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Robotics Plan in Support of DOME Testbed Operations

August 2023

Robotics architecture and recommendations for the remote disconnection and removal of irradiated reactors from the NRIC-DOME.

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REVISION LOG

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ABSTRACT

Various robotic tooling options have been evaluated for the National Reactor Innovation Center (NRIC) Demonstration of Microreactor Experiments (DOME) concept of operations (ConOps). Framatome was subcontracted to develop a wide-ranging list of commercial off-the-shelf (COTS) and custom robotic systems to consider for DOME ConOps functions. Subsequent project tasks from Framatome narrowed down the list and the most viable options were scored. The abbreviated list and associated scoring have been reviewed and assessed to provide formal recommendations for the robotic ConOps functions of DOME from the subcontractor and the INL project team. The overhead telescoping mast and Kraft arm assembly is recommended as the primary system for reactor demobilization and removal. The estimated cost is $700K with a timeline to develop and deliver in about 2 1/2 years. The mast and Kraft arm require an overhead lift system for mobilization and installation. Either the refurbished polar crane or a new gantry crane delivery platform could serve as the overhead lift and delivery system. The estimated costs for the refurbishment of the polar crane and new gantry crane systems are, respectively, $4.4M and $3M with about 2 1/2 years to develop and deliver. A Brokk and Kraft crawler and arm are recommended as a secondary robotic system to support the overhead mast and Kraft arm system. The Brokk and Kraft crawler and arm would cost an estimated $726K and would take about 1 1/2 years to develop and deliver. The Boston Dynamics SPOT robot is also recommended for the in-service monitoring during experimentation operations. The estimated cost is $220K with a timeline to deliver of 8–14 months. The Elios 3 RAD aerial drone is recommended to perform large area radiation-dose rate mapping and visual inspections. The estimated cost is a $100K and it will also need about 8–14 months to develop and deliver. It is also recommended to procure and employ a mockup rig to test and verify the robotic capabilities as well as provide training for operations personnel. It is estimated that a mockup rig would cost about $500K and would take up to a year to develop and build.

ACKNOWLEDGEMENTS

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ACRONYMS

BEA	Battelle Energy Alliance
ConOps	concept of operations
COTS	commercial off-the shelf
DOE	U. S. Department of Energy
DOME	Demonstration of Microreactor Experiments
ER	equipment reliability
INL	Idaho National Laboratory
NRIC	National Reactor Innovation Center
PM	preventative maintenance
ROM	rough order of magnitude

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DOME Robotic Tooling Recommendation

1. BACKGROUND

Robotic tooling options are being considered for the execution of the concept of operations (ConOps) functions in the Demonstration of Microreactor Experiments (DOME) testbed during the installation, experimental testing, demobilization, and removal of advance experimental reactors at Idaho National Laboratory (INL). Many of the ConOps cannot be performed by humans primarily due to radiological protection limitations; therefore, various robotic mechanical functions will be essential for the successful demobilization and removal of these advanced reactors.

The capability to perform remote robotic preventative maintenance (PM) and equipment reliability (ER) ConOps activities are also valuable to DOME Operations during each reactor experimentation cycle. These functions include the ability to provide quantitative visual and audio monitoring, thermal imaging, the in-service placement of remote monitoring devices, and possible mechanical manipulations (e.g., lifting, valve operations). Additional ancillary functions would be innovative for verifying modeling assumptions inside and outside the DOME testbed during operation. Radiation spatial mapping and qualitative visual inspections are examples of these ancillary functions.

2. FRAMATOME INVESTIGATION

Framatome was subcontracted to develop a wide-ranging list of available commercial off-the-shelf (COTS) and custom robotic technologies to be considered for performing the DOME ConOps functions (ref. Framatome report 51-9359453-000). The robotic system options on this list were then investigated, ranked, and compared to each other for supplementary screening. The highest scoring systems from the initial list were explored further to determine cost estimates as well as deployment timelines (ref. Framatome report 51-9360488-000). A final ranking of a consolidated list of robotic systems was performed and reported in Framatome report 51-9361177-000. This report summarizes the systems considered the most viable candidates. A summary of those results is found in Table 1.

2.1 Viable Robotic Options

Framatome narrowed down the list of the most viable robotic systems options. Descriptions of each system and their respective specifications and requirements can be found in the aforementioned Framatome reports. The following sketches and pictures illustrate these robotic options.

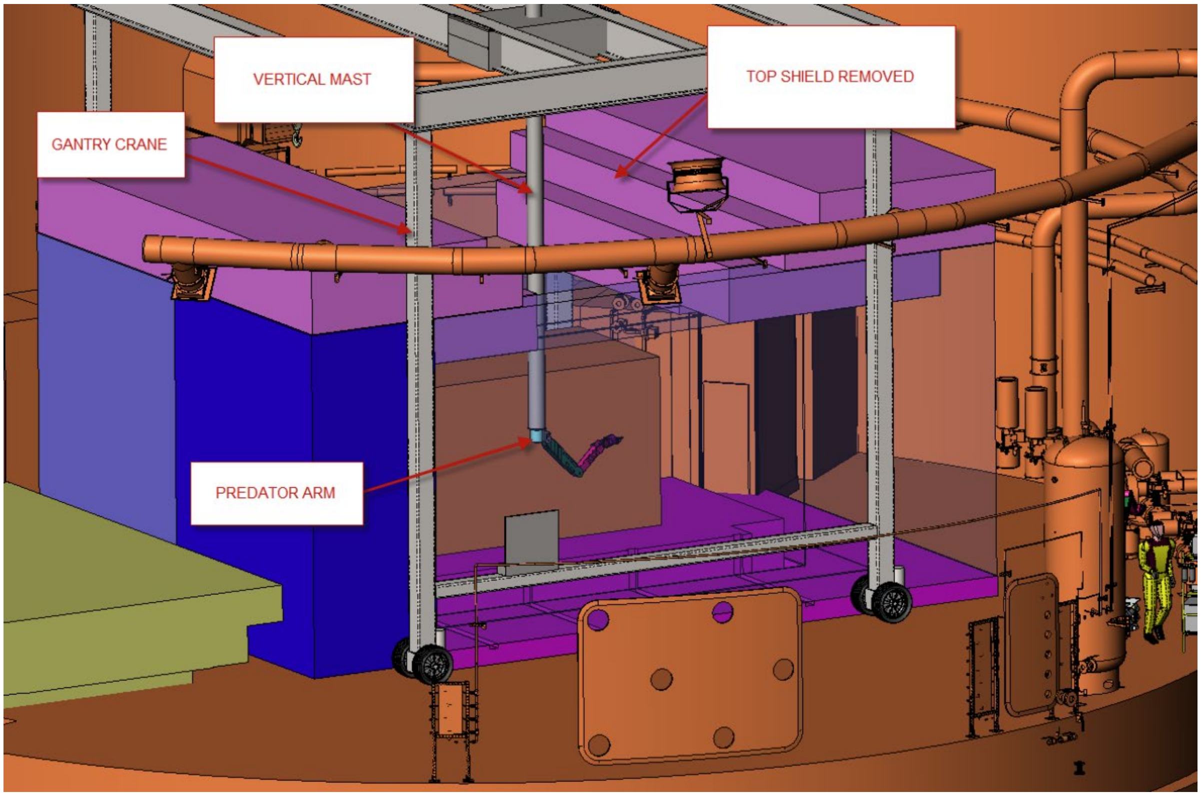

Figure 1. COTS Gantry Crane Mast and Kraft Arm.

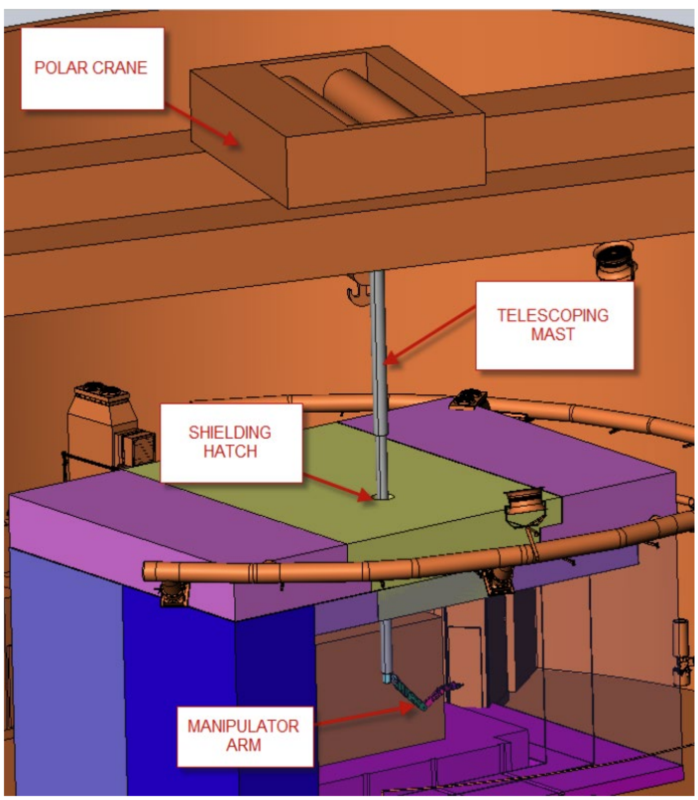

Figure 2. Refurbished Polar Crane Mast and Kraft Arm.

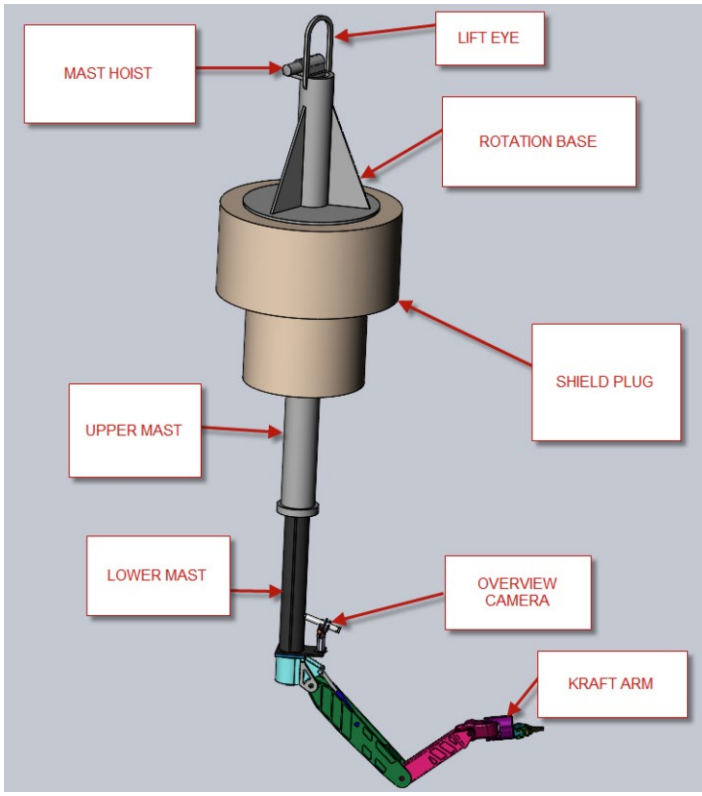

Figure 3. Shield Plug Mast and Kraft Arm.

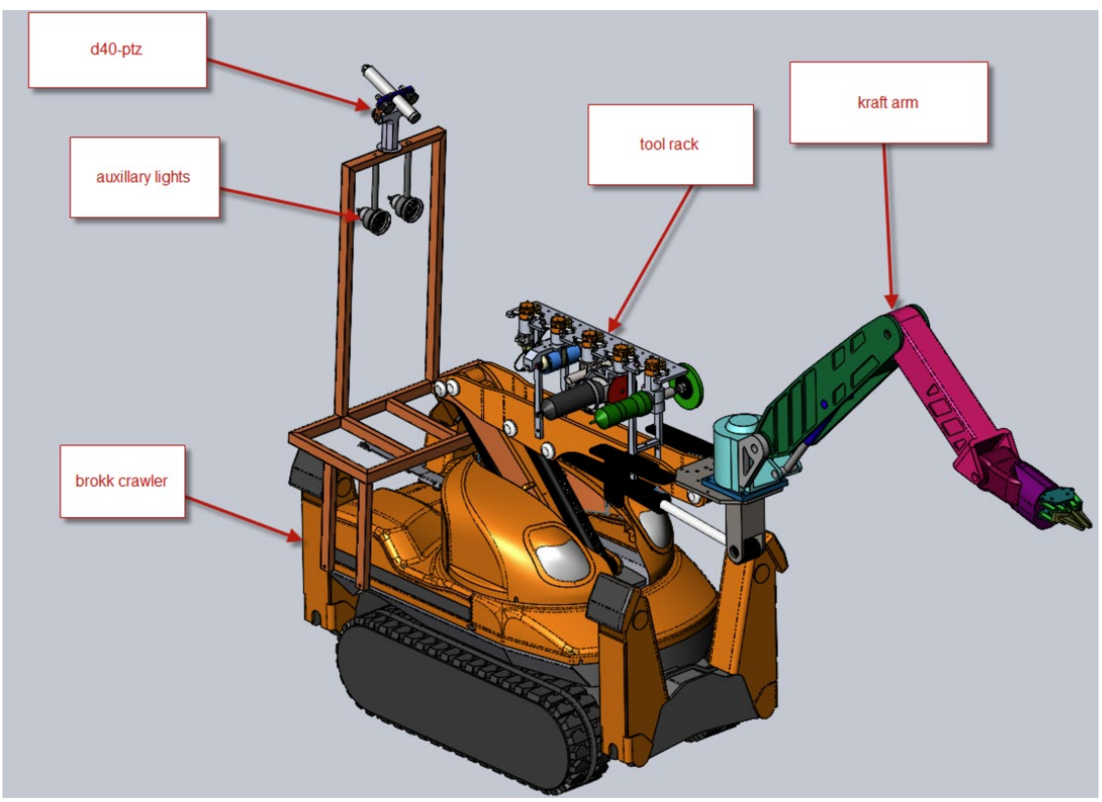

Figure 4. Brokk and Kraft Crawler & Arm.

Figure 5. Boston Dynamics SPOT with arm.

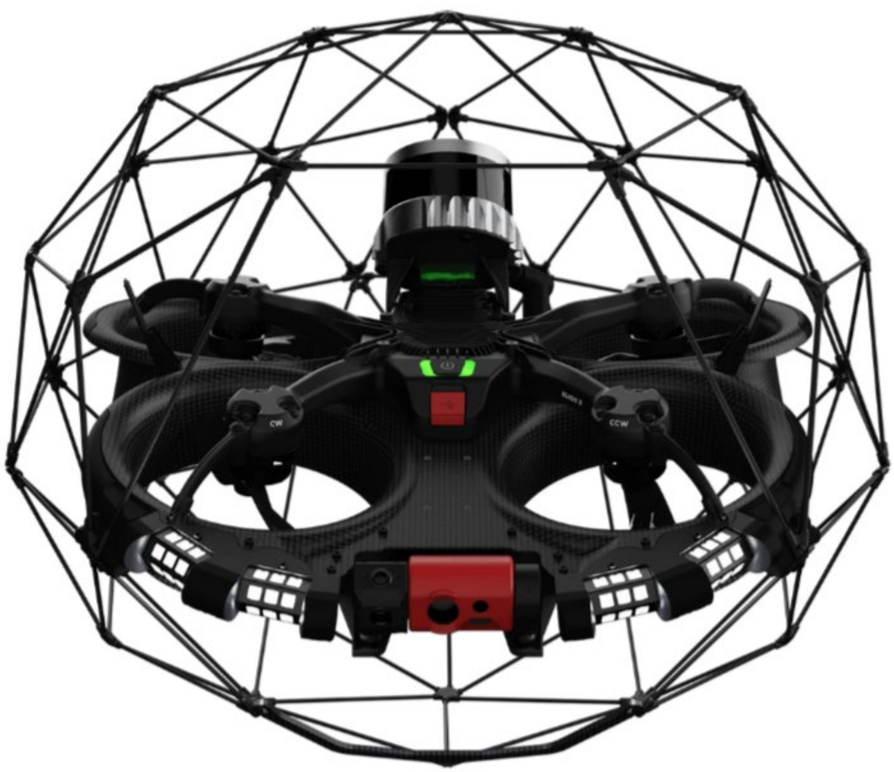

Figure 6. Elios 3 RAD aerial drone.

2.2 Framatome Pugh Matrix Scoring and Cost Estimates

To compare all the robotic system options, Framatome used a Pugh Matrix scoring methodology. The following criteria were used for each robotic system to be ranked and compared: footprint inside of DOME, work envelope/range of operation, infrastructure requirements, rough order magnitude (ROM) costs, platform versatility, timeline to use, and radiation tolerance. The different robotic systems under consideration were divided into two groups based on their ConOps capabilities: integrated solutions and low-radiation-tolerant systems. The larger integrated systems included additional grading criteria to further evaluate and rank the robotic system options: lifting capacity, system complexity, and life expectancy.

The integrated solutions system options under consideration consist of a telescoping mast and Kraft arm assembly deployable via a refurbished polar crane, new COTS gantry crane, and shield plug or the Brokk and Kraft crawler and arm. The low-radiation-tolerant robotic systems include small robotic systems used for ConOps monitoring activities and include the Boston Dynamics SPOT quadruped and several aerial drones.

Of the integrated solution platforms, the refurbished polar crane received the highest Framatome score for the mast and Kraft Arm assembly delivery system (as seen in Table 1) and the Elio 3RAD aerial drone scored the highest among the low radiation robotic traveling systems.

Table 1. Framatome Pugh matrix scoring and cost estimates.

System	Pugh Score	Cost Estimate
COTS Gantry Crane Mast and Kraft Arm	186	$2.8M–3M
Refurbished Polar Crane Mast and Kraft Arm	235	$4.4M
Shield Plug Mast and Kraft Arm	205	$694K
Brokk and Kraft Crawler & Arm	219	$524K–726K
Low-Radiation-Tolerant Robotic Solutions		
Boston Dynamics SPOT with arm	193	$220K
Elios 3 RAD aerial drone	217	$100K
Skycopter aerial drone	216	$15K–30K

NOTE: The Framatome cost estimates have not been independently verified by Battelle Energy Alliance, LLC (BEA) and these estimates do not include any BEA overhead costs.

3. IDAHO NATIONAL LABORATORY REVIEW AND ASSESSMENT

The INL assessment takes into account information from the Framatome reports 51-9359453-000, 51-9360488-000, and 51-9361177-000, but does not dwell on capabilities practically performed equally among the different options. Rather, the focus is put on the different capabilities between the various systems. Also, the radiation tolerance of the low-radiation-tolerant robotic systems was reconsidered with in-service PM and ER ConOps applications were likewise included in this assessment. The inclusion of the PM and ER capabilities was not directly encompassed in the Framatome evaluation but was considered to be instrumental in the view of this INL assessment.

Significant remote mechanical work will be required for reactor demobilization and removal following each respective advanced reactor experimentation cycle. The mast and Kraft arm assembly, and the associated tooling accessories are believed to be capable of performing these ConOps functions. This assembly along with a delivery platform is classified by Framatome as the integrated solution option. According to the Framatome rankings the crane delivery platform options have high lifting capacities compared to the shield plug and Brokk and Kraft Crawler & Arm options. Beyond the lifting capacities, the only differences of these integrated solution options are the inherent range of travel and accessibility limitations of each delivery platform. Table 2 compares these capabilities and limitations.

Using the radiation dose model data provided for the DOME Reactor Supplemental Shielding Conceptual Design in report 1129-0298-RPT-001, it was determined that no high radiation regions would be present inside of DOME and outside of the shieling enclosure during experimental reactor operations (see Figure 7 and Figure 8). The anticipated radiation doses would therefore be lower than the previously observed operational radiation doses of all the robotic systems being considered. Per the Framatome report 51-9361177-000, the Boston Dynamics SPOT robot has the lowest assumed radiation tolerance of any of the robotic systems. Radiation and system performance testing of the SPOT robot have been performed up to a total absorbed gamma dose of 413 rem (413,000 mrem or 4.13 sieverts) and maximum dose rate of 200 rem/hour without any system failures (ref. 51-9360488-000). The actual absorbed dose limit for SPOT is anticipated to be that much higher than 413 rem. Conservatively assuming that if SPOT was inside DOME and constantly exposed to a 5 mrem/hour gamma radiation field, it would take about 9.4 years to reach an absorbed gamma dose of 413 rem. Reactor demobilization and removal activities may present short-term higher radiation dose rates but would likely need much less frequent robotic monitoring. Consequently, the justification to exclude radiation tolerance from this assessment is acceptable.

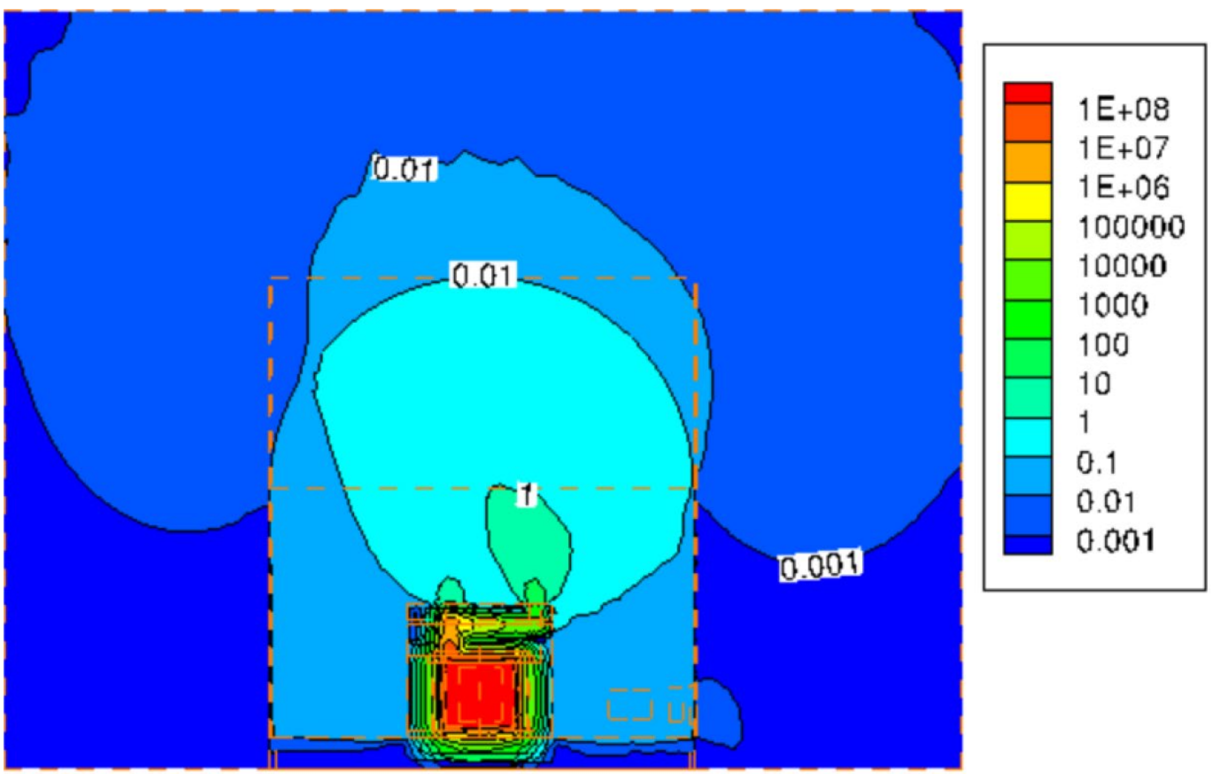

Figure 7. 10 MW reactor neutron dose XZ plane [mrem/hour] from 1129-0298-RPT-001.

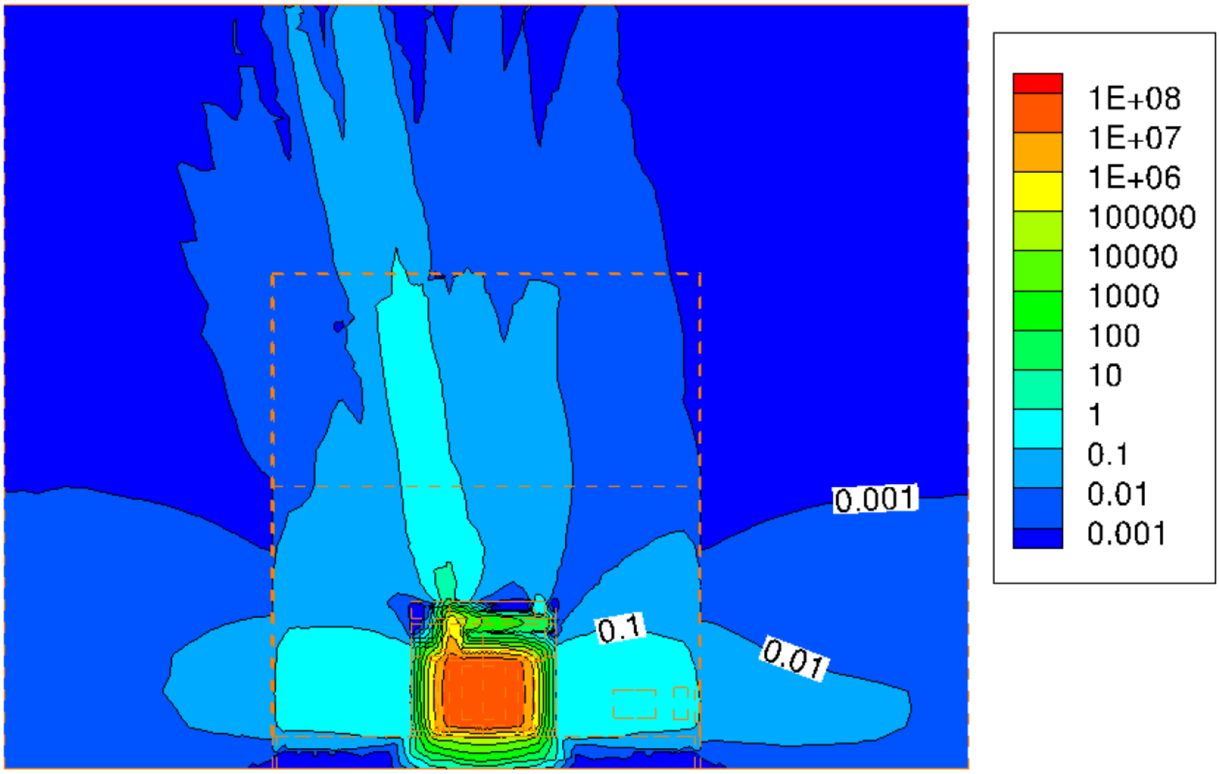

Figure 8. 10 MW reactor photon dose XZ plane [mrem/hour] from 1129-0298-RPT-001.

Several reactor cooling and support systems inside of DOME will need regular monitoring and prescribed inspections to detect and identify any leakage. Thermal imaging will be needed to perform leakage inspections for hot gases and potential hotspots on mechanical equipment. Other PM and ER activities can identify early equipment degradation via vibration, acoustic, and motion amplification monitoring. Performance of these activities during reactor experimentation would be invaluable in maintaining the reliable operation of DOME during operations. Table 2 (below) compares the SPOT capabilities to the generic abilities of aerial drones.

Like the Framatome methodology, the INL assessment divided the robotic option systems into two groups. Each group was renamed to emphasize the distinct applications: reactor demobilization and in-service monitoring systems. The "integrated solutions" category is called "Reactor Demobilization" systems and the "low radiation solutions" category is called "In-service Monitoring" systems. The various capabilities and limitations of each robotic system were used to compare the different systems. No additional ranking or scoring was included as part of this assessment. Moreover, the recommendations of this assessment from the subcontractor and the INL project team are based primarily upon the capabilities of the different robotic systems to perform the ConOps functions.

Finally, Table 2 outlines a summary of the advantages and disadvantages identified in the INL assessment for each robotic option considered.

Table 2. INL assessment summary.

	Advantages	Disadvantages & Limitations
Reactor Demobilization Systems		
Polar Crane and Mast	• Wall to wall range of travel • No floor space footprint • Higher lifting clearance	• Highest cost • Long time to deployment
Gantry Crane and Mast	• Possible shorter time to deployment • Lower initial costs	• Large footprint • Small range of travel and work envelope • Shorter lifting clearance
Shield Plug Mast	• Smaller floor space footprint	• Still requires a crane for deployment • Lower lifting capacity
Brokk and Kraft Crawler & Arm	• Mobile operations • Operation does not require a crane	• Limited accessibility • Umbilical connection required • Lower lifting capacity
In-service Monitoring Systems		
SPOT	• Mechanical manipulation capabilities with the Arm attachment • COTS thermal imaging • COTS acoustic monitoring	• Limited 3D mapping capability
Aerial Drones	• Larger range of travel • 3D radiation mapping • Verify large area dose rate models	• No mechanical manipulation capabilities • Low cost

3.1 Mockups

Mockups are used to ensure new equipment concepts and tooling are effective in form, fit, and function. Any robotic system employed in DOME should be tested and verified using mockups that will include the same electrical cable, piping, reactor support connections, valves, switches, etc. that will be used for the different advanced reactor experiments. Such mockups will be used to demonstrate successful reactor demobilization protocols and provide DOME Operations personnel with needed training to perform the demobilization processes and tasks.

A theoretical timeline to procure and employ a mockup system could look something like the following:

- Engineering conceptual and design work, 2–3 months. Needs to start once the design for reactor connections is completed and the lifting-handling design is established.

- Procure hardware and components for the mockups 4–6 months.
- Mockup fabrication could be concurrent with fabrication of the actual DOME systems.
- Testing setup, 1 month.
- Mockup testing and evaluations, 1 month.
- Operations training, as needed.

The process to procure and implement mockup testing should start about 1 year before the first reactor startup. The mockups should be finished prior to the first reactor installation but would need to be ready after Reactor Supplemental Shielding is mobilized. The cost for the mockups is estimated to be around $500K.

3.2 Recommendations

Below is a summary of the four recommendations for the robotic architecture and systems to be employed in the NRIC DOME. An additional 6 months of development and delivery timeline has been added to provide more margin to the Framatome estimated timelines.

3.2.1 Reactor Demobilization System

1. Recommendation 1 – Mast and Kraft arm assembly
    - Justification: The telescoping mast and Kraft arm assembly can be used for mechanical manipulation activities both inside and outside of the shield structure and is very radiation tolerant.
    - Timeline:
        - 2 1/2 years to develop and deliver (see Appendix A for cost and time breakdowns).
        - Arrive on site 9 months prior to first reactor experimentation to verify accessibility of critical components and test demobilization ConOps.
    - Estimated Cost: $700K (this estimated cost is based on the shield plug mast assembly costs).

NOTE: The telescoping mast and Kraft arm assembly would still require an overhead lift system for mobilization and installation. Either the refurbished polar crane or a new gantry crane delivery platform could serve as the overhead lift and delivery system. The estimated costs for the refurbishment polar crane and new gantry crane systems are respectively $4.4M and $3M with timelines for use of about 2 1/2 years.

2. Recommendation 2 – Brokk and Kraft Crawler & Arm
    - Justification: Able to access both sides of the reactor during demobilization activities and provide multiple working angles and arms for the disassembly of the connecting reactor piping, cables, and support components. Contingency for failure of overhead mast and Kraft arm assembly. For example, if one robotic system were to become stuck during a high radiation activity, the other could be used to liberate the stuck tooling and minimize the risk of increased personnel radiation exposure during emergent mitigating actions.
    - Timeline:

        - 1 1/2 years to develop and deliver (see Appendix A for cost and time breakdowns).
        - Arrive on site 9 months prior to first reactor experiment to verify accessibility of critical components and test demobilization ConOps.
    - Estimated cost: $726K.

In-service Monitoring Systems

3. Recommendation – Boston Dynamics SPOT
    - Justification: SPOT can perform the PM and ER activities more effectively than the aerial drones, especially if any light-duty mechanical manipulations are needed during operation. The SPOT COTS options are readily obtainable and have a reliable performance history in nuclear applications.
    - Timeline:
        - 8–14 months to develop and deliver (see Appendix A for cost and time breakdowns).
        - Arrive on site 6 months prior to first reactor experiment to test PM and ER ConOps.
    - Estimated cost: $220K.
4. Recommendation – Elios 3 RAD Aerial Drone
    - Justification: Elios 3 RAD can perform 3-D radiation dose rate mapping as well as various visual inspections.
    - Timeline:
        - 8–14 months to develop and deliver. May need a custom remote docking station designed.
        - Arrive on site 6 months prior to first reactor experiment to and test/ radiation dose rate monitoring capabilities.
    - Estimated cost: $100K.

Mockup Testing

5. Recommendation – a mockup test rig
    - Justification: Verify robotic capabilities and demonstrate successful reactor demobilization and personnel training.
    - Timeline:
        - 9–12 months to develop and deliver (see Appendix A for cost and time breakdowns).
        - Arrive on site 6 months prior to first reactor experiment.
    - Estimated cost: $500K.

Appendix A

Framatome Cost Breakdowns

Table 3. Framatome shield plug mast cost breakdown.

Shield Plug Mast			
Cost Description	**Timeline**	**Price estimate**	**Notes**
PM, PE, and Design, including drawings, and documentation	LOE	$139,500	Robotic arm with telescoping mast deployed with shield plug No mark up on Kraft arm due to partnership
Kraft arm integration	3-6 months	$200,000	
Mast Materials and Arm Integration	1 year	$165,200	
Post-mod Testing	1 month	$55,400	DOME Installation and testing will be T&M based on site schedule is not included in this estimate
Pack and Ship	1 Month	$18,000	
Contingency (20%)		$115,620	
Totals	**~2 years**	**$693,720**	
Notes			
Shield Plug Masts must have some type of jib or overhead crane to deploy. Recommend having two deployable shield plug masts to access both sides or ends of the micro reactor simultaneously.			

Table 4. Framatome polar crane refurbishment with robotic arm cost breakdown.

Polar Crane Refurbishment with Robotic Arm			
Cost Description	**Timeline**	**Price Estimate**	**Notes**
Crane Refurb	~1 year	$1,900,000** $3,000,000**	**American Crane ballpark estimate: $1.9M to CMAA and $3M to ASME NOG-1.
PM, PE, and Design, including drawings and documentation	LOE	$589,000	
Materials and Integration	1.5 years	$987,960	
Testing (trolley and mast)	1 month	$105,400	
Pack and Ship	2 months	$79,000	DOME Installation and testing of mast and robotics at T&M is not included in this estimate
Contingency (20%)		$652,272	
Totals	**~ 2 years**	**$4,393,632 CMAA**	
		$5,713,632 NOG-1	
Notes			
Framatome would rely on American Crane for the refurbishment of the polar crane. Framatome would develop the addition of the mast in collaboration with the crane refurbishment. Walkdown and inspection is necessary to establish current state of the crane. The mast addition could be added on one or both trolleys The crane mast would be rad hardened with use of hydraulics or by shielding or by distancing electrical components. Additional features to assist in addressing different or new ConOps are presented below:			
Polar Crane – Additional Features			
Cost Description	**Timeline**	**Price estimate**	**Notes**
Automatic tool exchange system on the mast or main crane platform.	3-6 months	$150,000	Timeline estimates are after test cycle of using system
Advanced tooling integration such as plasma cutting, and decontamination solutions	3-6 months	$40,000	Timeline estimates are after initial design is installed. Cost estimates are based on a per tool basis and are subject to change based on tool complexity
Mast and Hook automatic Tracking and positioning. Preprogrammed automatic move capabilities	6 months	$232,500	6-month timeline is in addition to original project scope and will require coordination with American Crane during refurbishment. Cost estimate is a rough estimate on materials, design, integration, and testing.

Table 5. Framatome 500-ton gantry crane cots cost breakdown.

500 Ton Gantry Crane COTS			
Cost Description	**Timeline**	**Price estimate**	**Notes**
PM, PE, and Design, including drawings and documentation	LOE	$604,500	500 ton hydraulic 4 wheel-based, telescoping legs on rails that will need upper beams to connect y- direction mobile gantry crane. Wireless control capability. Robotic arm with mast near COG, minimal lateral loads, meets CMAA requirements.
Materials and Integration	1.5 years	$1,510,200	($625k for COTS gantry crane SBL585 - Enerpac)
Rail and Beam system	n/a	$100,000	
Post-mod Testing	2 months	$105,400	
Pack and Ship	3 Months	$174,000	DOME Installation and testing will be T&M based on site schedule is not included in this estimate
Contingency (20%)		$498,820	
Totals	**~2 years**	**$2,992,920**	
Notes			
Purchasing a COTS crane and implementing radiation hardening techniques would provide a significant cost savings as opposed to designing a fully custom gantry crane. Framatome would implement radiation hardening techniques to the crane so that exposed crane components subject to high dose, i.e., the top and upper sides containing hoist, hook, mast, and robotic arm of the crane, would be able to withstand high dose rates (>1,000+ r/hr.). The lower sides of the crane housing electronics and drive systems would be protected by the reactor shield package. Additional features could be added later to assist in addressing different ConOps or to increase automation and accuracy of the crane system.			
Additional Features			
Cost Description	**Timeline**	**Price estimate**	**Notes**
Automatic positioning system for the crane and programmable moves with robotic arm	6 months	$232,500	Six month timeline is in addition to refurb, rad hardening and robotics project scope and will involve working with the subcontracted vendor during refurb. One year timeline is if features are added after initial design. Cost estimate is a rough estimate on materials, design, integration, and testing.

Table 6. Framatome Electric Brokk and Kraft Crawler and arm cost breakdown

Brokk + Kraft - Near Term Cost Breakdown - High Rad (Electric)			
Cost Description	**Timeline**	**Price estimate**	**Notes**
Brokk 110	COTS (in stock)	$180,000.00	
Electronics extraction	6-8 months	$180,000.00	+100% base cost
Framatome design (includes drawings and documentation)	LOE	$30,000.00	tool interface, tool rack
Kraft arm integration	3-6 months	$200,000.00	No mark up on Kraft arm due to partnership
Hold Position Tool	COTS (in stock)	$10,000.00	Extremely helpful for anchoring Brokk during Kraft arm movements
Cable Management System	COTS	$5,000.00	Cable reel for powered cable retracting; Additional infrastructure (festooning) likely required for overhead cable management
Contingency (20%)		$121,000	
Totals	~ **1+ year**	**$726,000.00**	

Notes
It is recommended to have a secondary system as a backup. This would have high radiation tolerance and would require little to no maintenance due to radiation exposure. This is still a fully electric Brokk with an electric cable umbilical and hydraulic lines only for the Kraft. A powered cable management reel is recommended for the system as well as overhead routing of cable using a cable festoon or similar.

Table 7. Framatome hydraulic Brokk and Kraft Crawler and arm cost breakdown

Brokk + Kraft - Near Term Cost Breakdown - High Rad (Full Hydraulic)			
Cost Description	**Timeline**	**Price estimate**	**Notes**
Brokk 110	COTS (in stock)	$180,000.00	
Fully Hydraulic version	6-8 months	$180,000.00	+100% base cost
Framatome design (includes drawings and documentation)	LOE	$30,000.00	tool interface, tool rack
Kraft arm integration	3-6 months	$200,000.00	No mark up on Kraft arm due to partnership
Hold Position Tool	COTS (in stock)	$10,000.00	Extremely helpful for anchoring Brokk during Kraft arm movements
Cable Management System	COTS	$5,000.00	Cable reel for powered cable retracting; Additional infrastructure (festooning) likely required for overhead cable management
Contingency (20%)		$121,000	
Totals	**~ 1+ year**	**$726,000.00**	
Notes			
It is recommended to have a secondary system as a backup. This system would have a high radiation tolerance and would require little to no maintenance due to radiation exposure. This system is a fully hydraulic Brokk integrated with the Kraft robotic arm. This system has a bundle of 7 hydraulic lines tethered to the Brokk. Specialized cable management will be required. A powered cable management reel is recommended for the system as well as overhead routing of cable using a cable festoon or similar.			

Table 8. Framatome Boston Dynamics SPOT cost breakdown.

Spot (AMORAC)			
Cost Description	**Timeline**	**Price estimate**	**Notes**
Spot Base System	2-3 weeks	$75,000.00	This is the base bot and includes: Spot robot Spot battery (2x) Spot charger Tablet controller and charger Robot case for storage and transportation
Arm attachment	COTS in stock	$55,000.00	Estimated arm costs
Upgrade + autonomy package	COTS	$35,000.00	360 cameras, lights, better comms, and a Velodyne VLP-16
Self Charging Station		$15,000.00	
Radiation sensors		$15,000.00	
Engineering mech/software (sensing)		$25,000.00	
Totals	**8 months**	**$220,000.00**	
Notes			
UK's Atomic Energy Authority (UKAEA) has priced the premium version of the Spot with Arm with all ancillary equipment to be priced at $204K. This is for the premium package and excludes integration of radiation sensing technology (added separately). The base system is tested and rated to be tolerant of 413 rem @ 16 R/hr. peak exposure rate at a distance of 1 meter (up to a rate of 200 R/hr. of the Spot frame). Did not run radiation test to failure - just what was exposed to thus far.			