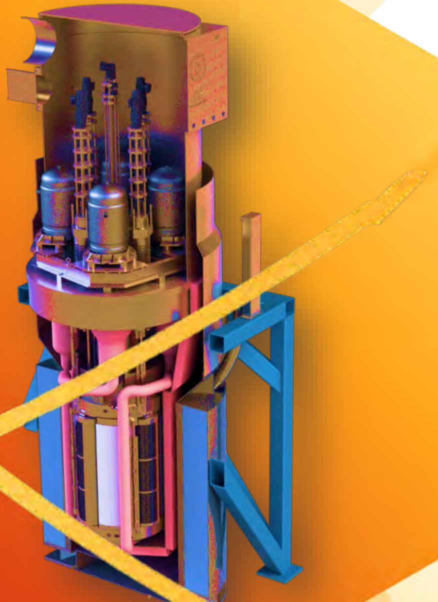
(Microreactor Applications Research, Validation & EvaLuation), 2024

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

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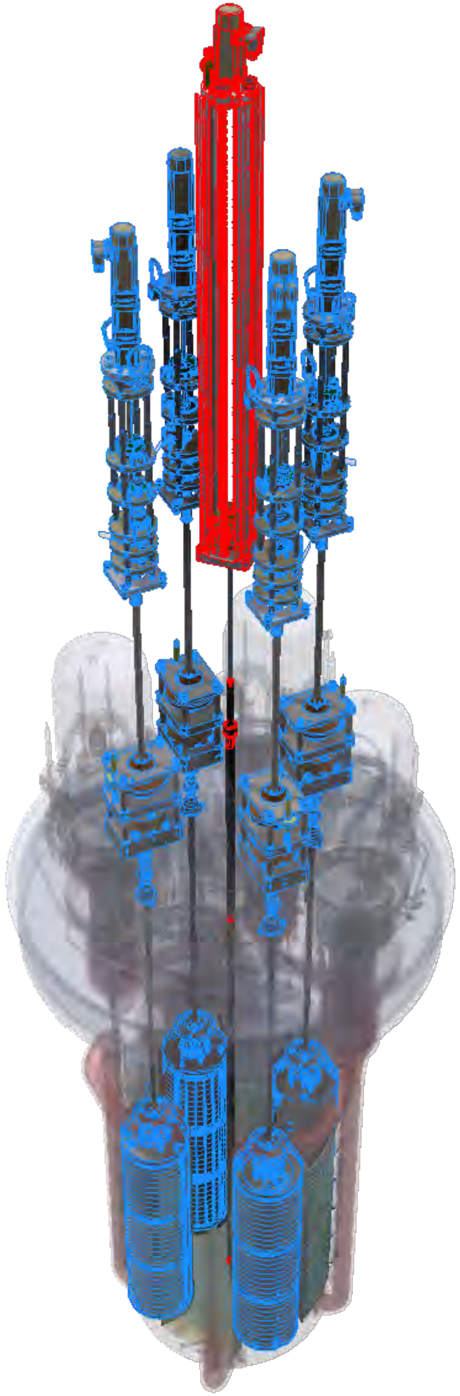
Requirements

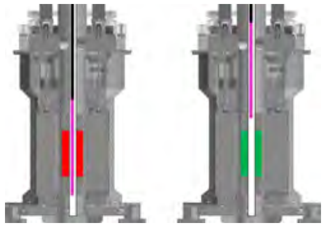
- FOR-868, Functional and Operational Requirements: Microreactor Applications Research Validation and Evaluation (MARVEL) Project, Rev.0, March 16, 2023.
  - Rev. 1 Pending

- TFR-2578: Technical and Functional Requirements: MARVEL Reactivity Control System (RCS), Rev. 0, March 22, 2023.
  - Rev. 1 Pending

Overview of System

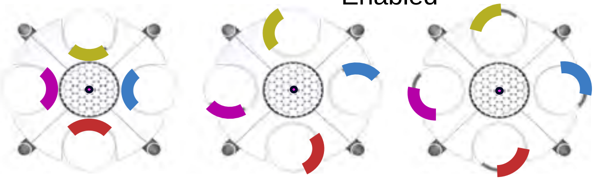
- Two Diverse Reactivity Control Methods
  - 4 Control Drums
    - Peripheral
    - Drums
    - Rotation
    - Torsional Spring Return
  - 1 Central Insurance Absorber Rod
    - Center
    - Rod
    - Translation
    - Gravity Return





CIA In

Criticality Enabled

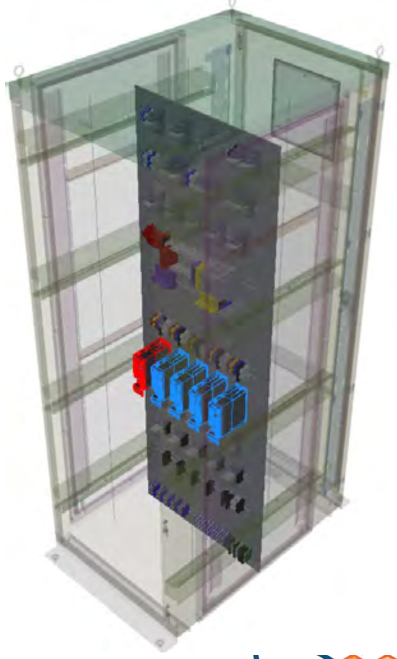


Full-in: Shutdown

Partial Out: Initial Criticality

Full Out: Maximum Reactivity

*Will be set below full out (180 degree) using a tuned hard stop



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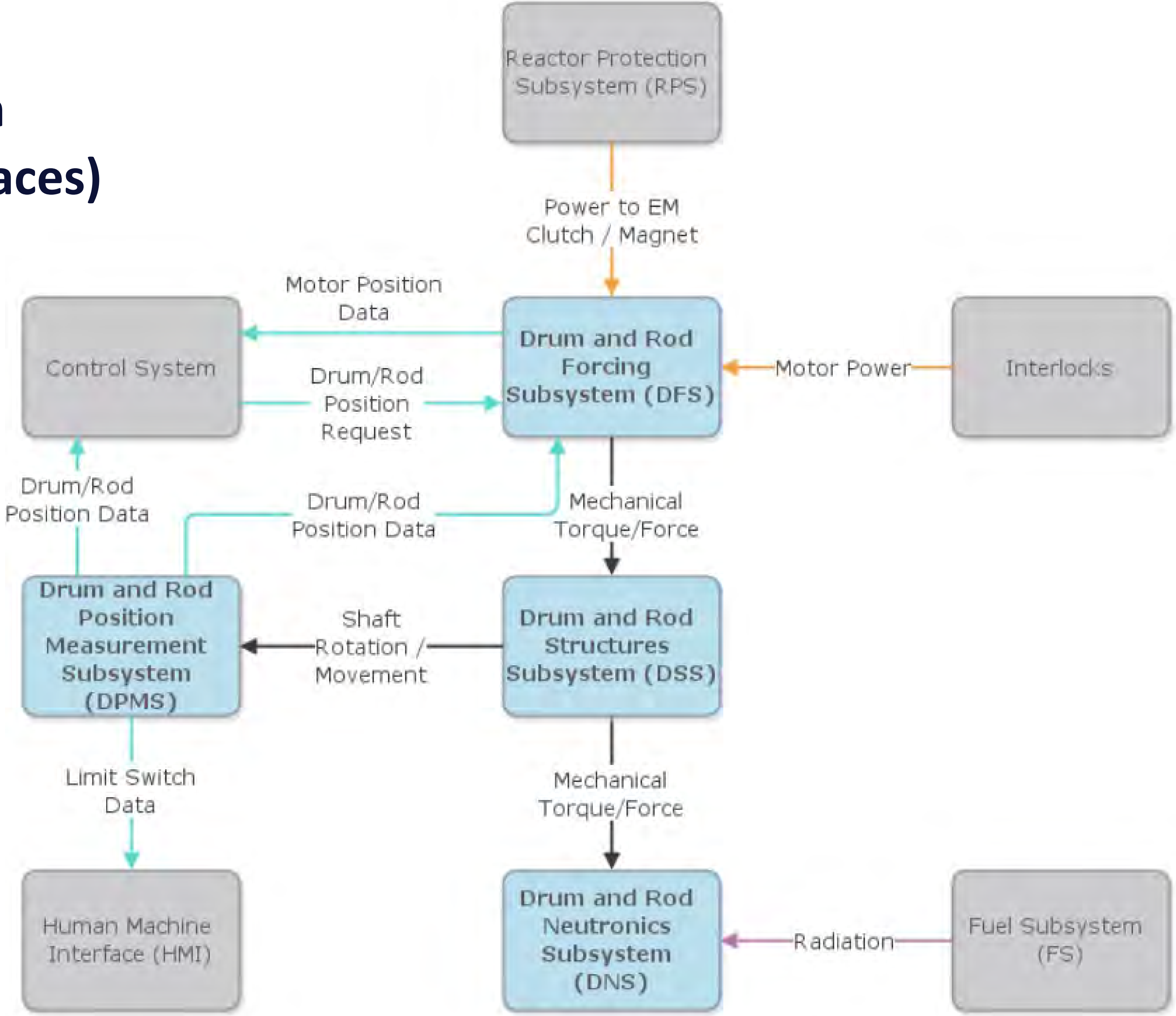
Overview of System (Subsystems, Interfaces)



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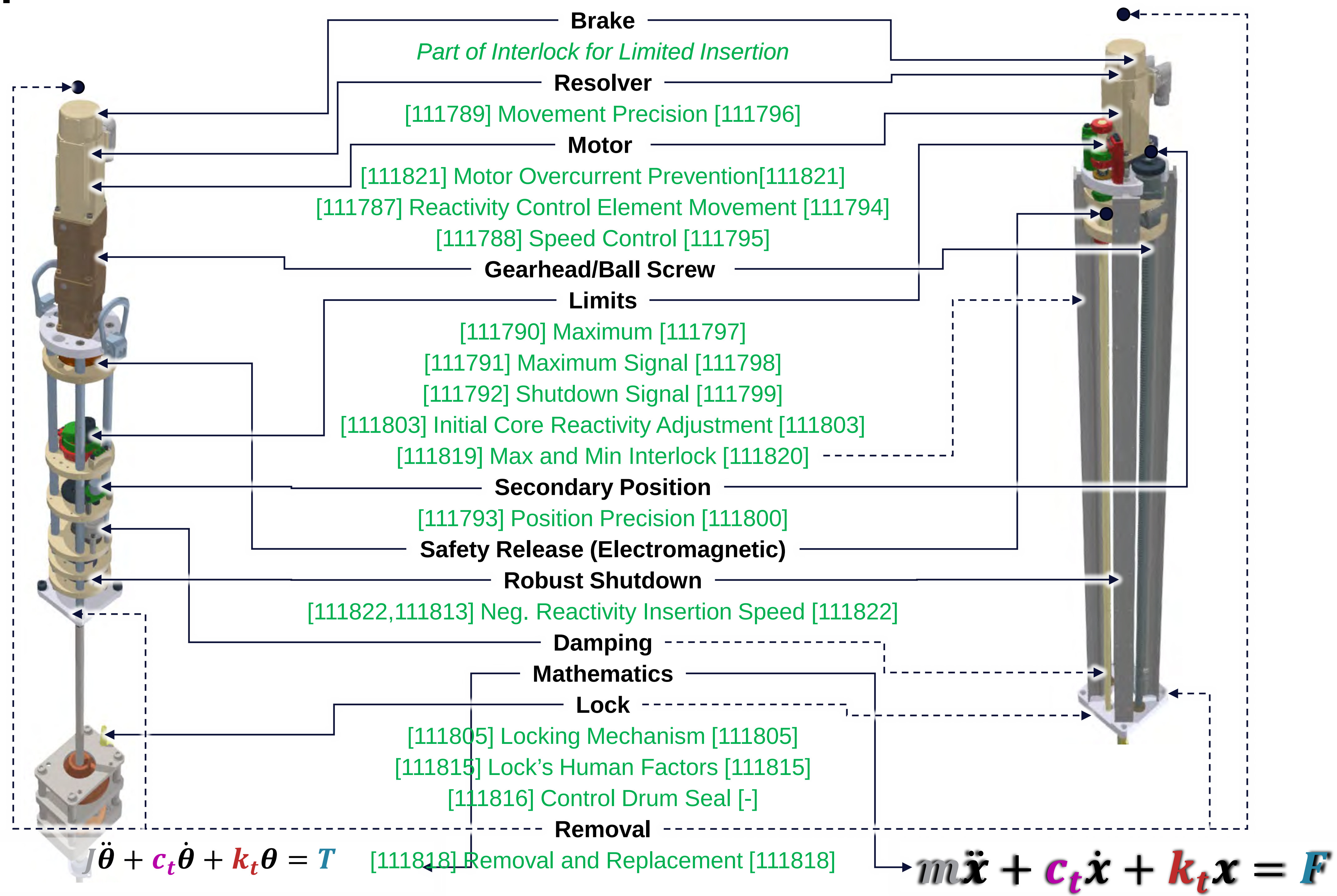
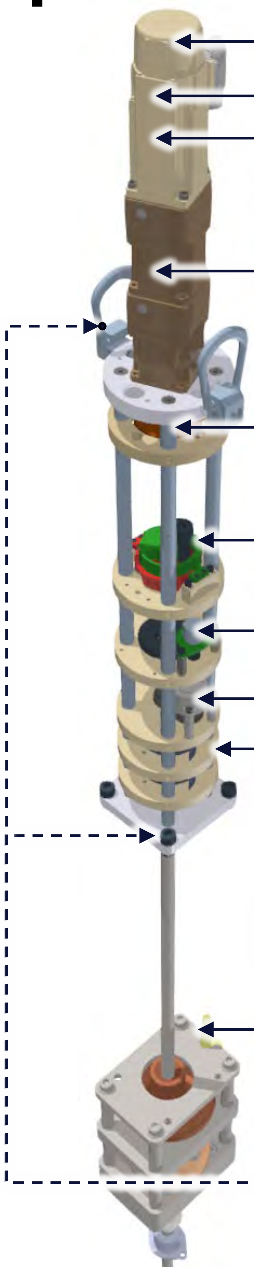


Brake
Part of Interlock for Limited Insertion
Resolver
[111789] Movement Precision [111796]
Motor
[111821] Motor Overcurrent Prevention[111821]
[111787] Reactivity Control Element Movement [111794]
[111788] Speed Control [111795]
Gearhead/Ball Screw
Limits
[111790] Maximum [111797]
[111791] Maximum Signal [111798]
[111792] Shutdown Signal [111799]
[111803] Initial Core Reactivity Adjustment [111803]
[111819] Max and Min Interlock [111820]
Secondary Position
[111793] Position Precision [111800]
Safety Release (Electromagnetic)
Robust Shutdown
[111822,111813] Neg. Reactivity Insertion Speed [111822]
Damping
Mathematics
Lock
[111805] Locking Mechanism [111805]
[111815] Lock's Human Factors [111815]
[111816] Control Drum Seal [-]
Removal
[111818] Removal and Replacement [111818]
$J\ddot{\theta} + c_t\dot{\theta} + k_t\theta = T$
$m\ddot{x} + c_t\dot{x} + k_t x = F$

Requirement/Component Relationships



Brake

Potential Part of Interlock for Limited Insertion

Resolver

[111789] Movement Feedback Precision

Motor

[111821] Motor Overcurrent Prevention

[111787] Reactivity Control Element Movement

Gearheads (2x 100:1)

[111788] Speed Control Including Maximum

Hard Stop

[111819] Max and Min Interlock

[111790] Maximum

[111803] Initial Core Reactivity Adjustment

Limit Switches

[111791] Maximum Signal

[111792] Shutdown Signal

Secondary Position

[111793] Position Precision

Safety Release (Electromagnetic)

Robust Shutdown

[111822,111813] Neg. Reactivity Insertion Speed

Damping

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

Mathematics

Lock

[111805] Locking Mechanism

[111815] Lock's Human Factors

[111816] Control Drum Seal

Removal

[111818] Removal and Replacement

[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

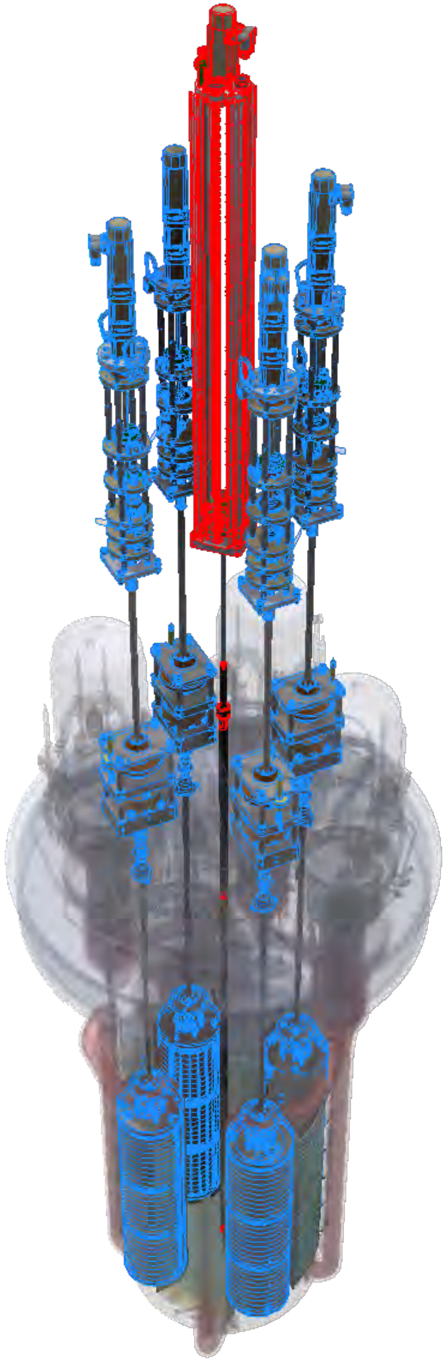
[111802] CD Positive Reactivity Worth

[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



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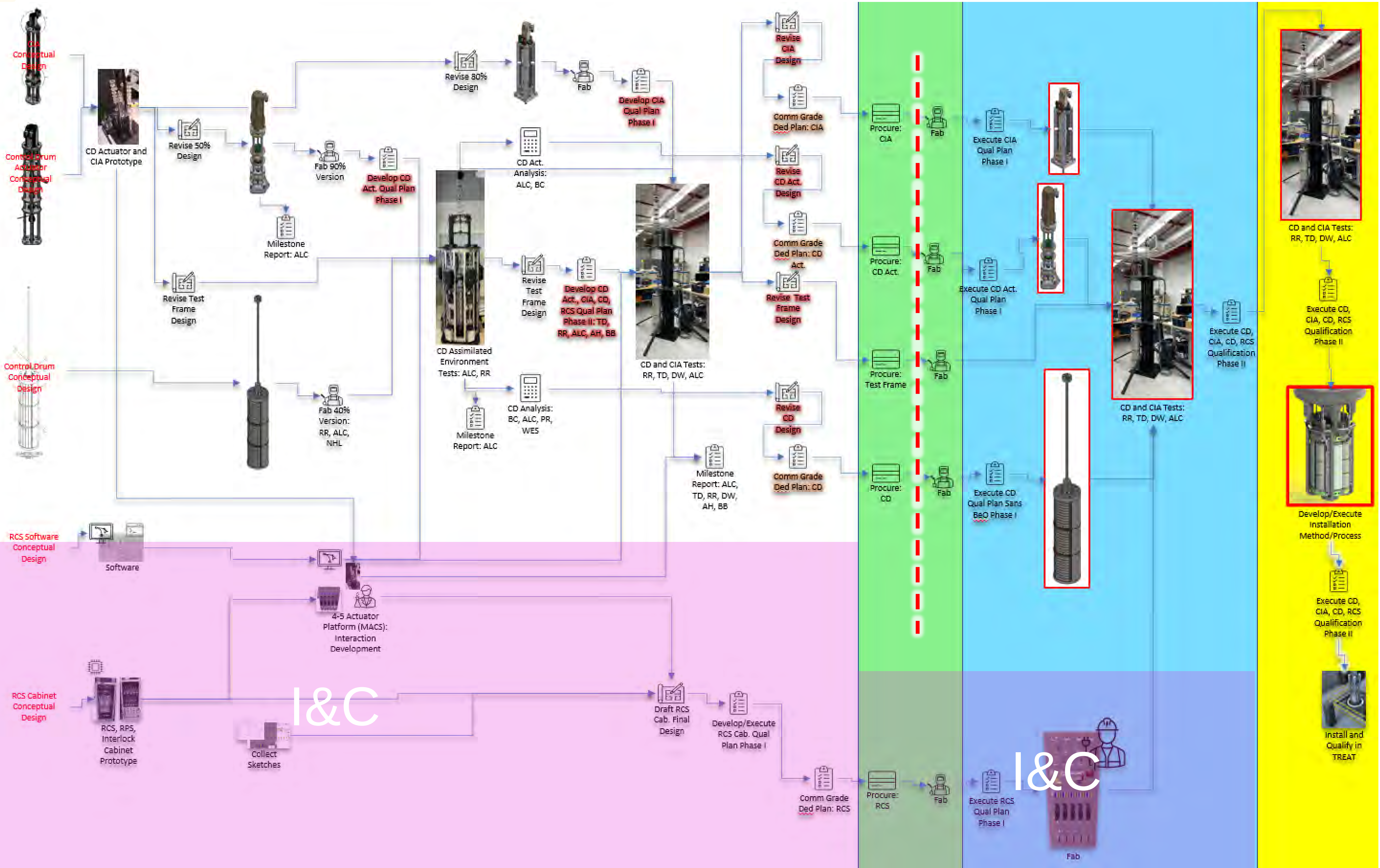
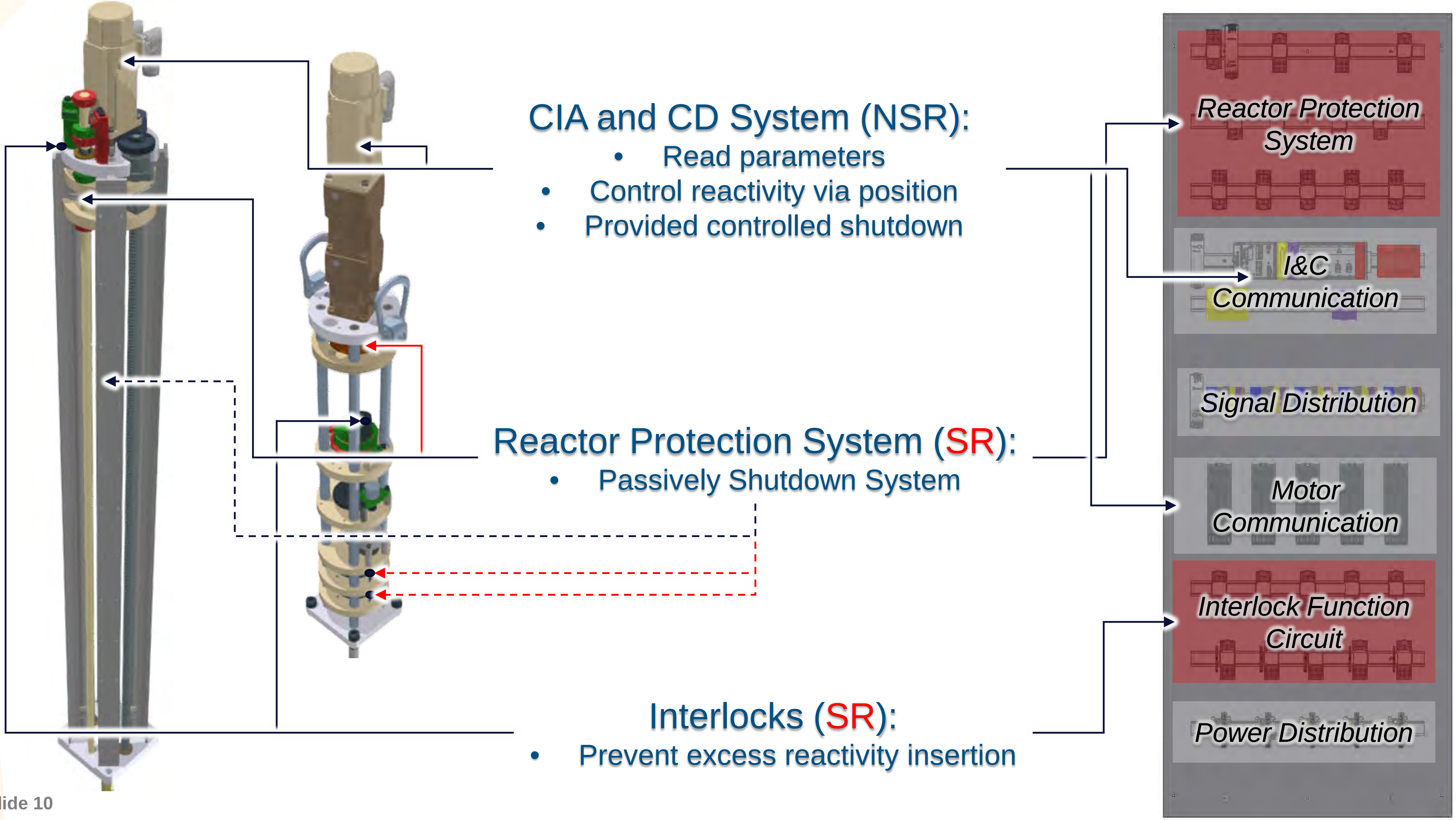
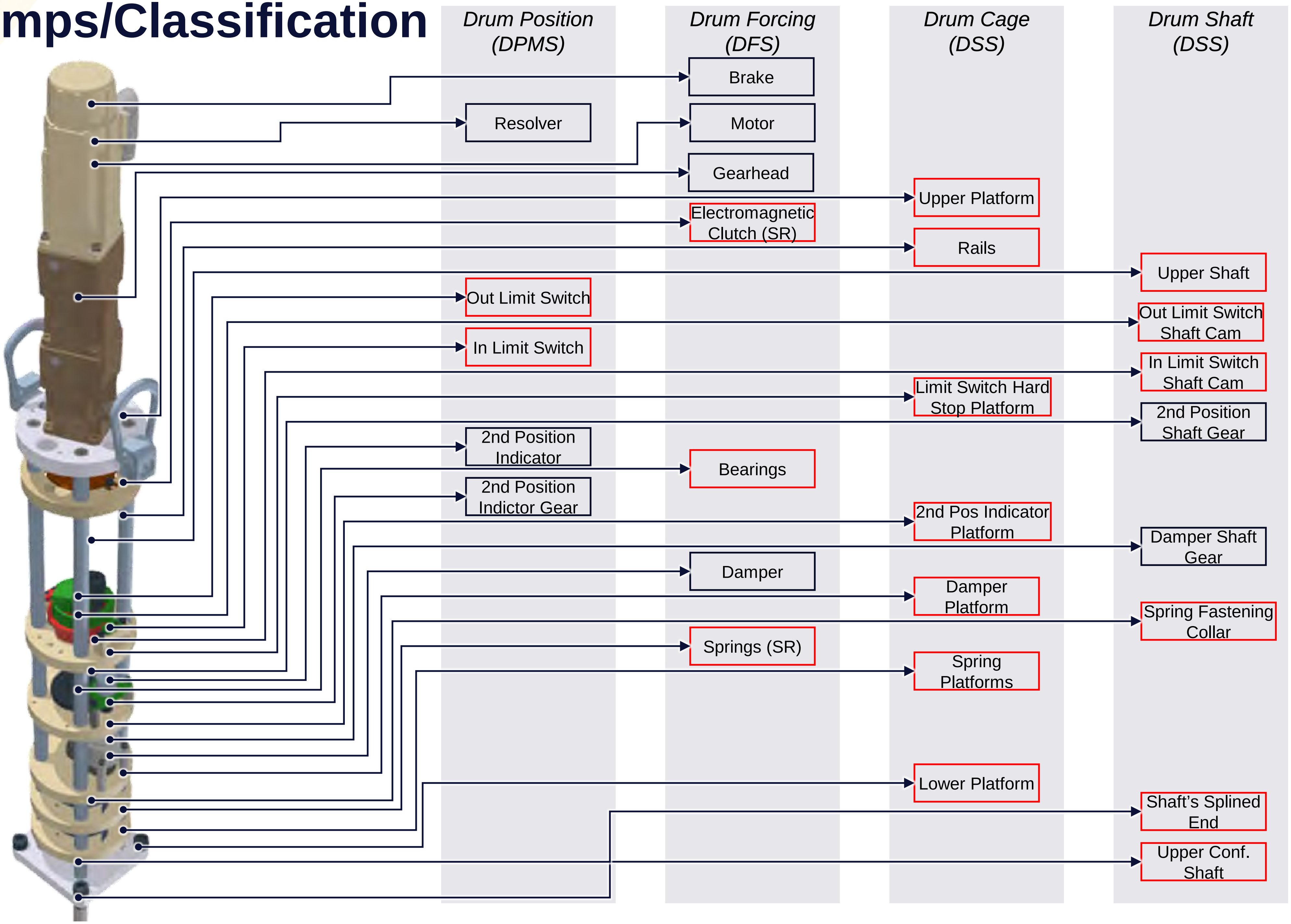
Status of Engineering Deliverables



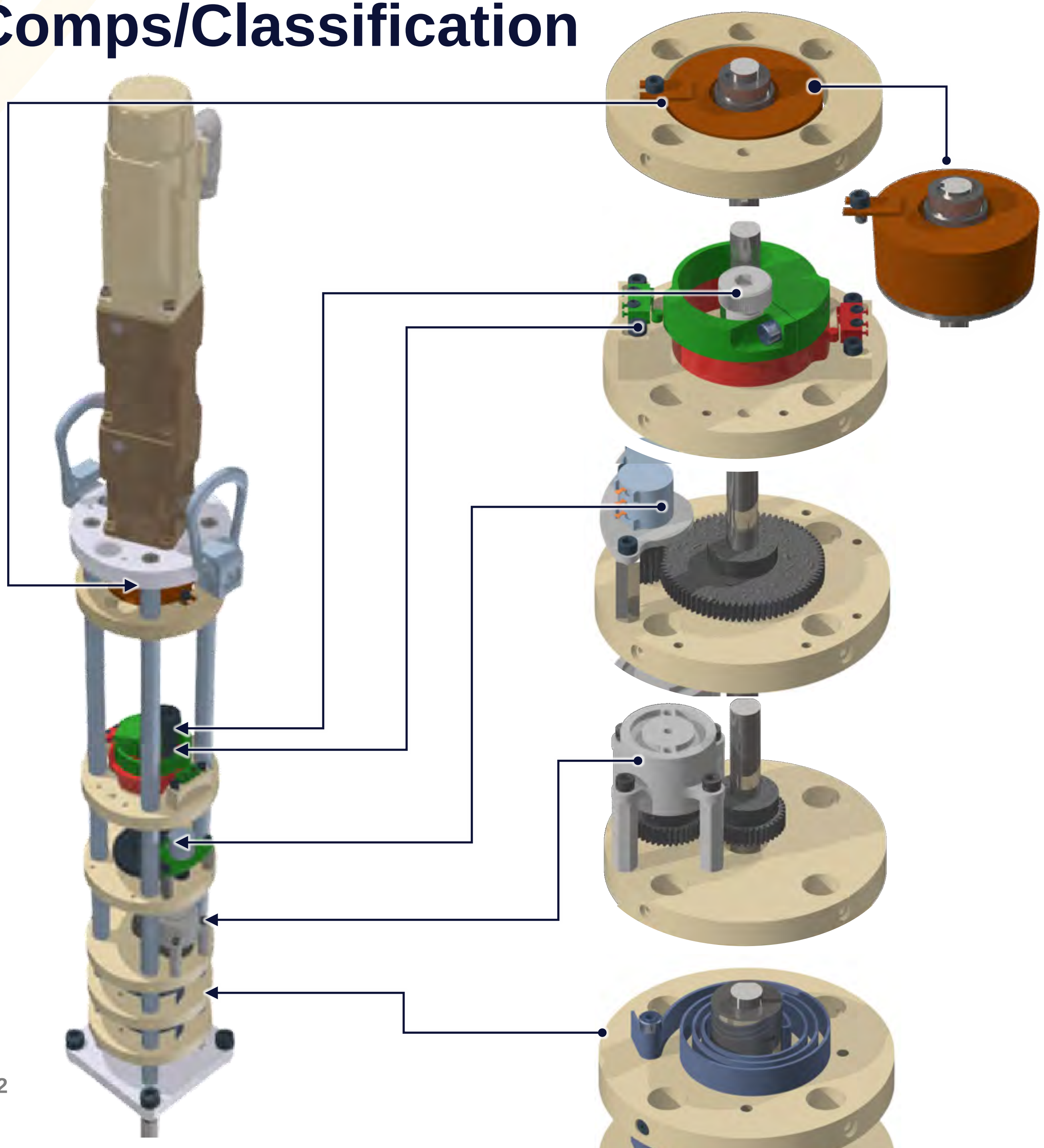
CD and CIA Functional Relationships with I&C



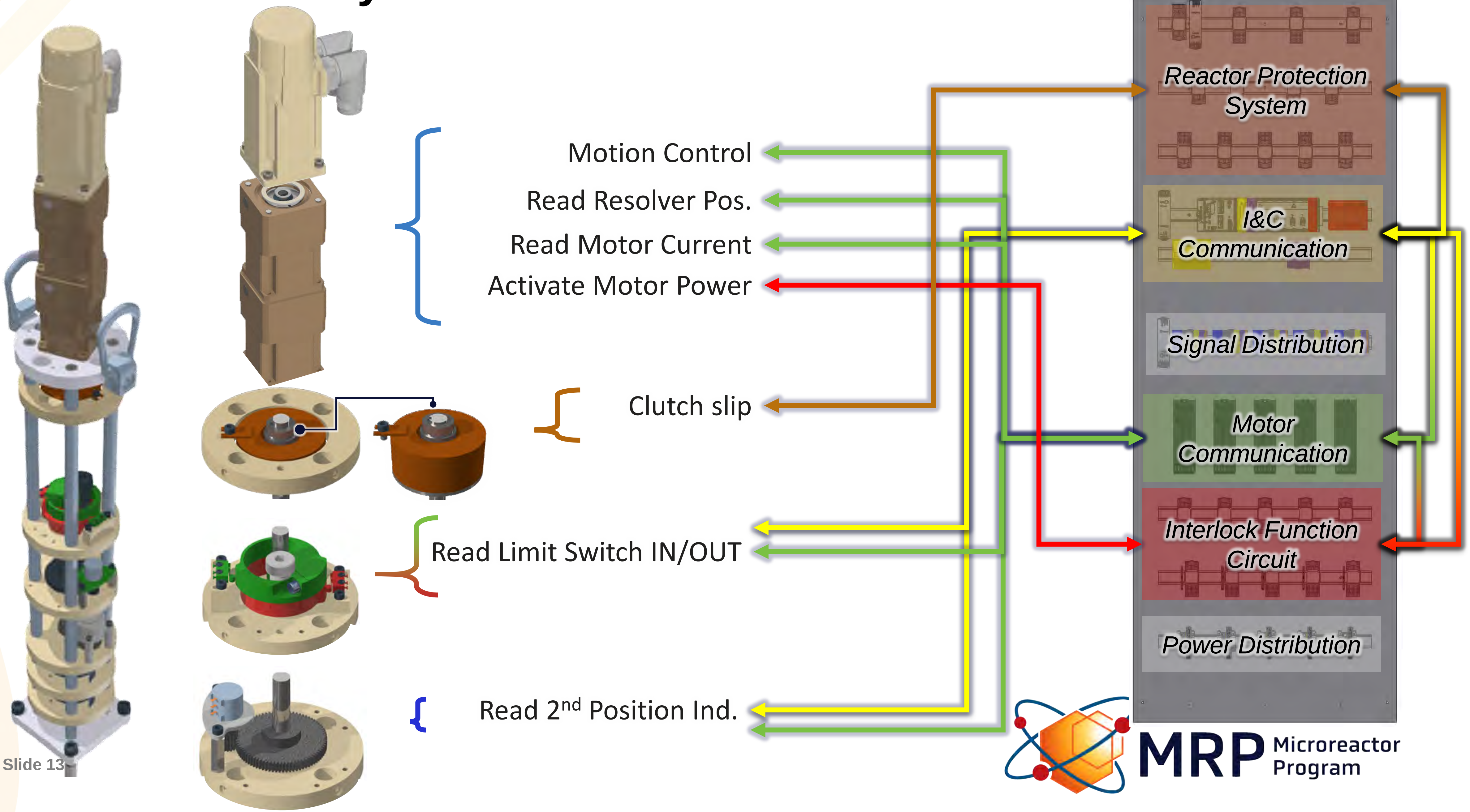
CD Comps/Classification



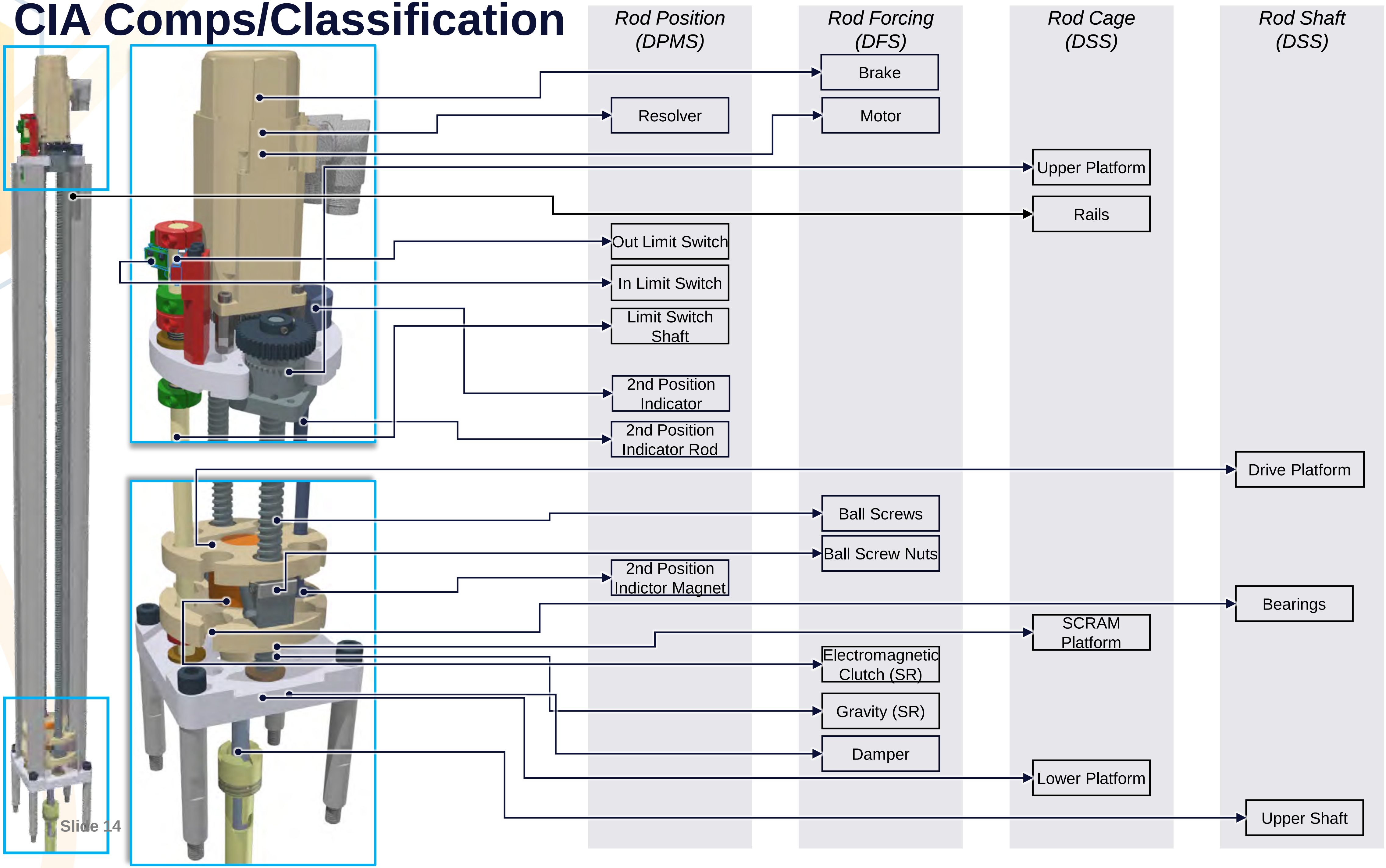
CD Comps/Classification



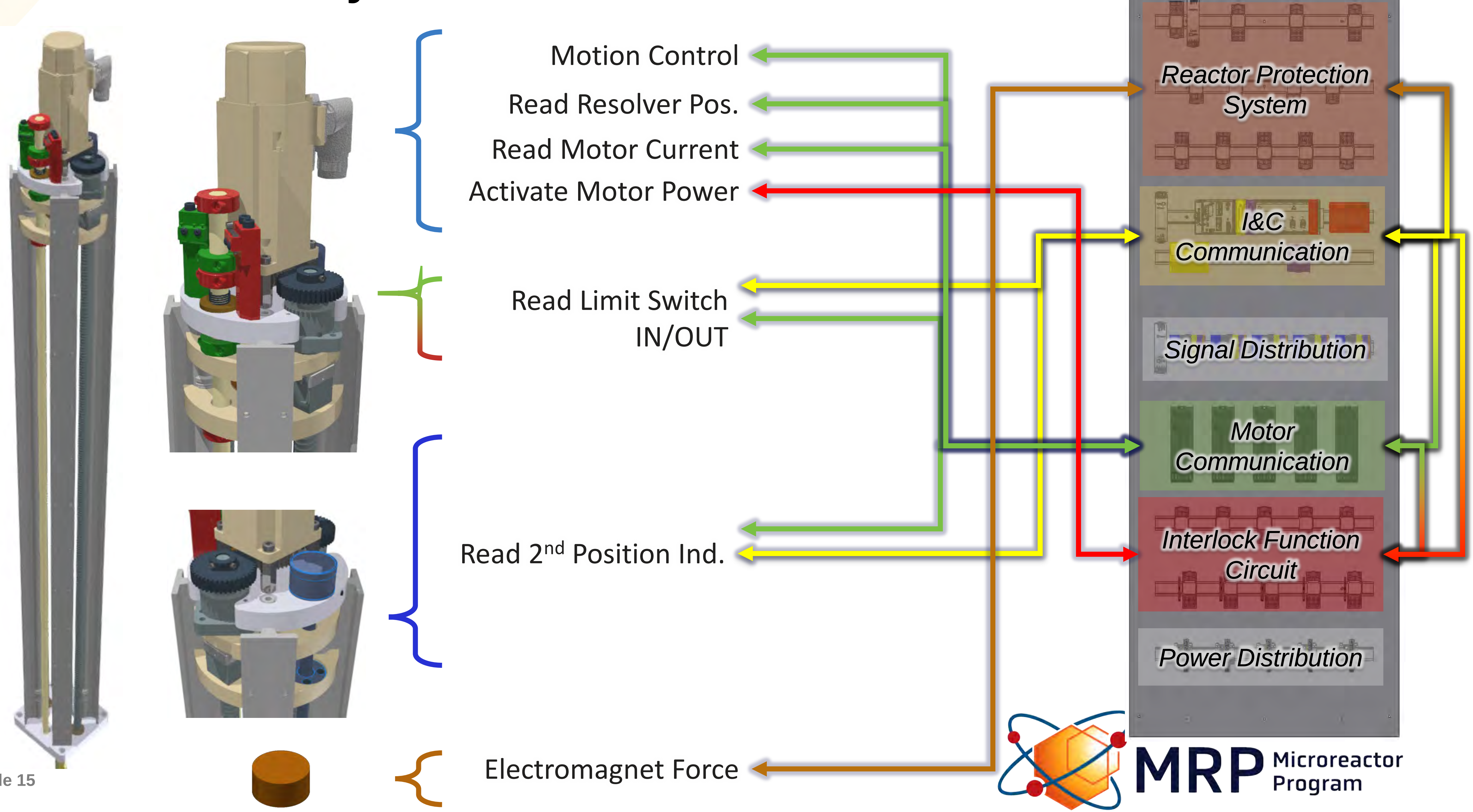
CD Actuator System Functional Interface with I&C



CIA Comps/Classification



CIA Actuator System Functional Interface with I&C



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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 encapsulated
  - Less prominent industry application
  - Torsional spring must be tuned, and material properties can change over time and temperature

Analysis and Testing

- 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

Analysis and Testing

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

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CD Actuator Analysis (Position)

Resolver (100%)

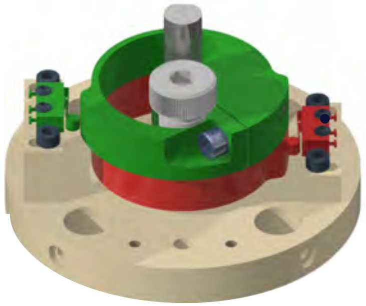
Very acceptable due to High Resolution * 10,000:1

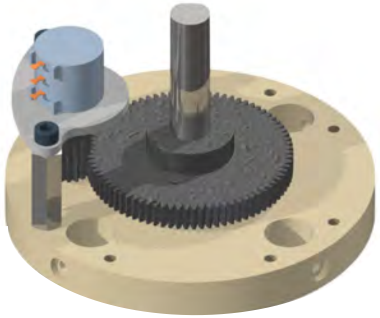
Limit Switches (100%)

Shaft cams designed to alight 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





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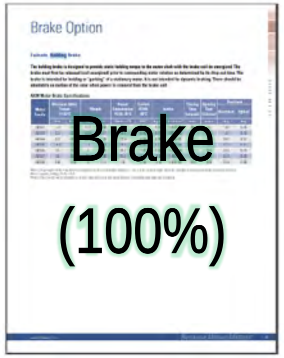
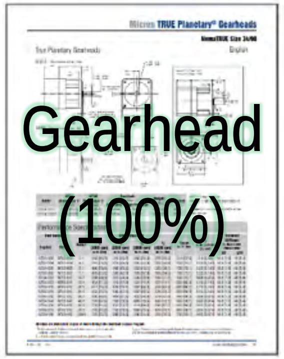
CD Actuator Analysis (Applied Torque)



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

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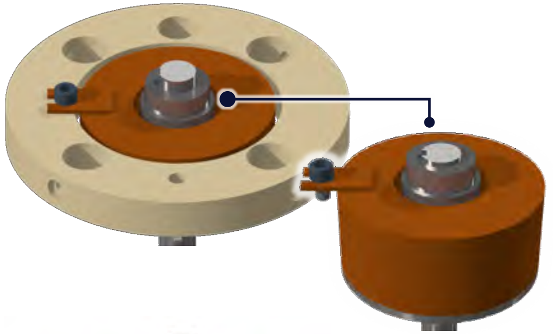
CD Actuator Analysis (Released Torque)

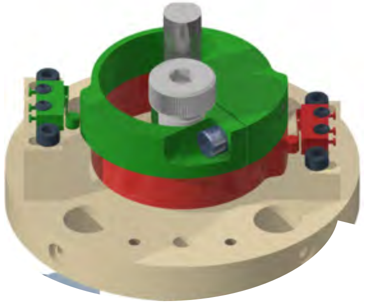
Clutch (100%)

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



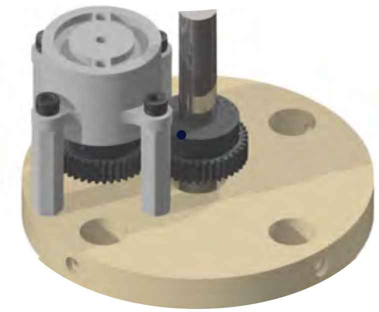
Hard Stop (100%)

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

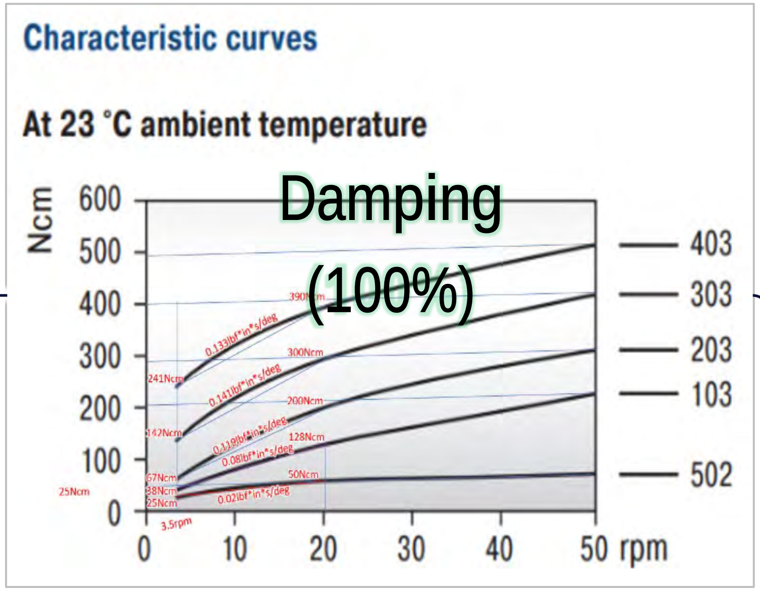


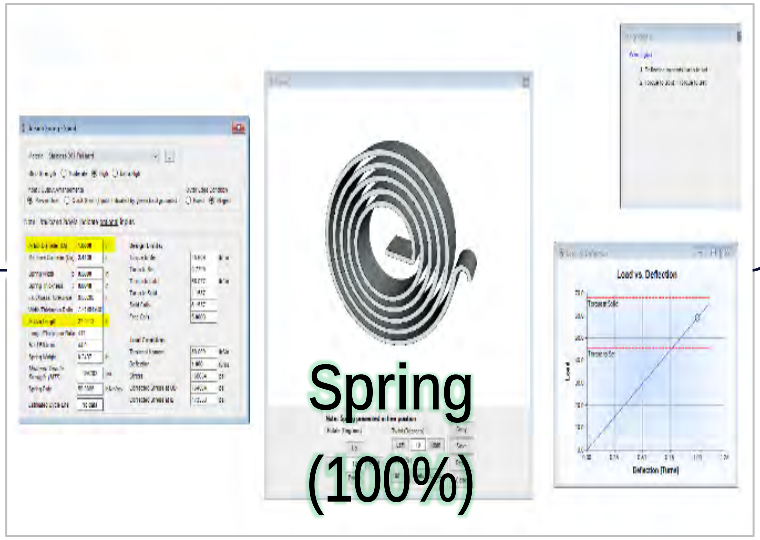
Springs (100%)

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

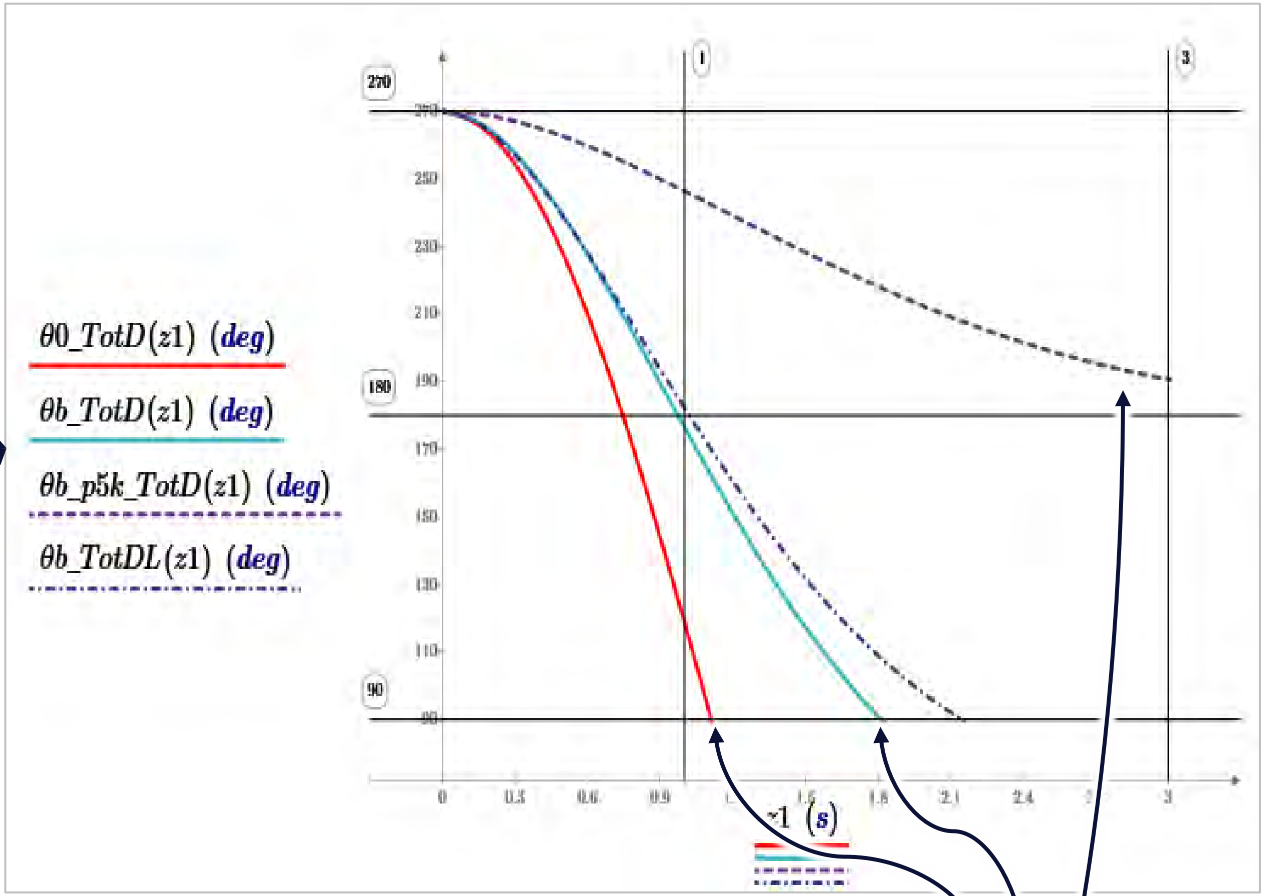
CD Actuator Analysis (Spring/Damper Sizing)

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



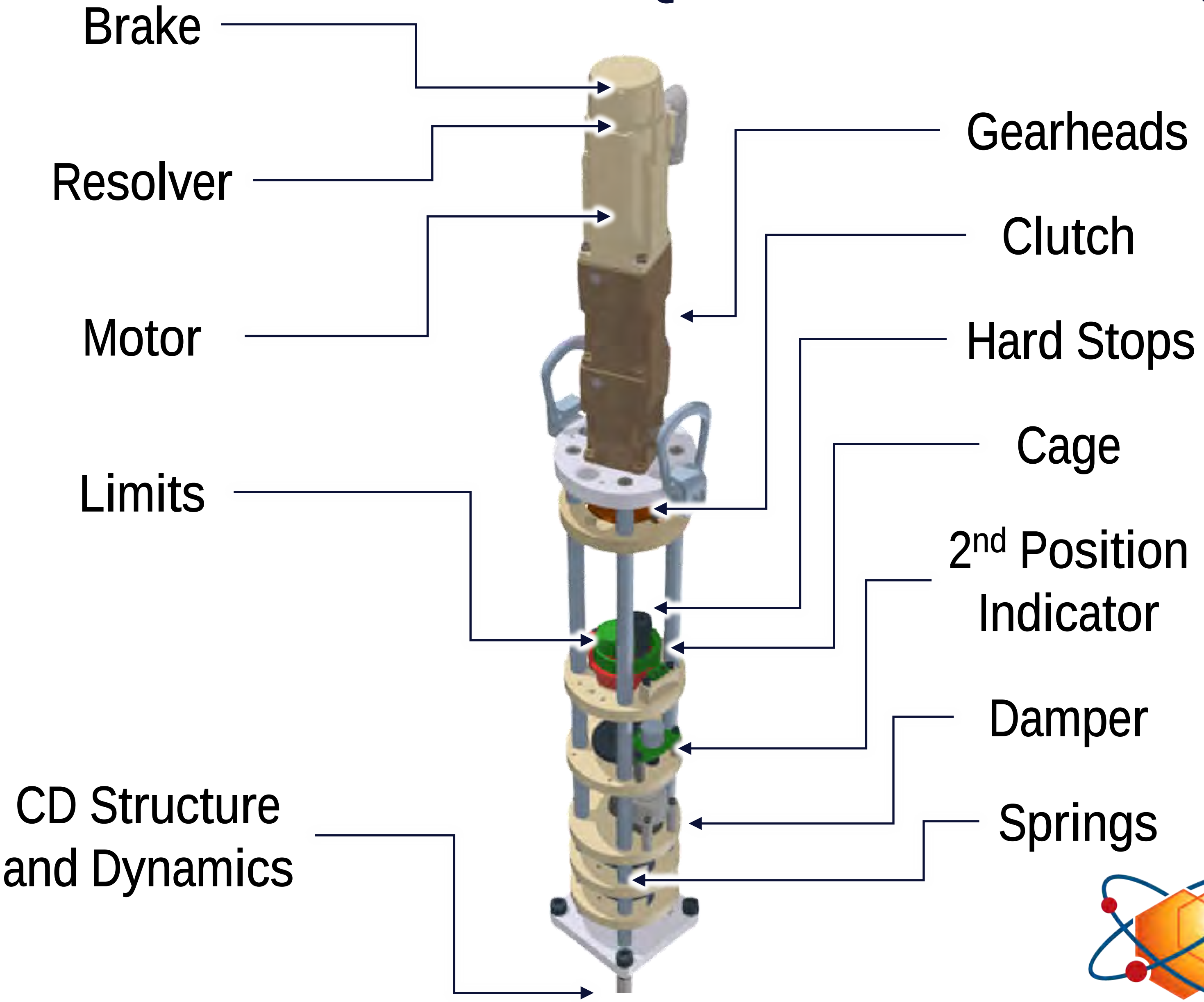


Friction Resistant Torque extracted from ECAR-7228 (12 lbf*in)



- 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



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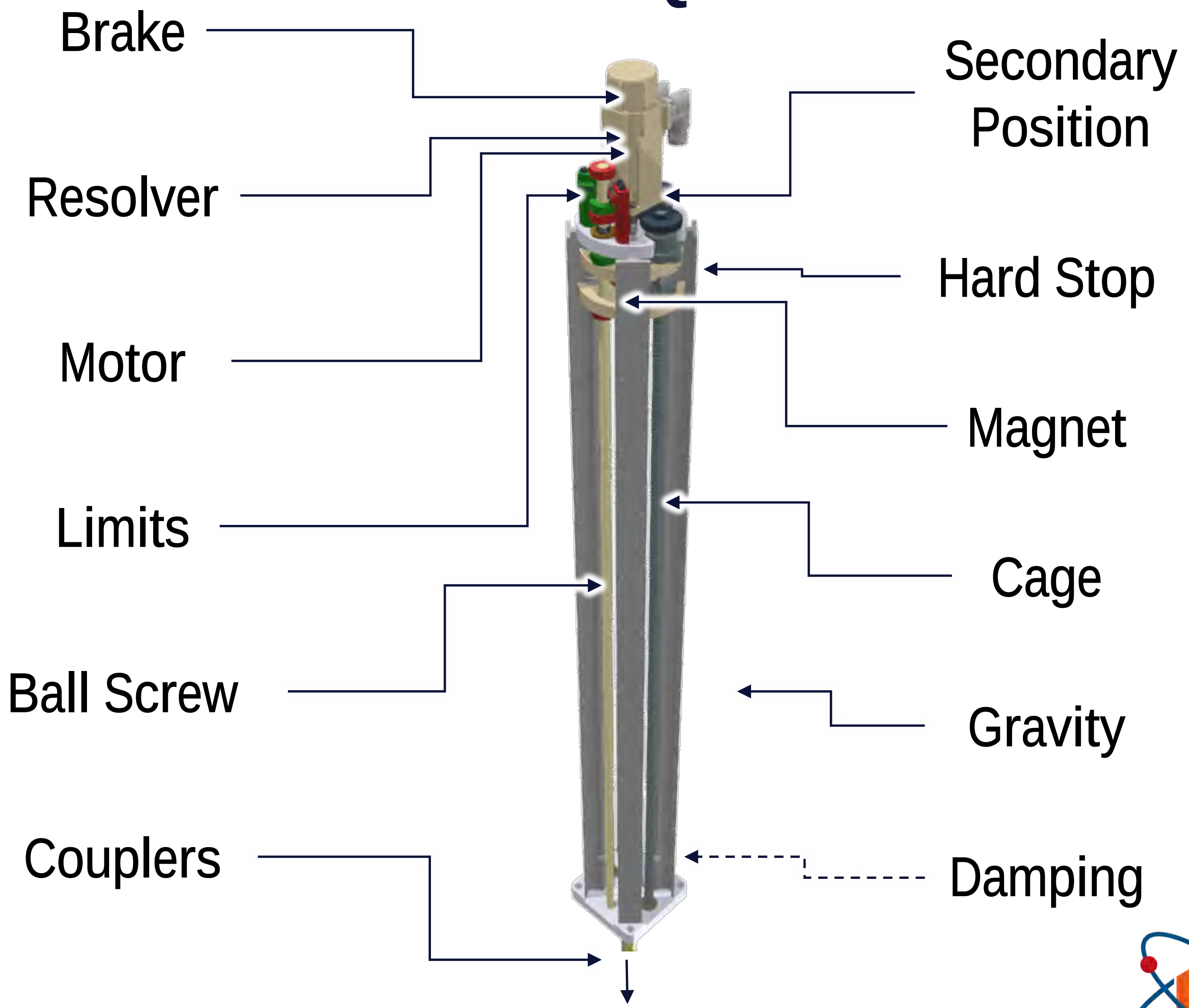
CIA Actuator Performance Verification Via Phase I &II Qualification Testing



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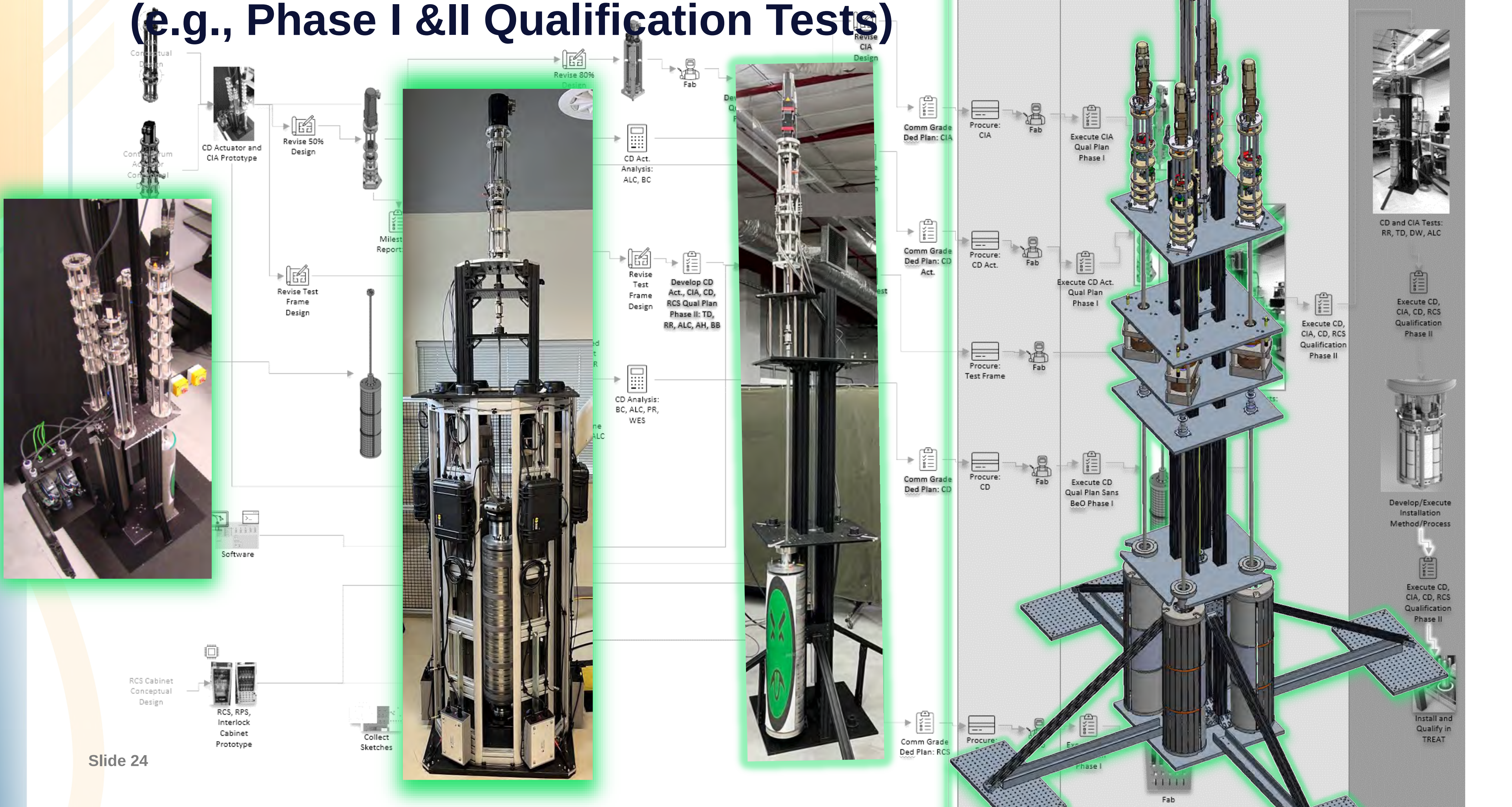
Major *Remaining* Items for Design Verification (e.g., Phase I &II Qualification Tests)



Testing Platform Strategy (Hardware) (Phase II)

Progress to date

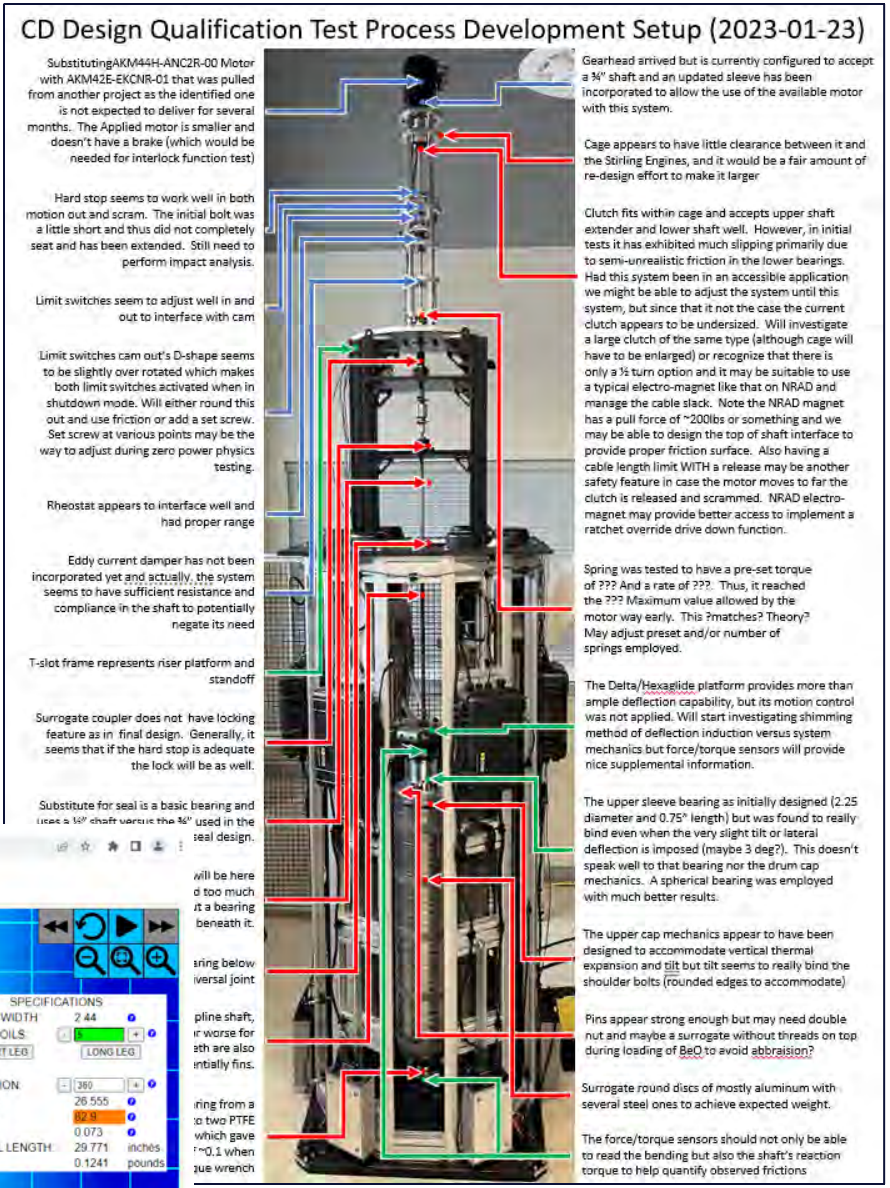
- Design verification via single axis very capable but underdeveloped and complex Double-Delta platform

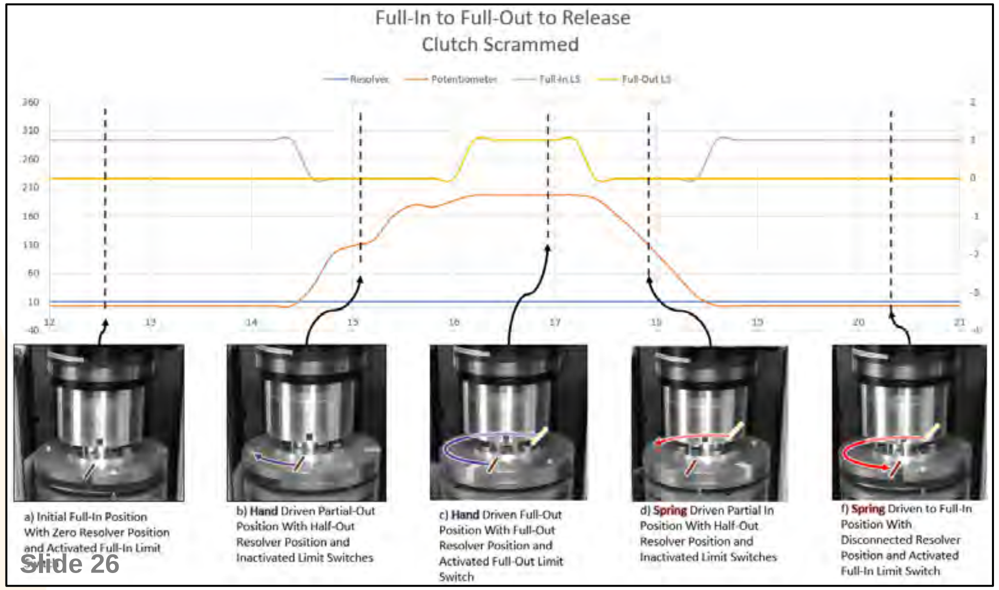
Path forward

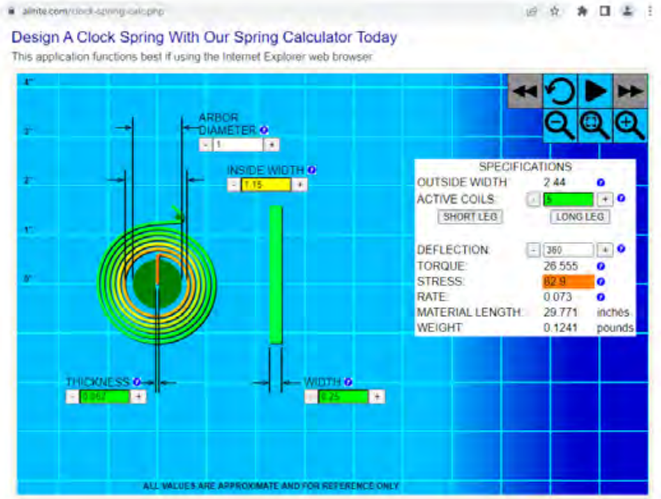
- Multi-axis accessible platform amenable to still test all functions but amenable for deployment methods and TREAT environment
- Deploy into reactor and test
- Deploy into

CD Single Axis Torque Chain Testing (Phase II)

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

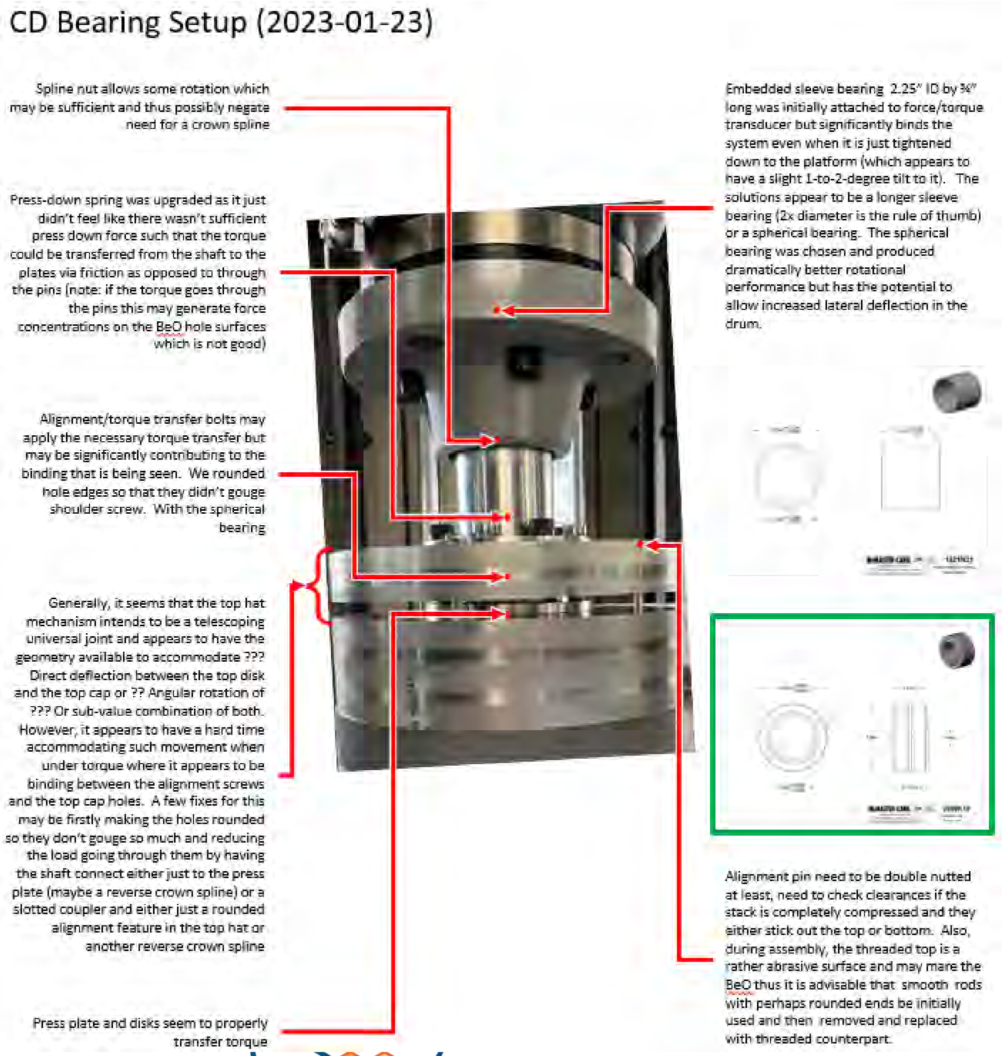






CD Single Axis Torque Chain Testing (Phase II)

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



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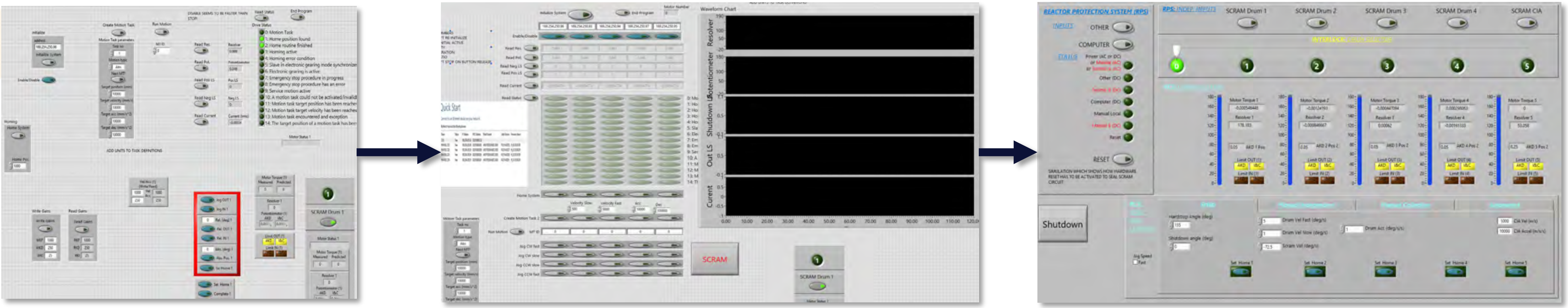
Testing Platform Strategy (Software) (Phase II)

- 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



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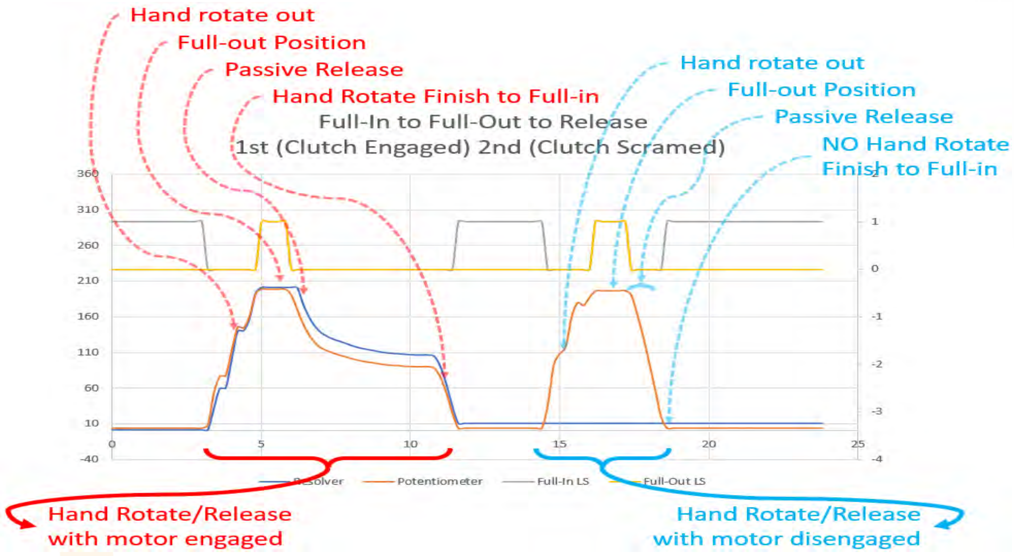
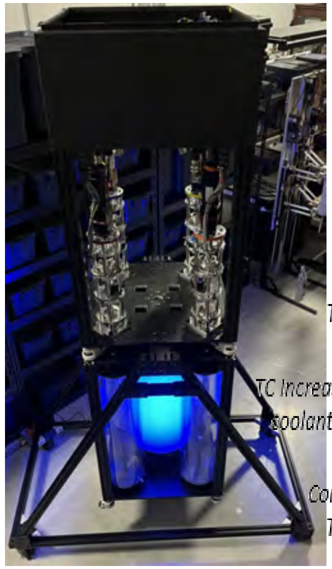
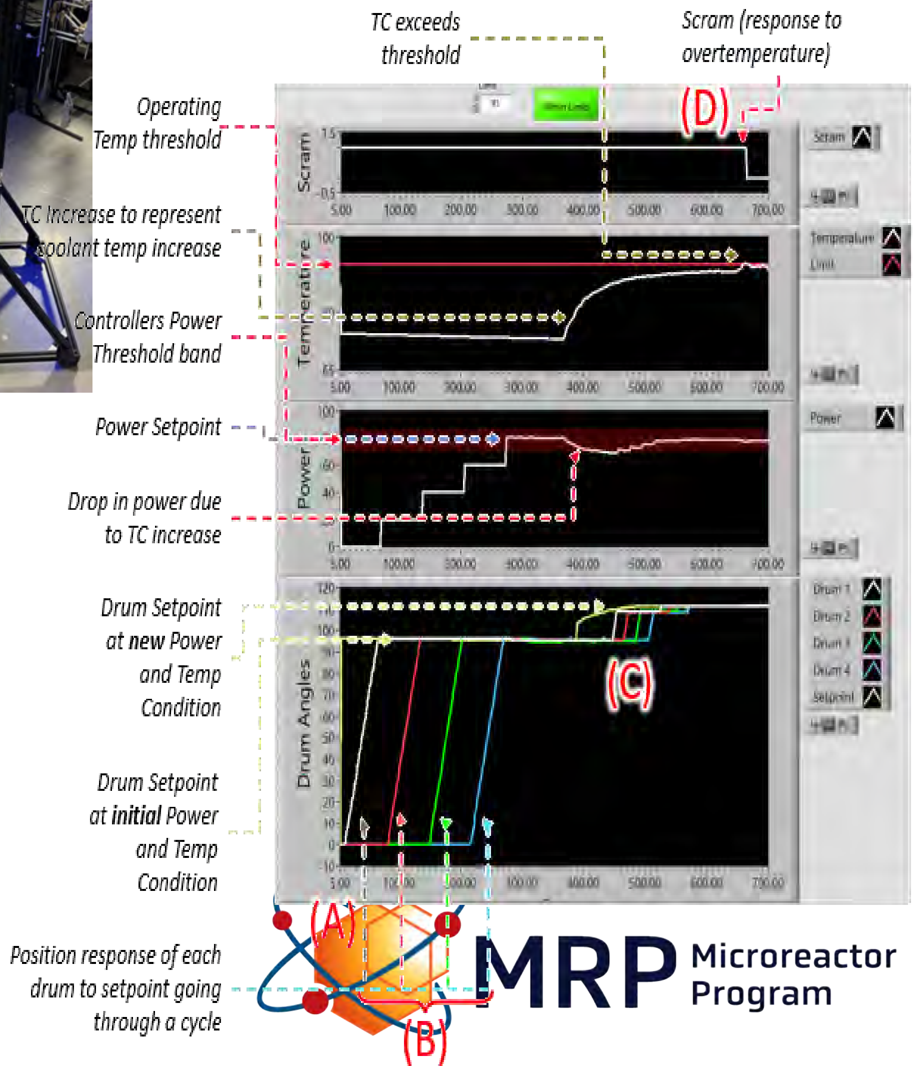
Testing Function Complexity (Software) (Phase II)

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







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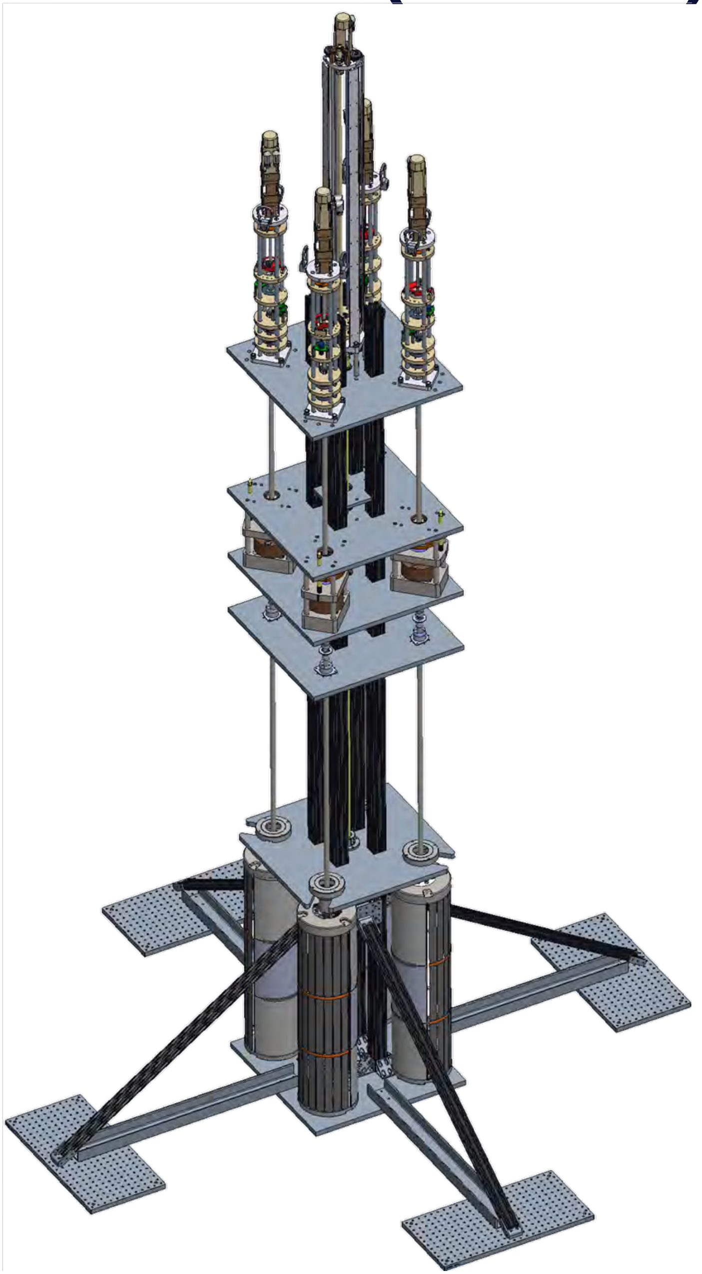
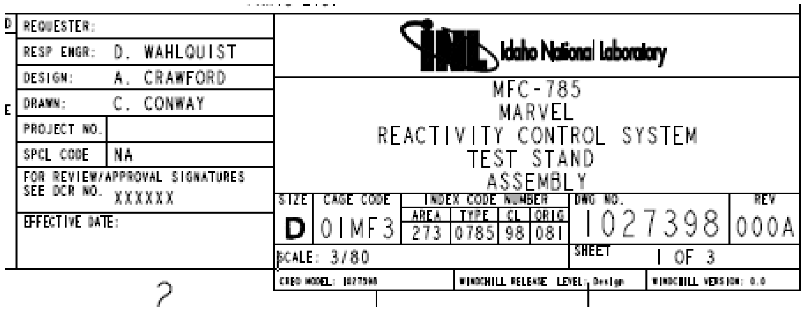
Major Remaining Items for Design Verification (e.g., Qualification Tests (Phase II))





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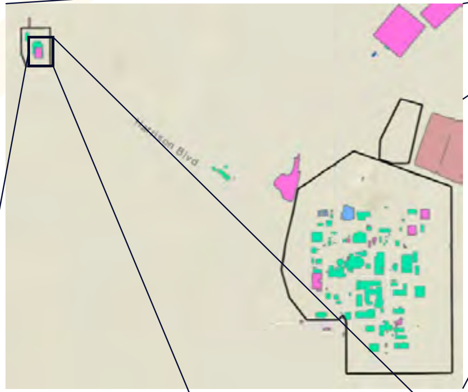
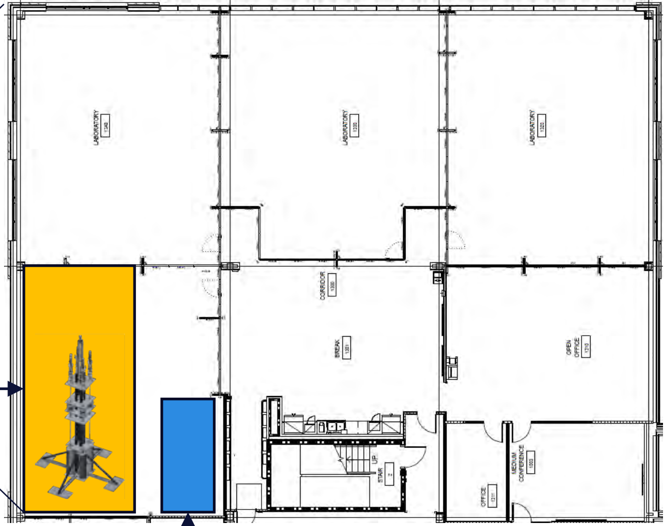
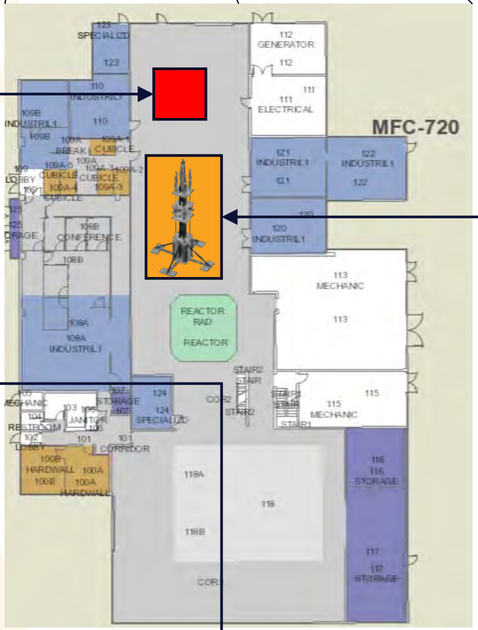
RCS Qualification Plan (Phase Locations)







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 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 III: TREAT High Bay Pit

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

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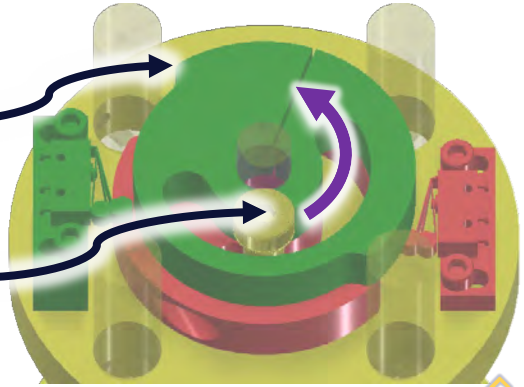
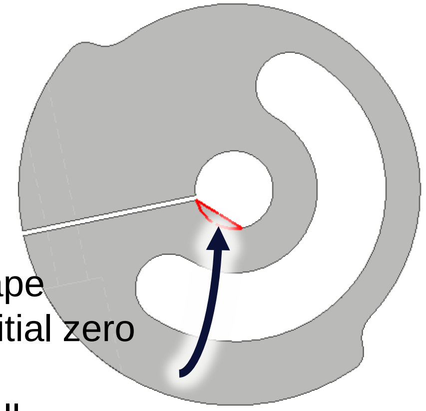
Phase III Qualification: Setting CD and CIA Interlock Hard Stops During Zero Power Physics Testing

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

Adjustable cam rotation

Bolt stops shaft rotation when it hits end of slot

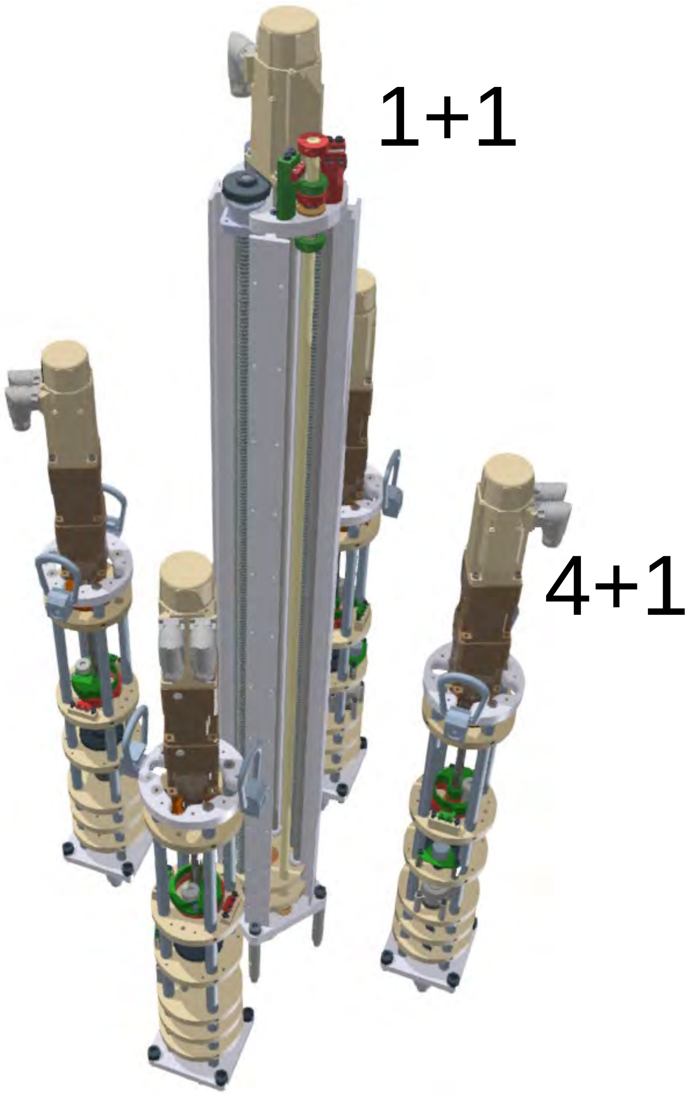


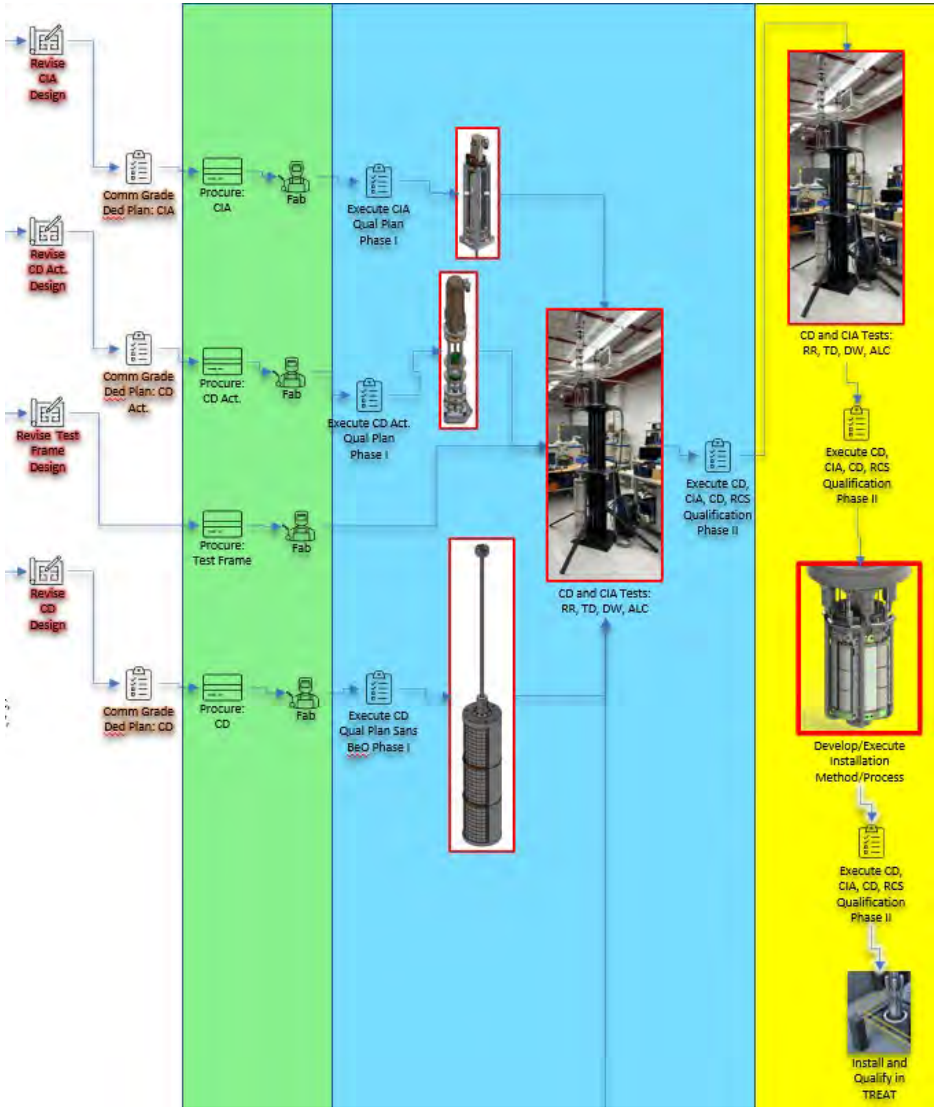


Fab final d-shape feature after initial zero power test
- Direct install
- Or tack weld in shim

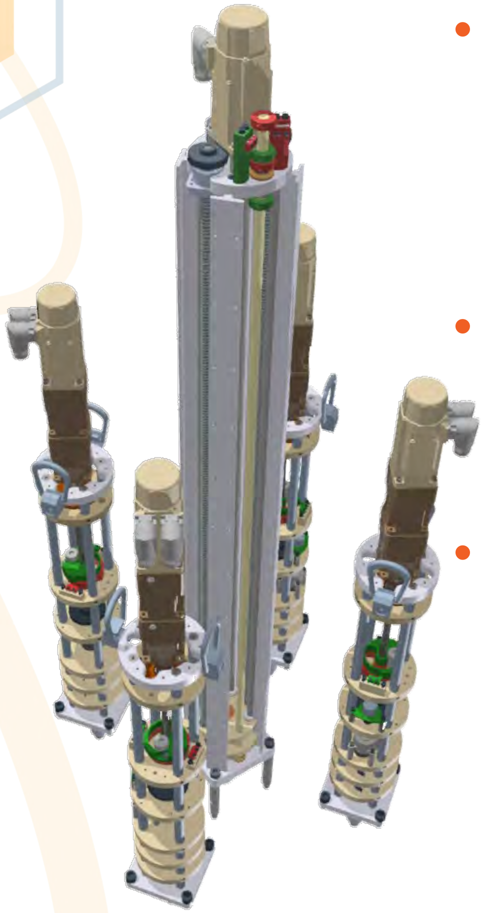
- Hard-stops at top and bottom

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

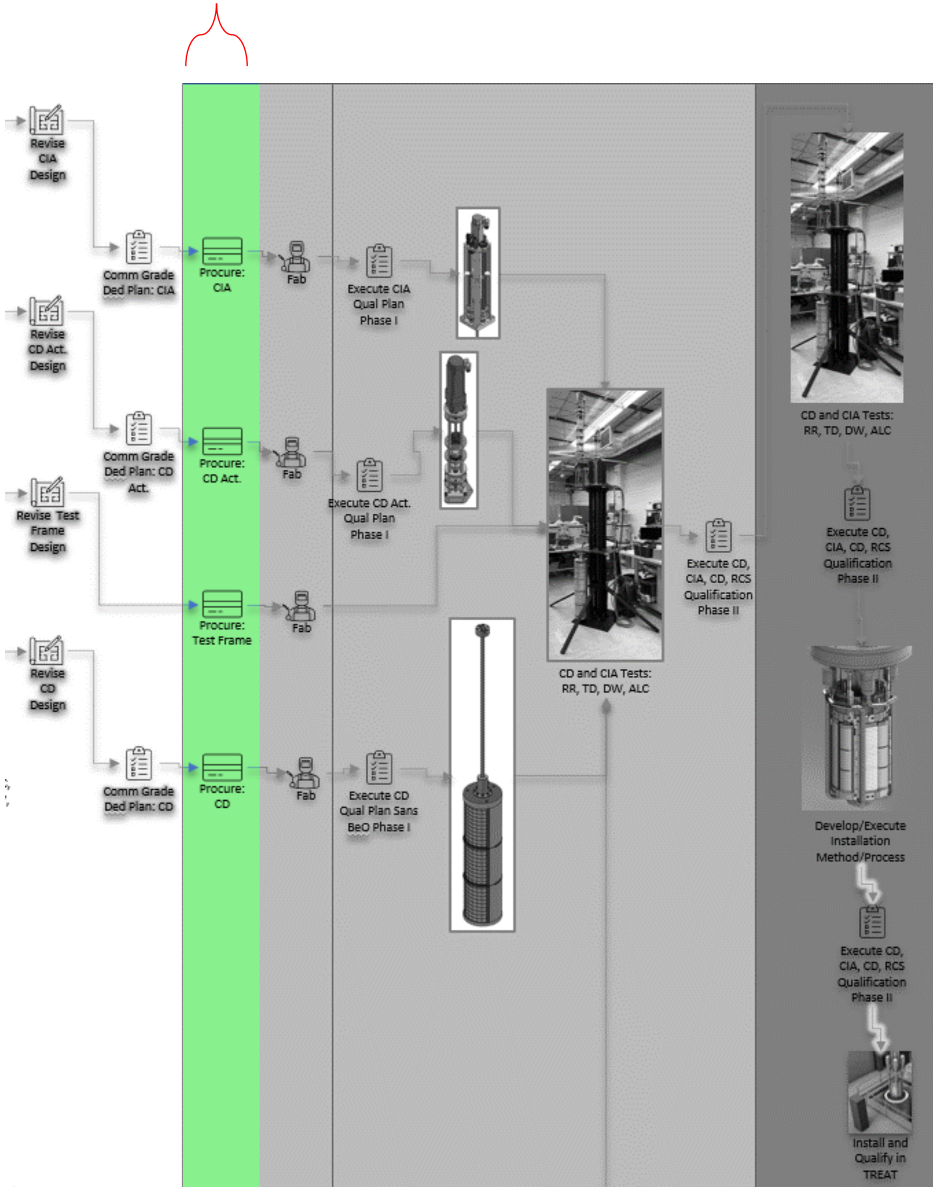




Procurement and Supply Chain



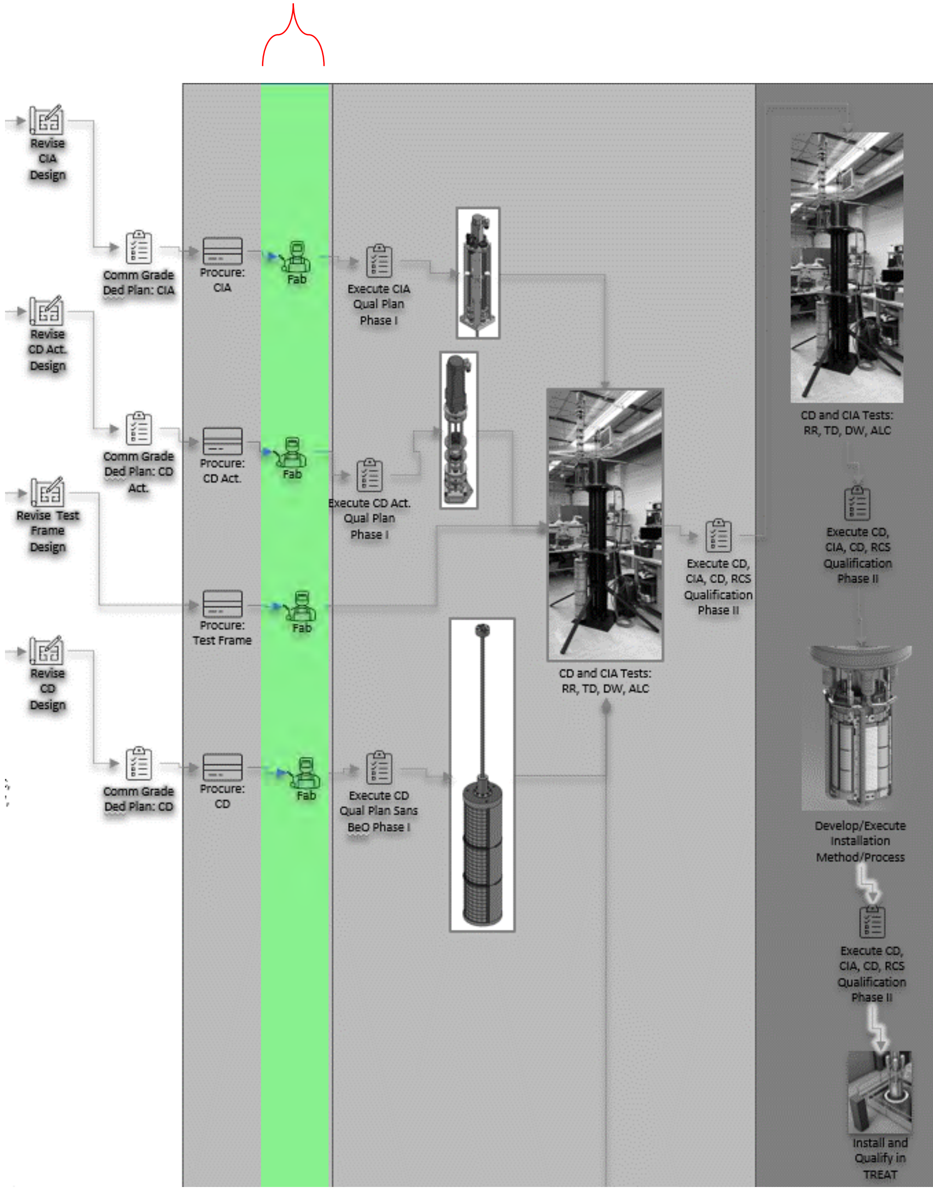
- Procurement of SR Components
  - NQA-1 Materials where available
  - CGD plans for items
- Procurement of Non-SR Components as Commercial
- Supply chain appears to have improved with Motors and Drivers appearing to be longer lead multiple month items



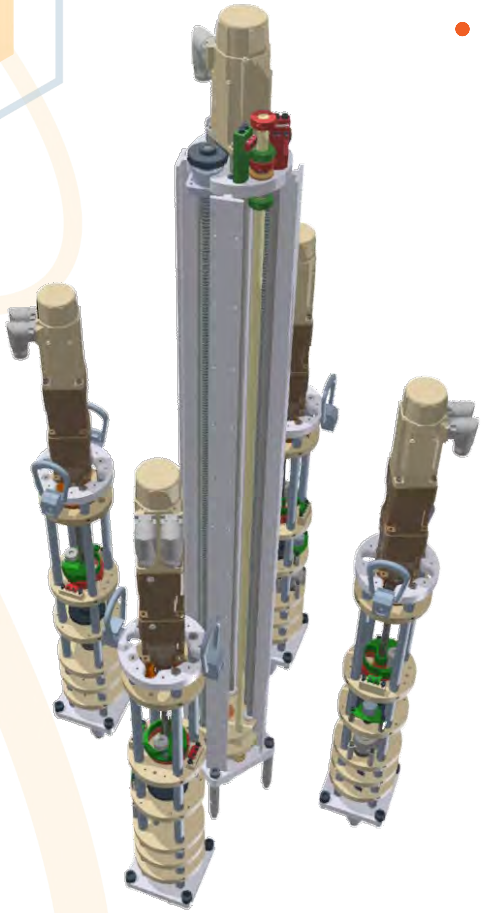
Construction Strategy

- Fabricate CD actuators and CIA actuators in house

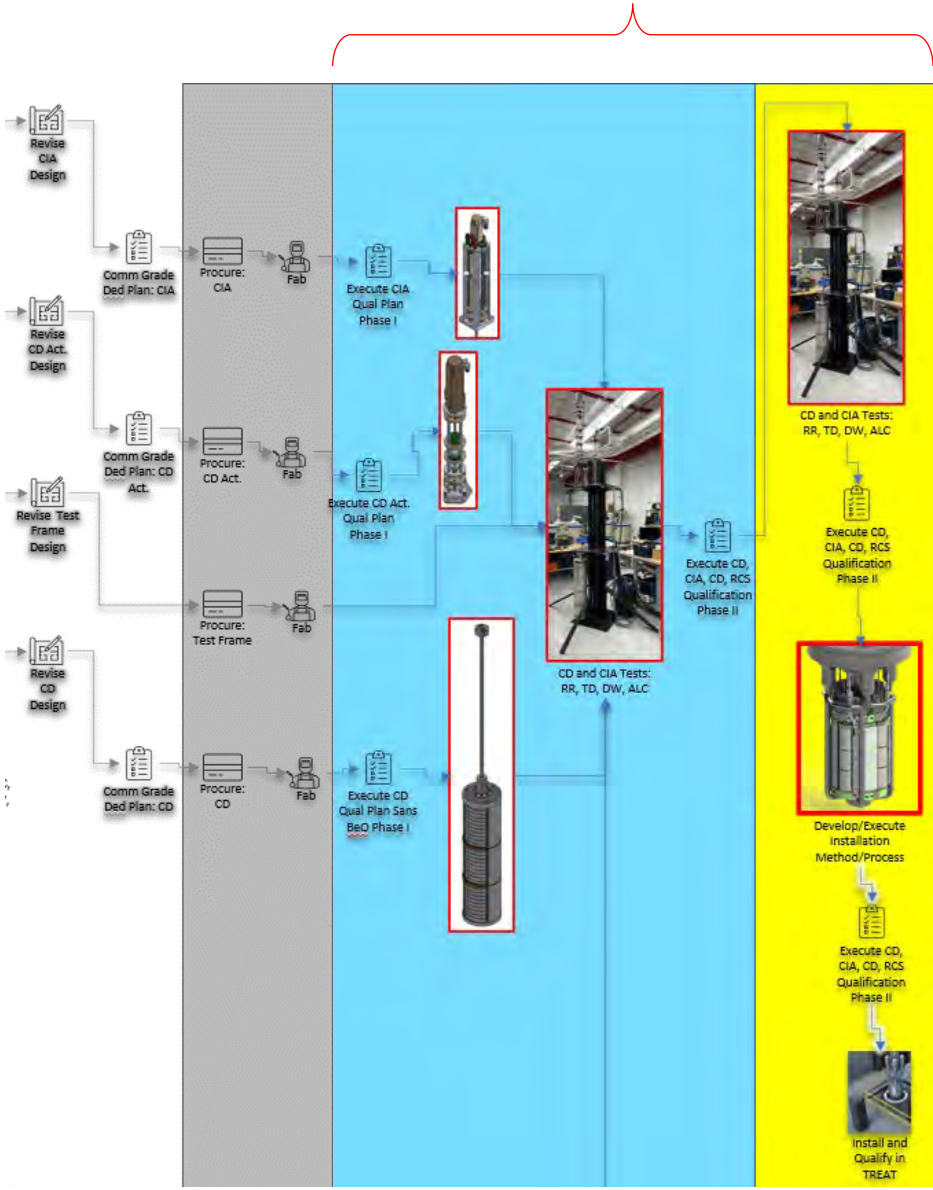
- Work in tandem with CD and CIA fabrications so to be aware of entire systems



Assembly Strategy

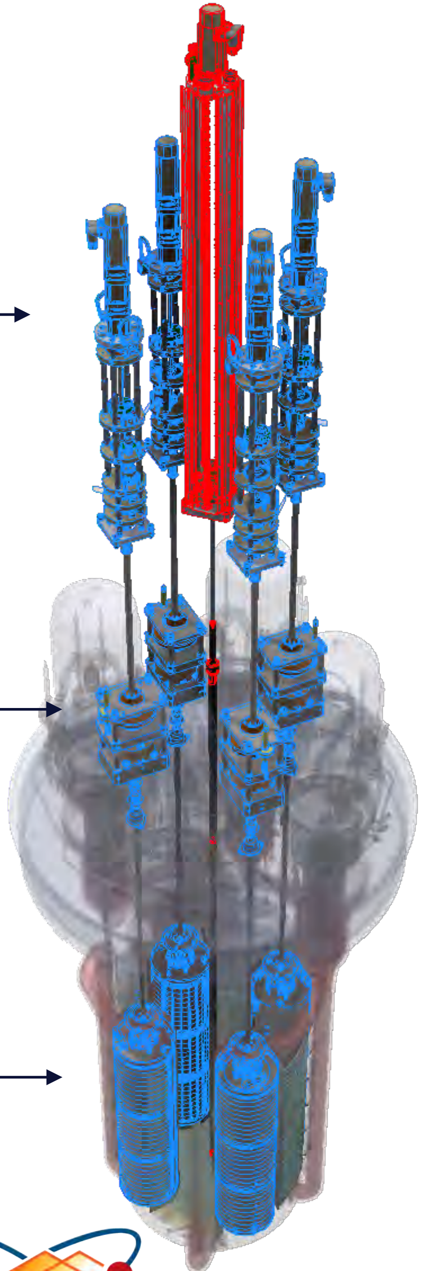


- Iterative strategy with testing achieved after each incorporation



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