

(Microreactor Applications Research, Validation & Evaluation),
2024

MARVEL

Microreactor Prototype

Sponsored by DOE-NE 5

MARVEL Technology Review: Reactivity Control System (RCS)

March 2024

Presented by: **Anthony L. Crawford Ph.D. P.E.** | MARVEL Mechatronics

Significant Contributions: Rhett Rovig, Ben Baker, Stu Bondurant, Matt Summers, Ben Coryell, Andrew Heim, Peter Ritchie, Tom DiSanto, Lisa Moore-McAteer, Dennis James, Dennis Wahlquist, Cory Conway, Rick Hatch, Eric Lumley, John Gray, Rosie Seymour, Casey White, Travis Neumann, Rowdie Shepherd, John Stevenson, Matt Floyd, etc.

Presentation Content

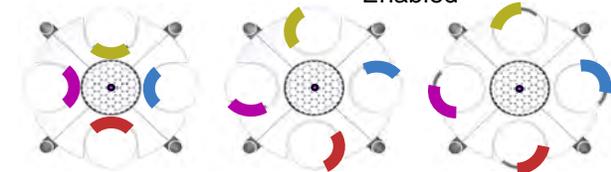
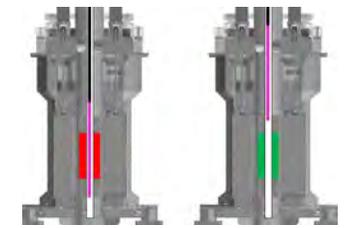
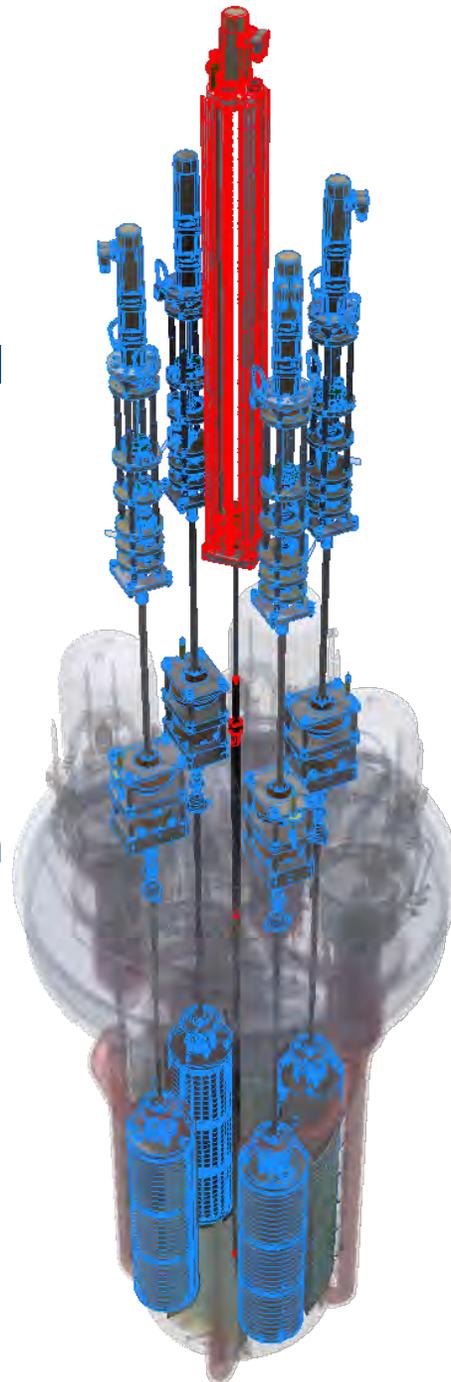
- Requirements
- Overview of system (SSC classification, subsystems, interfaces)
- Status of engineering deliverables (e.g., drawings, ECARs, reports, etc.)
- Summarize the system
- Major analyses or evaluations, V&V
- How review comments were addressed/resolved
- Major remaining items for design verification (e.g., qualification tests)
- Maintenance strategy, if applicable
- Procurement, supply chain, and construction strategy (high level)
- Questions

Requirements

- FOR-868, Functional and Operational Requirements: Microreactor Applications Research Validation and Evaluation (MARVEL) Project, Rev.0, March 16, 2023.
 - Rev. 1 Pending
- TFR-2578: Technical and Functional Requirements: MARVEL Reactivity Control System (RCS), Rev. 0, March 22, 2023.
 - Rev. 1 Pending

Overview of System

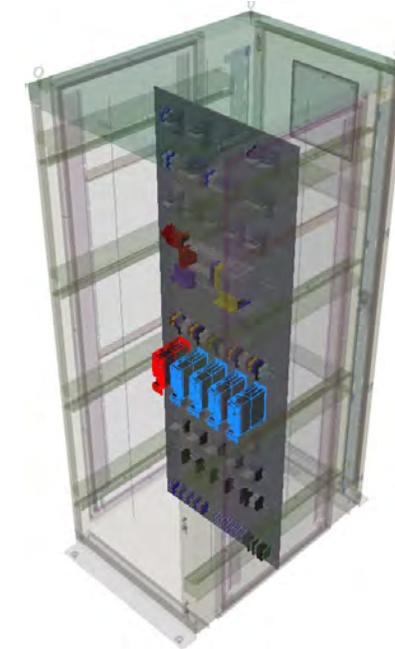
- Two Diverse Reactivity Control Methods
 - 4 Control Drums
 - Peripheral
 - Drums
 - Rotation
 - Torsional Spring Return
 - 1 Central Insurance Absorber Rod
 - Center
 - Rod
 - Translation
 - Gravity Return



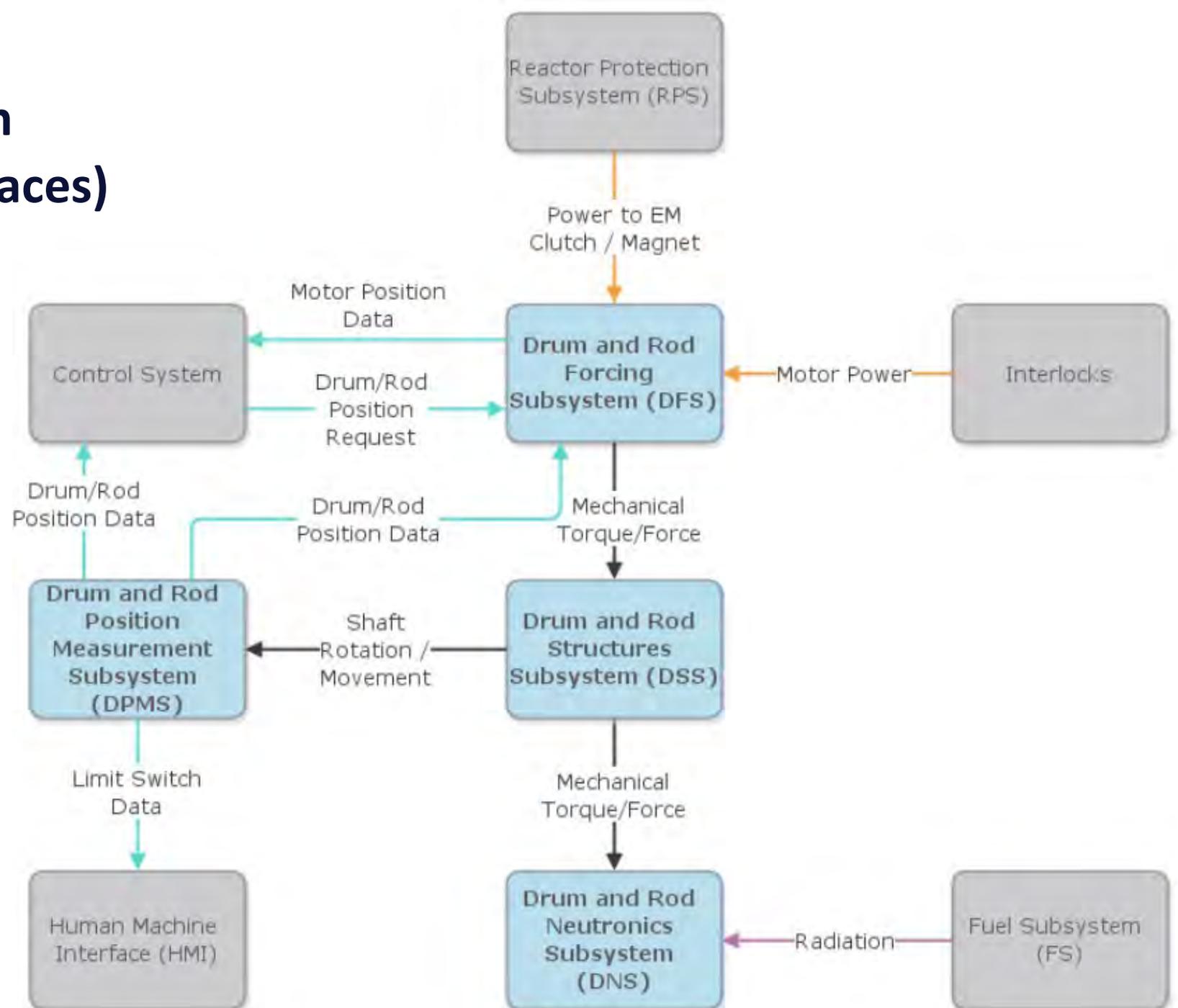
Full-in: Shutdown

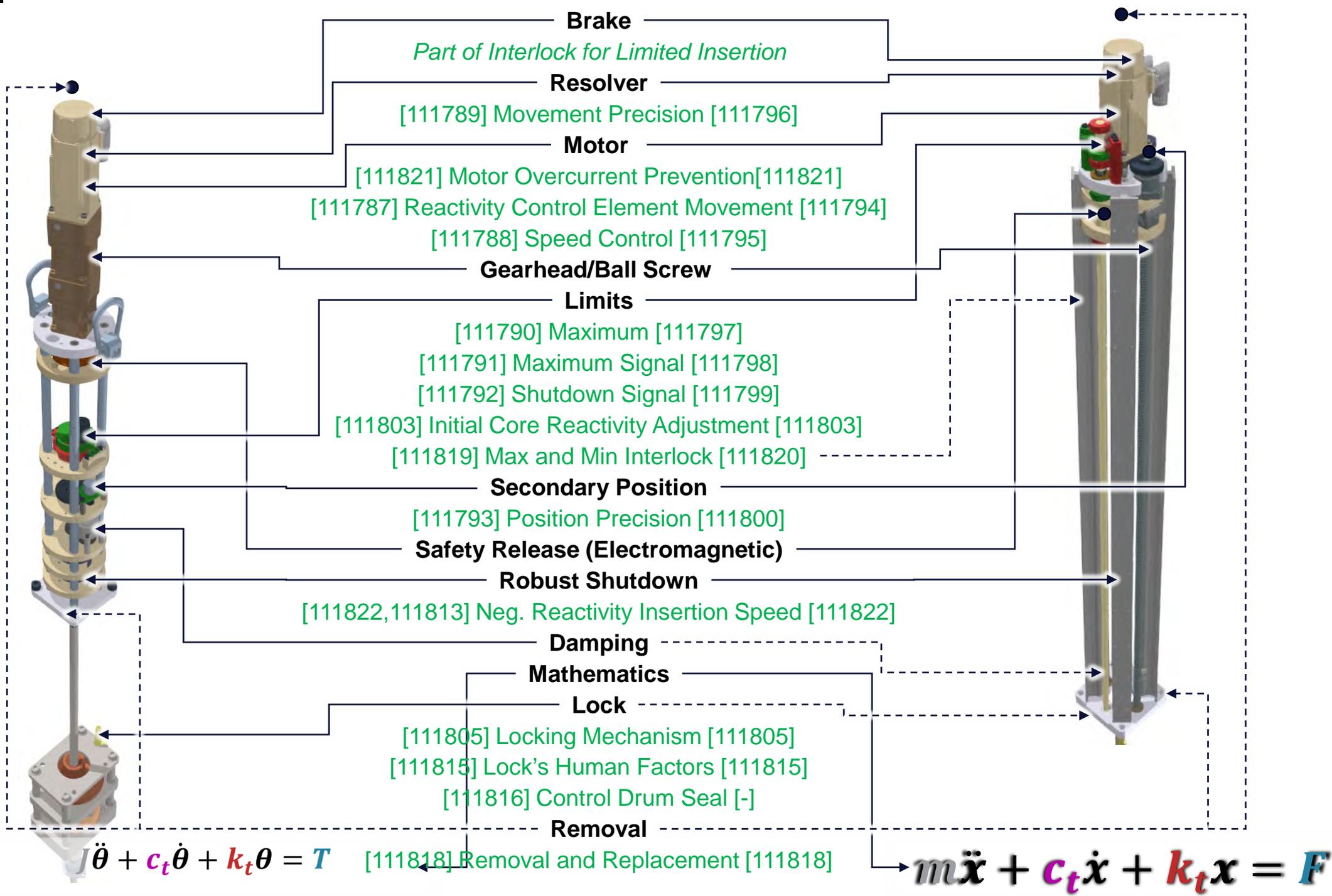
Partial Out: Initial Criticality

Full Out: Maximum Reactivity
*Will be set below full out (180 degree) using a tuned hard stop

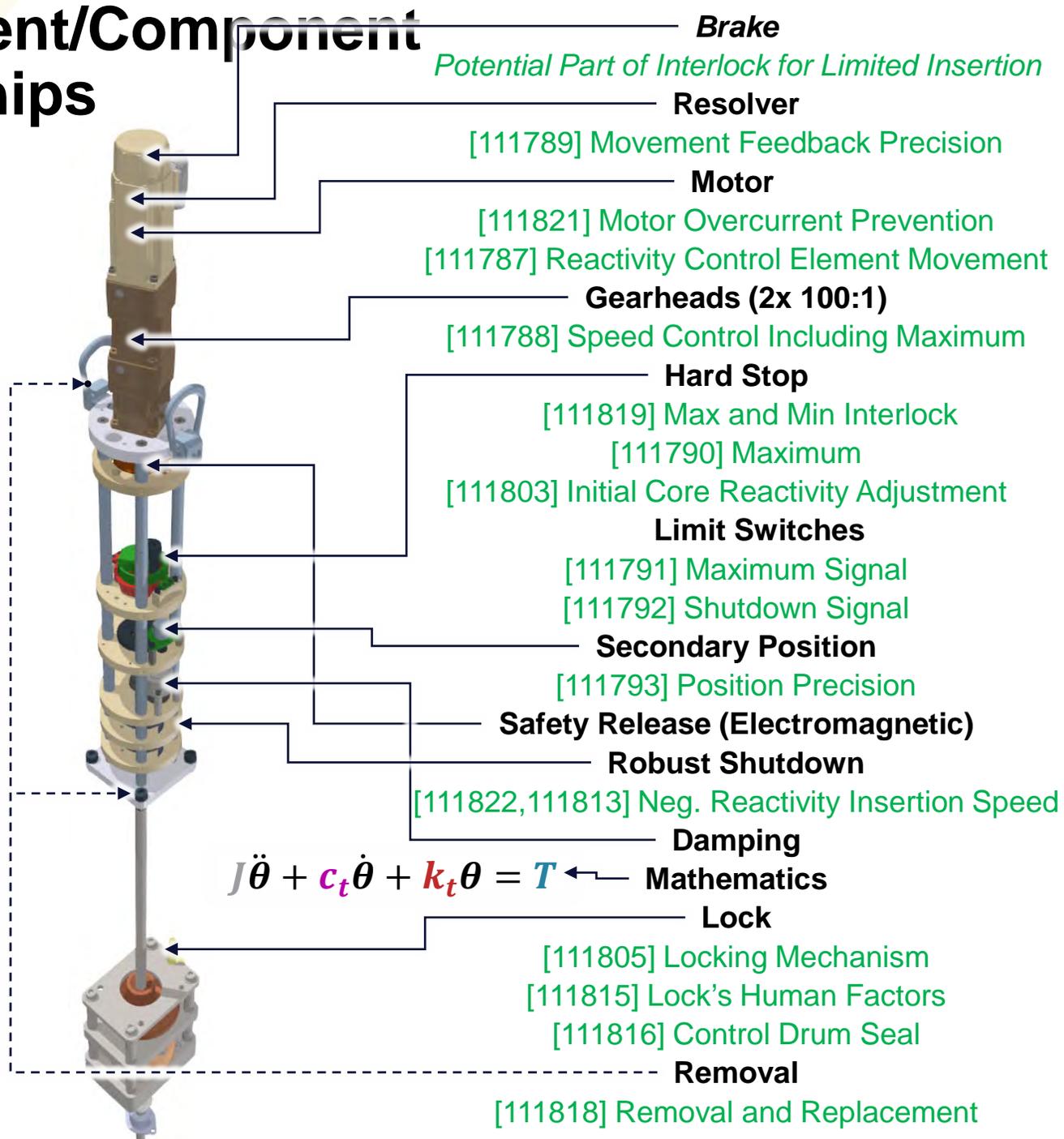


Overview of System (Subsystems, Interfaces)





Requirement/Component Relationships



[111814] EM Clutch Environmental Qualification

[111807] Radiation Environment for RCS
Components above Upper Shield

[111808] Reactivity Control Equipment in
TREAT Temperature Environment

[111806] Radiation Environment for RCS
Components in Guard Vessel

[111801] CD Negative Reactivity Worth

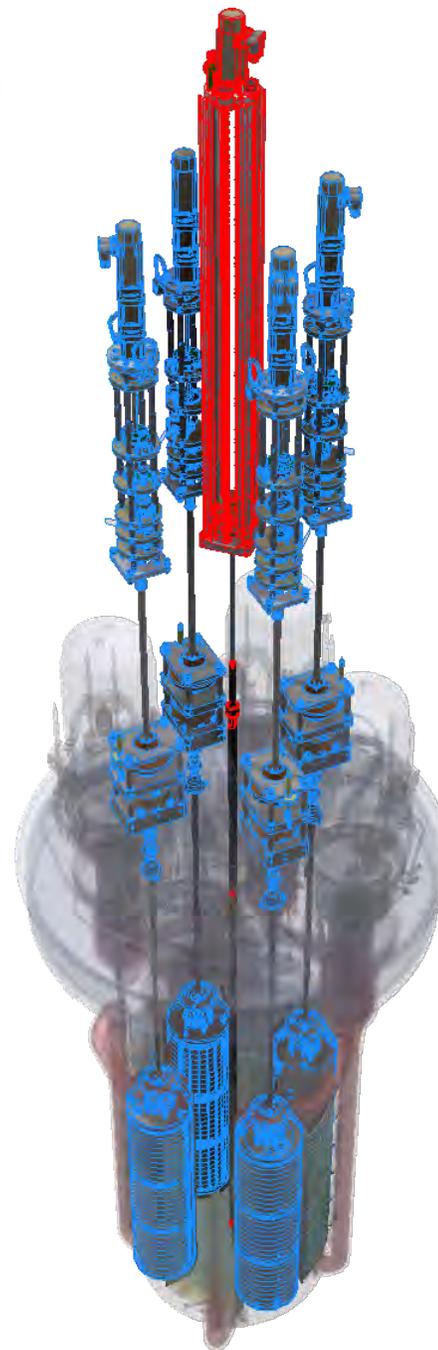
[111802] CD Positive Reactivity Worth

[111810] Control Drum Thermal Environment

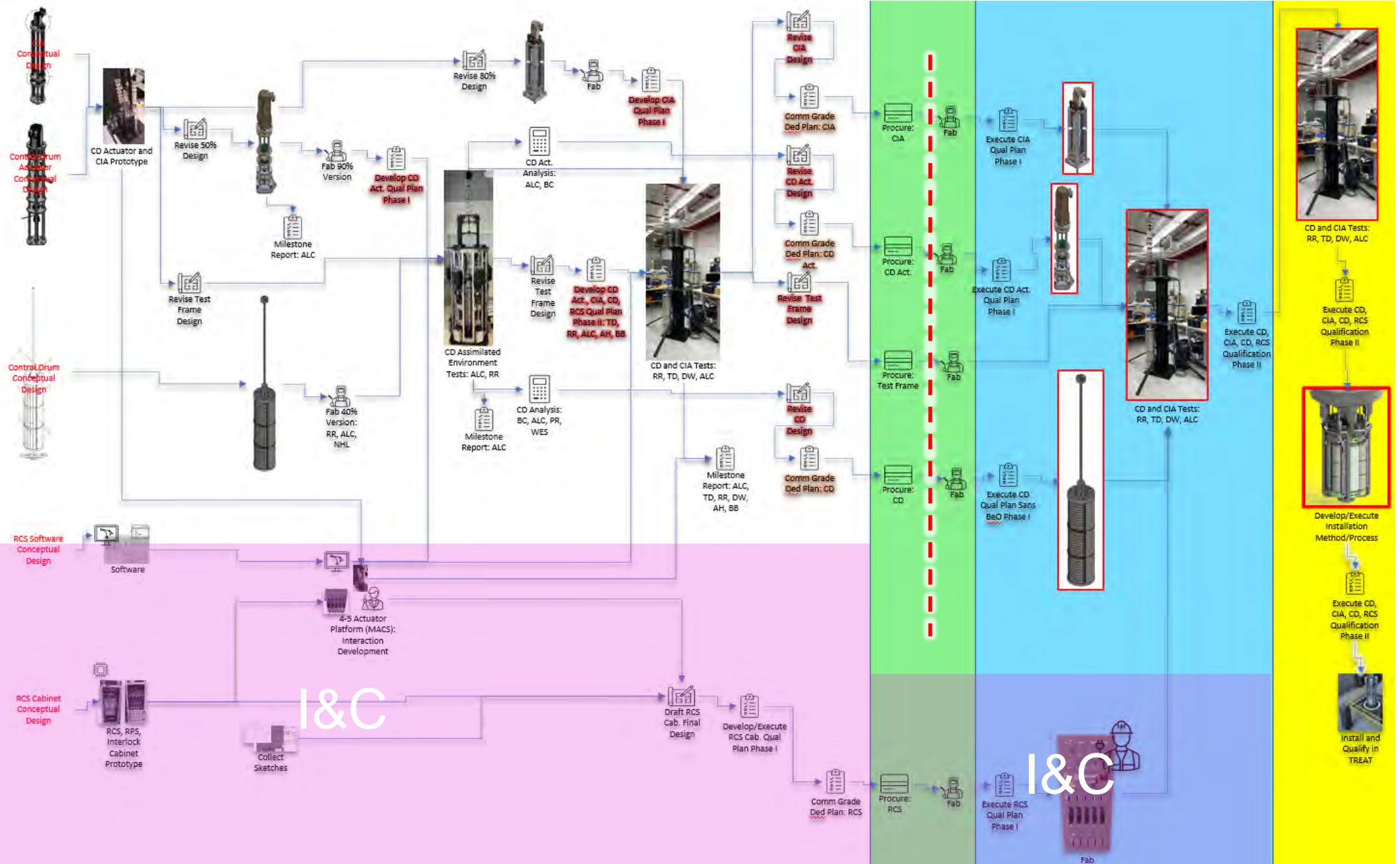
[111817] Decay Heat Removal from
Core Region via Control Drums

[111812] Control Drum and CIA
Rod Material Stress

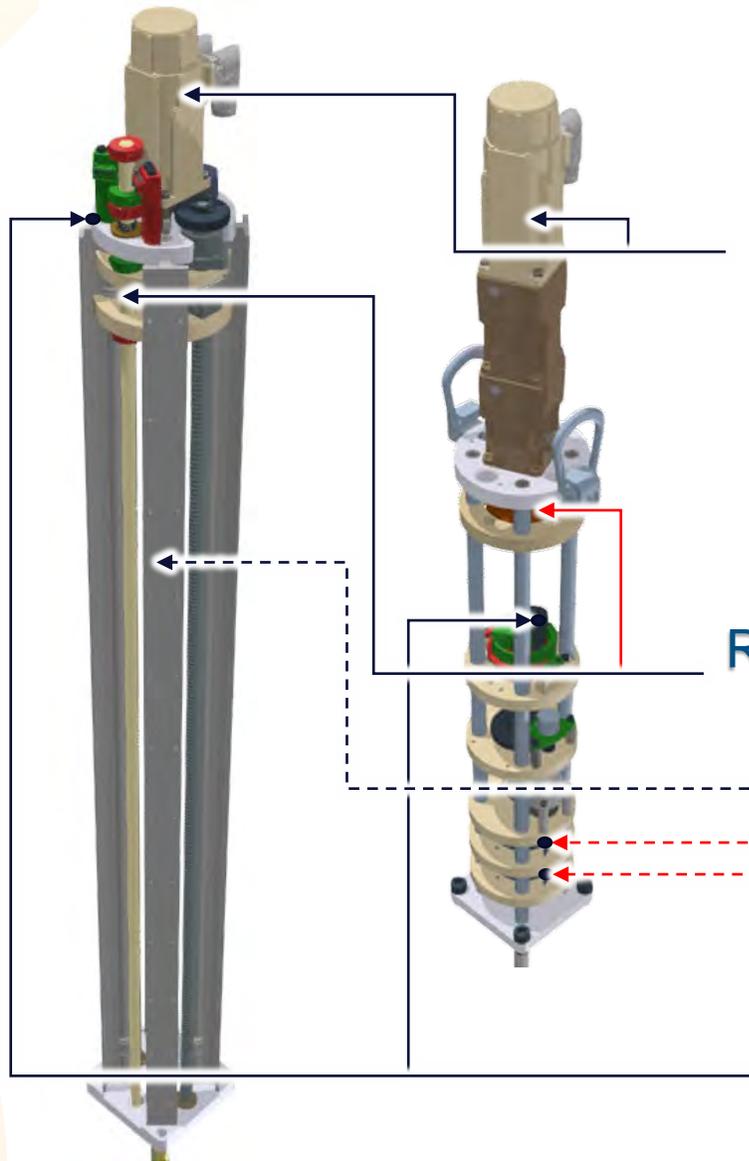
[111804] Waste Classification



Status of Engineering Deliverables



CD and CIA Functional Relationships with I&C



CIA and CD System (NSR):

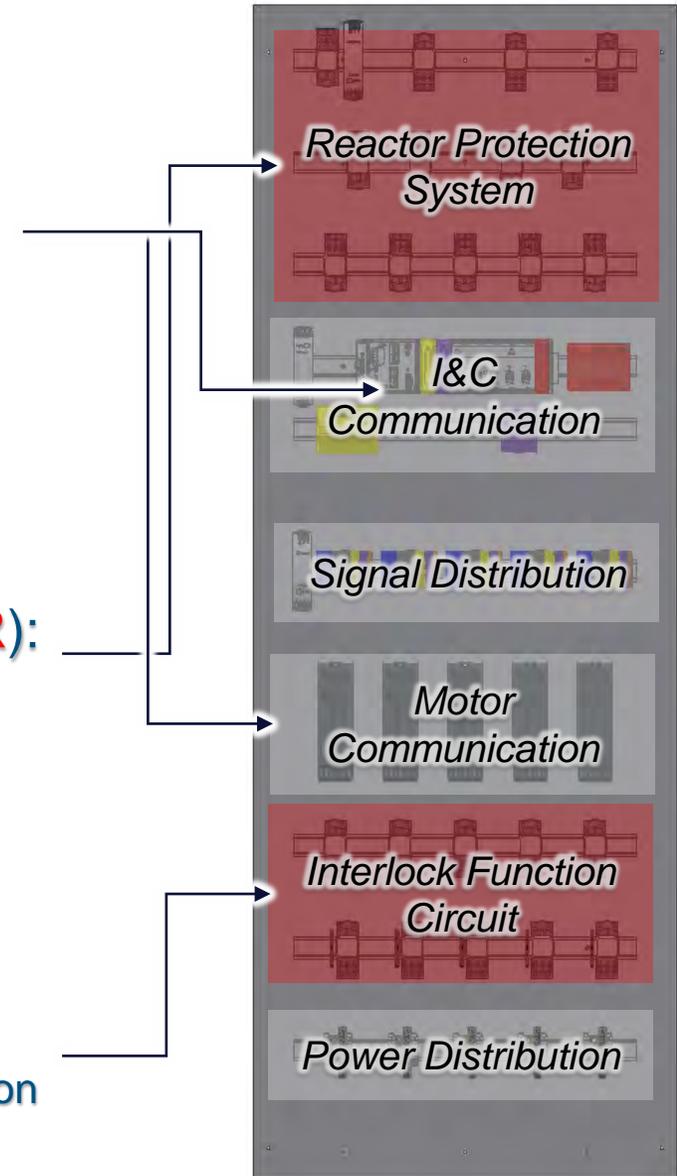
- Read parameters
- Control reactivity via position
- Provided controlled shutdown

Reactor Protection System (SR):

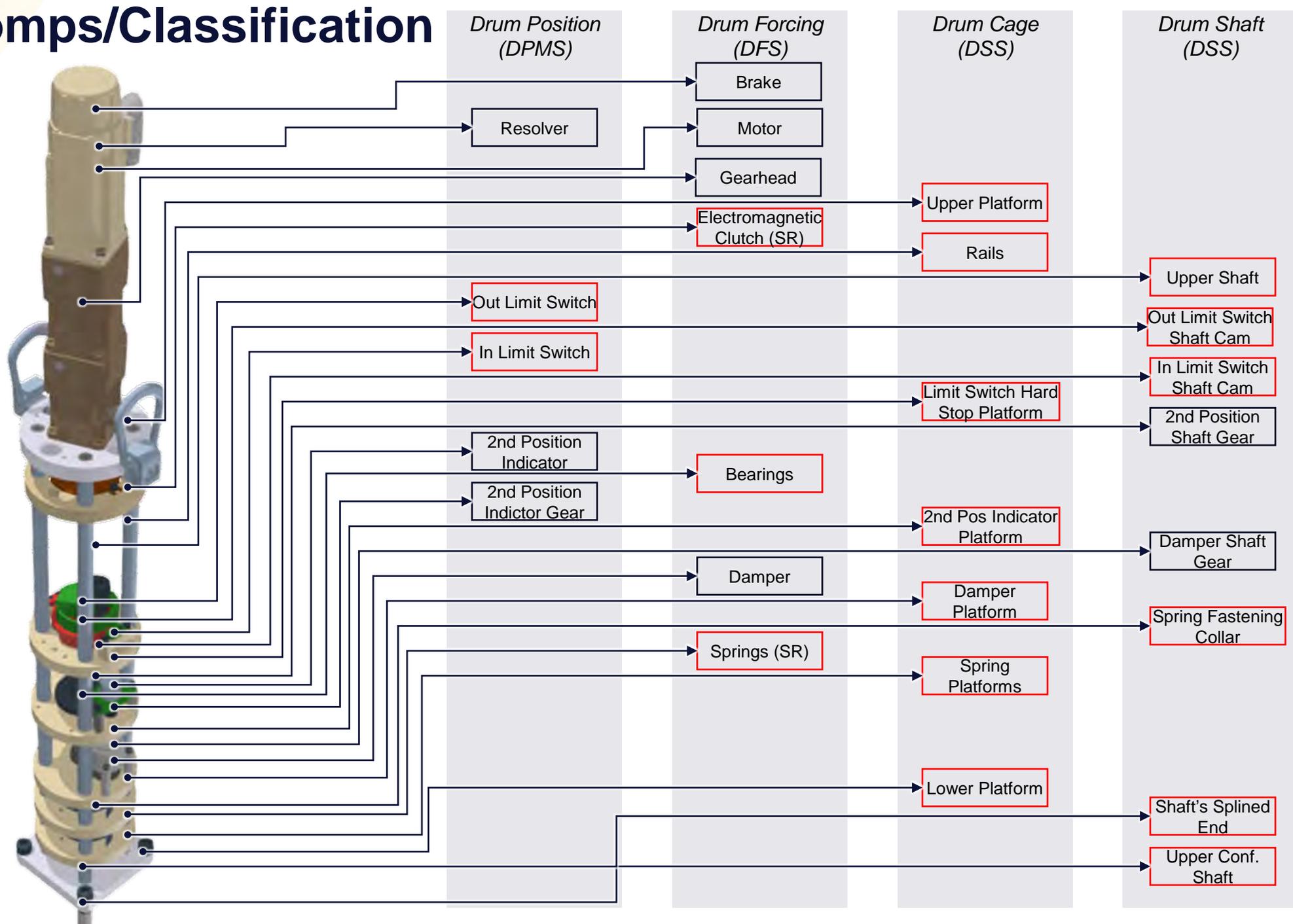
- Passively Shutdown System

Interlocks (SR):

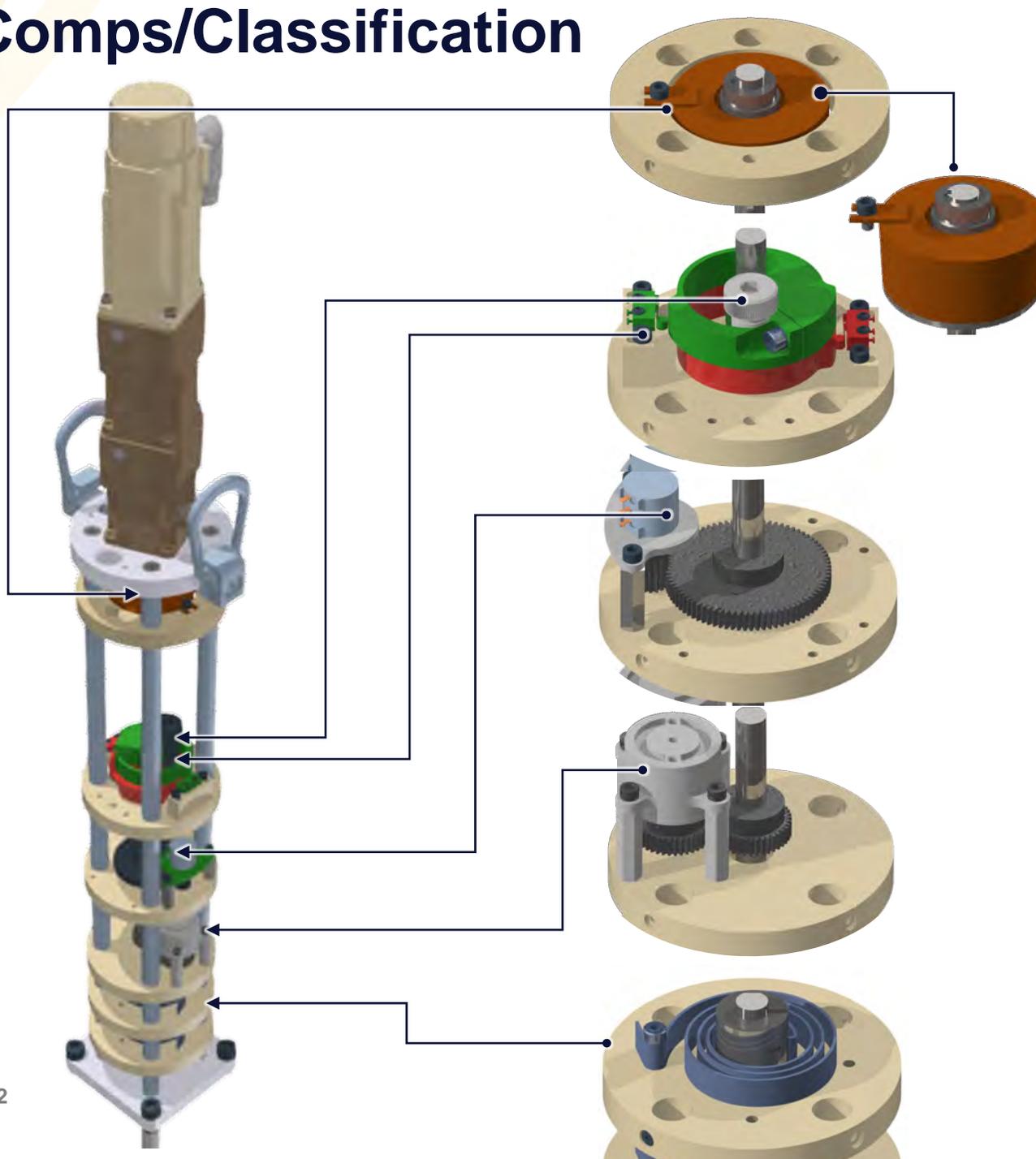
- Prevent excess reactivity insertion



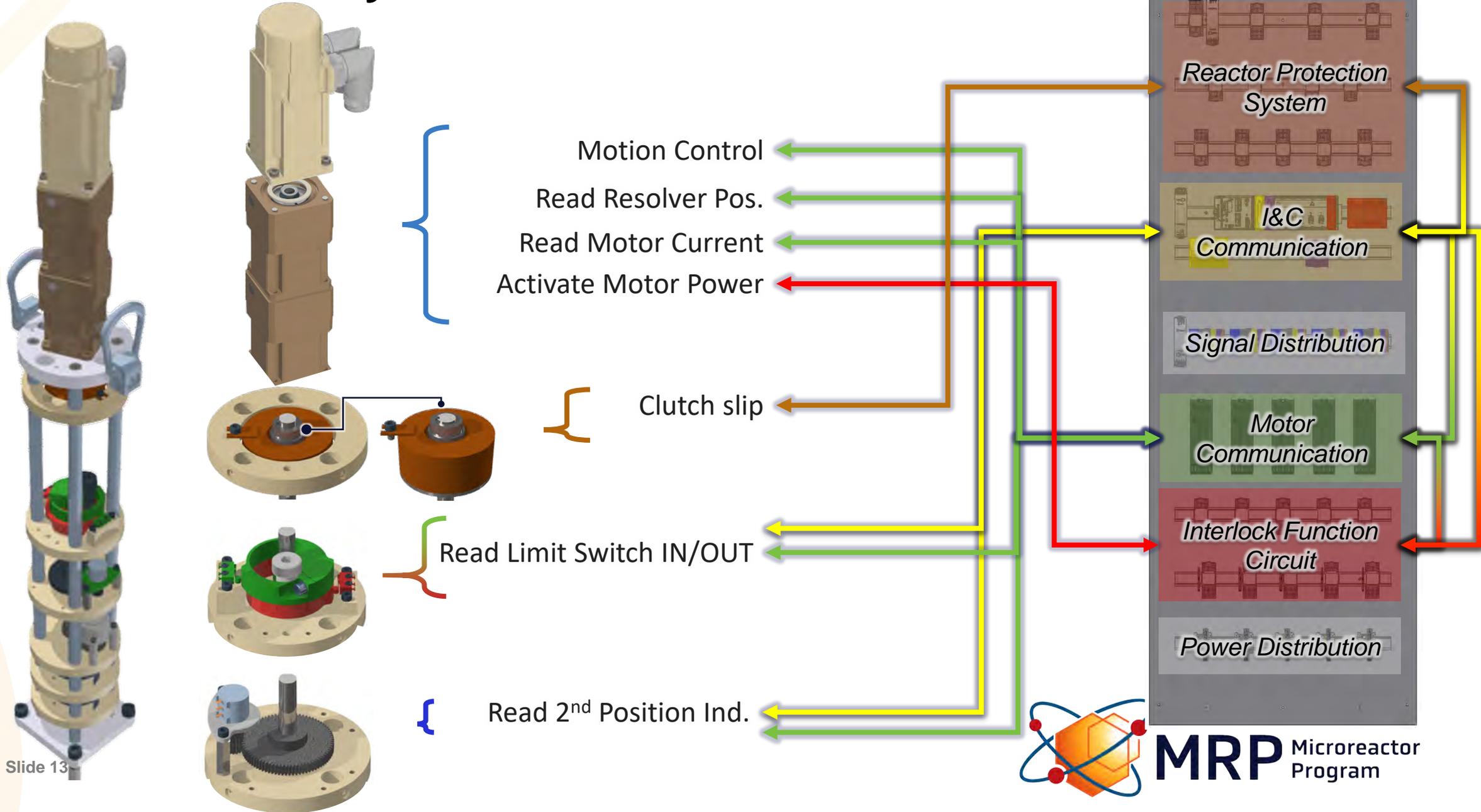
CD Comps/Classification



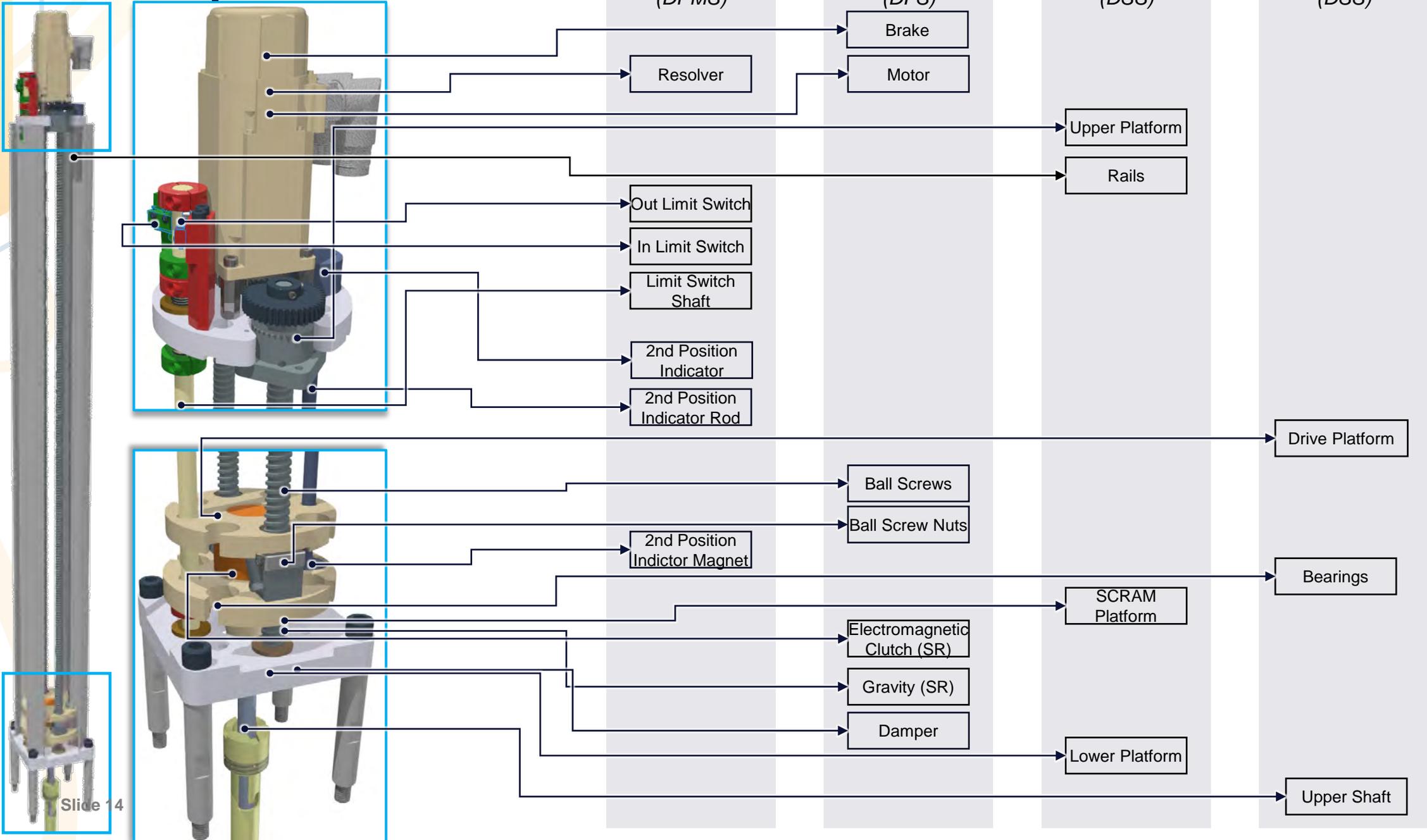
CD Comps/Classification



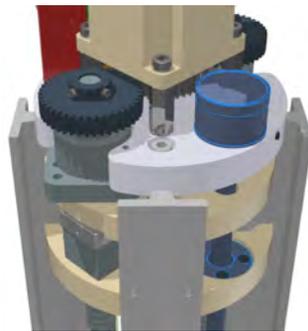
CD Actuator System Functional Interface with I&C



CIA Comps/Classification



CIA Actuator System Functional Interface with I&C

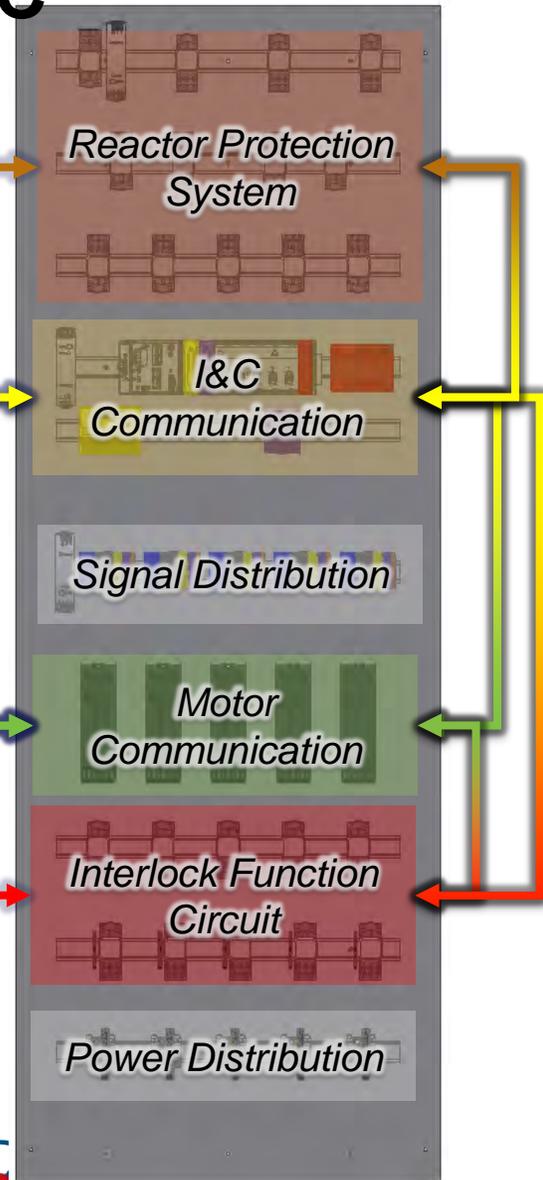


Motion Control
Read Resolver Pos.
Read Motor Current
Activate Motor Power

Read Limit Switch
IN/OUT

Read 2nd Position Ind.

Electromagnet Force



Characteristics Influencing Requirement Verification Strategies

- CDs

- Higher classification
- Higher performance requirements
- Drum is in a lower hazard but interacts with the structure via 6 bearings and is encapsulated
- Less prominent industry application

Torsional spring must be tuned, and material properties can change over time and temperature



- CIA

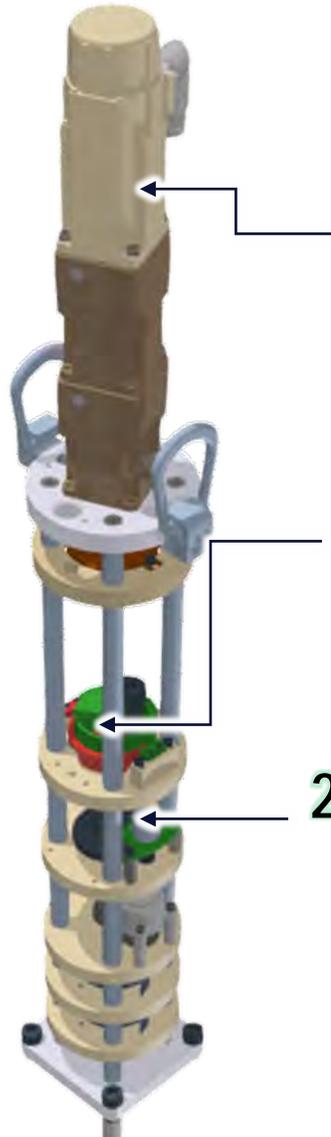
- Lower classification
- Minimal performance requirements
- Rod is in higher hazard area (center of core) but is not encapsulated.
- More prominent in industry applications
- Gravity is a robust shutdown resource



Major Analyses and Evaluations, V&V

- ECAR-7228, MARVEL Control Drum Actuator Stress Analysis
 - Three aspects of CD (thermal, stress, eigenvalue)
 - Appendix C: Actuator Component Sizing
- PLN-6874, MARVEL Reactivity Control System Assembly and Checkout (Phase I) and Functional Testing (Phase II) Plan
 - CD performance
 - CIA performance

CD Actuator Analysis (Position)



**Resolver
(100%)**

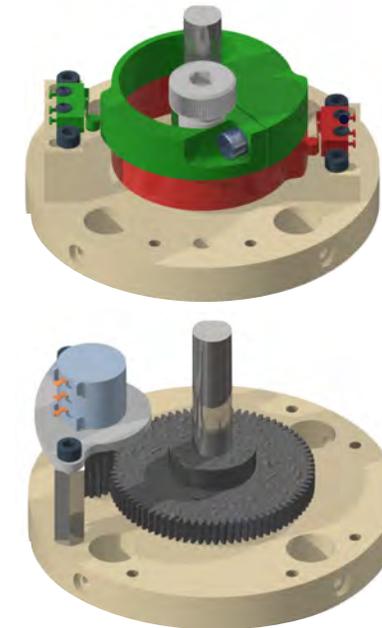
Very acceptable due to High Resolution * 10,000:1

**Limit
Switches
(100%)**

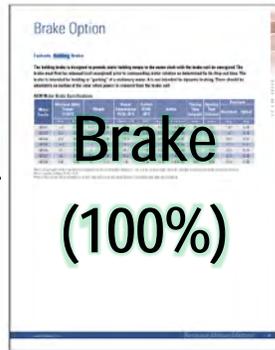
Shaft cams designed to align limit switches with hard stops and work within range

**2nd Position
(100%)**

3-turn potentiometer in accord with 5:1 gear ratio, proper input voltage, and noise considerations achieves target resolution



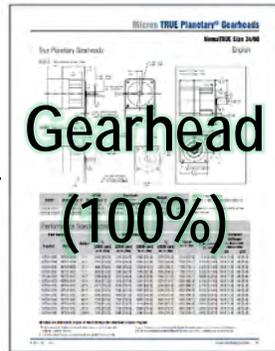
CD Actuator Analysis (Applied Torque)



Brake will hold motor torque but may not be needed due to high gear ratio in gearhead series



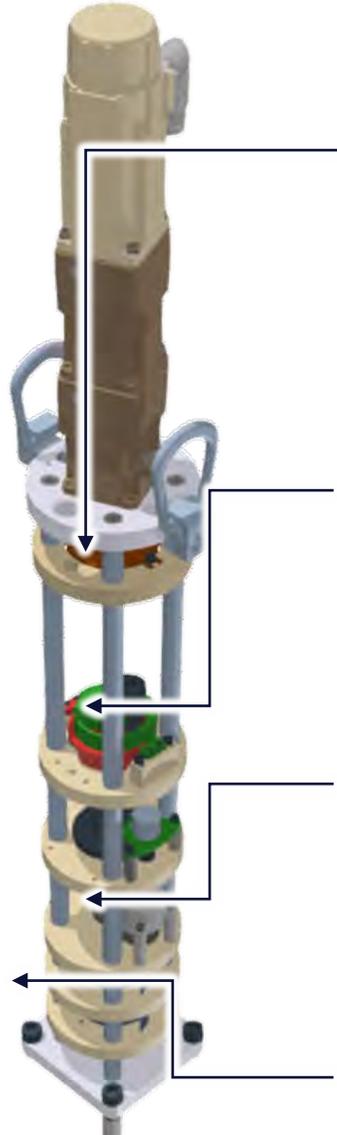
Proper max speed to work with gearhead to limit max reactivity insertion



Gearhead ratios $(100:1 * 100:1) = 10,000:1$ significantly reduces system's maximum possible speed to <2 deg/s



CD Actuator Analysis (Released Torque)



**Clutch
(100%)**

Clutch slip limit of 80 in-lbs turns out to drive system sizing

**Hard Stop
(100%)**

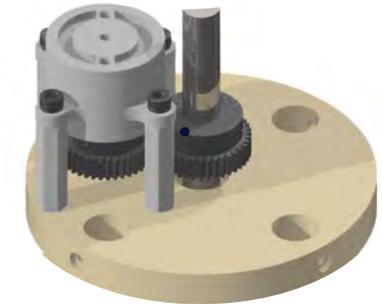
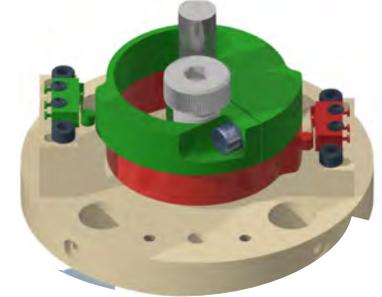
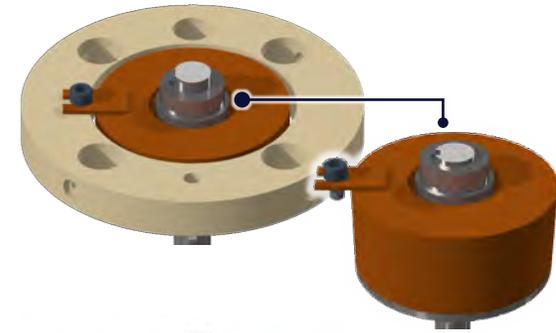
Very conservative impact analysis showed a 5/8" diameter hard stop to be sufficient

**Damper
(100%)**

Damper added to reduce hard stop impact but not so strong that it prevented 2s from full-out to shutdown requirement

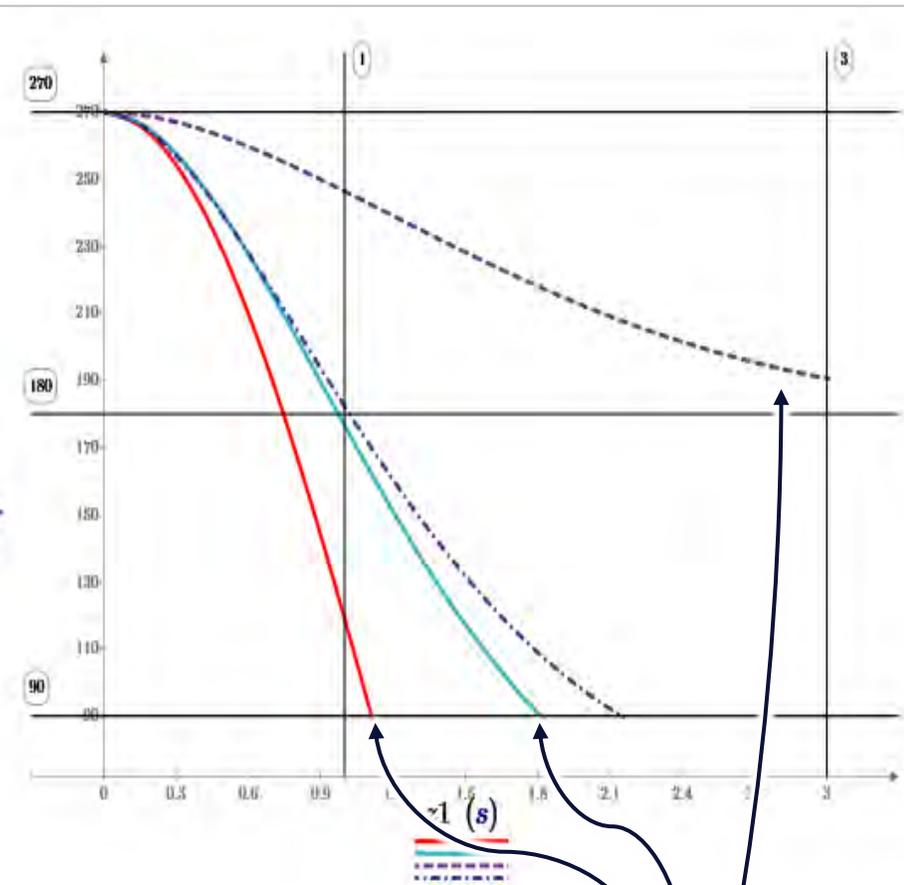
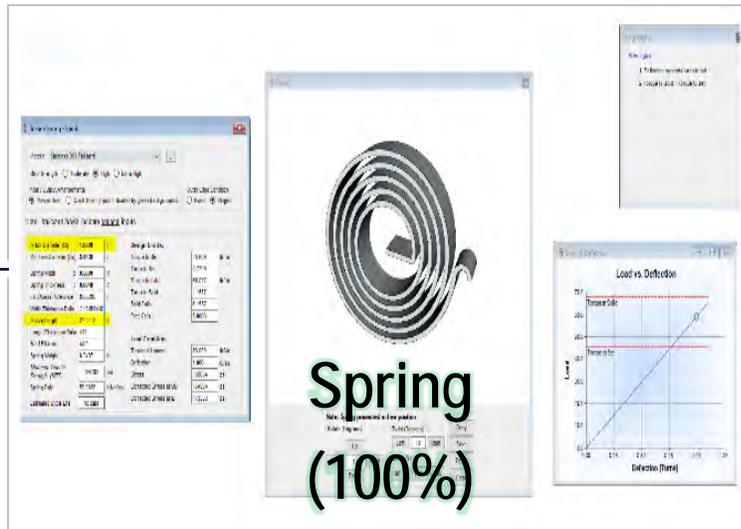
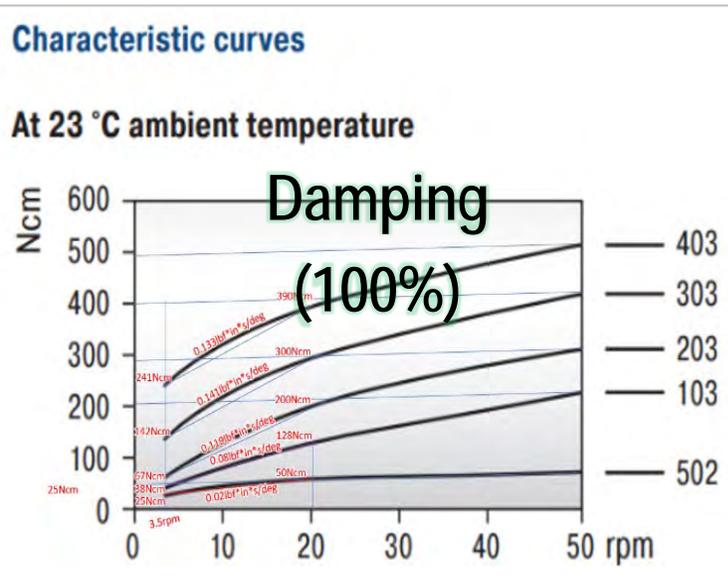
**Springs
(100%)**

- Two springs ~1s shutdown (no damping)
- Two springs <2s shutdown (damping)
- One spring ~4s to near or below subcritical



CD Actuator Analysis (Spring/Damper Sizing)

$$J\ddot{\theta} + c_t\dot{\theta} + k_t\theta = T$$

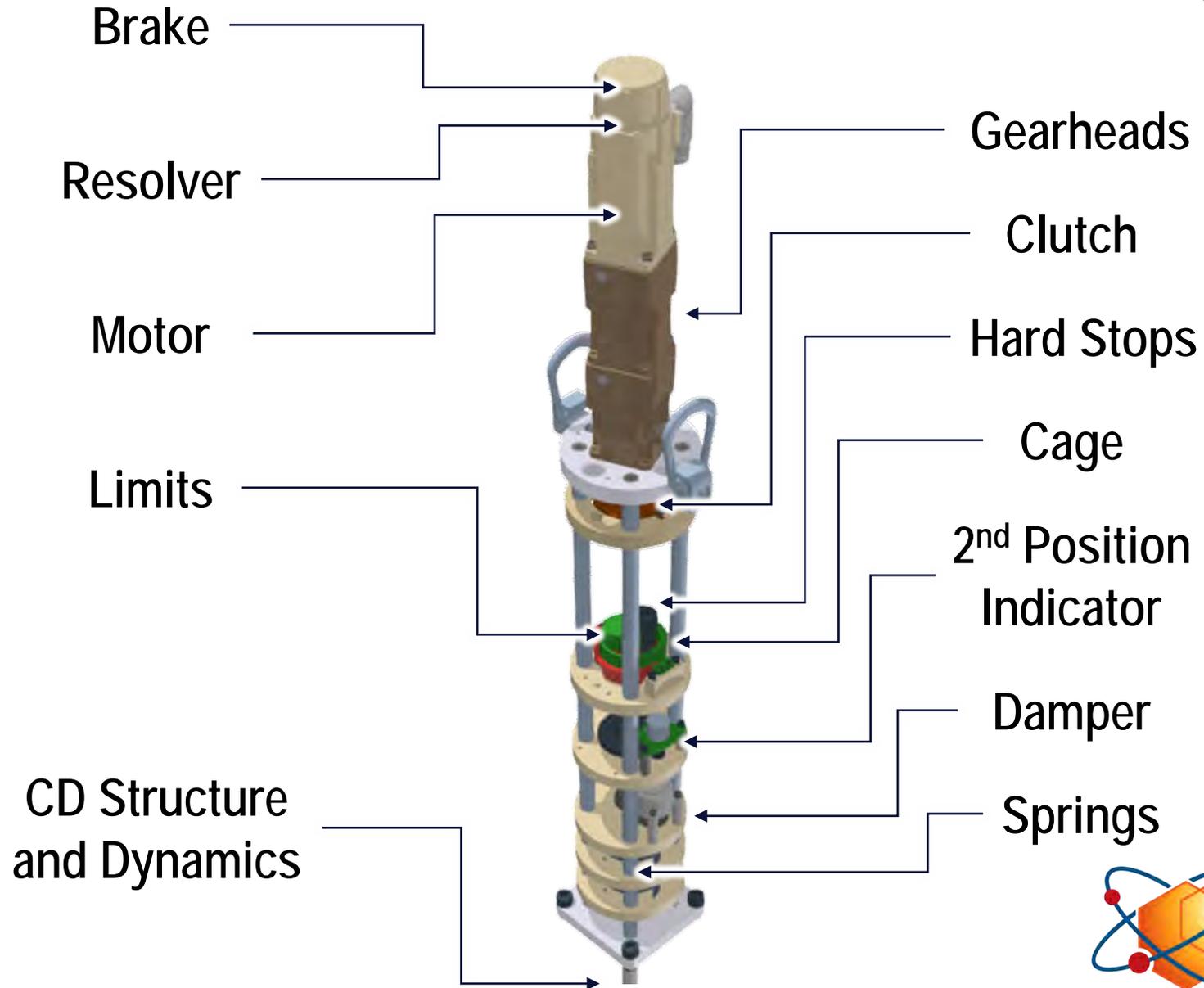


- $\theta_{TotD}(z1)$ (deg)
- $\theta_{b_TotD}(z1)$ (deg)
- $\theta_{b_p5k_TotD}(z1)$ (deg)
- $\theta_{b_TotDL}(z1)$ (deg)

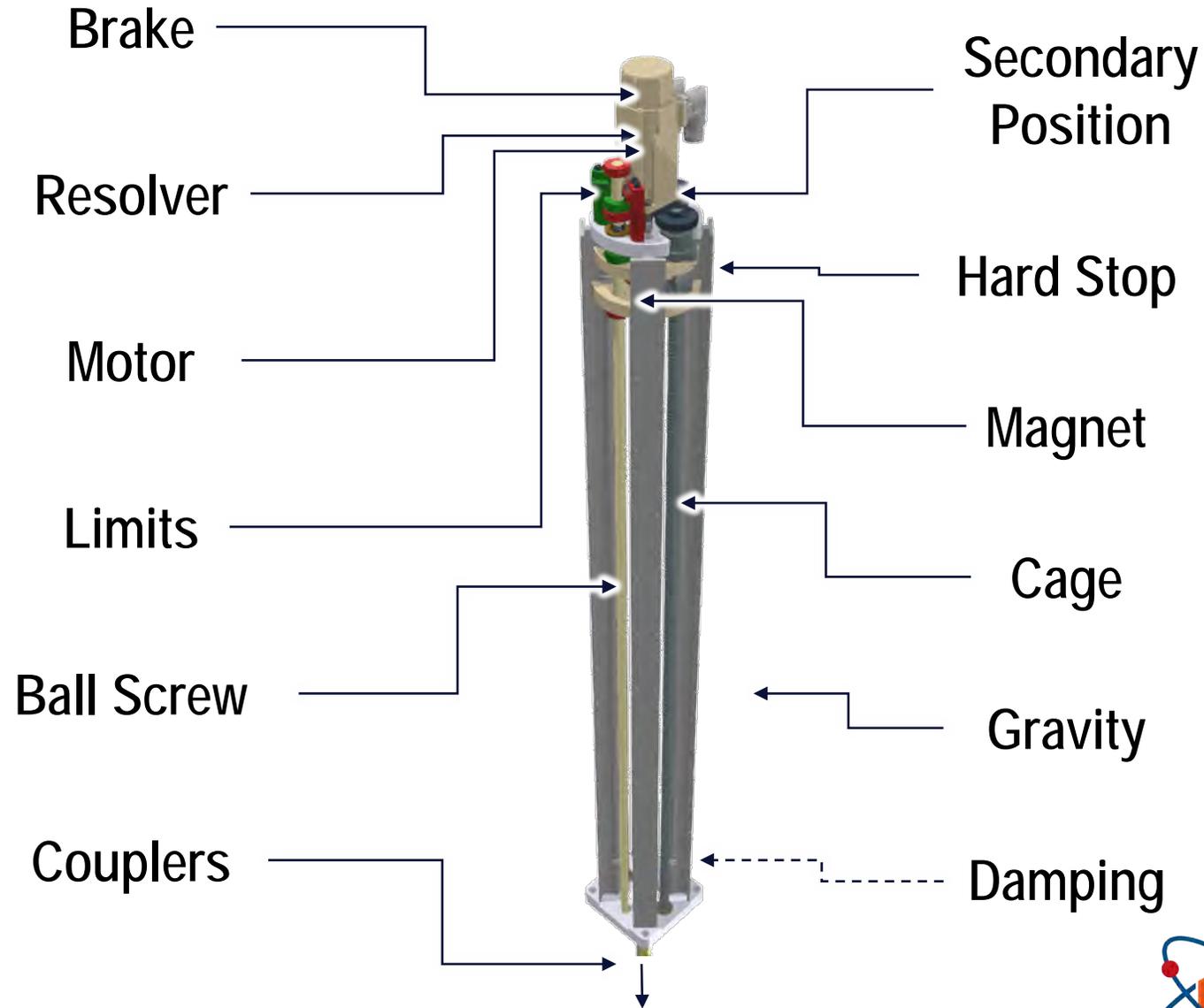
Friction Resistant Torque extracted from ECAR-7228 (12 lbf*in)

- Two springs ~1s shutdown (no damping)
- Two springs <2s shutdown (damping)
- One spring ~4s to near or below subcritical

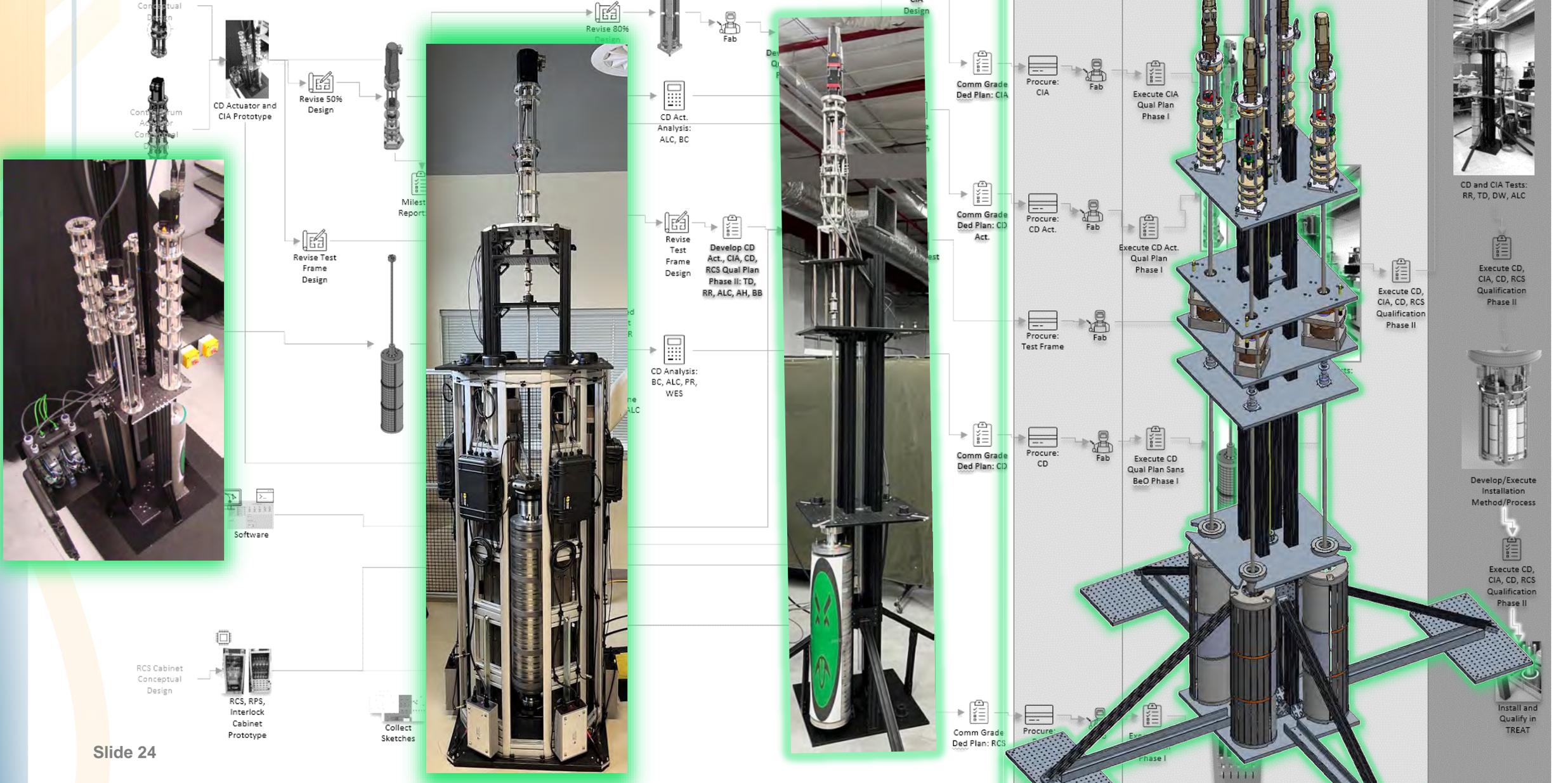
CD Actuator Performance Verification Via Phase I & II Qualification Testing



CIA Actuator Performance Verification Via Phase I & II Qualification Testing



Major Remaining Items for Design Verification (e.g., Phase I & II Qualification Tests)



Testing Platform Strategy (Hardware) (Phase II)



Progress to date

- Design verification via single axis very capable but underdeveloped and complex Double-Delta platform

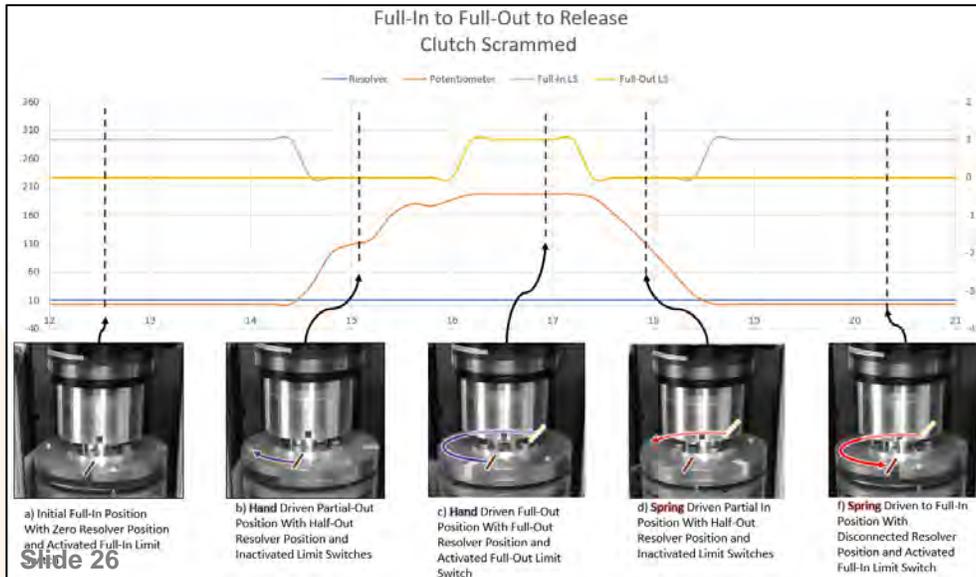
Path forward

- Multi-axis accessible platform amenable to still test all functions but amenable for deployment methods and TREAT environment
- Deploy into reactor and test
- Deploy into



CD Single Axis Torque Chain Testing (Phase II)

- Components
 - Entire chain
 - General software communication
- Functions
 - Position indication
 - Scram Function
 - Sizing validation



Slide 26

CD Design Qualification Test Process Development Setup (2023-01-23)

Substituting AKM44H-ANC2R-00 Motor with AKM42E-EKCNR-01 that was pulled from another project as the identified one is not expected to deliver for several months. The Applied motor is smaller and doesn't have a brake (which would be needed for interlock function test)

Hard stop seems to work well in both motion out and scram. The initial bolt was a little short and thus did not completely seat and has been extended. Still need to perform impact analysis.

Limit switches seem to adjust well in and out to interface with cam

Limit switches cam out's D-shape seems to be slightly over rotated which makes both limit switches activated when in shutdown mode. Will either round this out and use friction or add a set screw. Set screw at various points may be the way to adjust during zero power physics testing.

Rheostat appears to interface well and had proper range

Eddy current damper has not been incorporated yet and actually, the system seems to have sufficient resistance and compliance in the shaft to potentially negate its need

T-slot frame represents riser platform and standoff

Surrogate coupler does not have locking feature as in final design. Generally, it seems that if the hard stop is adequate the lock will be as well.

Substitute for seal is a basic bearing and use a 1/2" shaft versus the 3/4" used in the seal design.

will be here or too much it a bearing beneath it.

Spring below versal joint

pline shaft; it worse for sth are also initially fins.

ring from a to two PTFE which gave ~0.1 when the wrench

Head arrived but is currently configured to accept a 3/4" shaft and an updated sleeve has been incorporated to allow the use of the available motor with this system.

Cage appears to have little clearance between it and the Stirling Engines, and it would be a fair amount of re-design effort to make it larger

Clutch fits within cage and accepts upper shaft extender and lower shaft well. However, in initial tests it has exhibited much slipping primarily due to semi-unrealistic friction in the lower bearings. Had this system been in an accessible application we might be able to adjust the system until this system, but since that it not the case the current clutch appears to be undersized. Will investigate a large clutch of the same type (although cage will have to be enlarged) or recognize that there is only a 1/2 turn option and it may be suitable to use a typical electro-magnet like that on NRAD and manage the cable slack. Note the NRAD magnet has a pull force of ~200lbs or something and we may be able to design the top of shaft interface to provide proper friction surface. Also having a cable length limit WITH a release may be another safety feature in case the motor moves to far the clutch is released and scrambled. NRAD electro-magnet may provide better access to implement a ratchet override drive down function.

Spring was tested to have a pre-set torque of ??? And a rate of ??? Thus, it reached the ??? Maximum value allowed by the motor way early. This ?matches? Theory? May adjust preset and/or number of springs employed.

The Delta/Hexaglide platform provides more than ample deflection capability, but its motion control was not applied. Will start investigating shimming method of deflection induction versus system mechanics but force/torque sensors will provide nice supplemental information.

The upper sleeve bearing as initially designed (2.25 diameter and 0.75" length) but was found to really bind even when the very slight tilt or lateral deflection is imposed (maybe 3 deg?). This doesn't speak well to that bearing nor the drum cap mechanics. A spherical bearing was employed with much better results.

The upper cap mechanics appear to have been designed to accommodate vertical thermal expansion and tilt but tilt seems to really bind the shoulder bolts (rounded edges to accommodate)

Pins appear strong enough but may need double nut and maybe a surrogate without threads on top during loading of BeO to avoid abrasion?

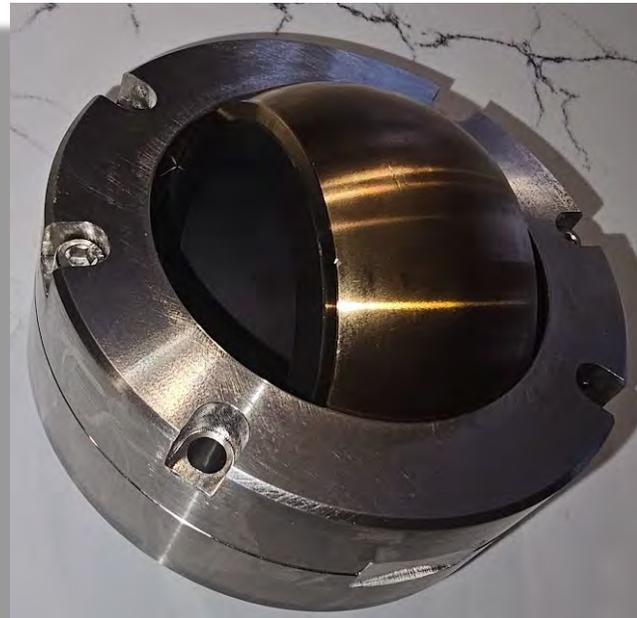
Surrogate round discs of mostly aluminum with several steel ones to achieve expected weight.

The force/torque sensors should not only be able to read the bending but also the shaft's reaction torque to help quantify observed frictions



CD Single Axis Torque Chain Testing (Phase II)

- Huge bearing issue
 - Any misalignment in upper drum bearing completely seized the system
 - Updating from sleeve to spherical throughout the chain



CD Bearing Setup (2023-01-23)

Spline nut allows some rotation which may be sufficient and thus possibly negate need for a crown spline

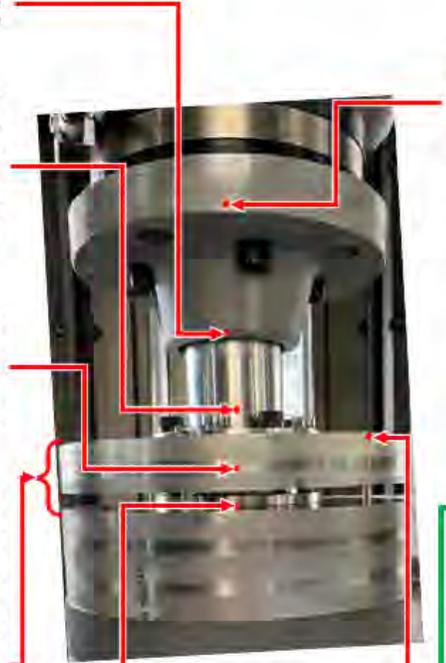
Press-down spring was upgraded as it just didn't feel like there wasn't sufficient press down force such that the torque could be transferred from the shaft to the plates via friction as opposed to through the pins (note: if the torque goes through the pins this may generate force concentrations on the BeO hole surfaces which is not good)

Alignment/torque transfer bolts may apply the necessary torque transfer but may be significantly contributing to the binding that is being seen. We rounded hole edges so that they didn't gouge shoulder screw. With the spherical bearing

Generally, it seems that the top hat mechanism intends to be a telescoping universal joint and appears to have the geometry available to accommodate ??? Direct deflection between the top disk and the top cap or ?? Angular rotation of ??? Or sub-value combination of both. However, it appears to have a hard time accommodating such movement when under torque where it appears to be binding between the alignment screws and the top cap holes. A few fixes for this may be firstly making the holes rounded so they don't gouge so much and reducing the load going through them by having the shaft connect either just to the press plate (maybe a reverse crown spline) or a slotted coupler and either just a rounded alignment feature in the top hat or another reverse crown spline

Press plate and disks seem to properly transfer torque

Embedded sleeve bearing 2.25" ID by 3/4" long was initially attached to force/torque transducer but significantly binds the system even when it is just tightened down to the platform (which appears to have a slight 1-to-2-degree tilt to it). The solutions appear to be a longer sleeve bearing (2x diameter is the rule of thumb) or a spherical bearing. The spherical bearing was chosen and produced dramatically better rotational performance but has the potential to allow increased lateral deflection in the drum.

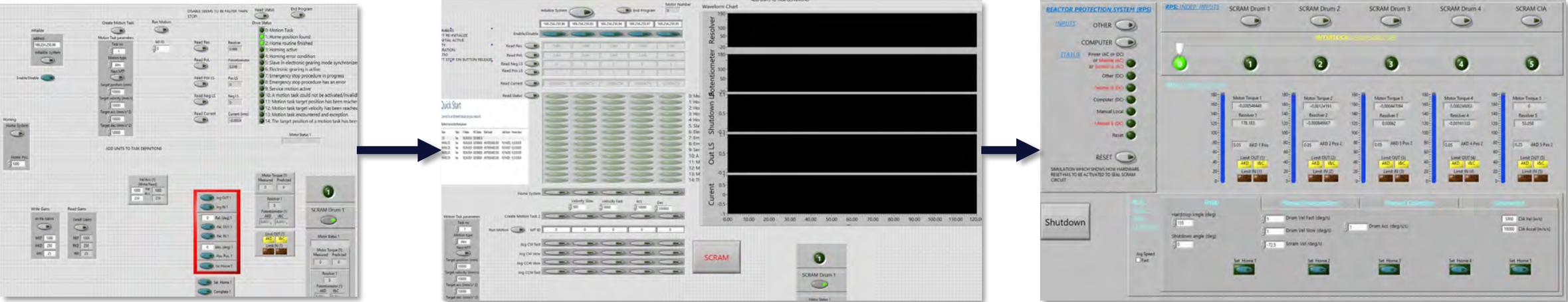


Alignment pin need to be double nutted at least, need to check clearances if the stack is completely compressed and they either stick out the top or bottom. Also, during assembly, the threaded top is a rather abrasive surface and may mar the BeO thus it is advisable that smooth rods with perhaps rounded ends be initially used and then removed and replaced with threaded counterpart.



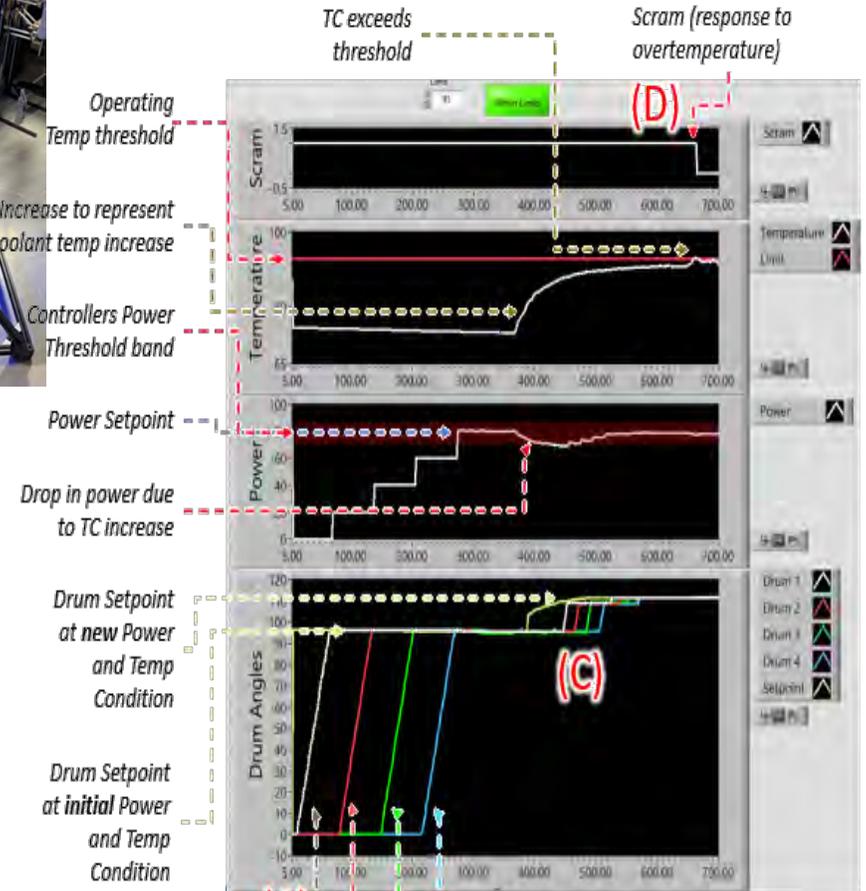
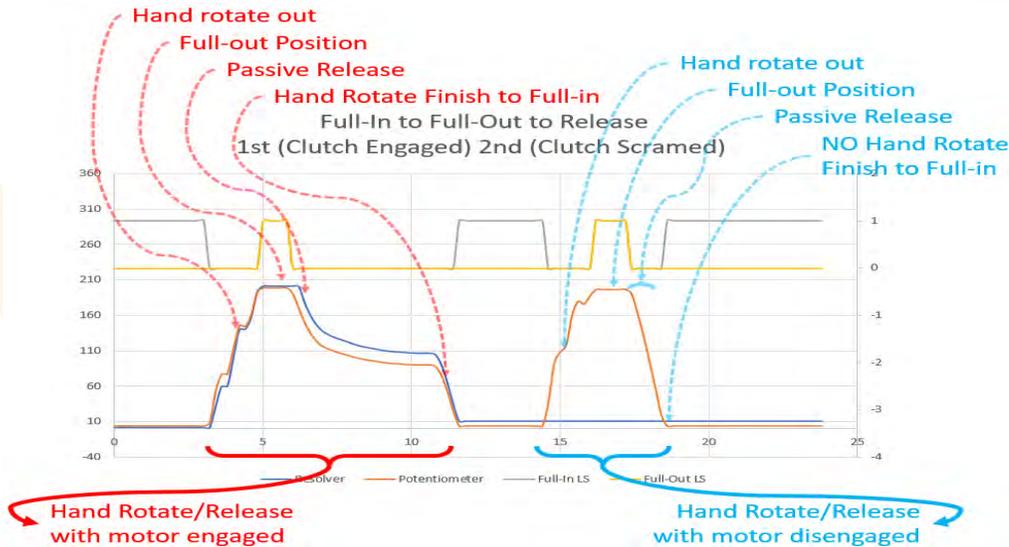
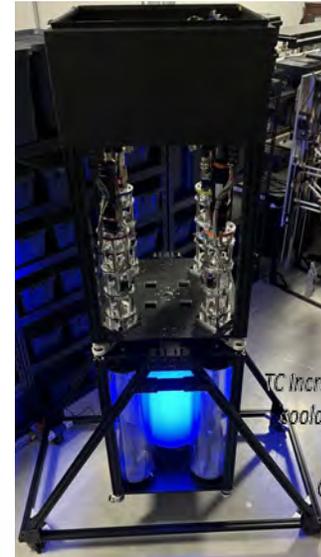
Testing Platform Strategy (Software) (Phase II)

- Andrew Heim and Ben Baker Adapting Software to operation from single axis system to multi-axis system in a format amenable to insertion in I&C framework



Testing Function Complexity (Software) (Phase II)

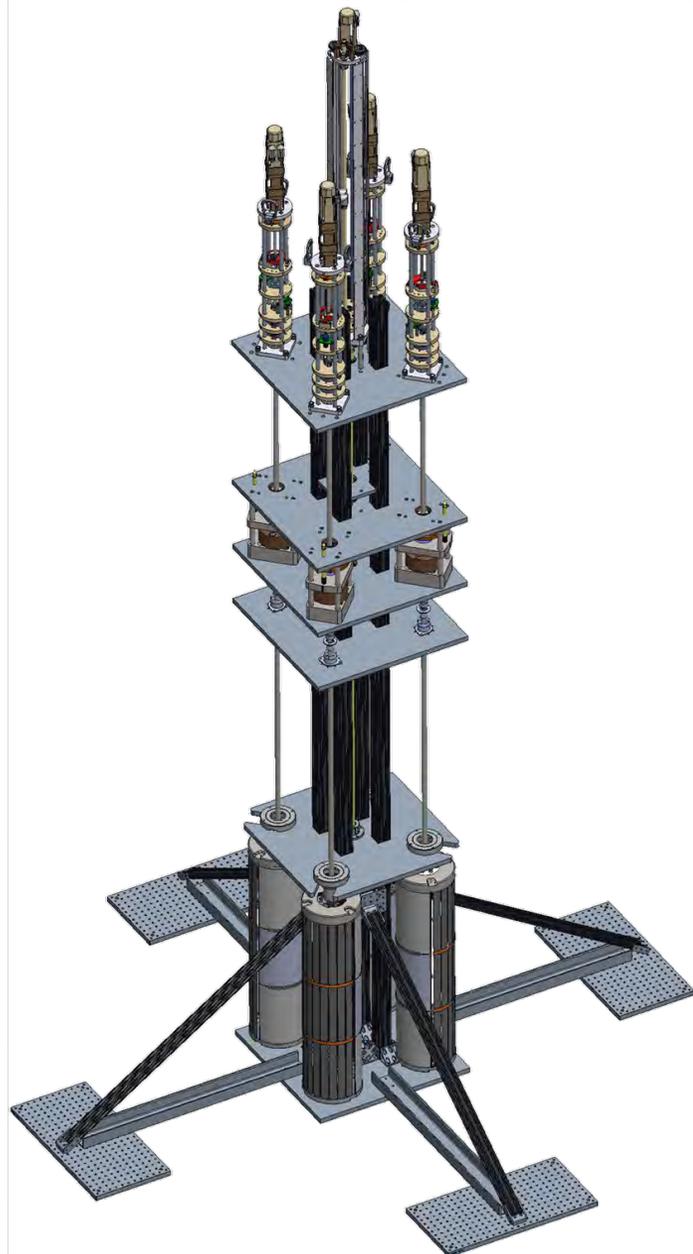
- Hand rotation with reads to automatic switching between drums and I&C interaction



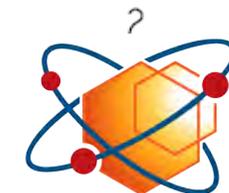
Position response of each drum to setpoint going through a cycle



Major Remaining Items for Design Verification (e.g., Qualification Tests (Phase II))

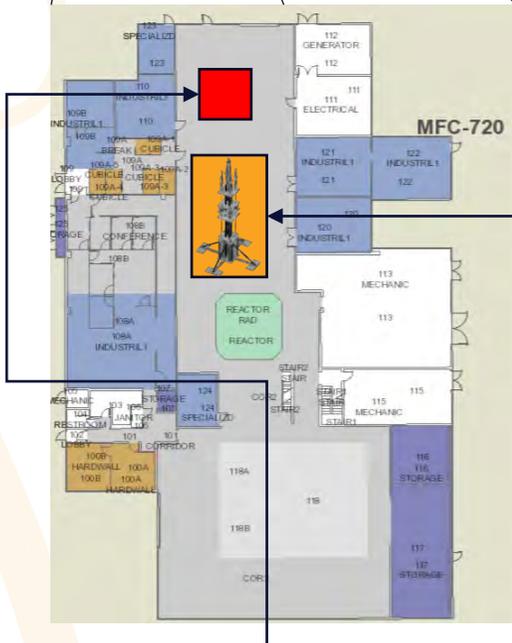
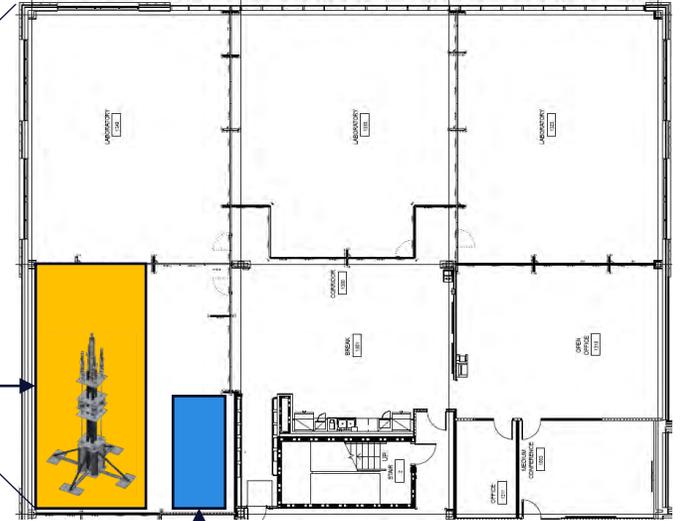
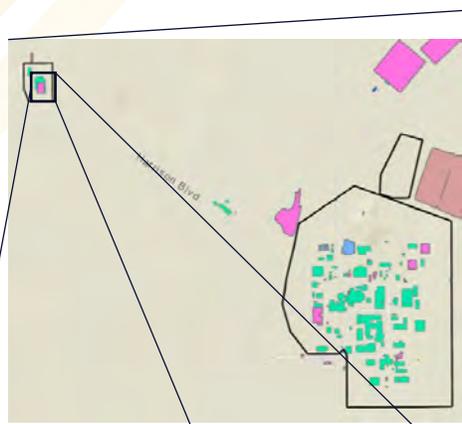


D. REQUESTER:					
RESP ENGR: D. WAHLQUIST					
DESIGN: A. CRAWFORD		MFC-785 MARVEL REACTIVITY CONTROL SYSTEM TEST STAND ASSEMBLY			
E. DRAWN: C. CONWAY					
PROJECT NO.:		SIZE: CAGE CODE: INDEX CODE NUMBER: DWG. NO. REV			
SPCL CODE: NA		D 01MF3 273 0785 98 081 1027398 000A			
FOR REVIEW/APPROVAL SIGNATURES SEE DCR NO. XXXXXX		SCALE: 3/80 SHEET 1 OF 3			
EFFECTIVE DATE:		CREW MODEL: 1077590 WINDHILL RELEASE LEVEL: 3/1/10 WINDHILL VERSION: 0.0			



MRP Microreactor Program

RCS Qualification Plan (Phase Locations)



Phase IIe-IIh: TREAT High Bay and I&C Room

- Mock-up Stand with Ind. Control Box Repeat
- I&C patch panel and
- In-Reactor Pre-Weld Repeat

Phase IIb-IId: ESRL

- Independently test final actuators with surrogates
- Group test final actuators with more mature electronics
- Group test final actuators with more mature connections

Phase I: ESRL

- QL1 Assembly

Phase III: TREAT High Bay Pit

- In-Reactor Install Repeat
- In-Reactor Zero Power Repeat
- In-Reactor Initial Criticality



MRP Microreactor Program

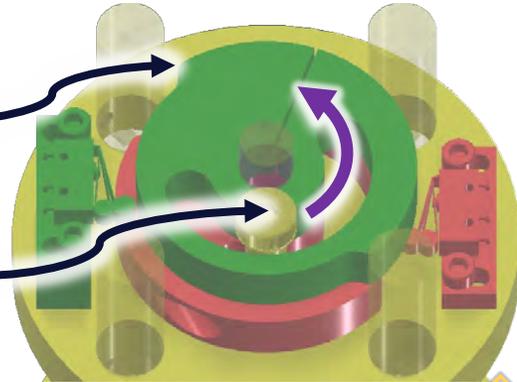
Phase II Qualification: Setting CD and CIA Interlock Hard Stops During Zero Power Physics Testing

- Repeat of Phase II
- Added Zero-Power Physics Testing
- Adjust Hard Stop Cam

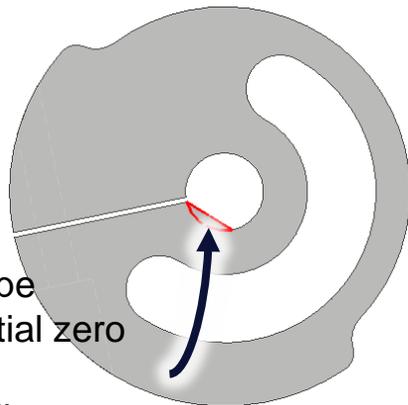
- Hard-stops at top and bottom

Adjustable cam rotation

Bolt stops shaft rotation when it hits end of slot

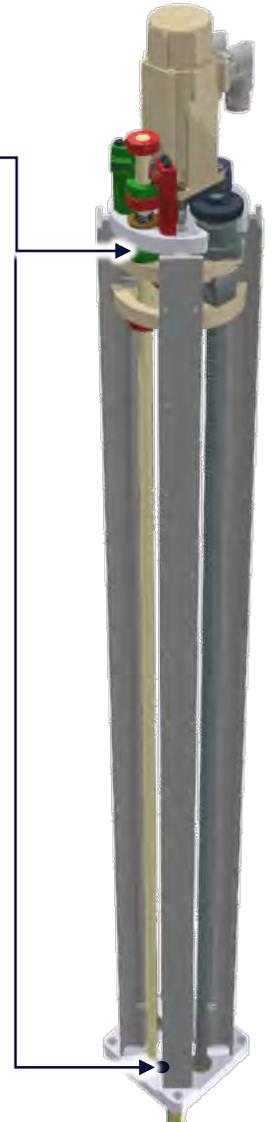


- Fab final d-shape feature after initial zero power test
- Direct install
 - Or tack weld in shim

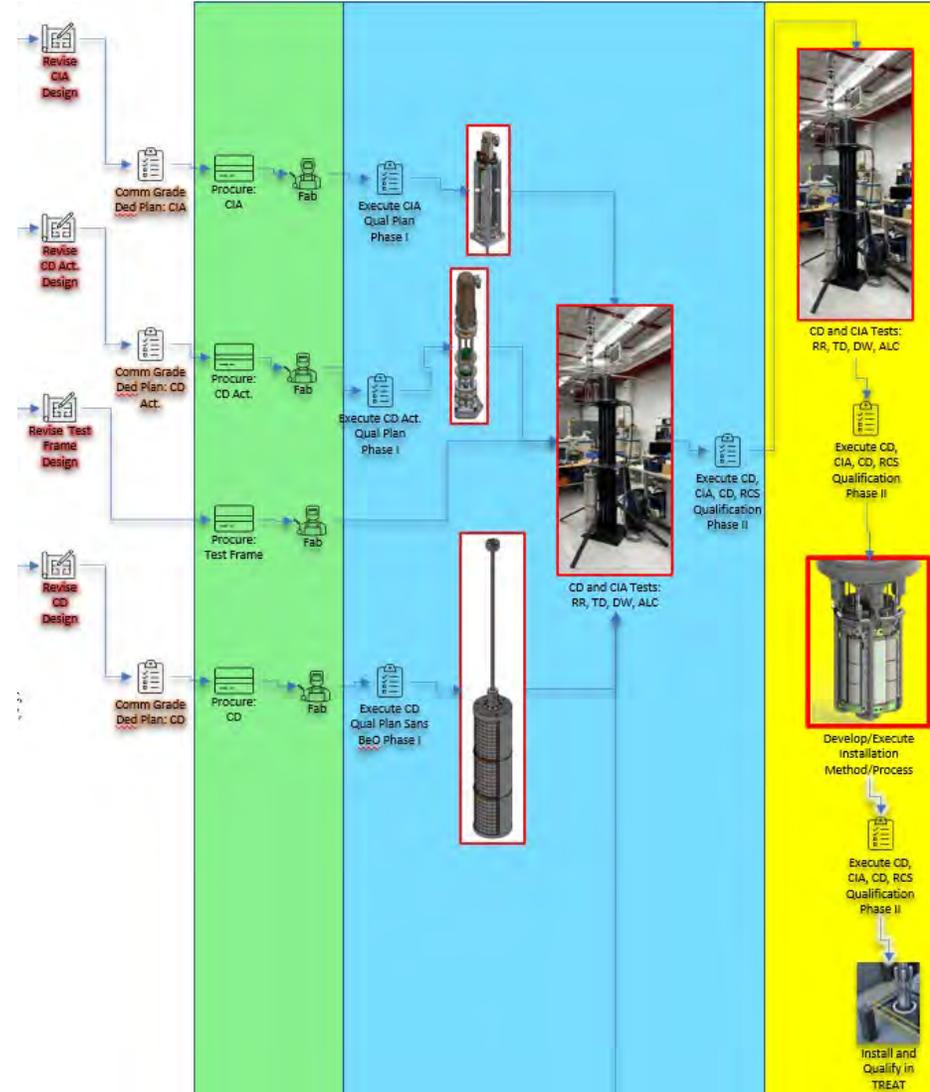
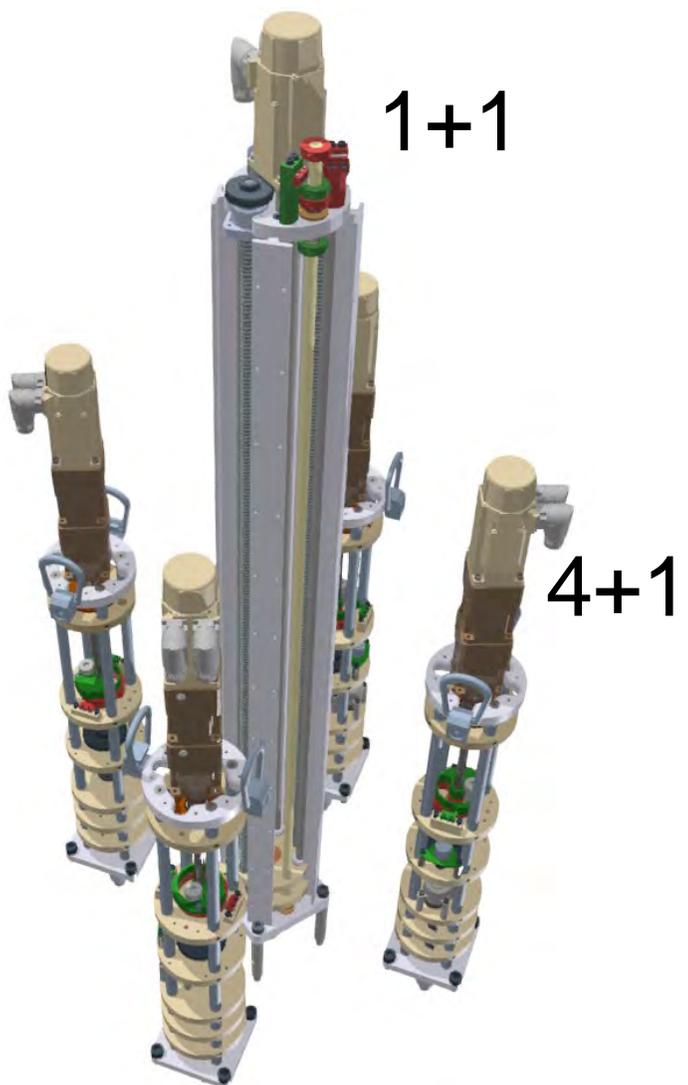


Set Limit at Zero Power

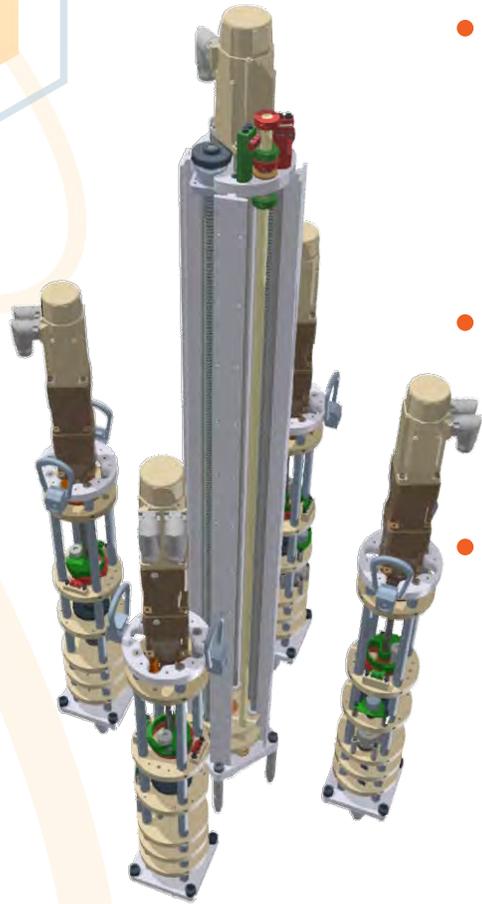
Critical



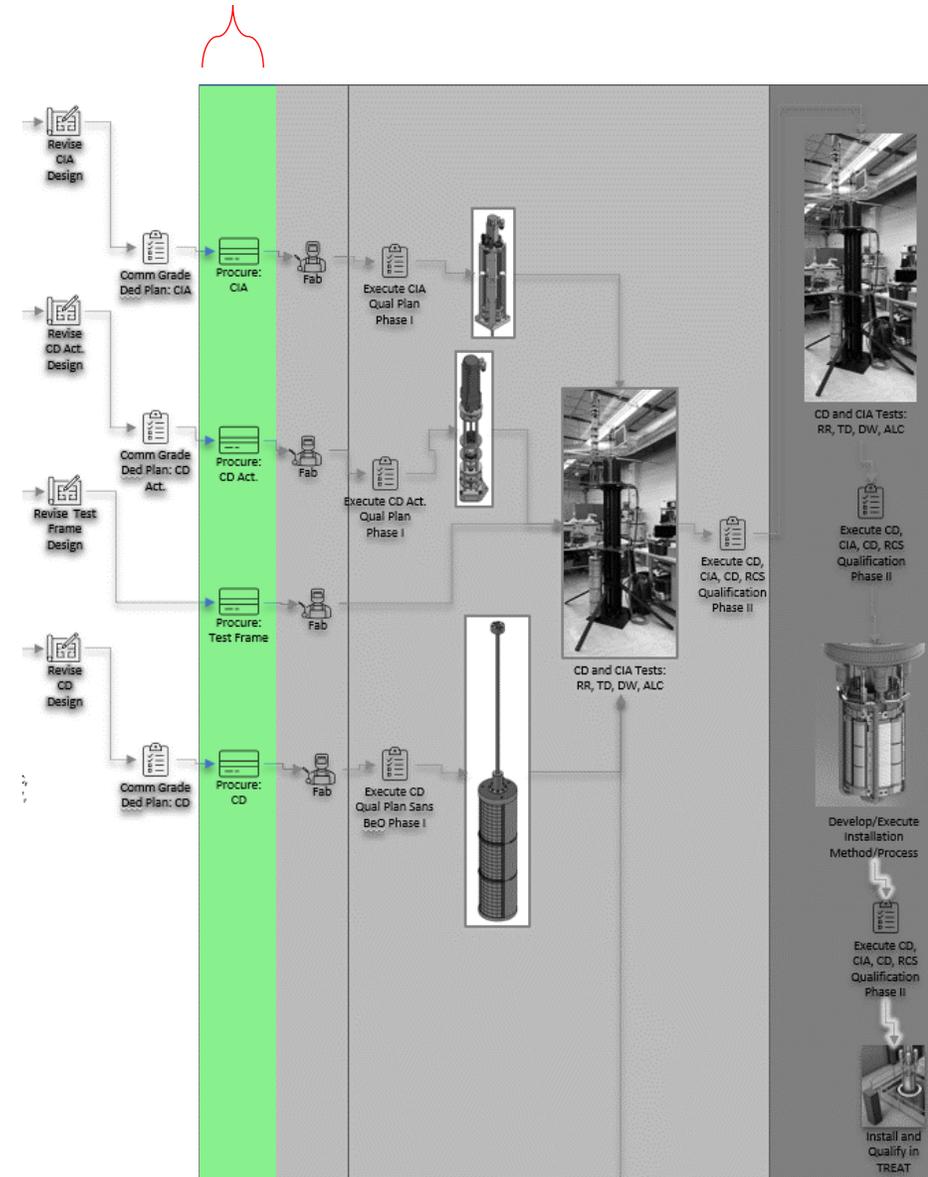
Procurement, Supply Chain, and Construction Strategy (High Level)



Procurement and Supply Chain

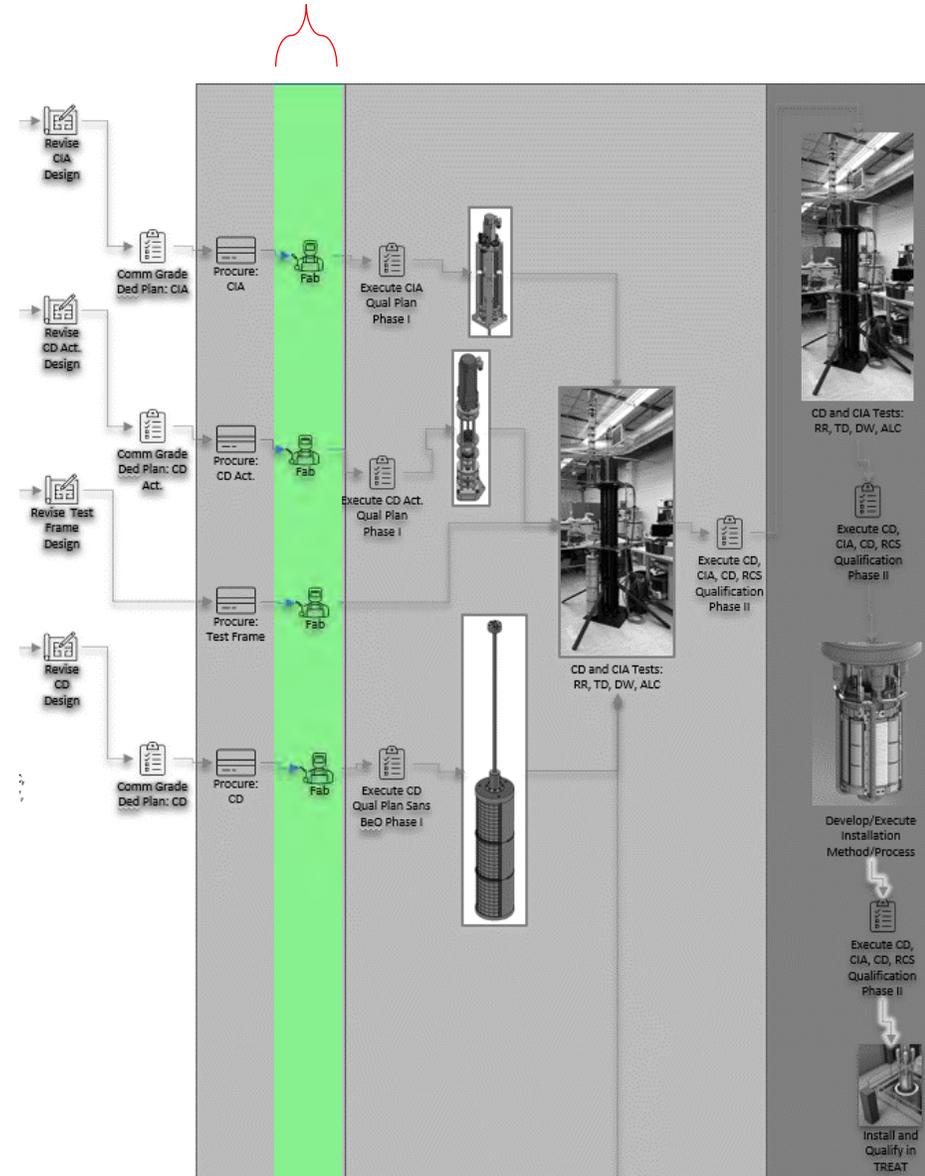
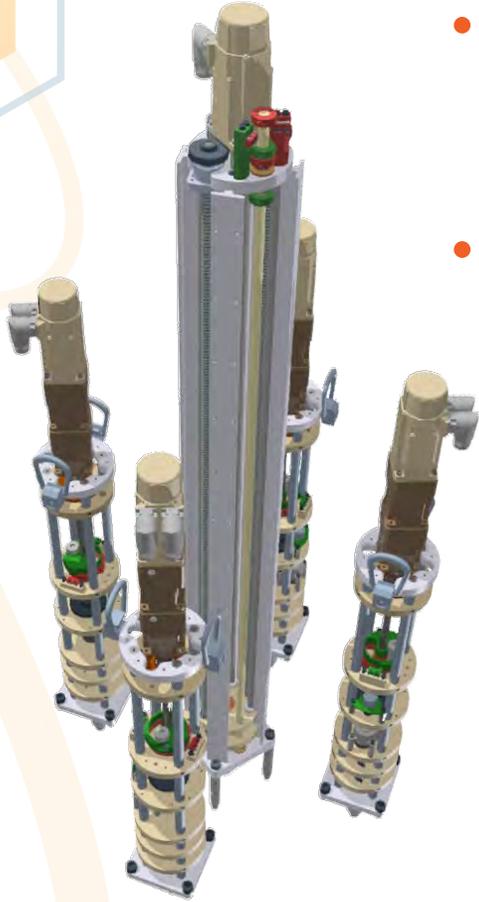


- Procurement of SR Components
 - NQA-1 Materials where available
 - CGD plans for items
- Procurement of Non-SR Components as Commercial
- Supply chain appears to have improved with Motors and Drivers appearing to be longer lead multiple month items



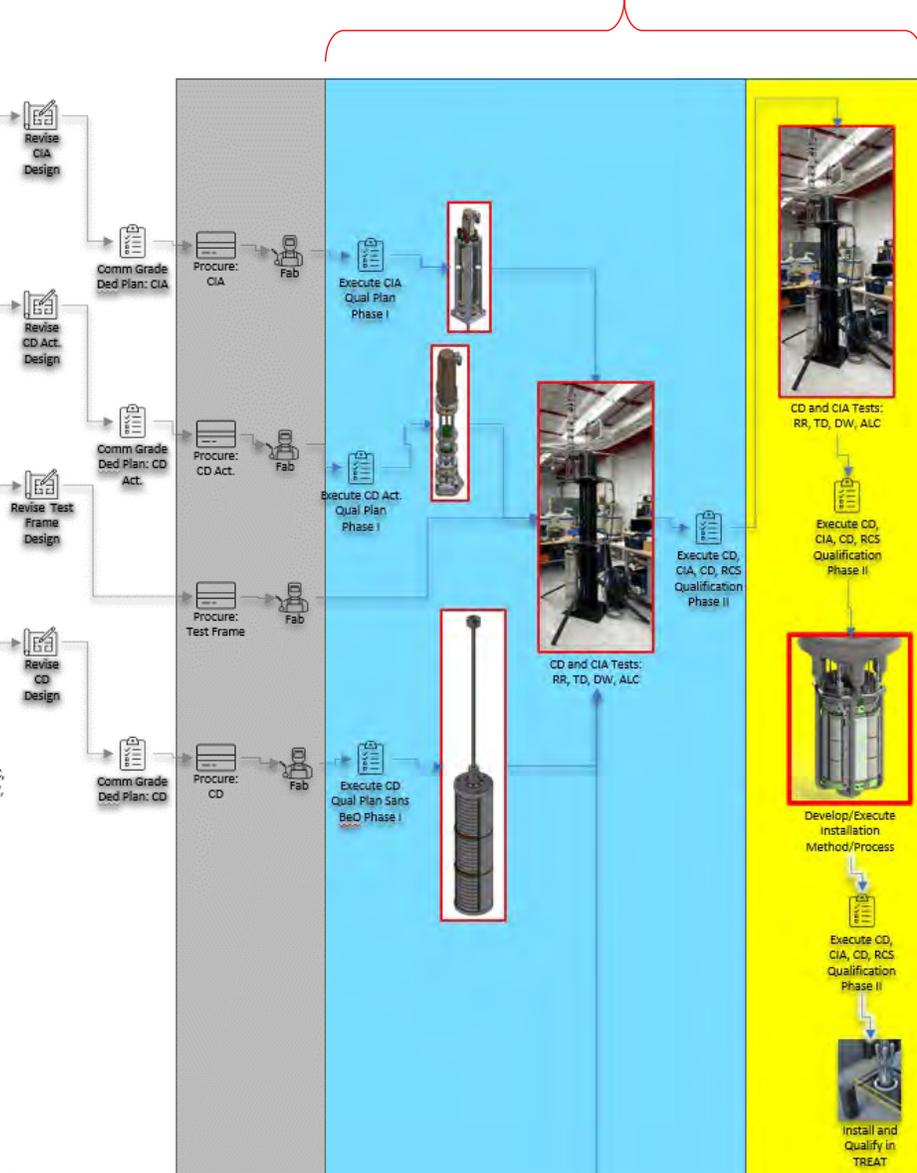
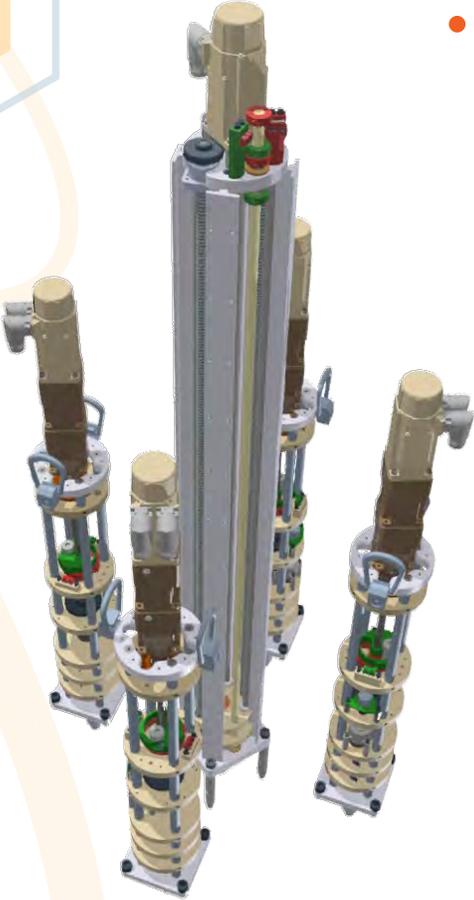
Construction Strategy

- Fabricate CD actuators and CIA actuators in house
- Work in tandem with CD and CIA fabrications so to be aware of entire systems



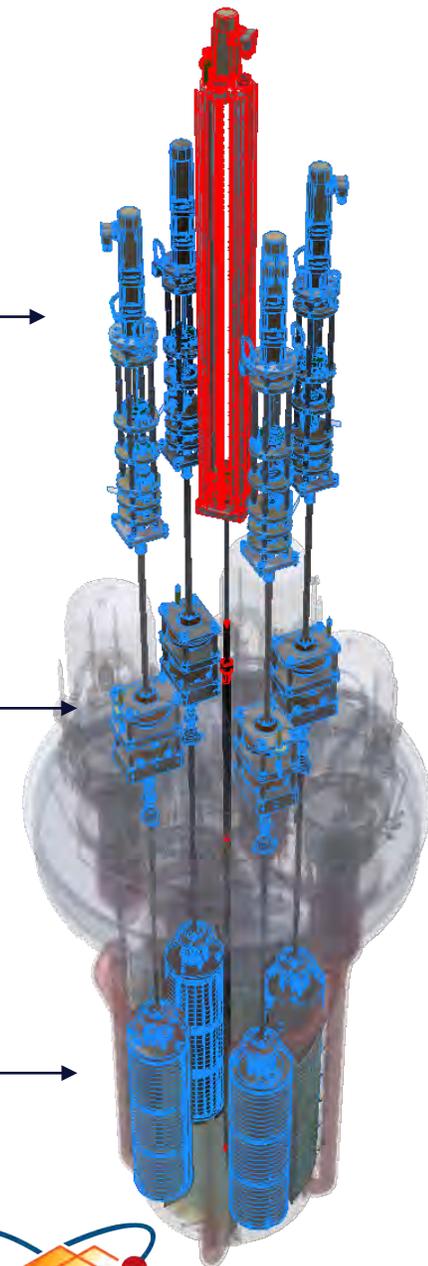
Assembly Strategy

- Iterative strategy with testing achieved after each incorporation



Maintenance Strategy

- Pre-Operation Checks
- Periodic Checks
 - Actuators are very accessible
 - Lock and seal are somewhat accessible
 - Below seal has minimal accessibility
 - Spline connection
 - Drum is all but inaccessible



Maintenance Strategy (CD Pre-Operational Checks)



- Pre-Operation:
 - Activate and check all systems
 - Unlock system
 - Adjust drum out hard stop to target
 - Home System to shutdown hard stop
 - Independently Test SR Out Hard Stop for each Drum
 - Independently Test SR Scram for each Drum
- Operation
 - Move to target Sub Critical Setpoint
 - Move Drum to Critical Position
 - *Check criticality necessary systems*
 - Adapt Position Based on Criteria Such as Load Following
 - Demonstrate Hitting Drum Out Hard Stop
 - Controlled Shutdown
 - Scram as necessary

Maintenance Strategy (CIA Pre-Operational Checks)



- Pre-Operation:
 - Adjust CIA hard stop to target if necessary
 - Activate and check all systems
 - Unlock system
 - Home System to shutdown hard stop
 - Demonstrate Hitting out hard stop
 - Test Scram
- Operation
 - Move to Top position
 - *check criticality measurement systems*
 - Demonstrate Hitting Out Hard Stop
 - Retain position during operation
 - Controlled Shutdown
 - Scram as necessary

Questions?

Thank You