



Space Technology Mission Directorate Game Changing Development Program

Erica Montbach | Samuel (Adam) Howard | Dust Tolerant Mechanisms (DMDev) | Annual Review Presentation | 09.15.2022
POC: Erica Montbach erica.n.montbach@nasa.gov

Dust Tolerant Mechanisms (DTM) Overview



➤ Technology Product Capability

- Develop advanced actuator seals for rotary joints and rotary bearing technologies for long-term sustained operation in lunar dust environments

➤ Technical Capabilities

- Identify candidate rotary seal technologies for a rotary joint
- Test Volatiles Investigating Polar Exploration Rover (VIPER) Lunar Terrain Vehicle (LTV) rotary actuator seals in an environment
- Identify and test rotary bearings in a lunar environment

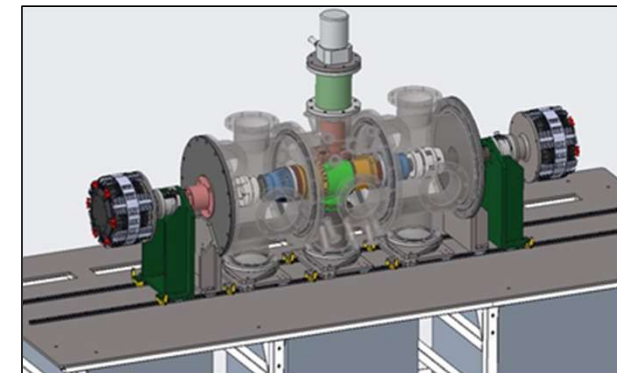
➤ Exploration & Science Applicability

- Applicable to mechanical rotary joints for space mechanisms
 - Rover wheels
 - Robotic arms
 - Antennas
 - Solar arrays
 - ISRU (drills, buckets, etc.)
- Current test platforms
 - VIPER and LTV
- Potential environments necessary
 - Lunar surface, Mars, and Gateway

FY22 Budget Reduction			
		Proposed (\$K)	Actual (\$K)
Dust Resistant Bearings	GRC	705	176
	KSC	551	92
Rotary Seals	JSC	244	0
	Total	1500	268



Bearing Test Rig Benchtop Functional Check



Large dusty, thermal vacuum chamber with dynamometer CAD model

Dust Tolerant Mechanisms (DTM) Team

Project Manager: GRC-MT/Erica Montbach

Lunar Dust Resistant Bearings

GRC

Lead Engineer: Samuel (Adam) Howard

- LMT/Samuel (Adam) Howard
- LMT/Robert Bruckner
- MT/Adam Marr

Rotary Seals

KSC

Project Manager: Jennifer Wilson
Lead Engineer: Jason Schuller

- UBE/Jason Schuler
- LASSO/Musashi Howe
- LASSO/Casey Clark
- NEL/Gabor Tamasy

JSC

Lead Engineer: Vinh Pham

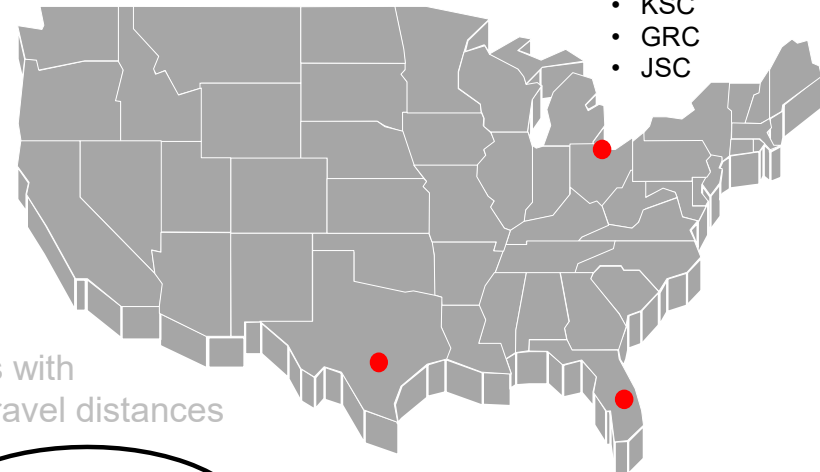
- ER/Vinh Pham
- ER/Ryan Stockton

Collaborations & Partnerships



NASA Centers

- KSC
- GRC
- JSC



➤ Infusion/transition plan

▪ Target applications

- Lunar dust resistant bearings:
 - EVA Suit, Pumps, Motors, Gearboxes, Mobility Systems, Robots, and Prospecting and Extracting equipment for ISRU
- Rotary seals:
 - Novel designs create custom test equipment
 - Increase lifetimes of sensitive mechanical joints and bearings with novel rotary seals as demanded for vehicles like LTV (must travel distances (11,000km) ~550x farther than previous efforts)

Rotary seal work paused due to budget reductions

▪ NASA missions impacted

- The Moon, Mars, Others Inside the Solar System, Foundational Knowledge, Artemis, Volatiles Investigating Polar Exploration Rover (VIPER), Lunar Terrain Vehicle (LTV), Exploration Extravehicular Mobility Unit (xEMU), Lunar Surface Manipulation System (LSMS), Robotic Excavation, Extravehicular Activity (EVA), Gateway, Ascent/Descent Elements, Habitats, Lunar Crew Module, Robotic Systems

Dust Tolerant Mechanisms Technology Goals & Project Objectives



DTM Technology Goals

Goal #1	Identify candidate rotary seal technologies for a rotary joint. Rotary Seals (RS)
Goal #2	Develop and demonstrate rotary actuator seals in a representative lunar environment. (RS)
Goal #3	Develop and demonstrate rotary bearings in a simulated lunar environment. Bearings (B)

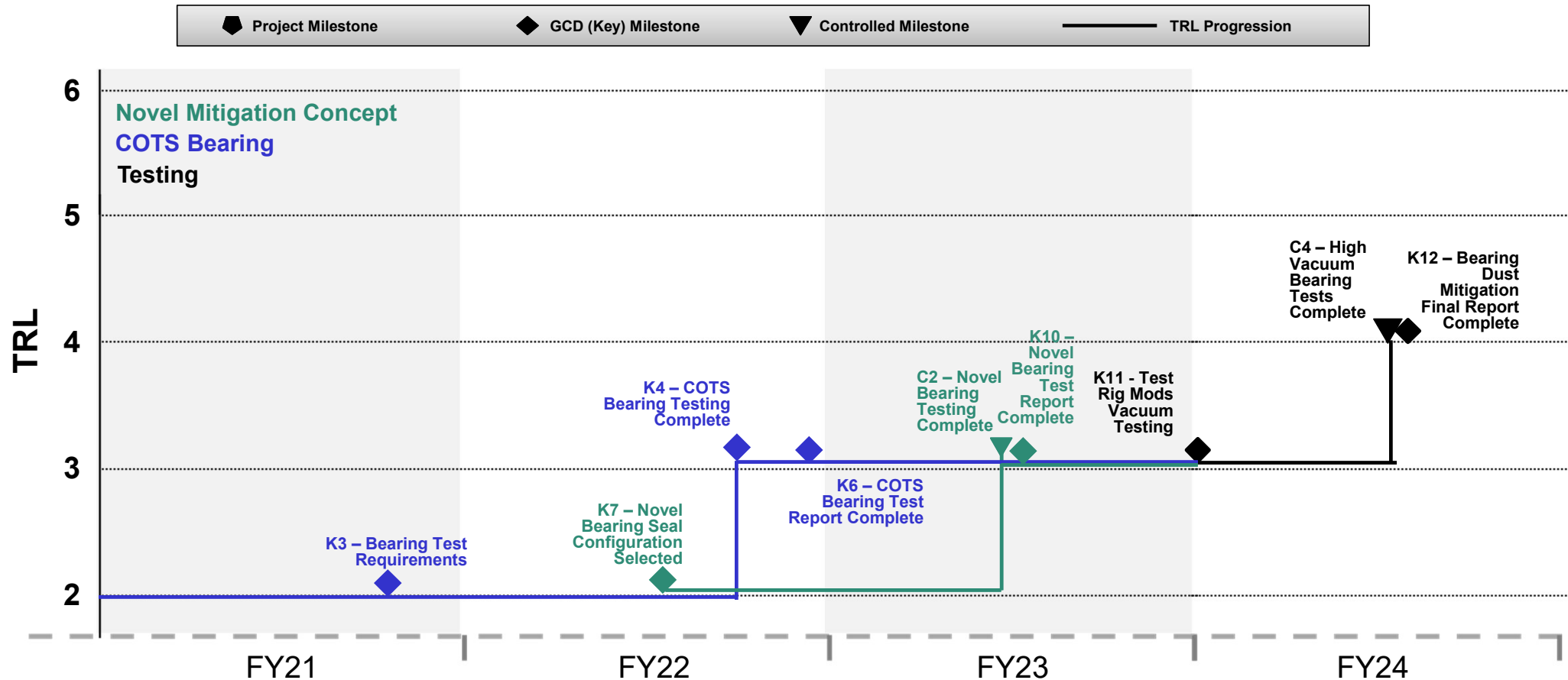
DTM Project Objectives

Objective #1	Determine the LTV operational lifetime of the propulsion actuator. (RS)
Objective #2	Determine the environmental conditions needed to test the operational lifetime of the VIPER and LTV actuators (temperature and pressure, etc.). (RS)
Objective #3	Determine how much regolith the actuator is expected to be exposed to and how to mimic that during testing. (RS)
Objective #4	Identify and performance test, including margin, advanced technologies/strategies to modify rotary seals to increase life expectancy in the presence of lunar dust. (RS)
Objective #5	Investigate and quantify the degree of dust infiltration in (grease-packed) space mechanism bearings using COTS and best practice sealing technologies. (B)
Objective #6	Identify and performance test advanced technologies/strategies to reduce dust infiltration and/or increase life expectancy of space mechanism bearings in the presence of lunar dust. (B)

Rotary Seals Task was paused in FY22 as part of Budget Cuts*

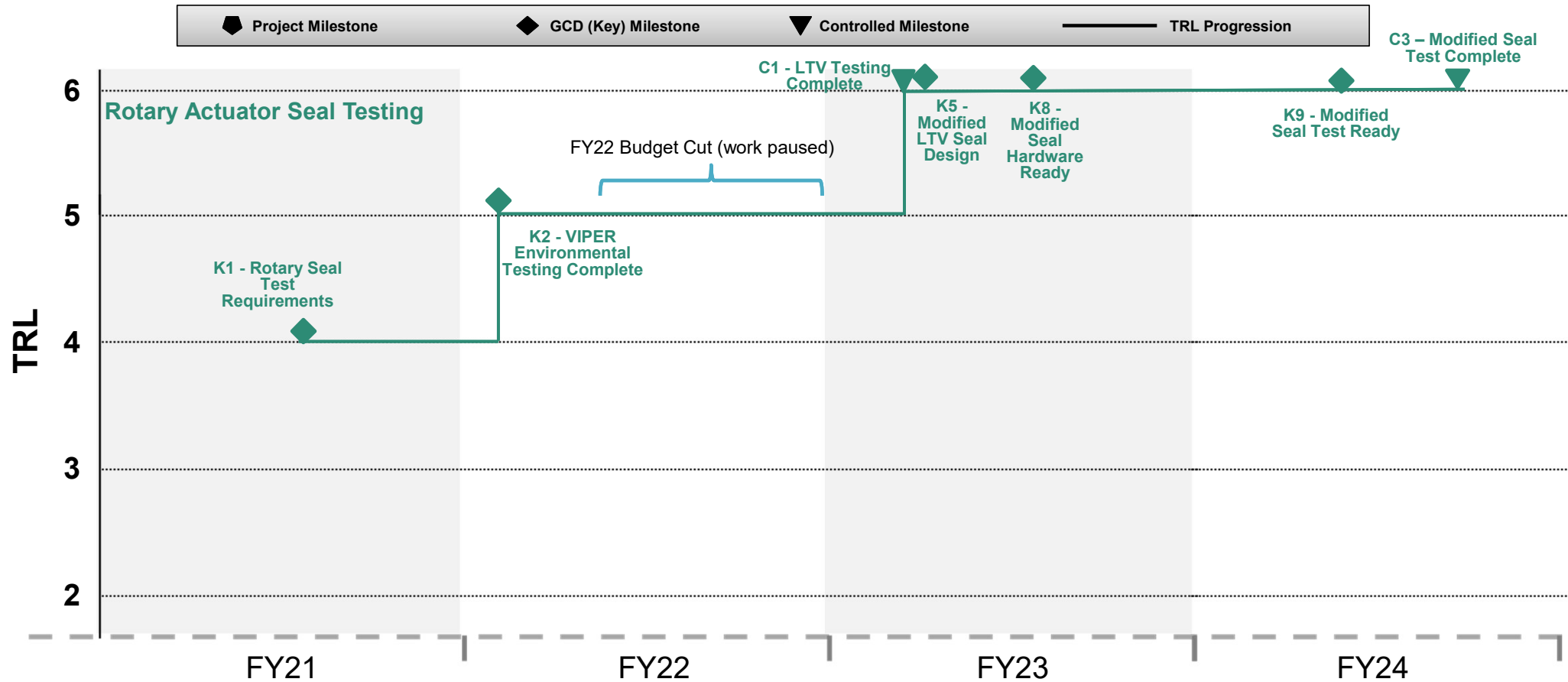
DM Dev: Dust Tolerant Mechanisms - Bearings

TRL Lifecycle



DM Dev: Dust Tolerant Mechanisms – Rotary Seals

TRL Lifecycle



Accomplishments



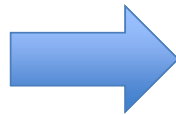
➤ Dust Mitigation for Lunar Bearings:

➤ New Bearing Inspector procured, installed, and in use in lab (*no simulant*)

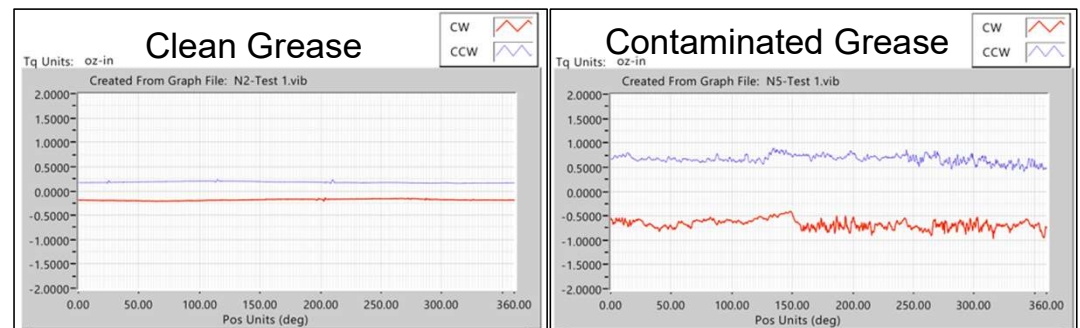
- Vibrac Precision Test Systems - Bearing Inspector II: High precision torque measurements of bearings.
- Utilized for pre-test torque evaluation of pristine bearings, followed by post-test evaluation of contaminated bearings
 - Characterize absolute torque of a clean bearing for a given configuration
 - Characterize absolute torque of a contaminated bearing
 - Characterize degree of impact of dust infiltration – i.e. change in torque after exposure
 - Characterize relative torque between different configurations, and relative effect of contamination on torque for various configurations – i.e. relative effectiveness of various dust mitigation strategies



Vibrac Bearing Inspector at GRC



Representative Bearing Inspector Torque Data

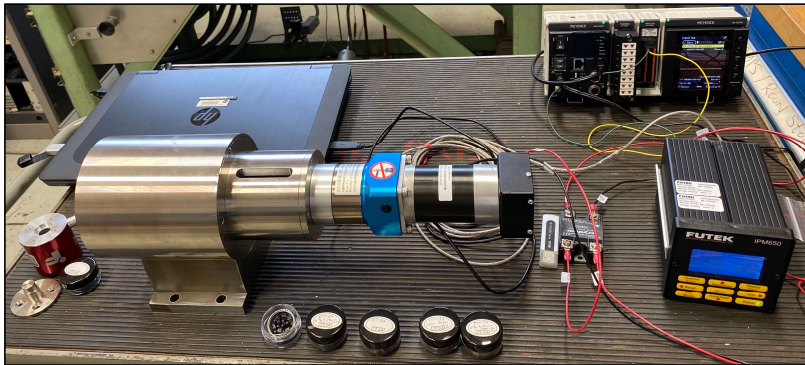


Accomplishments

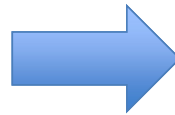


➤ Dust Mitigation for Lunar Bearings:

- A second new equipment Bearing Test Rig designed and built at GRC for exposing bearings to lunar simulant
 - Custom test rig with a simulant chamber exposes a rotating bearing specimen to lunar simulant while monitoring and recording torque as a means of condition monitoring
 - Characterize the change in torque over time as a bearing is exposed to simulant
 - Characterize differences in frictional loss (efficiency) of various mitigation strategies
 - Characterize effectiveness of mitigation strategies as they evolve in time (on order of millions of revolutions possible)



Bearing Test Rig on Benchtop at GRC
(permanent table mounting in process)



Representative Bearing Torque Evolution Over Time (~1,000,000 cycles)



Bearing after Testing in Simulant Chamber



Torque vs. Time for This Bearing

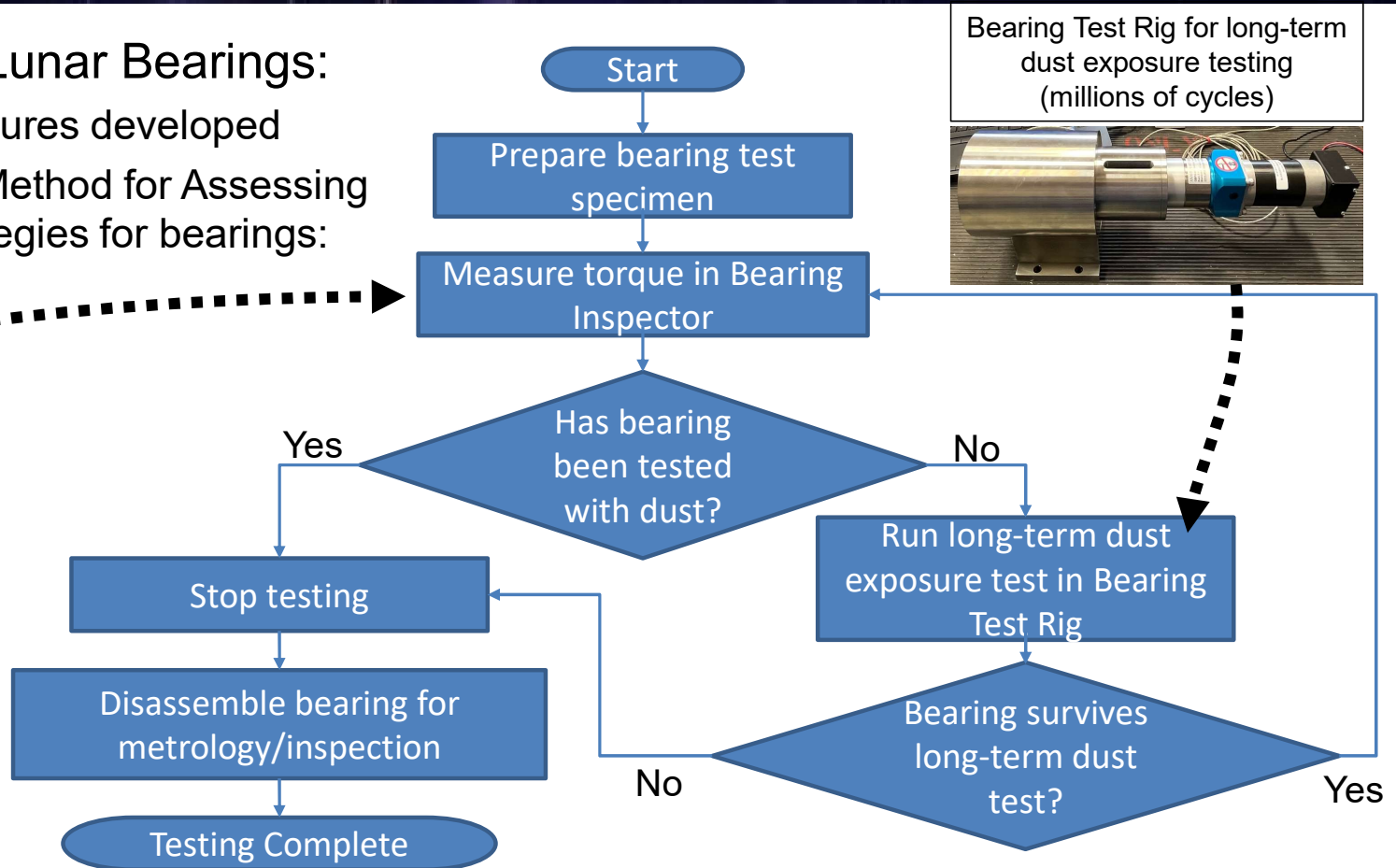
Accomplishments



- Dust Mitigation for Lunar Bearings:
 - Test Method/Procedures developed
 - Flow Chart of Test Method for Assessing dust mitigation strategies for bearings:



“Bearing Inspector” instrument for measuring start-up and rotational torque with high precision



Bearing Test Rig for long-term dust exposure testing (millions of cycles)

Accomplishments



➤ Dust Mitigation for Lunar Bearings:

- COTS bearing test completed July 29, 2022 - K4 milestone
- Three common bearing configurations (sealed, shielded, open) tested
 - Demonstrates capability of the test method to discern relative dust mitigation effectiveness
 - Serves as a baseline for comparison to future mitigation concepts
 - Technical report in progress

Data below is from custom Bearing Test Rig in Lunar Simulant

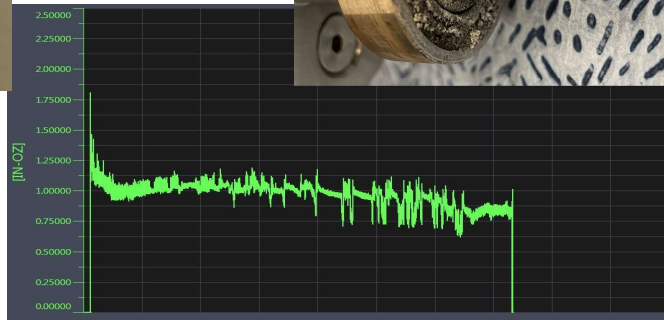
Sample Results, Post-test Images:

Bearing with Rubber Seal



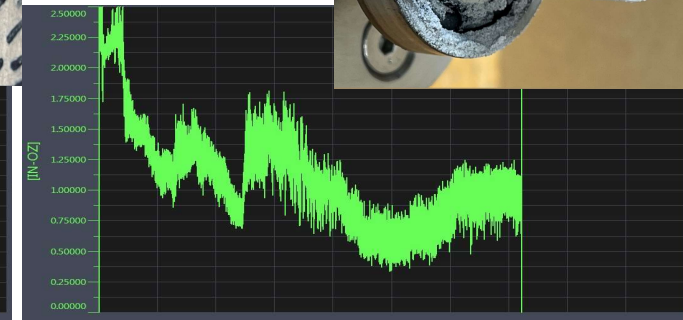
Time (72 Hrs ~ 1,000,000 revs)

Bearing with Metal Shield



Time (72 Hrs ~ 1,000,000 revs)

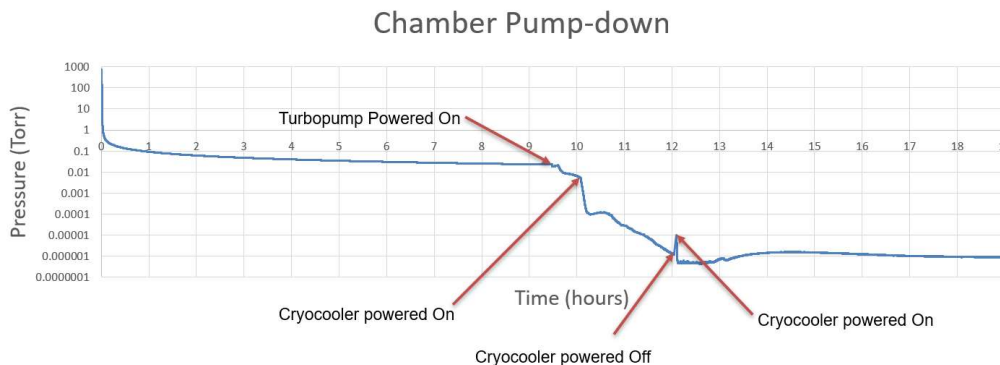
Open Bearing (no Seal or Shield)



Time (72 Hrs ~ 1,000,000 revs)

Accomplishments

- DTM – Rotary Seals - Work paused in April 2022 due to FY22 budget cuts
 - Multitude of software updates completed to allow easier and more efficient testing of actuators in a “dirty” thermal vacuum environment
 - Turbopump and cryo-pumping now allow the chamber to pump down to $\approx 10E-6$ torr over ~ 8 hours



Chamber pump down data indicates now able to reach 10^{-6} Torr by including turbopump and cryocooler.



Dusty Vacuum chamber for dynamic seal testing at KSC GMRO Lab 12

Accomplishments



➤ DTM – Rotary Seals

- Mechanical Updates:
 - After initial testing and before state-of-the-art testing, Lunar Terrain Vehicle (LTV) actuator seized on both sides.
 - It was determined through disassembly and inspection that simulant was not the cause, as no simulant entered through the seals.
 - Further disassembly of the actuator found the root cause of seizing was due to the first stage planetary gears failing on both sides.
 - Closer inspection is ongoing to determine the nature of the failures.
 - Replacement gears have been ordered.



Seals at the LTV actuator outputs removed to check for any simulant inside.

Project Assessment Summary



Project Name	Performance				Comments
	C	S	T	P	
Mid Year	Y	R	Y	Y	<p>Technical – Incredible descope of efforts due to significant budget cut will adversely impact the reach of research activities to contribute to a sustained lunar presence.</p> <p>Cost – Dramatic cuts in CR budget and FY22 budget will significantly impact work across all tasks.</p> <p>Schedule – Dramatic cuts in CR budget and FY22 budget will require milestones to be shifted or removed entirely.</p> <p>Programmatic – Project life-cycle extended.</p>
Annual	R	Y	G	R	<p>Technical – No technical issues.</p> <p>Cost – Significant FY22 budget cuts halted rotary dust seal work (KSC, JSC), Lunar dust resistant bearings work reduced to 0.6FTE.</p> <p>Schedule – Schedule for lunar dust resistant bearings has been shifted due to budget cuts by 6 months.</p> <p>Programmatic - Program life-cycle shifted out due to budget cuts.</p>

Plans Forward and Transition / Infusion Plan



Infusion/transition plans:

➤ **Current Infusions**

- VIPER and Lunar Terrain Vehicle (LTV)

➤ Results from the VIPER and LTV tests will be used to inform any modifications necessary to the sealing system for future actuators.

➤ Successful dust mitigation strategies for bearings will be available for future missions.

➤ **NESC – Mechanical Systems Presentation**

- Bearing test procedure and interim results of COTS bearing testing with simulant exposure will be presented to the NASA NESC Mechanical System Technical Discipline Team (govt/industry group of SMEs) for status/discussion.

➤ **Potential infusion** of both seals and bearings into actuator projects including:

- Motors for Dusty and Extremely Cold Environments (MDECE)
- SBIR Phase IIE: Distributed Extreme Environments Drive System (DEEDS)

Education/Public Outreach



EPO Involvement

- Attended the Society of Tribologists and Lubrication Engineers 2022 Annual Meeting, Orlando, FL May 15-19
 - Presented interim bearing data from “dirty” lubricant tests
 - “Lunar Dust Effects on Space Mechanism Ball Bearings for Sustained Human Lunar Operations”
 - Presentation was very well received, with significant industry interest in continued work

EPO Calendar Outlook (High Priorities):

30 Day Look-Ahead	
Lunar Surface Innovation Consortium (LSIC) – Dust Mitigation monthly meeting	Sept. 22
60 Day Look-Ahead	
Lunar Surface Innovation Consortium (LSIC) – Dust Mitigation monthly meeting	Oct. 15
ASCEND conference	Oct. 24-26

Summary



➤ Accomplishments

- Rotary Seals
 - Completed evaluation of VIPER wheel actuator in dusty, cold environment.
 - Evaluated LTV actuator in dusty, cold environment using recently developed larger, modular test rig.
- Dust Resistant Bearings
 - Vibrac Precision Test Systems - Bearing Inspector II procured and in use to evaluate bearings with high precision torque measurements.
 - Custom Bearing Test Rig - designed, fabricated and in use to evaluate rotating bearings with lunar simulant while monitoring torque as a key bearing performance metric.

➤ Impacts

- Significant FY22 budget cuts.
- **All Rotary Seals work (KSC, JSC) halted.**
- **Dust Resistant Bearing work reduced to 0.6FTE and lifecycle extended by 6 months.**

FY22 Budget Reduction			
		Proposed (\$K)	Actual (\$K)
Dust Resistant Bearings	GRC	705	176
Rotary Seals	KSC	551	92
	JSC	244	0
Total		1500	268

➤ Tech Mat

- The techniques and equipment developed for rotary seal and bearing testing will inform and be utilized by other actuator projects at NASA and external partners.

Supplemental Information



REQUIRED

Do NOT include these slides in your Presentation Package that you upload in Teams.

This section only goes in the Presentation Package you upload on your Project Tile in SharePoint.



Project Plan - Milestone Status

Milestone Title (Mirror Project Plan)	Baseline Date	Actual Date	Variance Explanation
<i>Status of milestones due since March 2022</i>			
K7 - Novel Bearing Seal Configuration Selected (B)	3/30/22	3/30/22	Completed on schedule
K9 - Modified Seal Test Ready (RS)	4/15/22	1/15/24	On Hold - GCD Budget cuts delayed task
K8 - Modified Seal Hardware Ready (RS)	4/15/22	4/17/24	On Hold - GCD Budget cuts delayed task
K4 – COTS Bearing Testing Complete	4/20/22	7/29/22	Completed - Supply challenges for test rig development
K6 - COTS Bearing Testing Report Complete / TAPR	8/11/22	9/21/22	Project is prioritizing last-minute end of year procurements as part of risk mitigation
<i>Status of milestones due between September 1, 2022 – March 30, 2023</i>			
	Baseline Date	Planned Date	
C2 - Novel Bearing Testing Complete	2/8/23	3/13/23	On track
K10 - Novel Bearing Testing Report Complete	2/8/23	3/13/23	On track

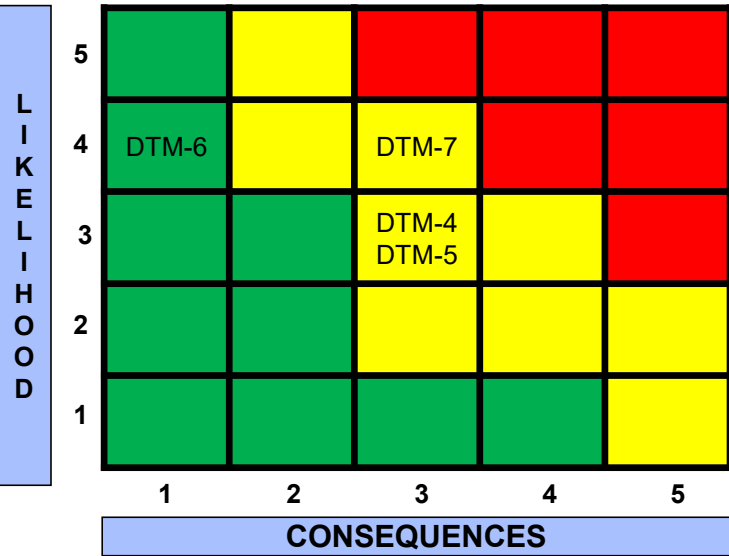
Slide 19

AMD(M1 K5 Need to add? Not on chart

Anderson, Michael D. (GRC-MB00), 8/25/2022



Risk Summary



Risk ID	Affinity/ Approach	Description/Status	Trend
DTM-4	T, Sc, W	New PI needed / Limited Budget	Paused
DTM-5	T, Sc, W	LTV Actuator Non-Function with Test Rig	Paused
DTM-6	Sc, M	On-site facilities approvals and outside assistance delayed from pre-COVID expectations	<input type="checkbox"/>
DTM-7	Sc, M	Due to budget reductions, there is no procurement budget in FY22, so all small acquisitions are delayed to FY23	<input type="checkbox"/>

Criticality

- High (Red)
- Med (Yellow)
- Low (Green)

L x C Trend

- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New Since Last Period

Approach

- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: T-Technical C-Cost Sc-Schedule Sa-Safety

Rotary Seals

New PI– Erica Montbach

Risk ID#

DTM-4

Trend

Paused

Criticality

Medium

Current L/C

3x3

Affinity Group

Performance, Schedule

Planned Closure

TBD

Open Date

30-Sep-2021

Risk Statement:

Given there is a limited budget to the project and a new PI is needed, there is a moderate likelihood that available resources will limit the laboratory work needed to advance the technology.

Context:

In FY22, GCD program had significant budget cuts occurring in Mar-Apr 2022, resulting in the rotary actuator task being cut. The task will start up in FY23 but a new PI will likely be needed at this time.

Status:

01-APR-2022 - Risk paused due to task funding cut

Approach: Watch

Mitigation Steps	Dollars to Implement	Trigger/Start Date	Schedule UID	Completion Date	Resulting L/C

(Note: The Schedule UID is the unique id no of the mitigation step in your schedule if appropriate.
Dollars to implement are not extra approved \$ from the Program Office but \$ set aside as part of project budget to mitigate.)

Rotary Seals

LTV Actuator – Erica Montbach

Risk ID#

DTM-5

Trend

Paused

Criticality

Medium

Current L/C

3x3

Affinity Group

Performance, Schedule

Planned Closure

TBD

Open Date

30-Sep-2021

Risk Statement:

Given that a new design is needed, there is a significant likelihood that the LTV actuator will not function with the JSC test rig, resulting in schedule delays and task performance degradation

Context:

LTV actuator has never been tested with the JSC test rig. We don't know if it will function as intended.

Status:

01-APR-2022 - Risk paused due to task funding cut

Approach: Watch

Mitigation Steps	Dollars to Implement	Trigger/Start Date	Schedule UID	Completion Date	Resulting L/C

(Note: The Schedule UID is the unique id no of the mitigation step in your schedule if appropriate.
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Lunar Dust Resistant Bearings

Internal Approval Delays – Erica Montbach

Risk ID#

DTM-6

Trend

New

Criticality

Low

Current L/C

4x1

Affinity Group

Schedule

Planned Closure

TBD

Open Date

13-Jun-2022

Risk Statement:

Given that the DTM project requires various NASA GRC permits and approvals in order to develop technology, there is a high likelihood that unexpected schedule delays will occur due to staffing and other challenges due to the COVID pandemic

Approach: Watch

Context:

Prior to COVID, safety permits, calibrations, etc were completed more timely than the current reality.

Status:

13-JUN-22 - Risk Opened

Mitigation Steps	Dollars to Implement	Trigger/Start Date	Schedule UID	Completion Date	Resulting L/C

(Note: The Schedule UID is the unique id no of the mitigation step in your schedule if appropriate.
Dollars to implement are not extra approved \$ from the Program Office but \$ set aside as part of project budget to mitigate.)

Lunar Dust Resistant Bearings

FY22 Budget Reductions – Erica Montbach

Risk ID#

DTM-7

Trend

New

Criticality

Medium

Current L/C

4x3

Affinity Group

Schedule

Planned Closure

TBD

Open Date

13-Jun-2022

Risk Statement:

Given that the DM Development project received severe budget cuts, there is no procurement budget for critical acquisitions needed in FY22. It is likely that an acquisition will be needed that the project cannot immediately purchase, resulting in a moderate schedule impact to the critical path milestones.

Context:

Severe budget cuts were announced in April 2022, resulting in the elimination of the acquisition budget. Some acquisitions were made in FY22, however, it is more likely than not that a purchasing delay due to lack of funds will impact the schedule

Status:

11-AUG-22 - Mitigation strategy developed
13-JUN-22 - Risk Opened

Approach: Mitigate

Mitigation Steps	Dollars to Implement	Trigger/Start Date	Schedule UID	Completion Date	Resulting L/C
Project is keeping a detailed purchase list of needed items and will request funding swap before end of FY22	\$0	FY22 Q4	N/A	When FY23 Budget is Determined	2x2

(Note: The Schedule UID is the unique id no of the mitigation step in your schedule if appropriate.
Dollars to implement are not extra approved \$ from the Program Office but \$ set aside as part of project budget to mitigate.)

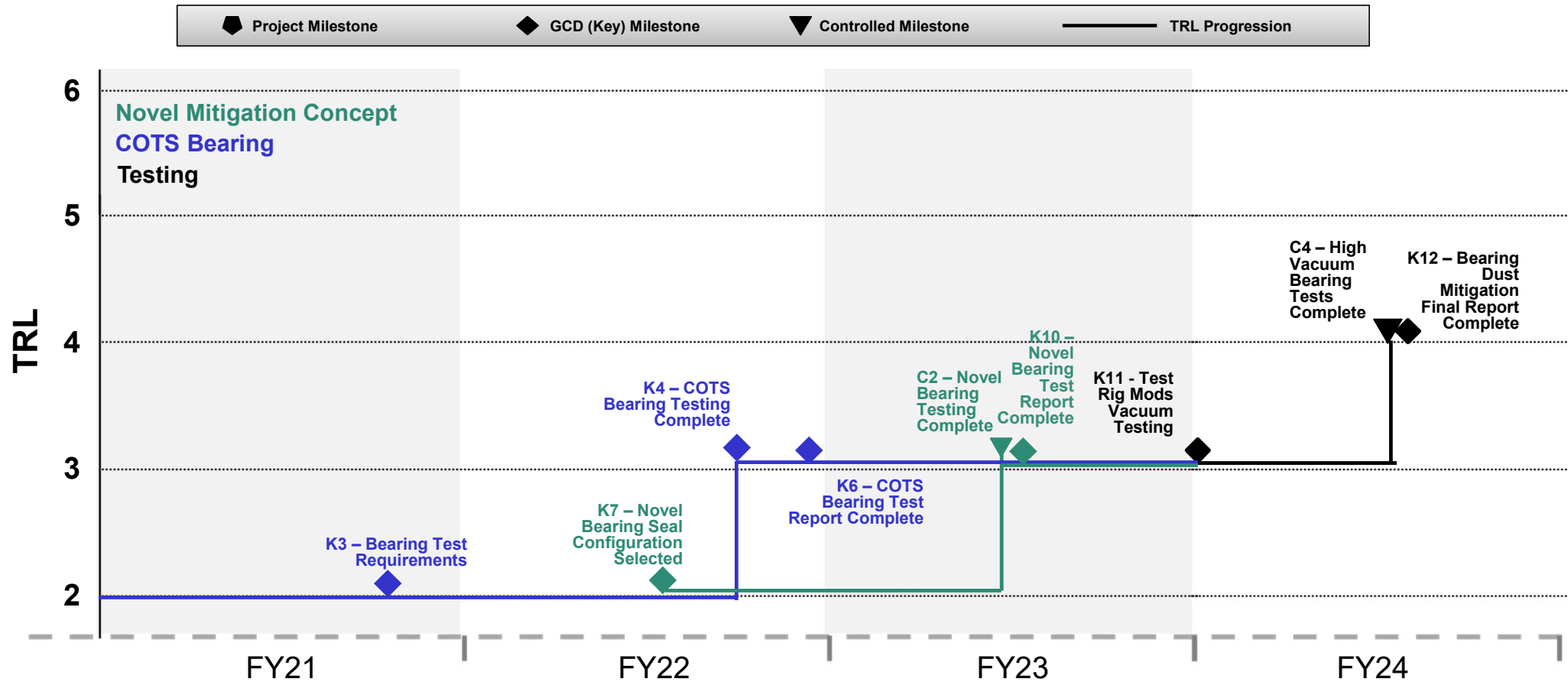
Technical Assessment



Technical Elements	TRL				AD ²	
	Entry	Current ¹	Exit	Verification	Entry	Current
COTS Bearings (B)	2	3	4	TRL 3 - K4 – COTS Bearing Testing Complete (7/29/22) TRL 4 - C4 – High Vacuum Bearing Tests Complete (3/12/24)	5	6
Novel Bearings (B)	2	2	4	TRL 3 - C2 – Novel Bearing Testing Complete (3/13/23) TRL 4 - C4 – High Vacuum Bearing Tests Complete (3/12/24)	TBD	TBD
Rotary Actuator Seal Testing (RS)	4	4	6		TBD	TBD

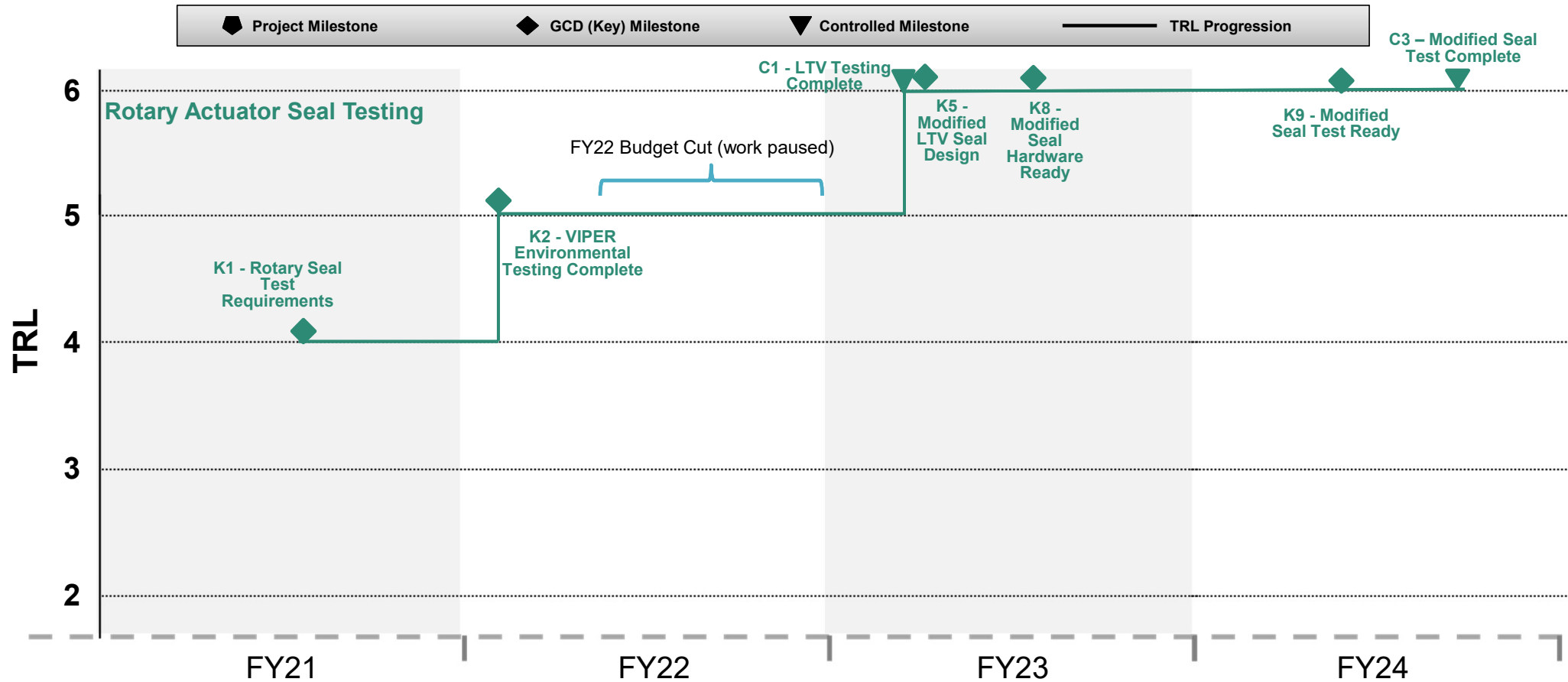
DM Dev: Dust Tolerant Mechanisms

TRL Lifecycle



DM Dev: Dust Tolerant Mechanisms

TRL Lifecycle



DMDDev - DTM Key Performance Parameter (KPP) Status



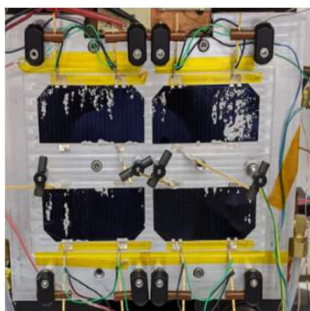
Key Performance Parameters								
Parameter Name	Unit	State of the Art	Threshold Value	Project Goal	Current Value to Date	TBoE for the Provided Current Value	Expected Exit Value	TBoE for the Provided Exit Value
Sealed actuator operational output revolutions	Revolutions	55000	2250000	4500000	TBD	Estimated	TBD	Estimated
Rotatory bearing dust infiltration	%	100	85	70	TBD	Estimated	TBD	Estimated
Rotatory bearing wear (life-limiting)	%	100	100	80	TBD	Estimated	TBD	Estimated

KPP Definition Notes		
KPP	Attribute Name	Note
Sealed actuator operational output revolutions	Parameter Name	Future lunar surface hardware will operate for extended durations. Both the LTV and VIPER teams
Rotatory bearing dust infiltration	Parameter Name	Bearing dust mitigation features must reduce infiltration of dust into the lubricant. (ex: 85% =
Rotatory bearing wear (life-limiting)	Parameter Name	Effective mitigation technologies will not be a life-limiting, wear-out feature, will be measured in mg.

KPPs are not yet in an approved state. 28

DM Dev - DTM - Cover Slide

Annotated Cover Slide Images



Initial experimental set up of solar panel performance after simulant contamination



Lunar Roving Vehicle (LRV) spraying dust, Apollo 16 (NASA Photo S72-37002)



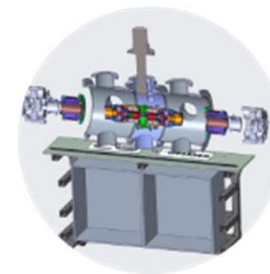
Illustration depicting astronaut in dusty lunar environment



VIPER actuator ready for testing



NASA's Volatiles Investigating Polar Exploration Rover, VIPER, is a mobile robot searching for water ice. Credits: NASA Ames/Daniel Rutter

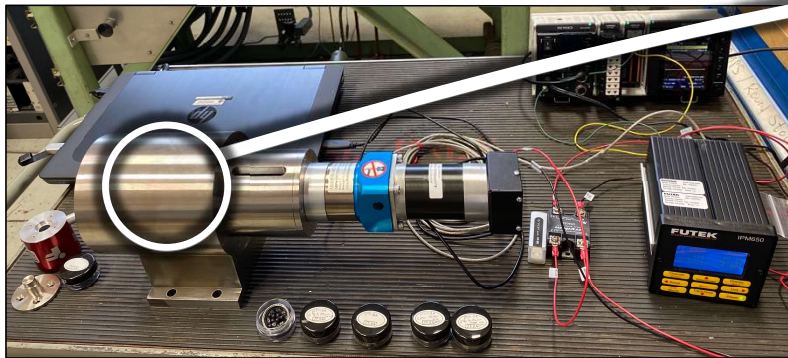


Large dusty, thermal vacuum chamber with dynamometer CAD model

Accomplishments

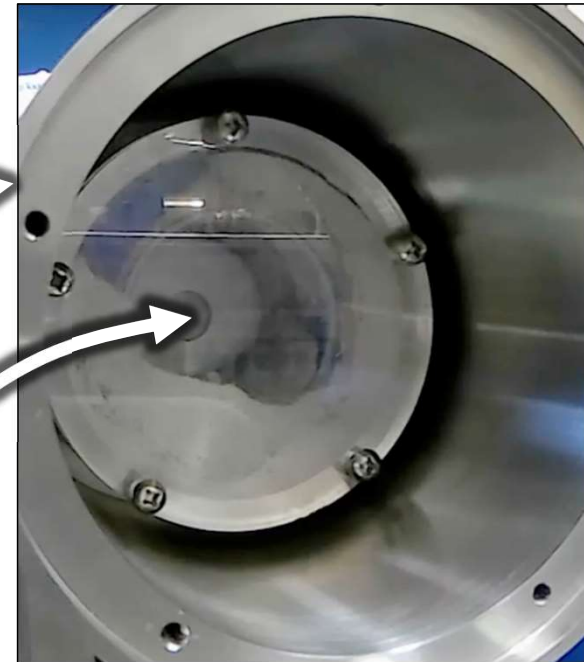


- Dust Mitigation for Lunar Bearings:
 - A new bearing test rig for exposing bearings to lunar simulant designed, built, and in service on benchtop



Video of inside chamber

Checking for sufficient dust distribution while running



Looking into Dust Chamber (bearing removed/plastic cover for visual access)

Bearing Test Rig on Benchtop at GRC

Accomplishments



- DTM – Rotary Seals - Work paused in April 2022 due to FY22 budget cuts

Software Updates:

- Implemented error handling that updates the potential errors to be viewed on the Front Panel
- Utilized EtherCAT to communicate with the Elmo motor drives
 - Reads the velocity, current, and position of the motor
- Created a robust state machine which handles the sequence of events that will take place before, during and after testing
- Tuned the motor pairs on both sides of the LTV actuator in a master-slave configuration
- Enabled the velocity to be updated from the Front Panel
- Added a *test scheduler* that is capable of translating testing parameters from the test plan to a executable task, permitting autonomous testing conditions
- Calculates gear efficiency, as well as makes relevant conversions involving the input readings from the elmo drive (torque, velocity, position, current)

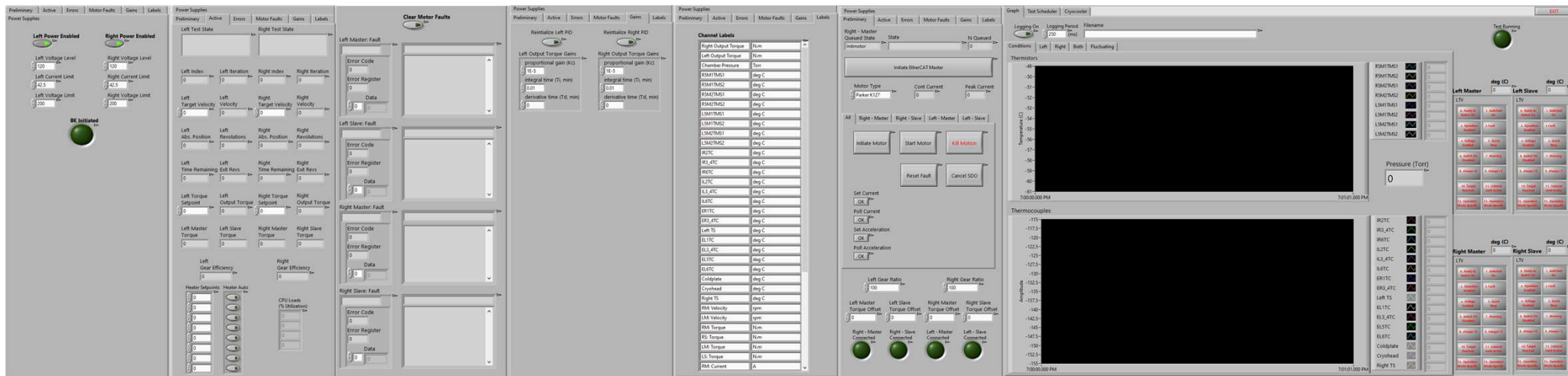


Accomplishments

➤ DTM – Rotary Seals - Work paused in April 2022 due to FY22 budget cuts

Software Updates

Front Panel:



Power Supplies:

- Allows the power supplies to be powered On/Off
- Enables the voltage and current to be changed

Active:

- Manually control the velocities of test motors
- Manually control the output torque
- View pertinent test information
- Manually change heater setpoints

Motor Faults:

- Displays detailed messages regarding specific motor faults for each motor drive

Gains:

- Manually control the gains for the output torque of the pneumatic brakes

Labels:

- Manually change the labels/units of the data to be logged, as well as displayed

Preliminary:

- Manually input motor/actuator information
- Communicate to the motor drives via EtherCAT

Graph:

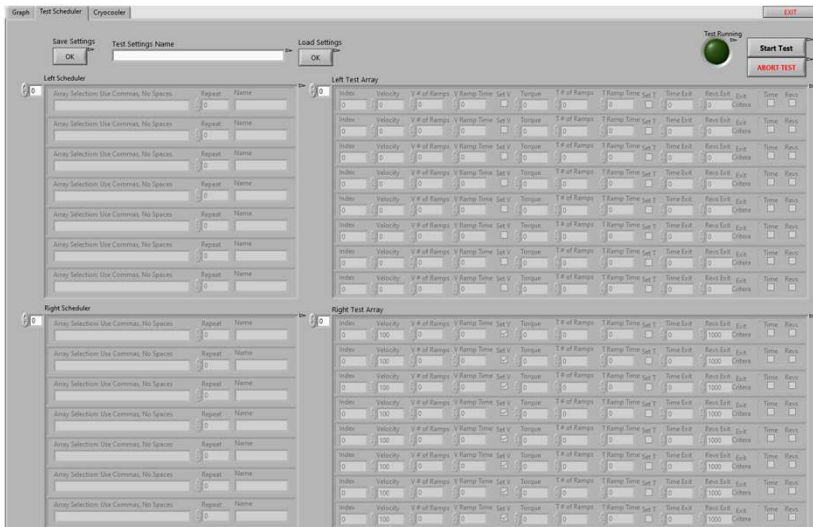
- View the temperature readings from the thermocouples/thermistors with labels set in the *Labels* tab
- View motor current, velocity, relative & absolute position, torque, and gear efficiency



Accomplishments

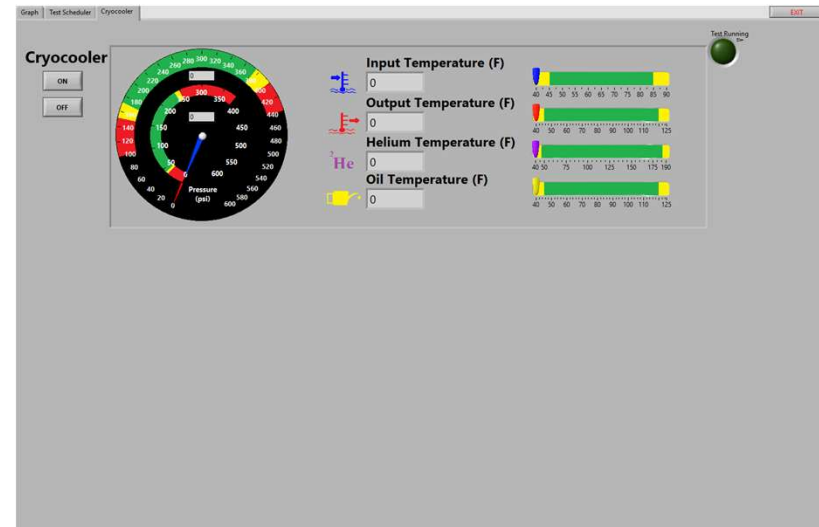
➤ DTM – Rotary Seals

Front Panel:



Test Scheduler:

- Generate a full test scheduler based upon velocity, incremental velocity intervals, torque, incremental torque intervals, as well as exit criteria (time vs. # of revolutions)



Cryocooler:

- Allows the cryocooler to be powered On/Off
- Monitors vital temperature and pressures of the cryocooler