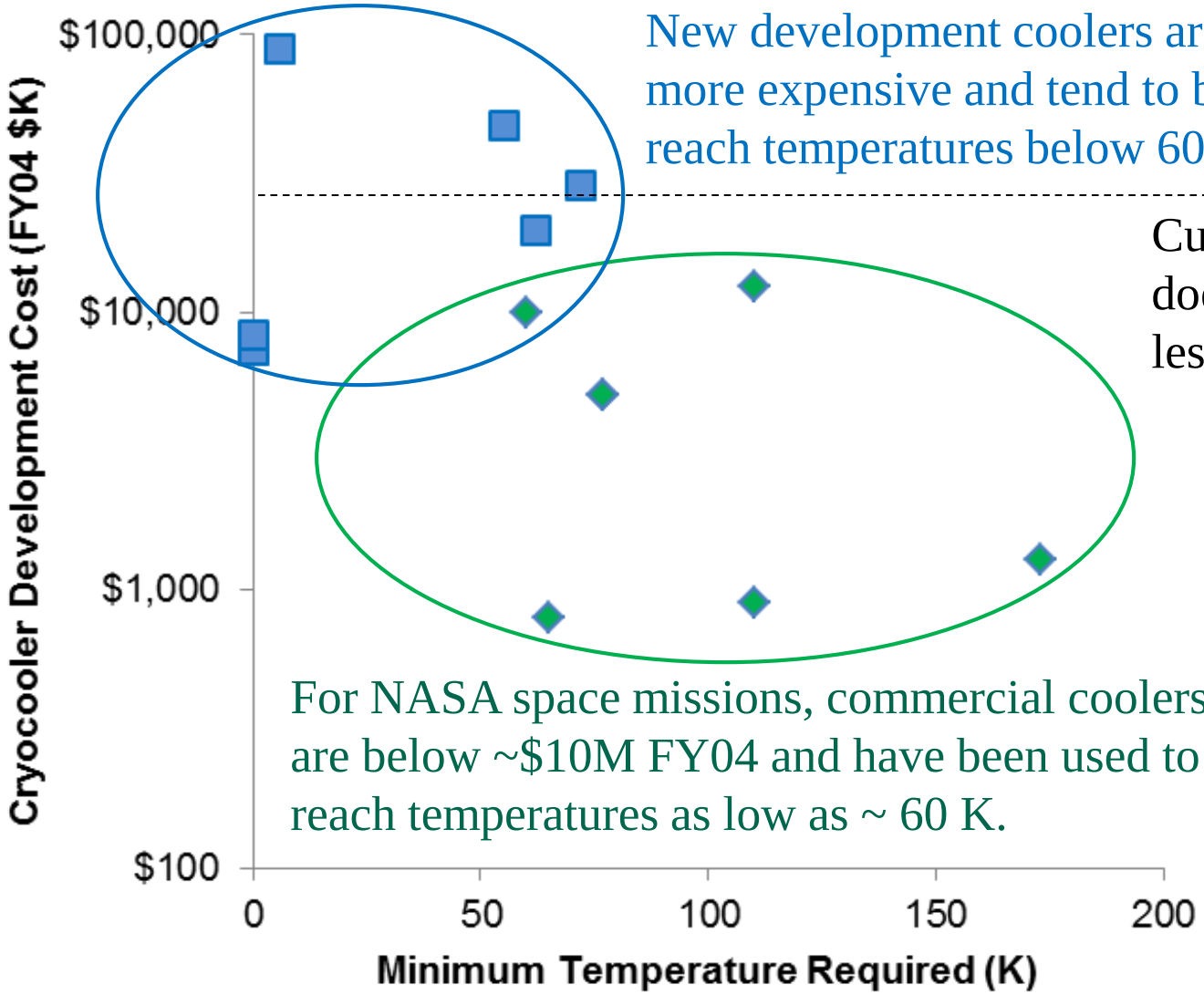


Our original data attributes as seen from the two primary axes of variation.
Note the directions they point…

# of Stages goes up as the Minimum Temp Required goes down: Reaching lower temperatures tends to require more stages in the cryocooler system.

Cost increases with # of Stages, but the stronger correlation (so far) is with the Minimum Temp Required.

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.

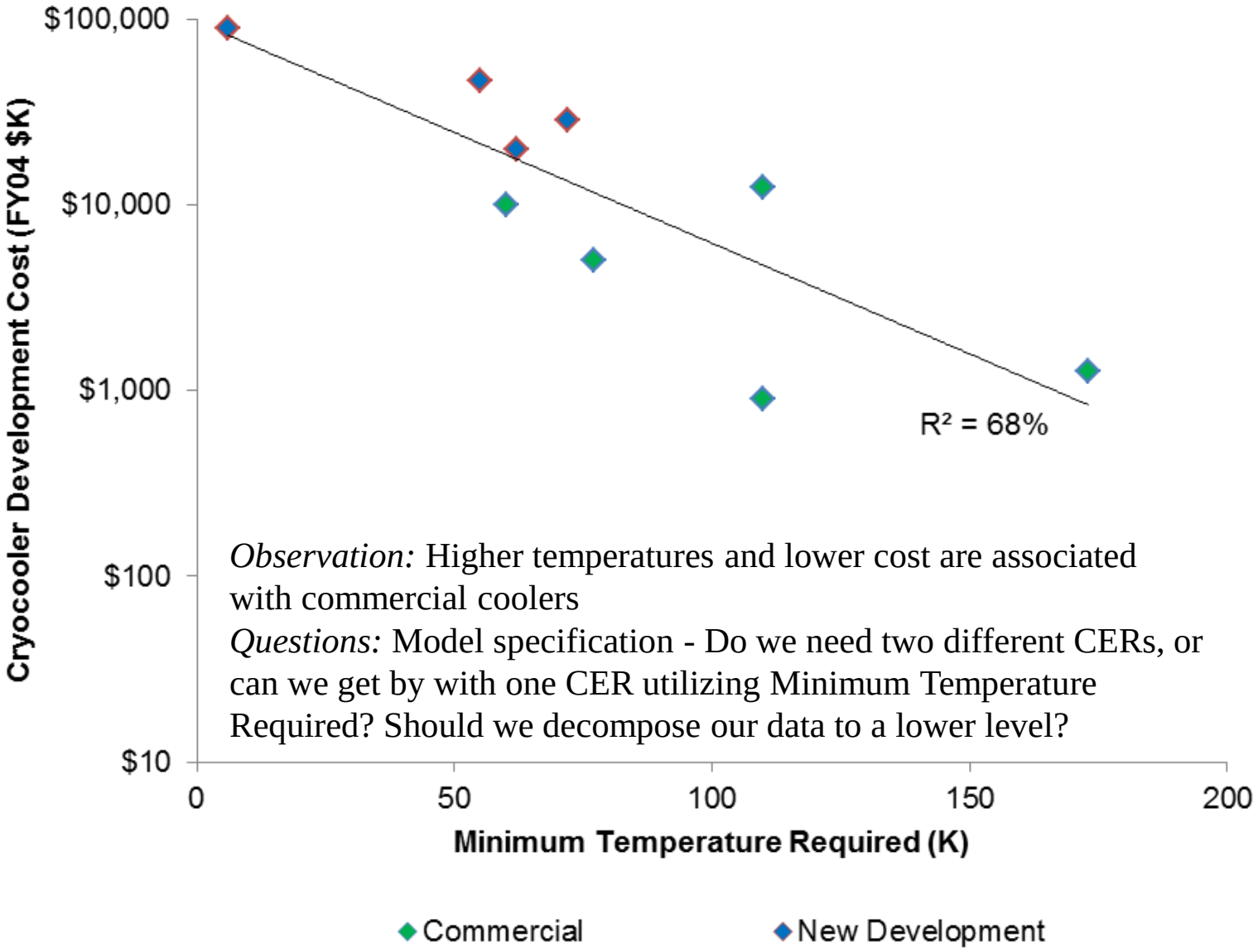
For NASA space missions, commercial coolers are below ~$10M FY04 and have been used to reach temperatures as low as ~ 60 K.

Note: Dewars not shown on graph.

Moving Towards a Regression Analysis…

- Look at the "Active Heat Pumping" systems identified in the cluster analysis
  - Most likely cooler technology employed
  - Dewars are becoming a less likely design choice for future applications
  - Not enough data for ADRs at this point in time.
- Additional data exist and are being normalized – this will feed into the analysis and NICM VIII.
- **Two CERs shown here are preliminary and meant for discussion only**
  - Only 9-10 data points to work with for this subset of cryocoolers
  - SE = "Standard Error": a measure of variance of a model given its data

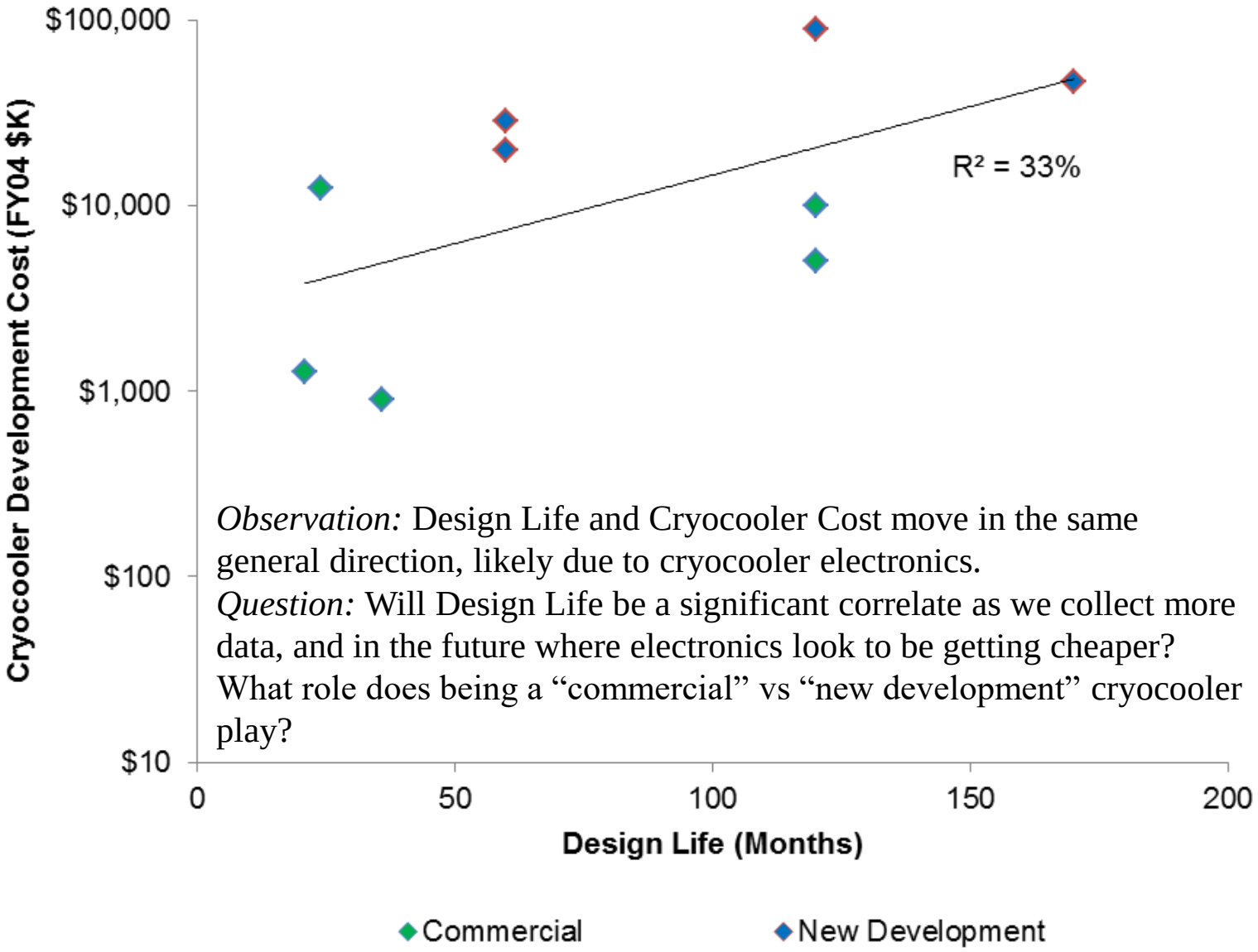
Minimum Temperature Required is a Cost Driver



Observation: Higher temperatures and lower cost are associated with commercial coolers

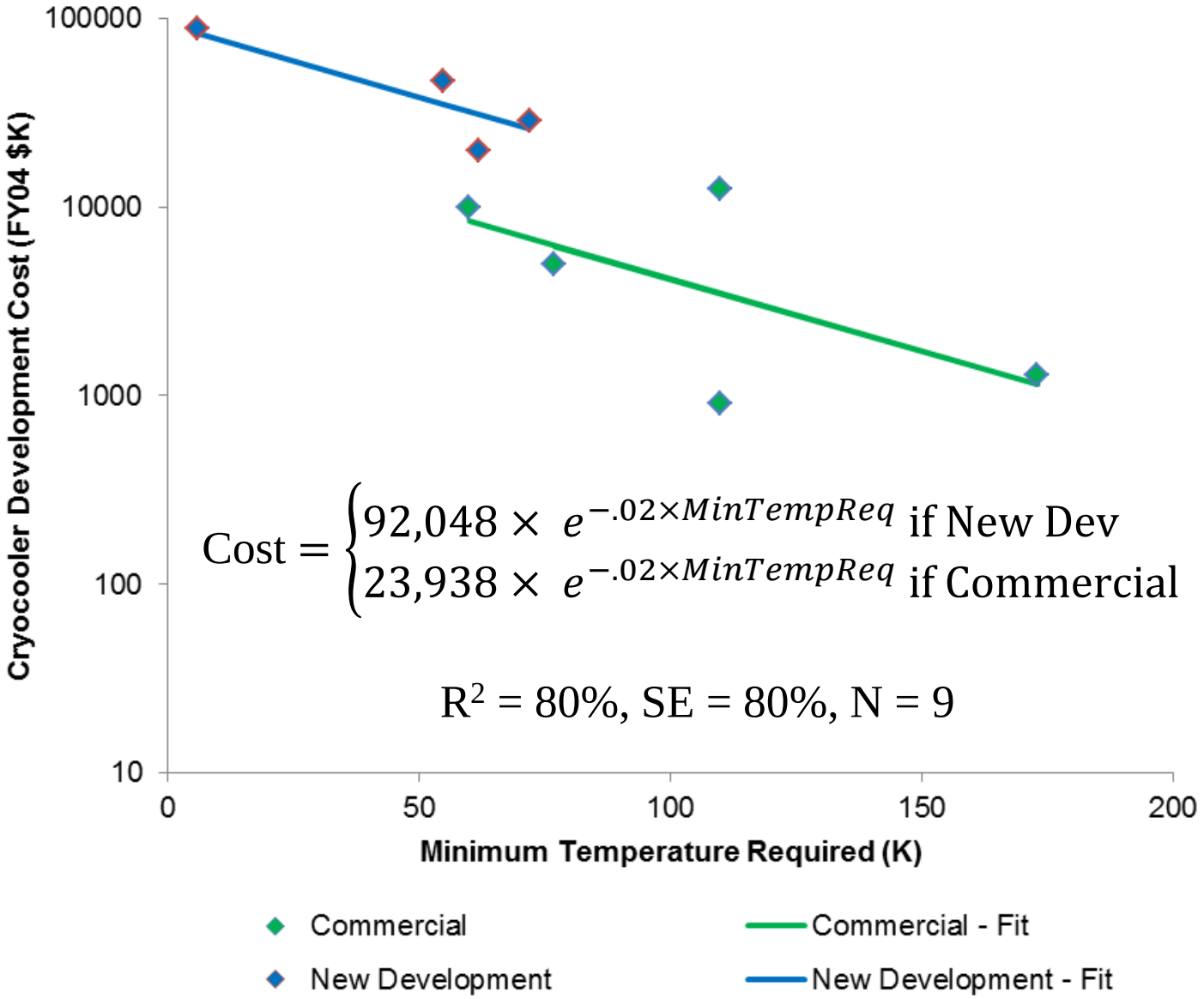
Questions: Model specification - Do we need two different CERs, or can we get by with one CER utilizing Minimum Temperature Required? Should we decompose our data to a lower level?

Design Life could be a Secondary Cost Driver



Observation: Design Life and Cryocooler Cost move in the same general direction, likely due to cryocooler electronics.
Question: Will Design Life be a significant correlate as we collect more data, and in the future where electronics look to be getting cheaper? What role does being a "commercial" vs "new development" cryocooler play?

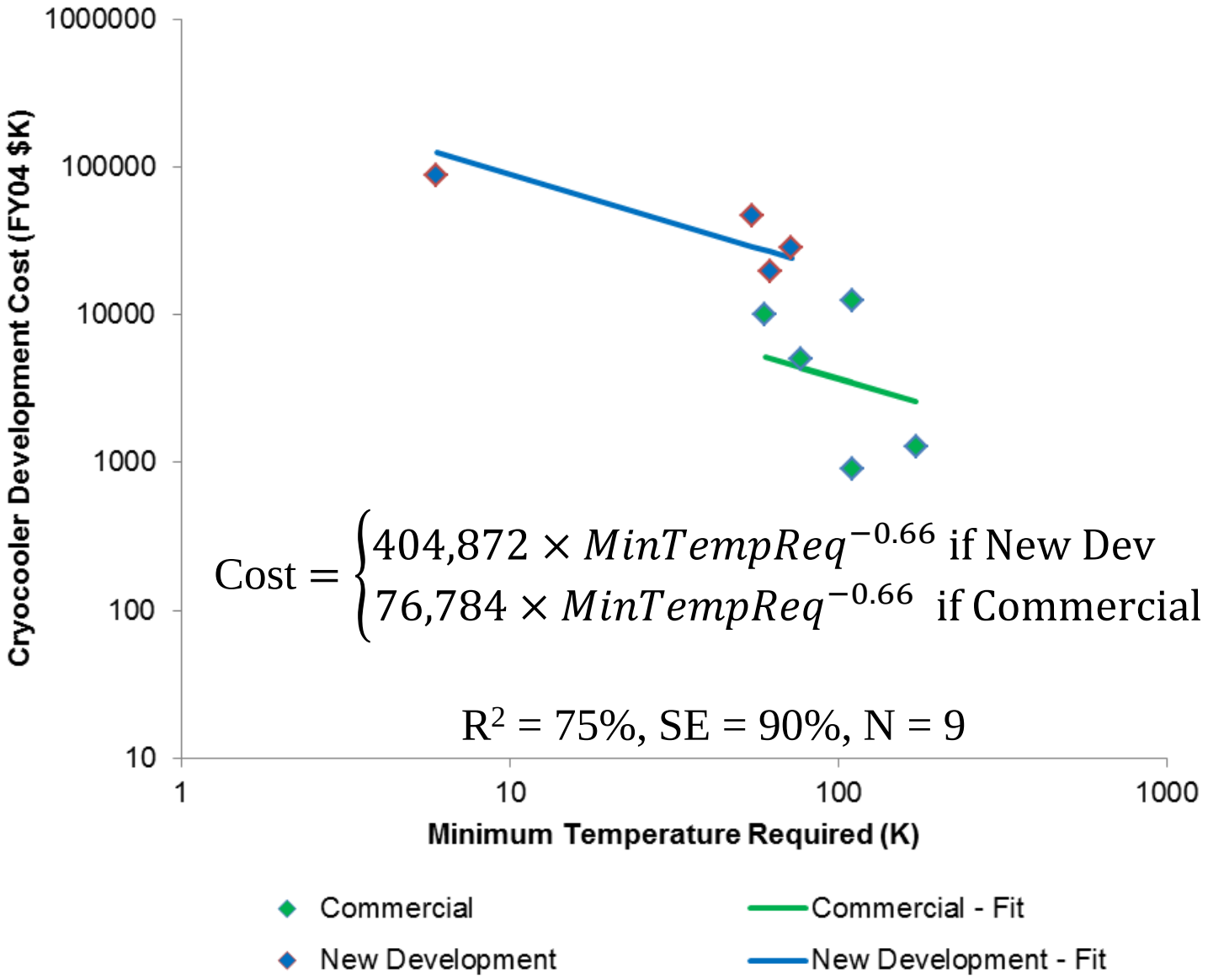
Preliminary Cryocooler CER #1



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

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

Preliminary Cryocooler CER #2



$$\text{Cost} = \begin{cases} 404{,}872 \times MinTempReq^{-0.66} \text{ if New Dev} \\ 76{,}784 \times MinTempReq^{-0.66} \text{ if Commercial} \end{cases}$$

R^2 = 75%, SE = 90%, N = 9

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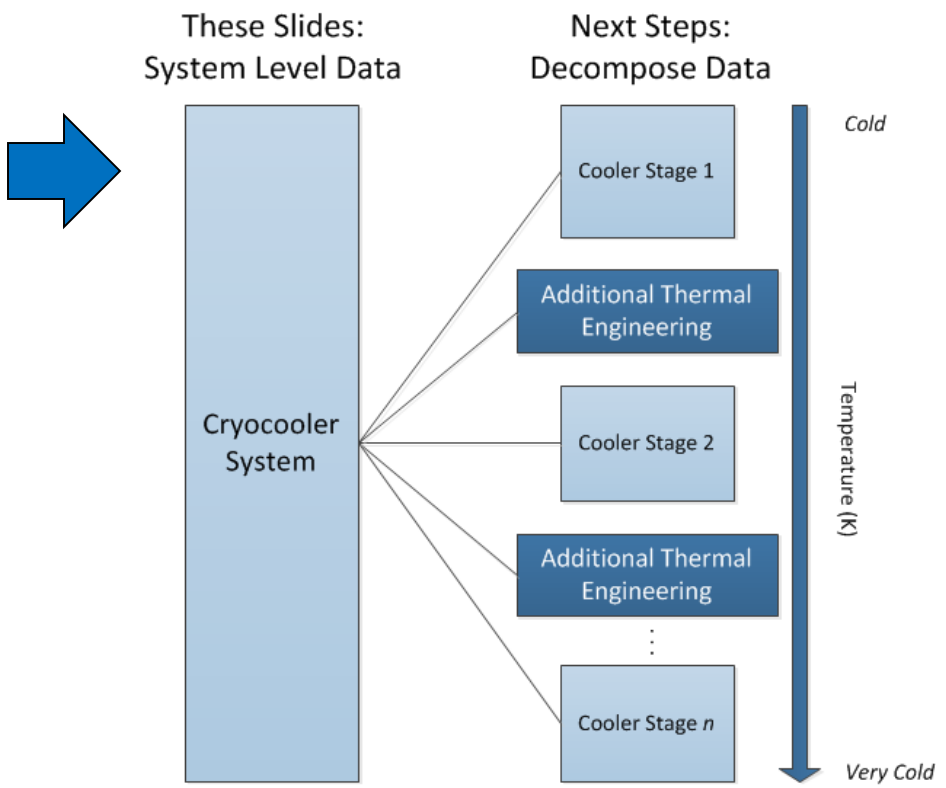
Concluding Remarks & Future Work

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

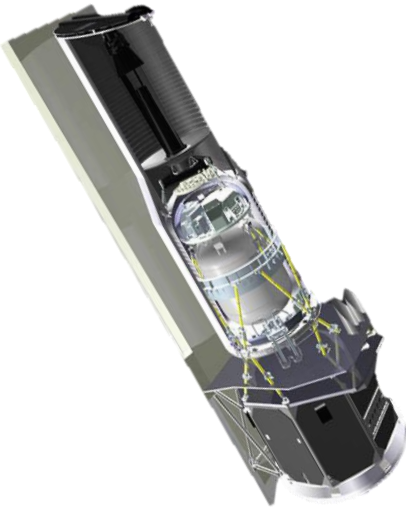


Backup

Space Cryocoolers

- Cryocoolers are critical technology for space missions operating in infrared, gamma-ray and x-ray spectrums
- Cooling technologies typically used to cool detectors
- Design challenge:
  - Minimize vibration, efficient thermal performance, and low electromagnetic interference – and of course at the lowest cost!

"Cold Finger" tip



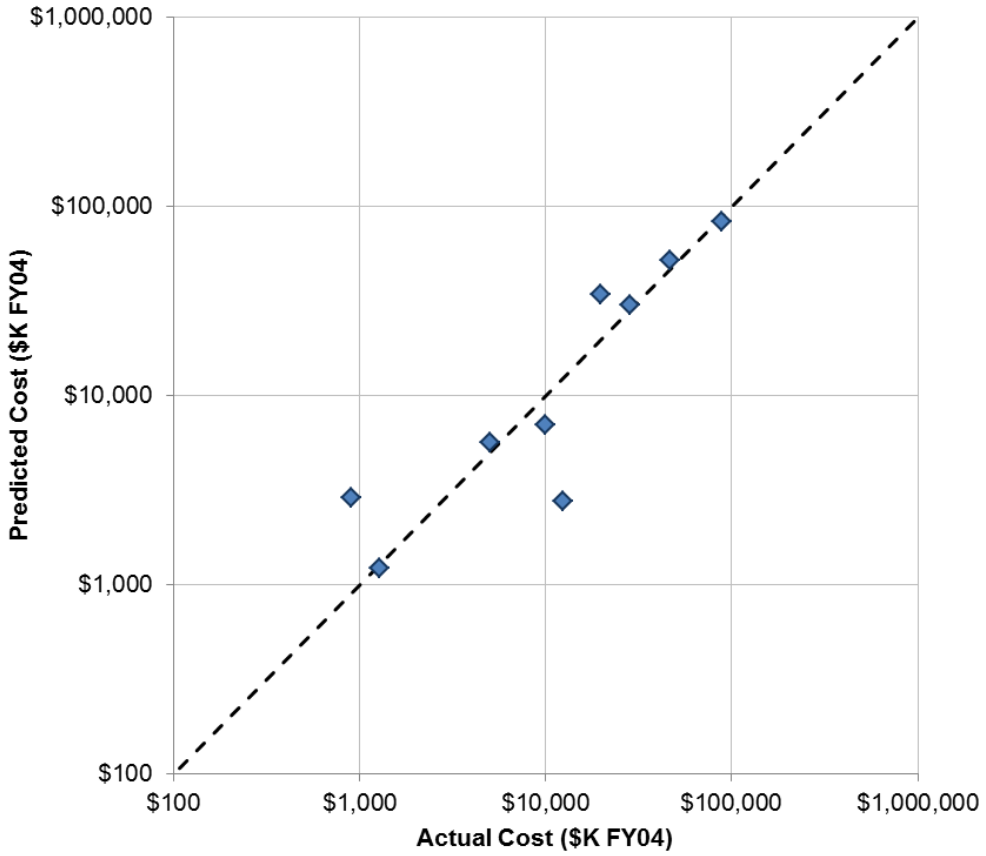
SPITZER Dewar Cryostat

JWST Cooler Assembly

Preliminary Cryocooler CER using Design Life

$$\text{Cost} = \begin{cases} 25{,}680 \times e^{-0.01 \times MinTempReq + 0.01 \times DsgnLife} & \text{if New Dev} \\ 8{,}840 \times e^{-0.01 \times MinTempReq + 0.01 \times DsgnLife} & \text{if Commercial} \end{cases}$$

R^2 = 75%, SE = 83%, N = 9



- More data needed to evaluate this CER
- Design Life is not showing statistical significance at this point in time, but needs further study

Cryocooler Cost Modeling