Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks

an Integrated Research Project sponsored by NEUP

Presented by: Cliff Lissenden, Penn State

DOE Used Fuel Disposition Meeting

Las Vegas, NV

June 7-9, 2016

PennState College of Engineering

NEUP Nuclear Energy University Programs

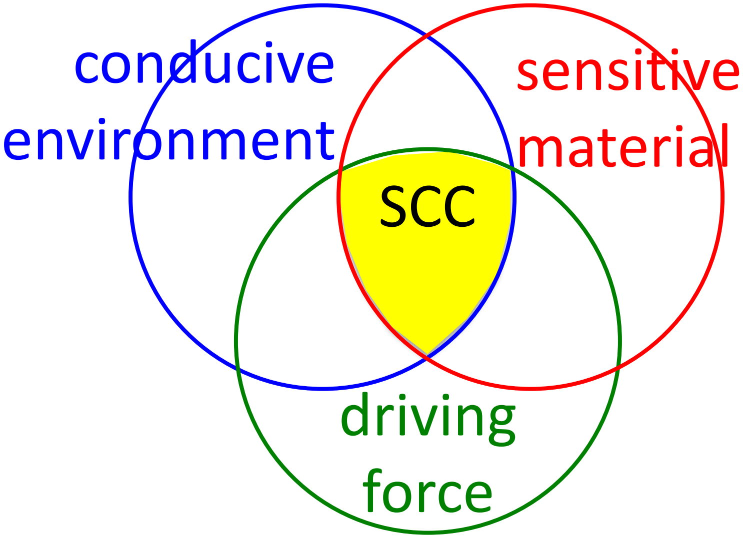
U.S. Department of Energy

Problem: dry storage casks designed for intermediate term storage as part of the fuel cycle, must now provide extended storage

Aging Management Programs are now required for ISFSIs

Casks were not designed with **inspection** in mind

Concerns: CISCC and concrete degradation



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Canister NDI
Cliff Lissenden
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Engng Sci Mech
Matt Lindsey
Struct Integrity Assoc


Surface Composition
Arthur Motta
Samuel Le Berre
Penn State
Nuc Engng

Surface Composition
*Igor Jovanovic**
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Task Teams

Overpack NDI
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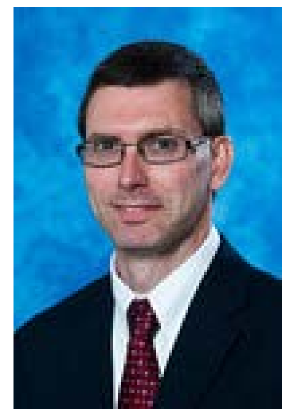
Appl Research Lab



Modeling
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Ryan Priest
Kyle Singer
South Carolina
Nuc Engng

Robotic Delivery
Sean Brennan
Bobby Leary
Ian Van Sant
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Mech Engng

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UNIVERSITY OF SOUTH CAROLINA

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Over the course of three years the project plans to achieve the following milestones:

1. Demonstrate that photonic bandgap fiber delivery of LIBS/RS based compositional analysis can detect salt residue on a stainless steel plate. Task 1. Report Date: Y2Q2 (3/30/16).
2. Make selection between EMAT and MST for canister NDI. Task 2. Report Date: Y2Q1 (12/30/15).
3. Benchmark EMAT/MST sensors with respect to bulk wave ultrasonics and eddy current methods. Task 2. Expected Date: Y3Q2 (3/30/17).
4. Validate data analysis schemes to characterize concrete degradation, given air-coupled sensor data. Task 3. Expected Date: Y2Q3 (6/30/16).
5. Demonstrate the guided wand robotic system mobility and positional tracking in lab mockups of dry storage systems. Tasks 4 and 6. Expected Date: Y2Q2 (3/30/16).
6. Calibrate radiation transport and thermal modeling with accepted standards. Task 5. Report Date: Y1Q3 (6/30/15).
7. Demonstrate fiber-based dosimeter capability. Task 5. Report Date: Y1Q4 (9/30/15).
8. Verify that the data collection system stores data in an efficient useful manner. Task 6. Expected Date: Y2Q4 (9/30/16).
9. Demonstrate sensor delivery and data acquisition with the guided wand robotic system. Task 7. Expected Date: Y2Q4 (9/30/16).
10. Demonstrate the multisensory robotic system within dry storage mockups provided by our industrial partners. Tasks 1-7. Expected Date: Y3Q4 (9/30/17).

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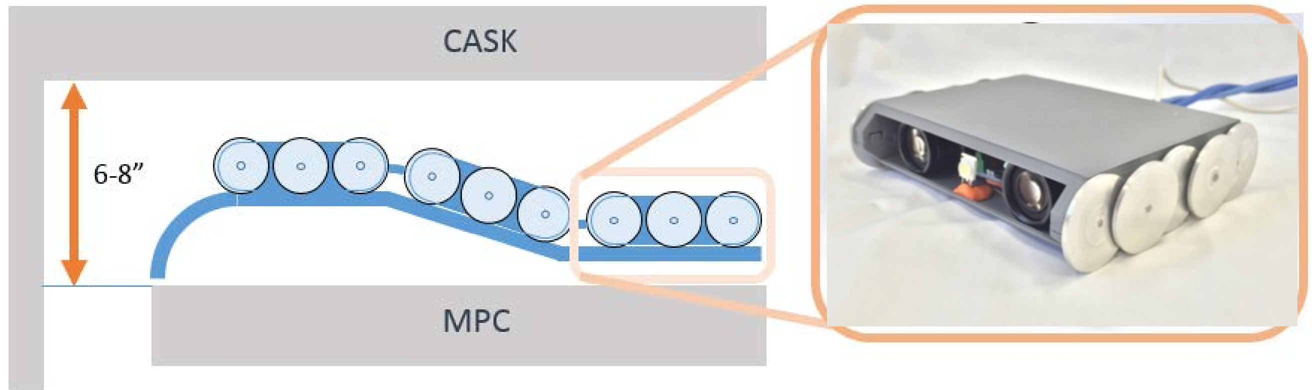
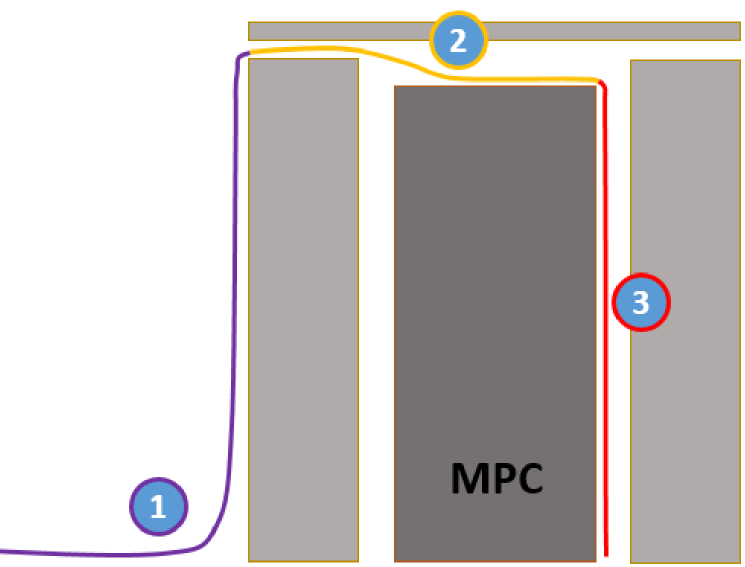
Delivery Progress:

through 1.5 of 3 years

Delivery system will enter exhaust vent, align sensor cars from atop the MPC lid, and then deploy sensor cars in gap between MPC and overpack.

Sensor Car Deployment





1. Ambient air:
   natural convection
   80 - 120 F

2. Stagnant air above MPC:
   natural convection
   ~350 F

3. Ventilation air in channel:
   forced convection (3 m/s)
   ~250 F

Command Center
(low γ rad)

Robot Maneuvering
(high γ rad)

Sensors Operate
(high γ rad)

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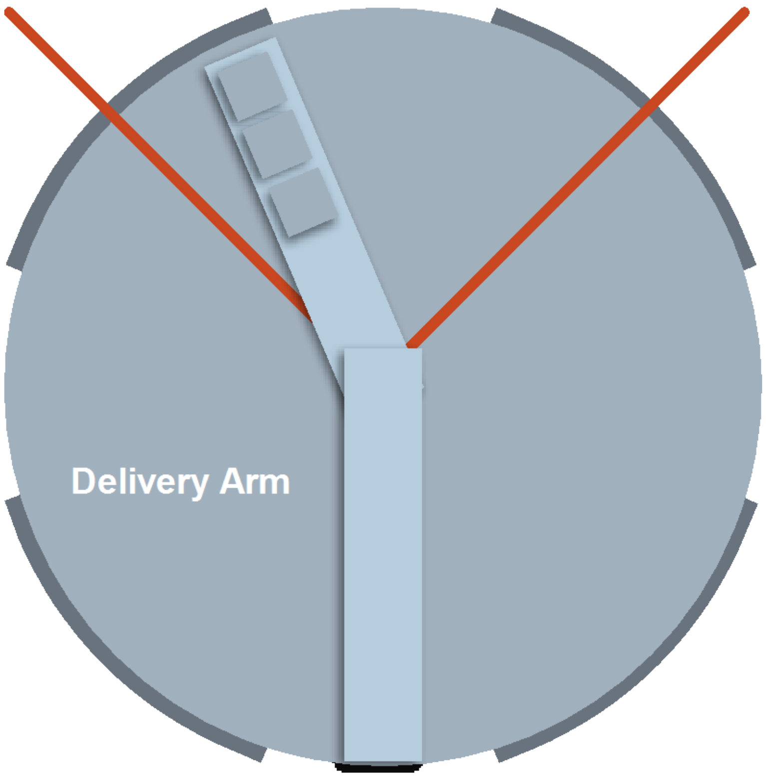
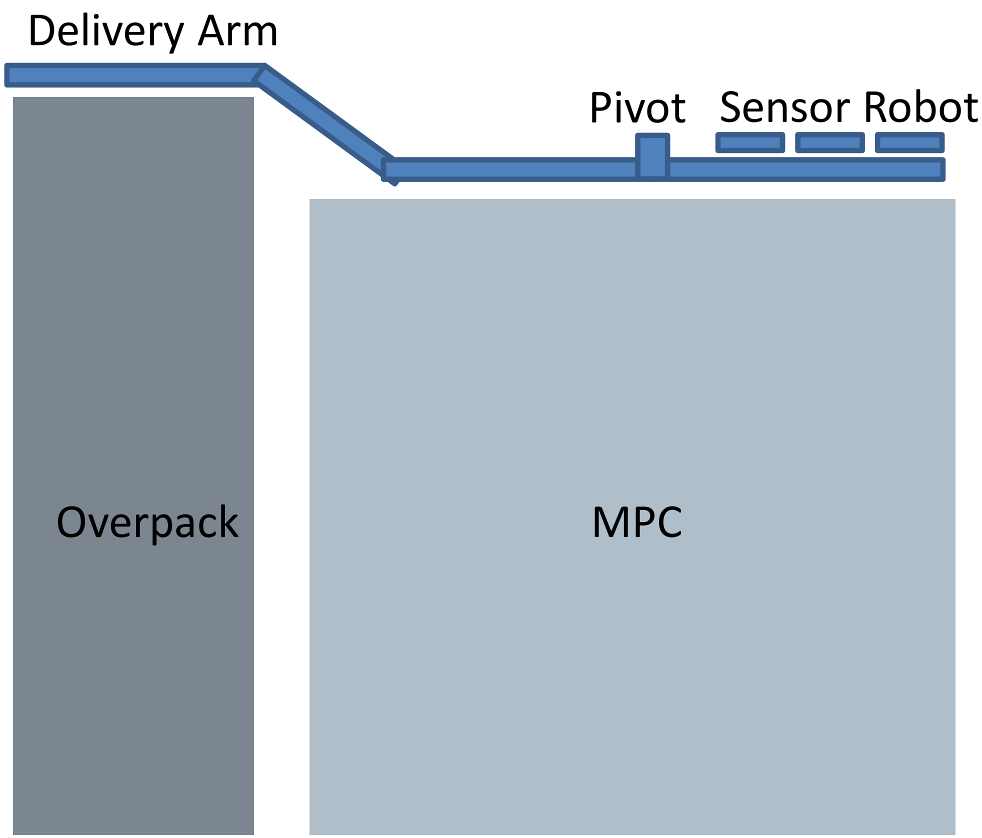
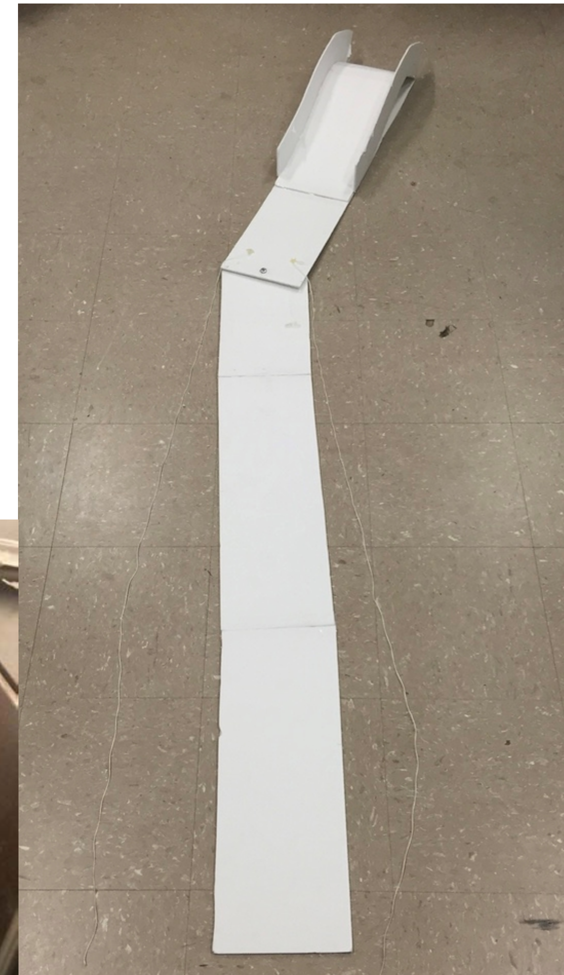
The concept of an externally actuated delivery arm to position the sensor cars is being prototyped and tested.





The concept of an externally actuated delivery arm to position the sensor robot is being prototyped and tested.



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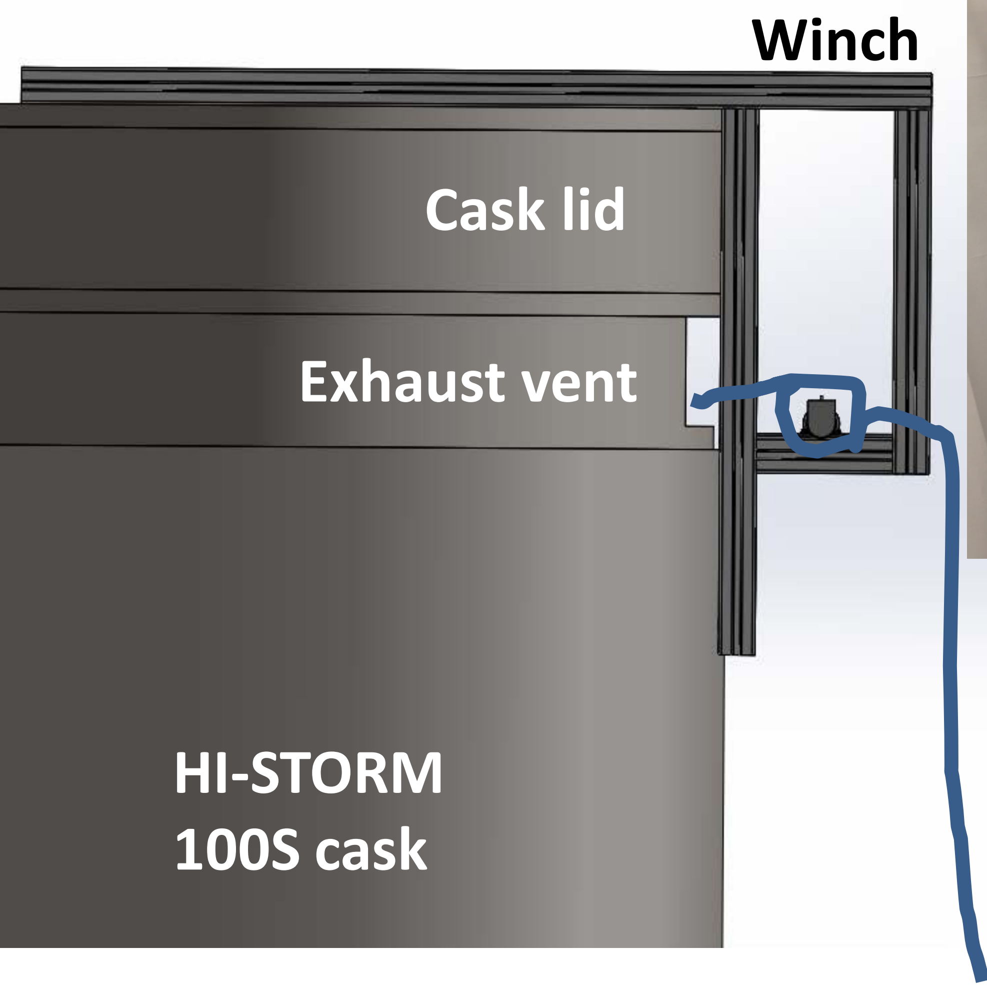
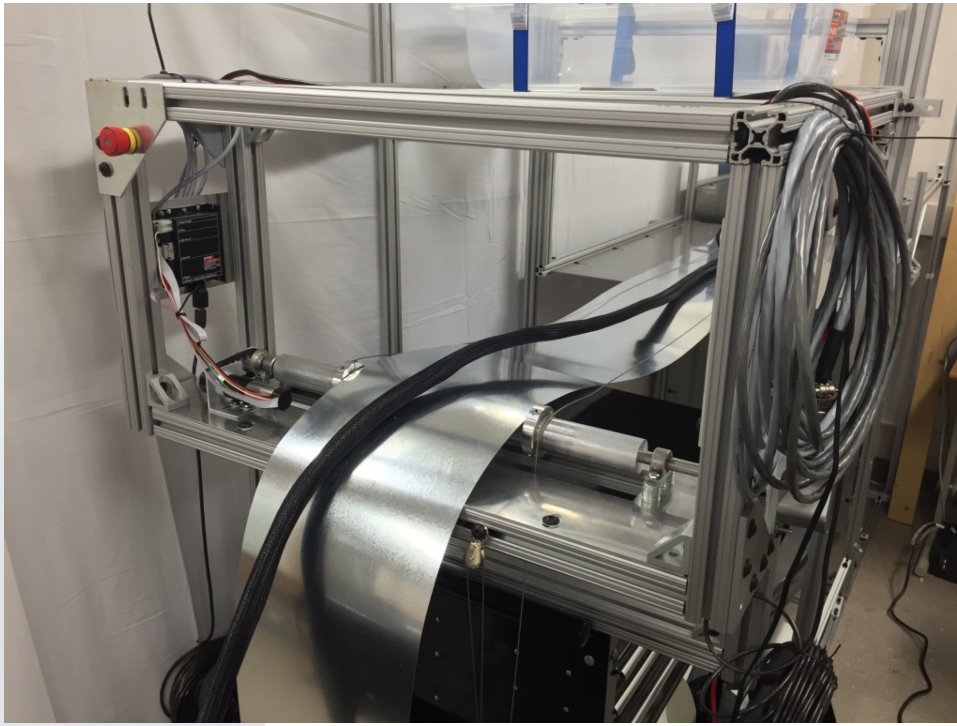
A winch located outside of the cask will spool cabling to raise/lower the sensor robot within a guide channel gap.





Philosophy: limit electronics inside cask

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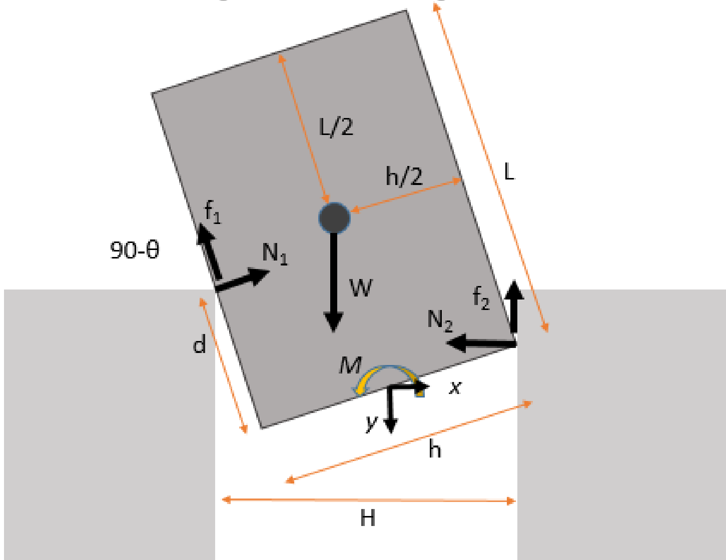
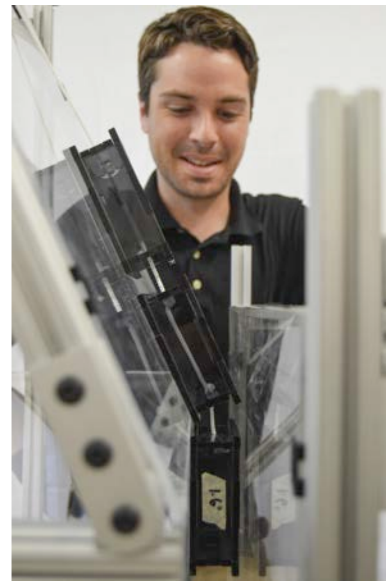
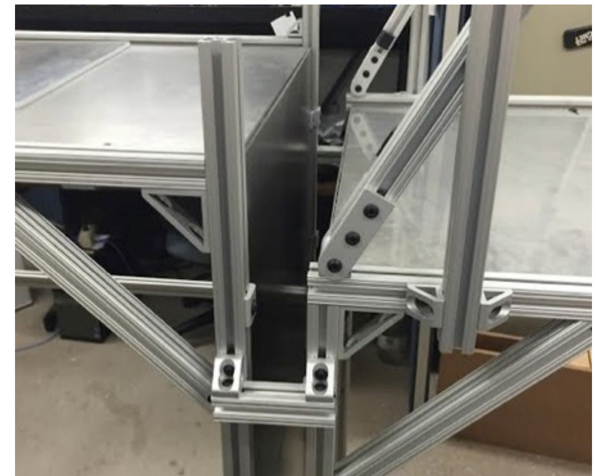
Theoretical and experimental analyses have found the maximum size of the sensor cars to prevent wedging and jamming during insertion and extraction.

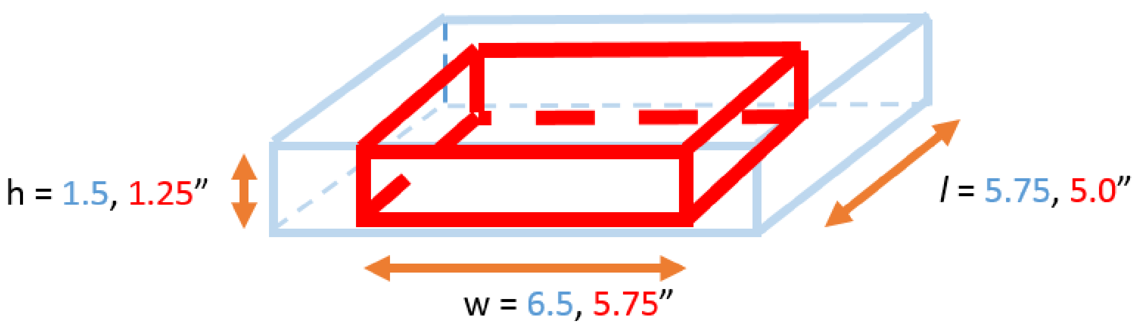


Free Body Diagram





variable gap mock-up for testing wedging/jamming in the cask



Envelope: 1.5x5.75x6.5"

Payload: 1.25x5.0x5.75"

These dimensions ensure passive removal even in tightest offset within cask.

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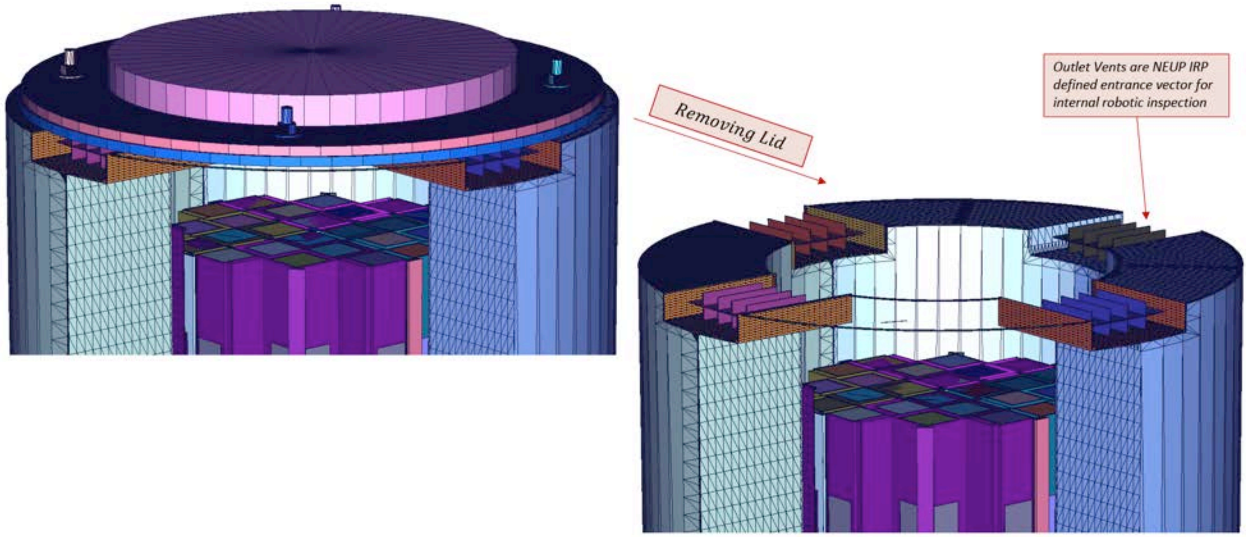
The current prototype for the front-most car contains cameras, LED lighting, two lasers for localization, and EMATs.

Detailed geometry models of six MPC/overpack designs for radiation transport and thermal modeling have been completed.



METCON	24 Assembly	32 Assembly	68 Assembly
HI-STORM 100	MPC-24	MPC-32	MPC-68
HI-STORM 100S	MPC-24E	MPC-32F	MPC-68F
HI-STORM 100S v. B	MPC-24EF	-	MPC-68FF
-	-	-	MPC-68M

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Data acquisition is being developed along with system integration.

Sensors:
LIBS – composition
EMAT – cracks
Mini GM – radiation
TCs – temperature
EC – pits and corrosion
cameras
encoders
range finder

Tether:
Power
Data
Optical fiber
Air hose
Passive withdrawal

Command Center:
On pad outside cask
low radiation
ambient temperature

Localize measurements and return
High temperature – 350F
High γ radiation

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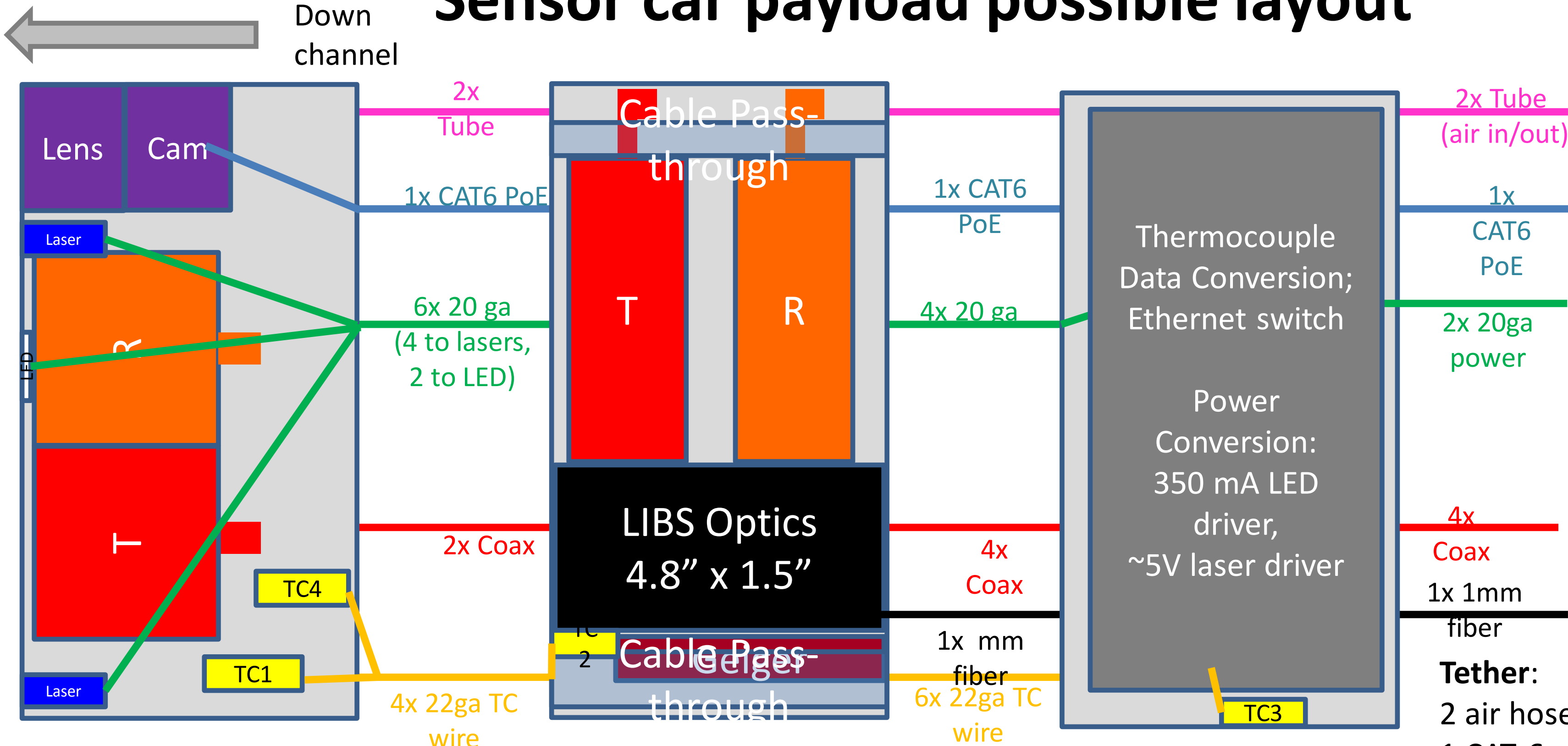
Sensor car payload possible layout



Tether:
2 air hoses
1 CAT-6 Ethernet
2 power wires
4 coax cables
1 1mm fiber
2 retraction cables

Car 1: 2 EMATs side-by-side, with straight connectors placed on short sides as shown, 1 or 2 laser pointers mounted parallel, and 1 Point Grey camera with CAT6a cable and power-over-Ethernet. EMAT mounting, deployment, and magnetic shield not included in diagram.

Car 2: 2 EMATs placed side-by-side, rotated 90 deg with right-angle connectors mounted on short sides as shown; these EMATs might not be needed. Geiger counter and LIBS optics: LIBS optics could use more space. Cables from Car 1 are routed through Car 2 along both sides in sections marked “Cable Passthrough.” EMAT mounting, deployment, and magnetic shield not included in diagram.

Car 3: Thermocouple data conversion to Ethernet data; Electronics to drive white LED and one or two laser pointers, from a single power supply twisted pair (prob +15V and GND)

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Characterization Progress:
through 1.5 of 3 years

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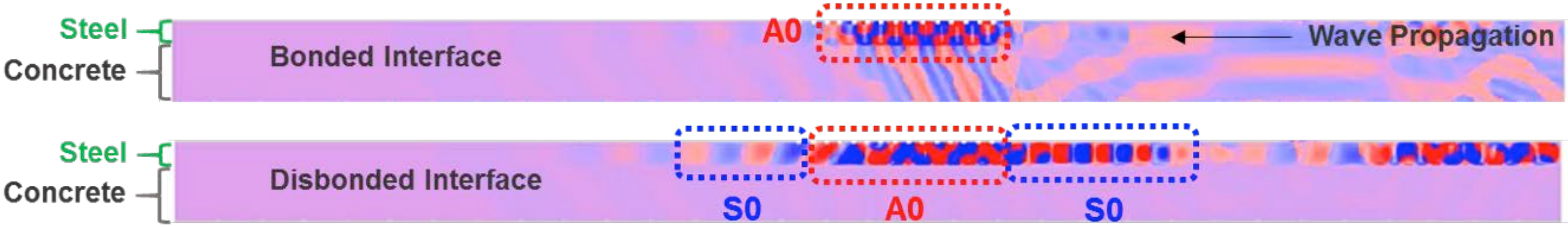
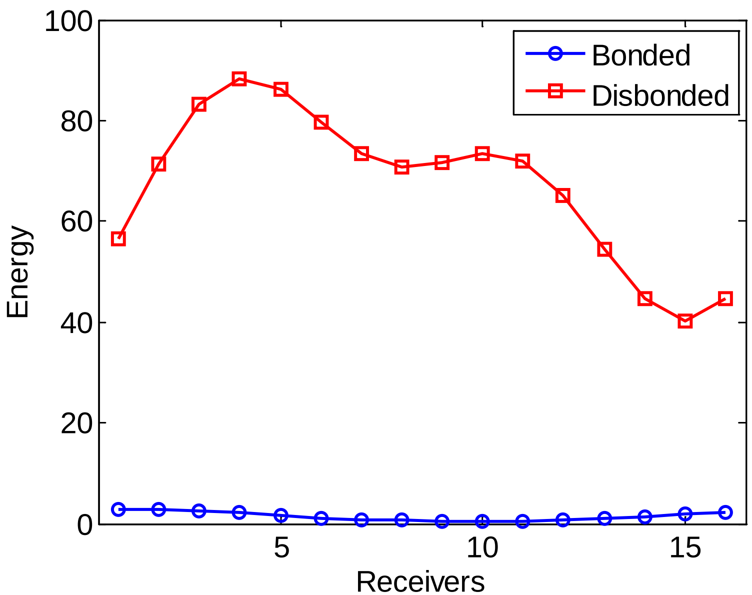
Simulations indicate that the S0 Lamb wave mode can indicate disbond between steel cladding and concrete.

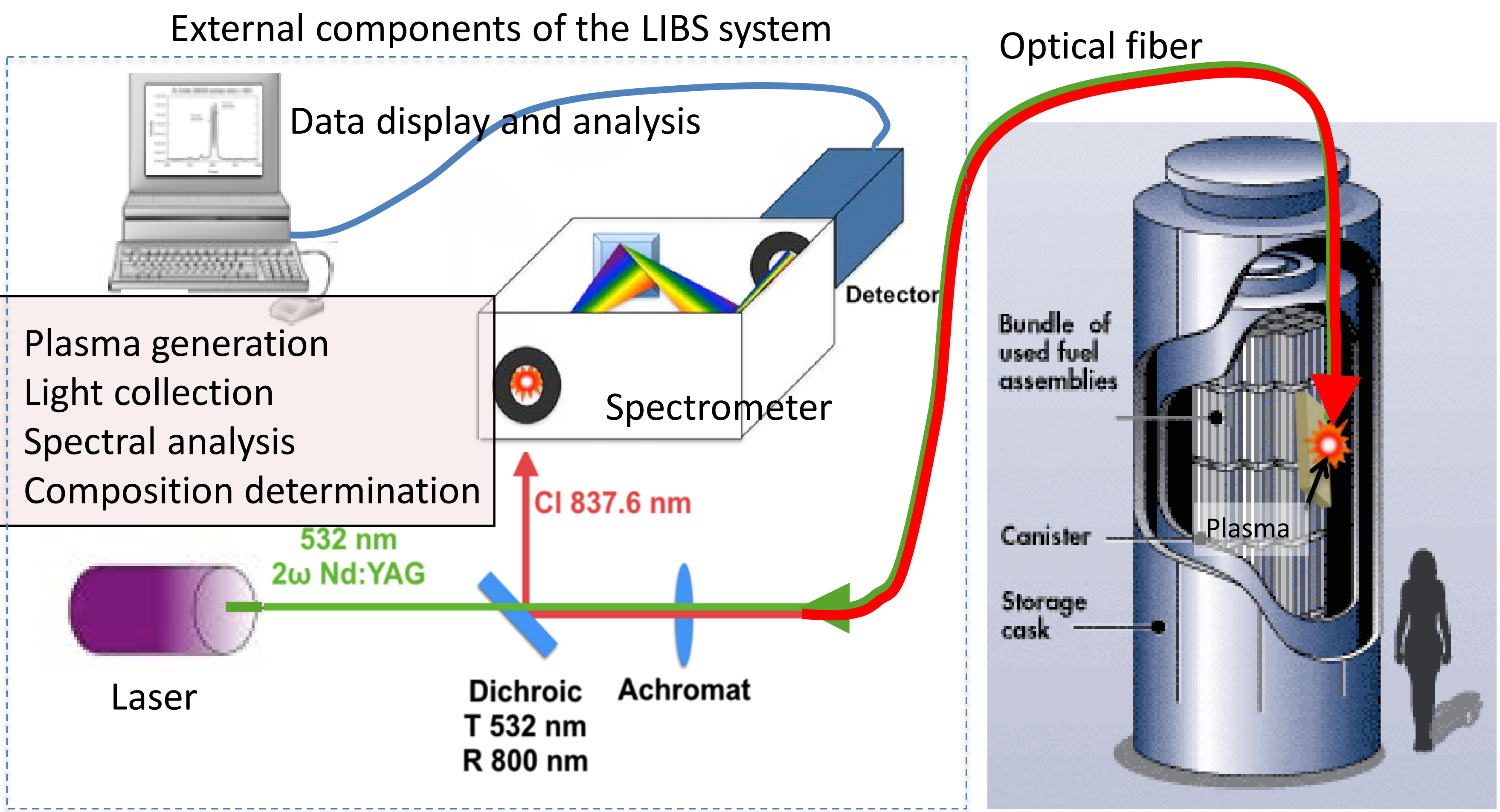




S0 Mode from simulation

The disbond-induced S0 Lamb wave mode can be extracted using 2D bandpass filtering in the frequency and wavenumber domains

Laser-induced breakdown spectroscopy (LIBS) is proposed to analyze surface composition. Is environment conducive to SCC?



- Plasma generation
- Light collection
- Spectral analysis
- Composition determination

Optical fibers will deliver the LIBS laser pulse and transport the collected optical emission for analysis

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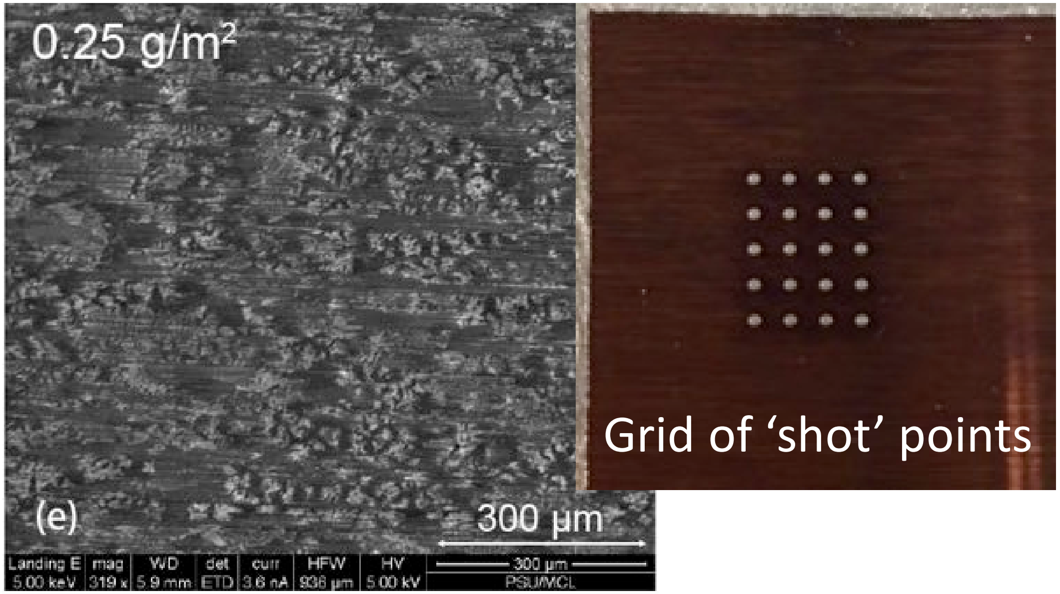
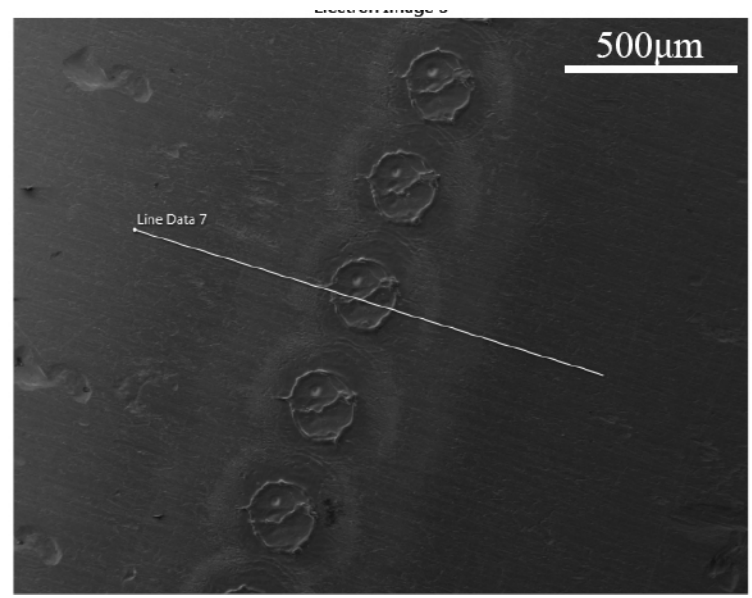
Diluted synthetic sea water (0.005 – 1 g/m^2 Cl) was deposited on stainless steel using nebulizer for uniformity.



SEM image



Single 'shot' scars

Multiple shot points are expected to be needed to account for nonuniformity of deliquesced salts.

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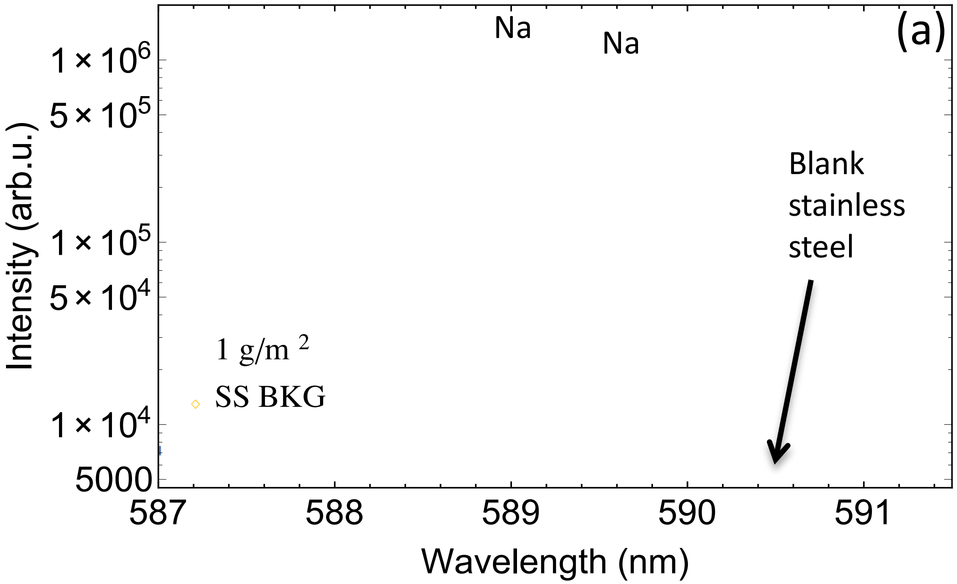
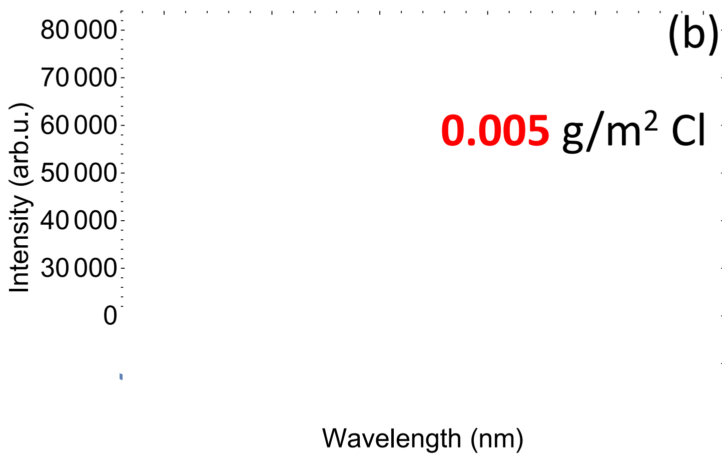
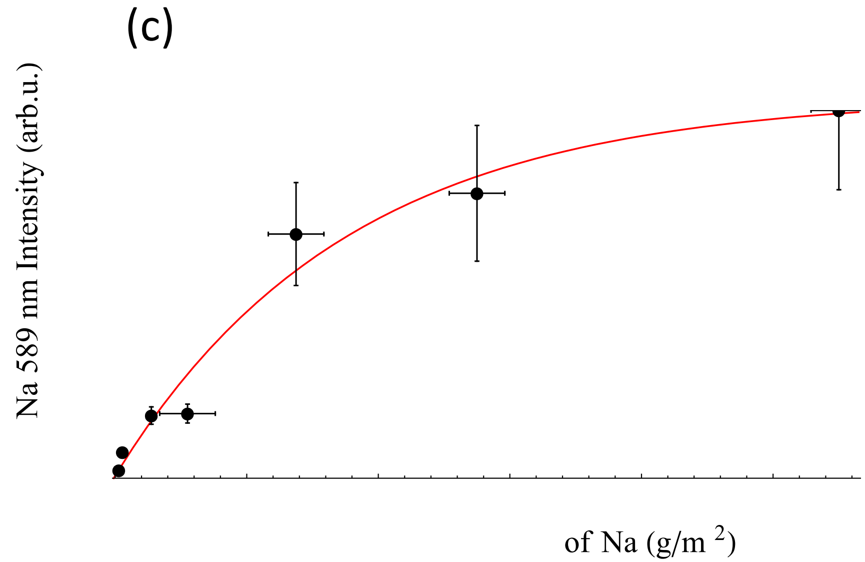
Open-beam delivery surrogate measurements of chlorine using Na I 589 nm have low detection limit (0.005 g/m² Cl).







(a) Na I emission spectrum (20 position averaged) and stainless steel BKG
(b) Multiple peak fit of Na lines
(c) Intensity of Na I emission (589 nm) versus calculated Na surface concentration

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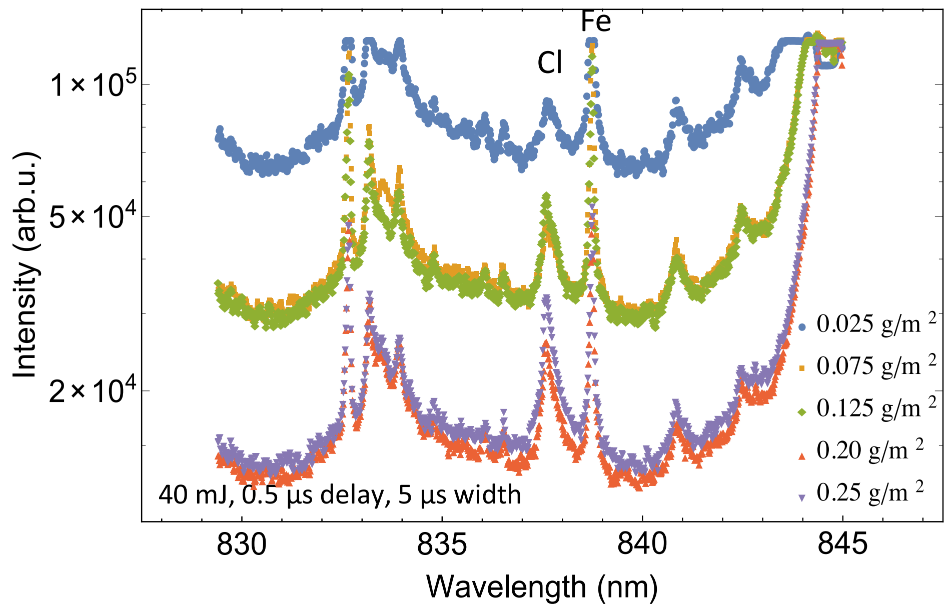
Open-beam delivery direct measurements of chlorine using Cl I 837.6 nm has lower detection limit (0.025 g/m^2 Cl) than previously measured.

Cl (837.6 nm) and Fe lines in Eto's spectrum (left) and recent LIBS spectrum (right)

Eto *et al.* 2013

30 mJ, 1.7 µs delay, 0.1 g/m^2

Intensity (arb.u.)



We are able to better separate Cl and Fe peaks using our spectrometer with much higher resolution than Eto.

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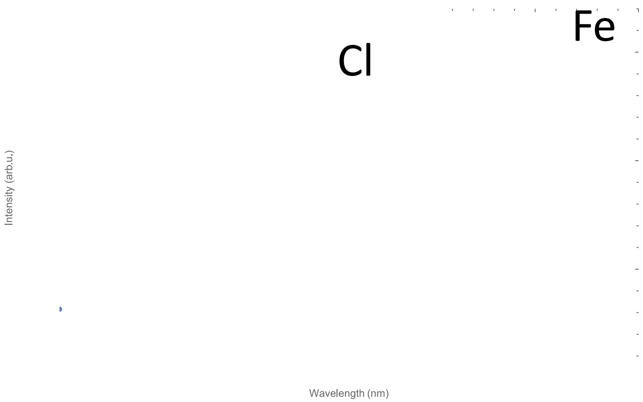
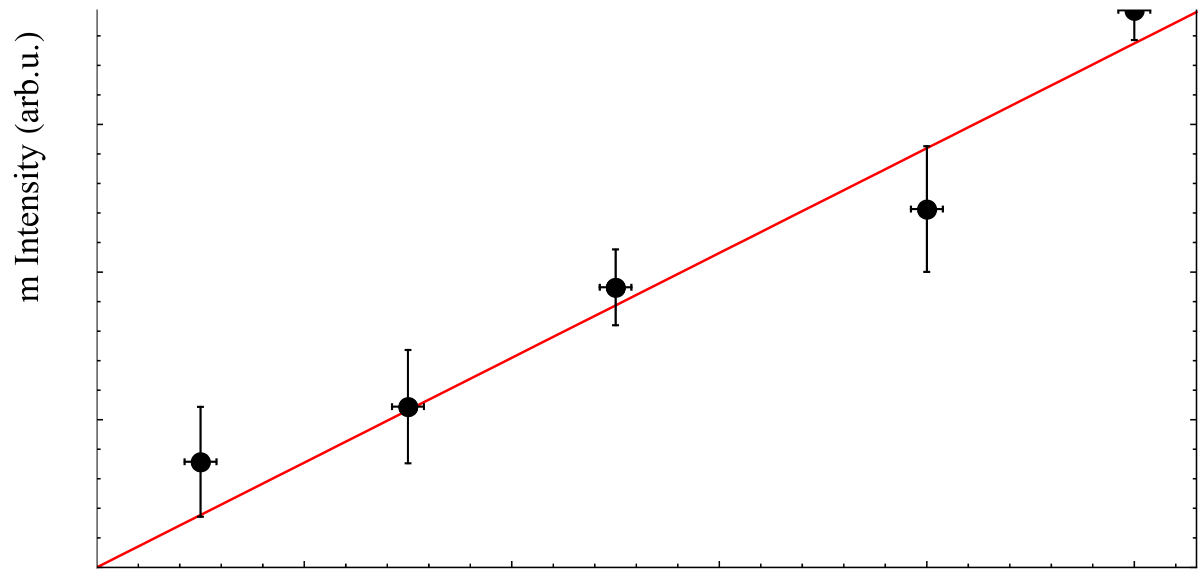
Open-beam delivery direct measurements of chlorine using Cl I 837.6 nm are more challenging/less sensitive than Na.

Multiple peaks fit of Cl I line at 837.6 nm (0.2 g/m^2)



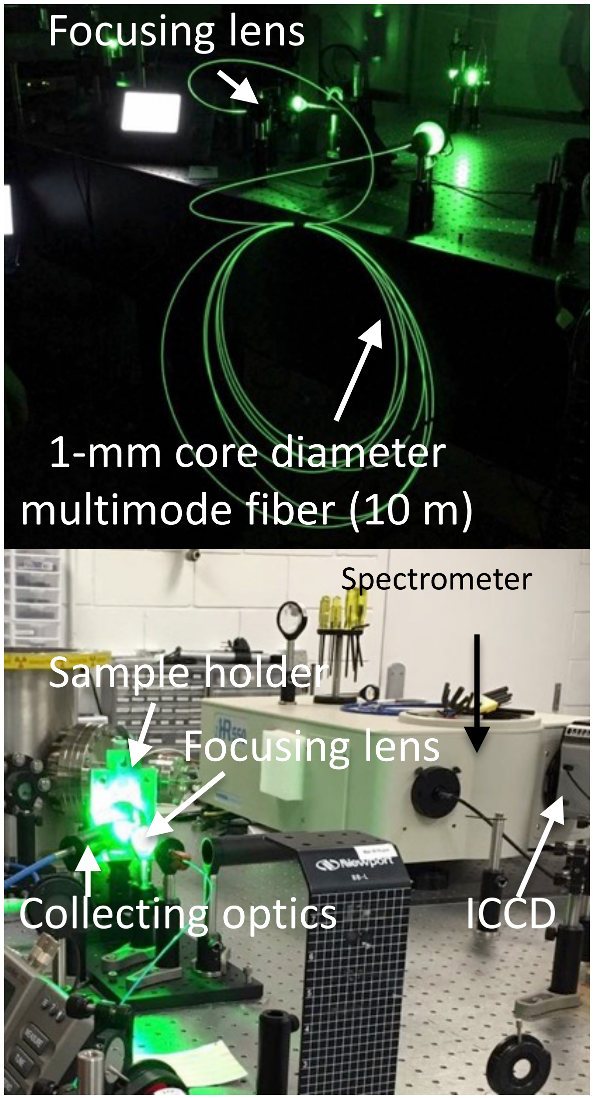
Calibration curve of Cl I (837.6 nm) emission intensity and the calculated Cl surface concentration



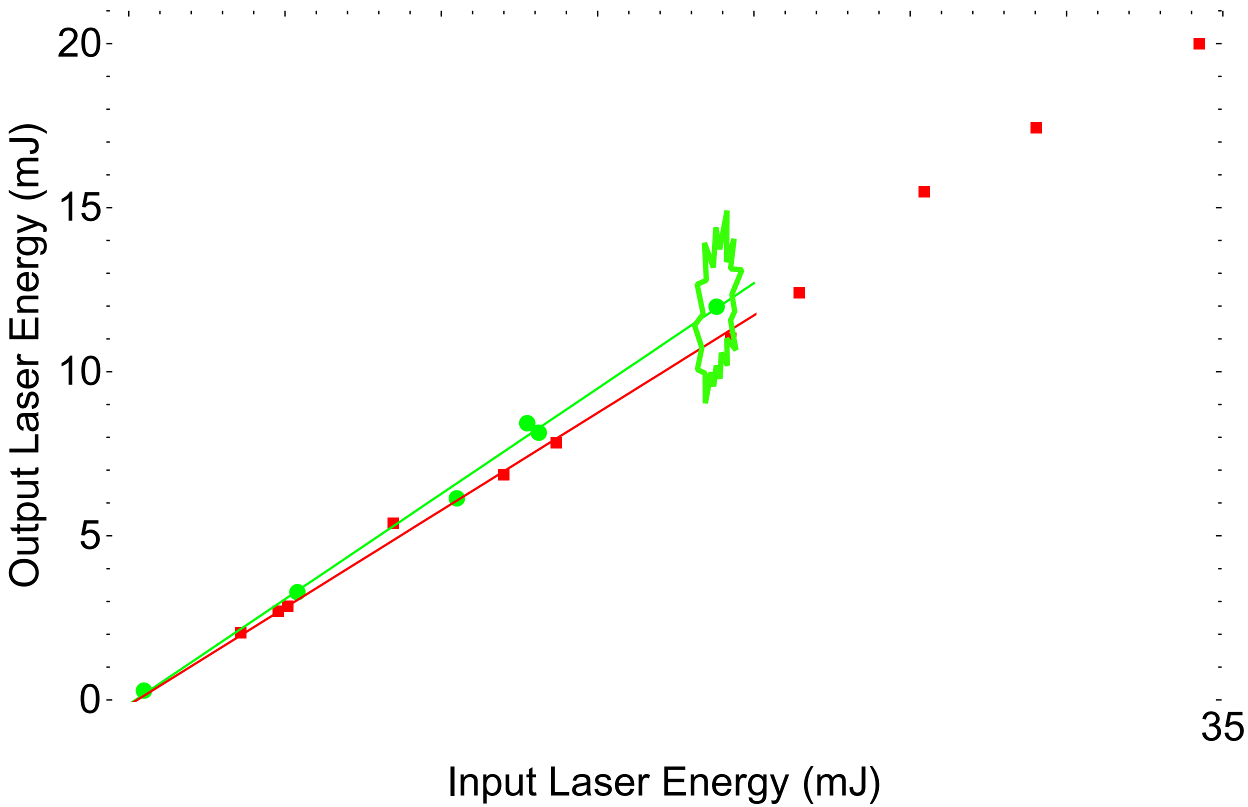
It is difficult to further reduce the limit of detection due to the convolution of several peaks and high excitation energy of Cl.

The transmission efficiency and damage threshold of 1-mm diameter/10-m long optical fiber was measured.

Fiber delivery of 532 nm laser pulse

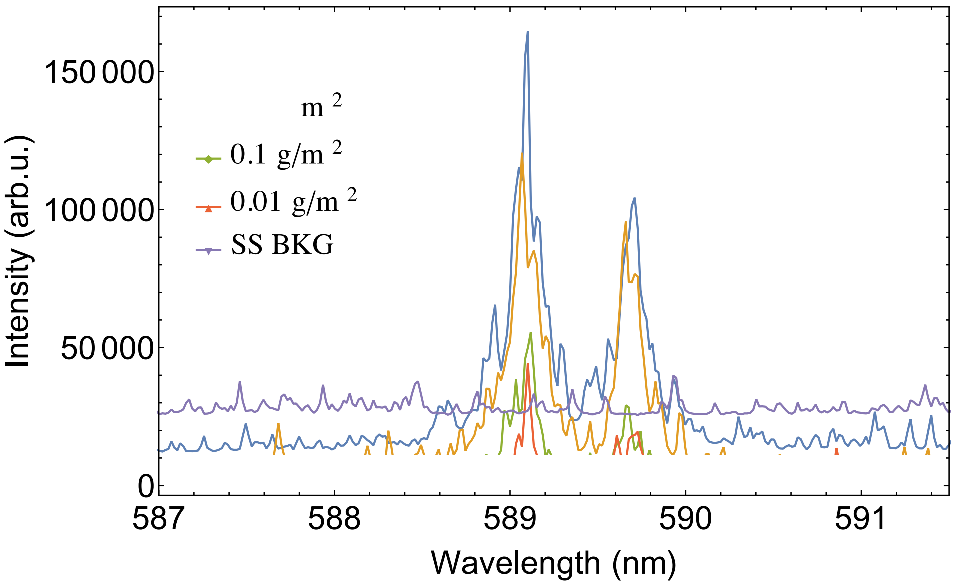


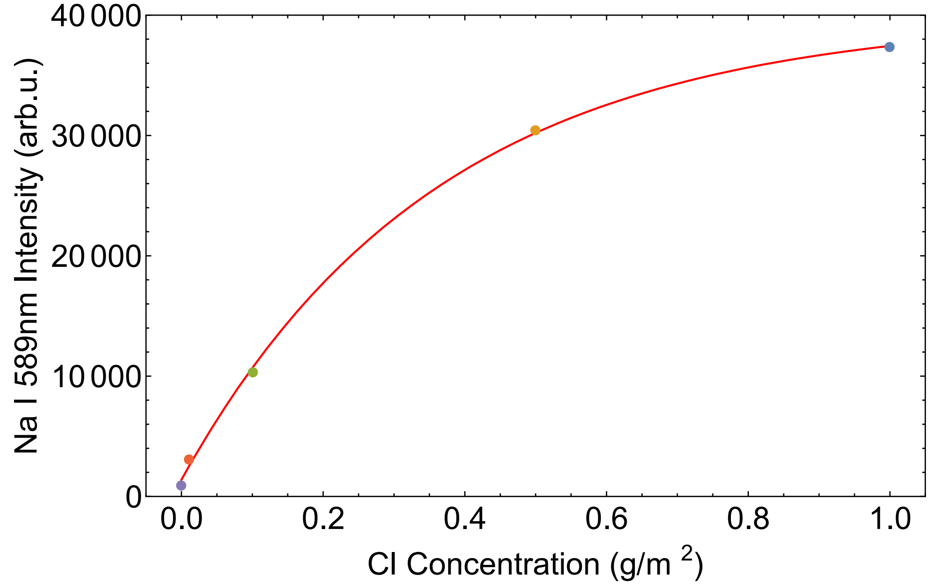
Coupling and transmission efficiency for 532-nm and 1064-nm laser pulses in the Thorlabs step-index 1-mm core diameter multimode fiber (FT1000EMT, 10 m)



Higher output energy (20 mJ) with efficiency of 60% can be transported at 1064 nm.

Surrogate measurements of chlorine via fiber delivery were successful with a threshold limit of 0.01 g/m².

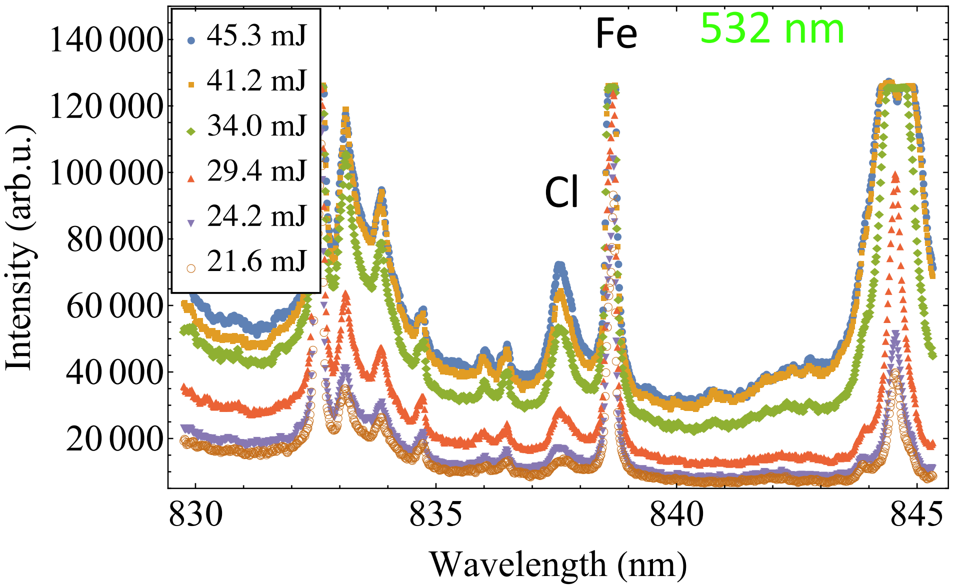


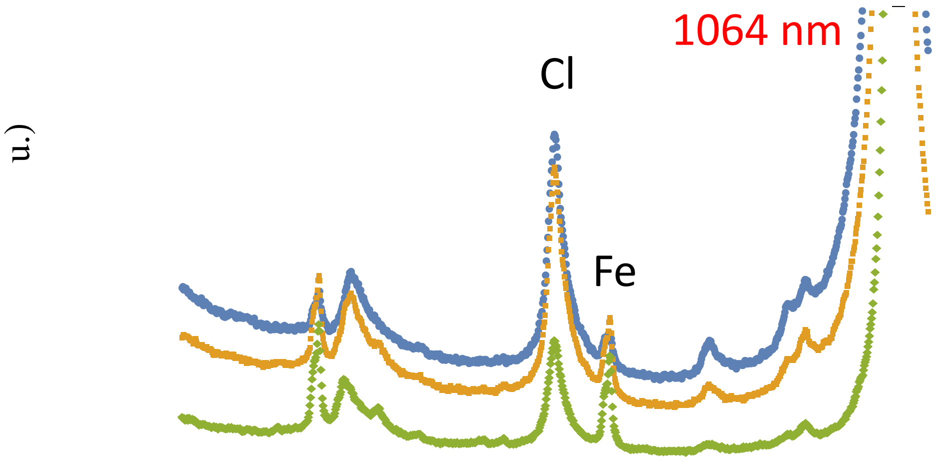


Na I emission spectrum of the standards at the chlorine concentration of 0.01-1 g/m² on stainless steel;
Dependence of Na I emission intensity at 589 nm on calculated chlorine concentration;
*Output **532 nm** laser energy of the fiber: ~**8 mJ.***

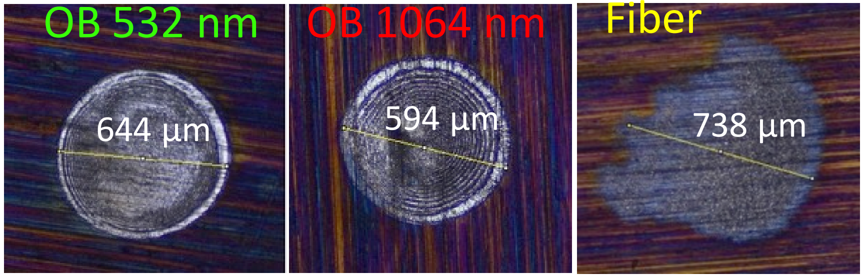
Direct chlorine detection using open-beam delivery with large spot size is in-progress.

Cl I emission spectrum of the standards with the Cl concentration of 1 g/m² on the stainless steel
Calibrated Laser energy: 21-45 mJ (left) and 18-51 mJ (right)*





The threshold for observation of Cl on stainless steel is 20-25 mJ at the output of the fiber at either 532 nm or 1064 nm.



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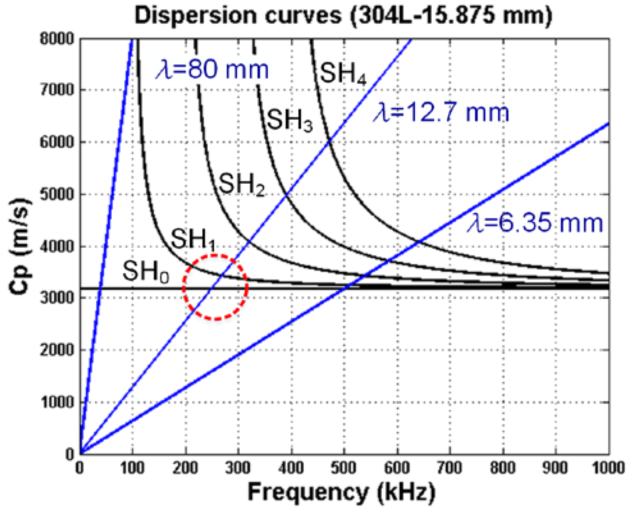
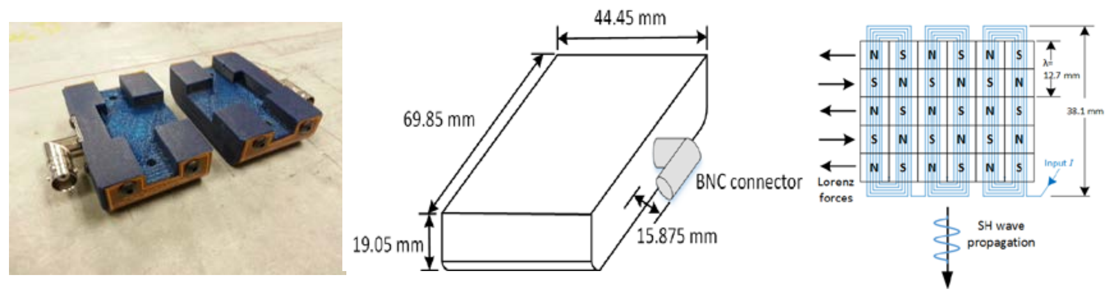
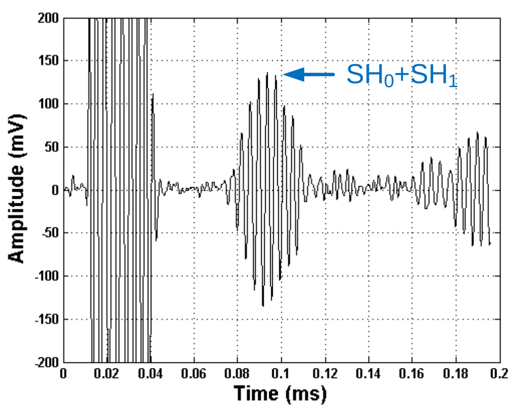
EMATs selected for Canister NDI (instead of MSTs) using SH waves and pulse-echo mode with separate send & receive transducers.

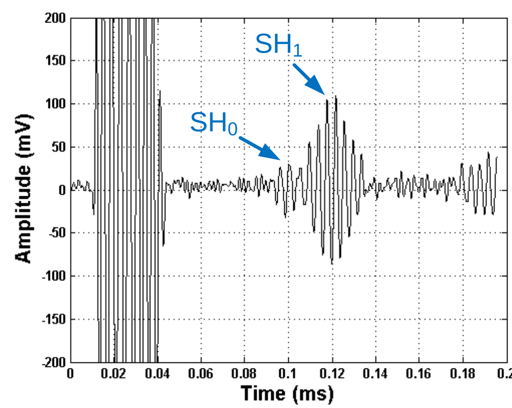




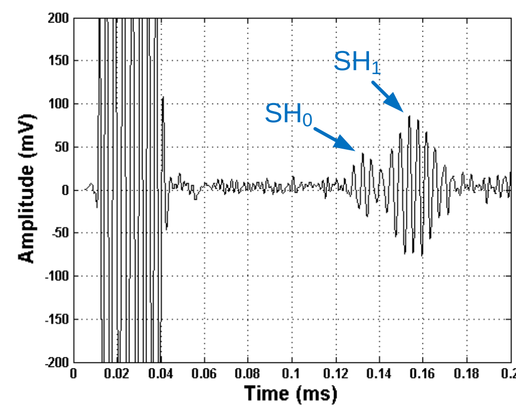
EMAT housing for magnets and electric coil



200 mm (7.87 inch)



280 mm (11.0 inch)



360 mm (14.2 inch)

Through-transmission waveforms show two modes

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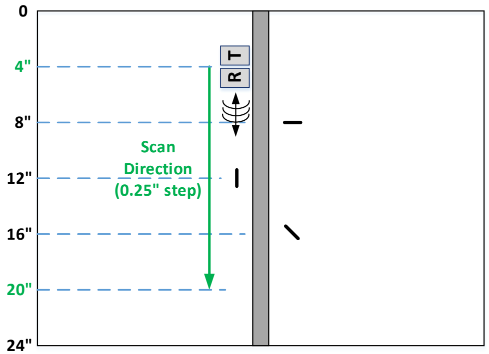
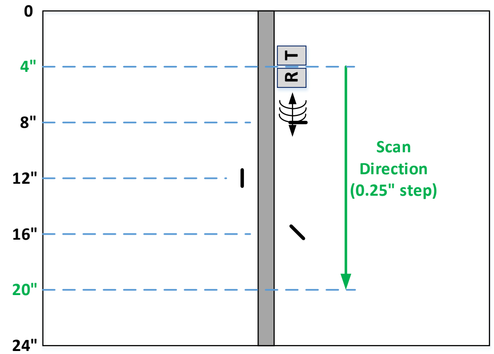
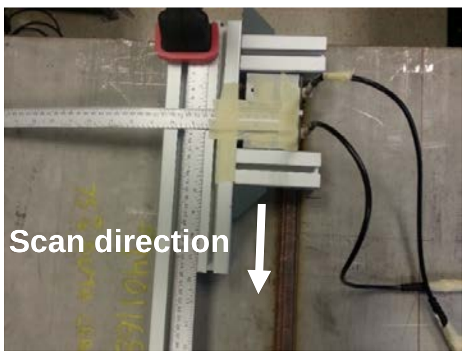
NDI of Circumferential and Bottom welds – wave vector along weld

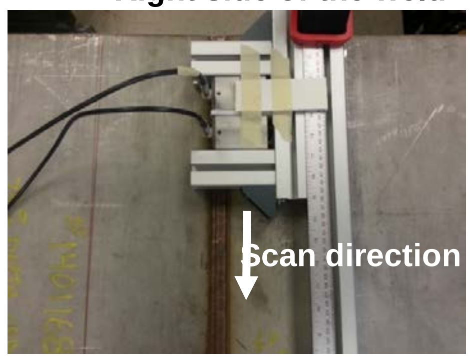


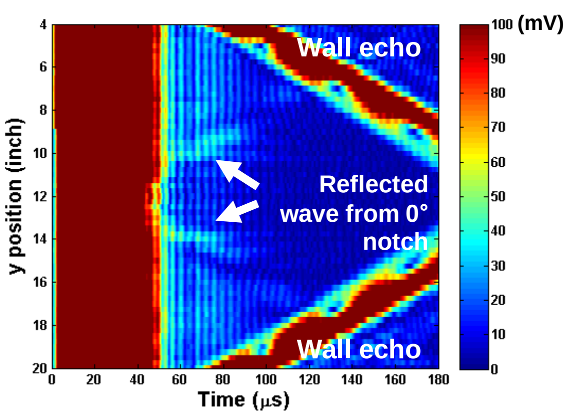


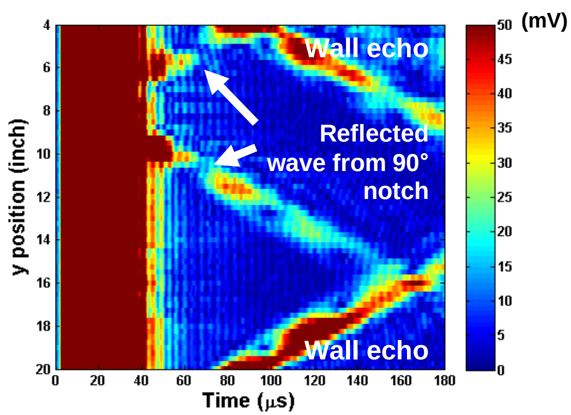
Left side of the weld

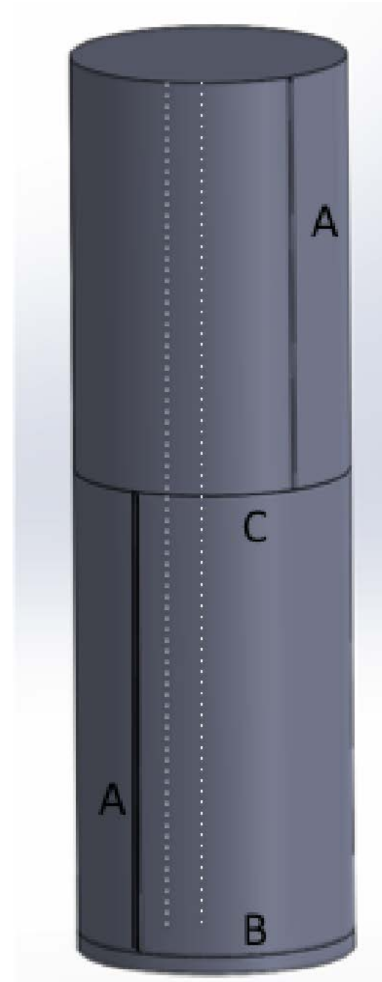


Right side of the weld









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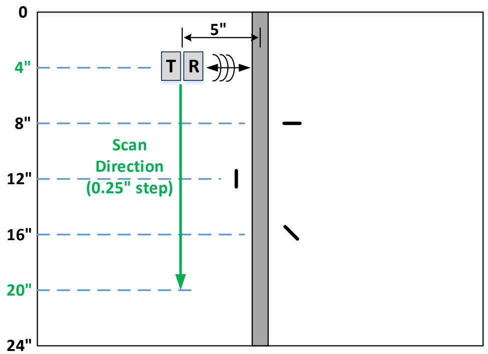
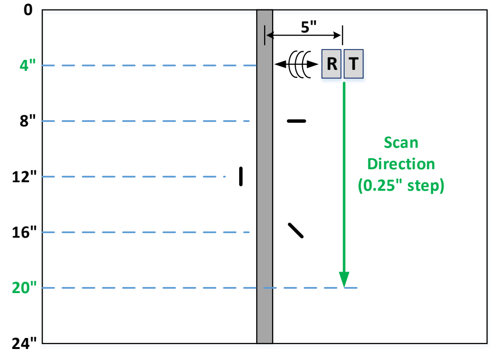
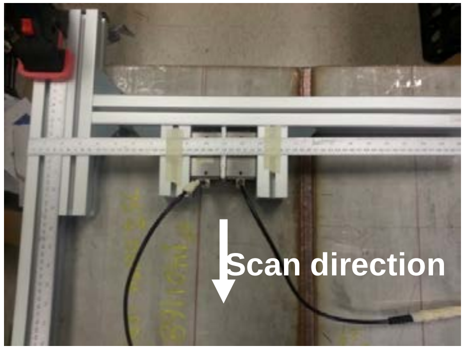
NDI of Axial welds – wave vector normal to weld and scan

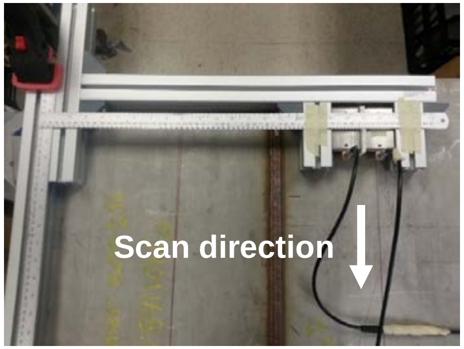


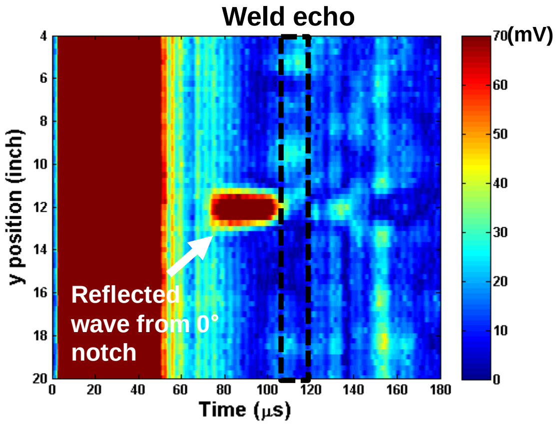


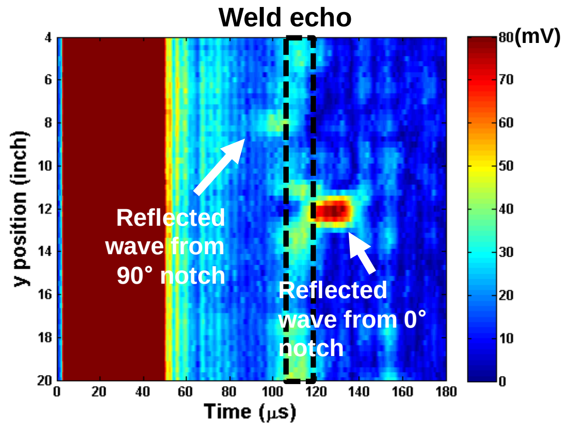
Left side of the weld

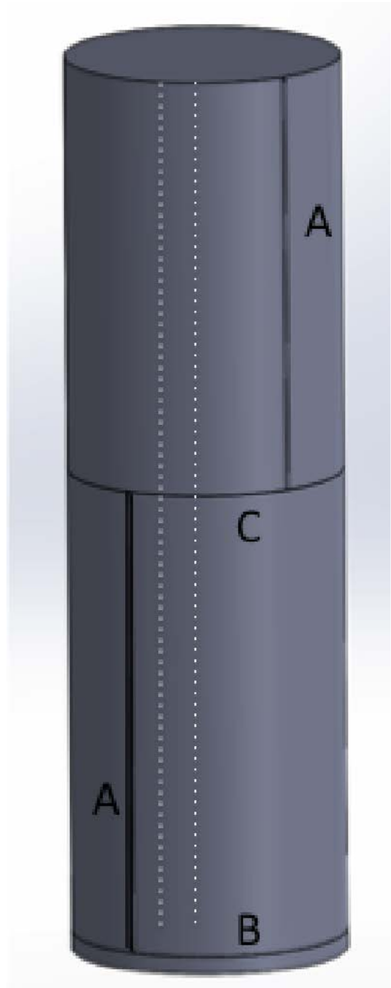


Right side of the weld



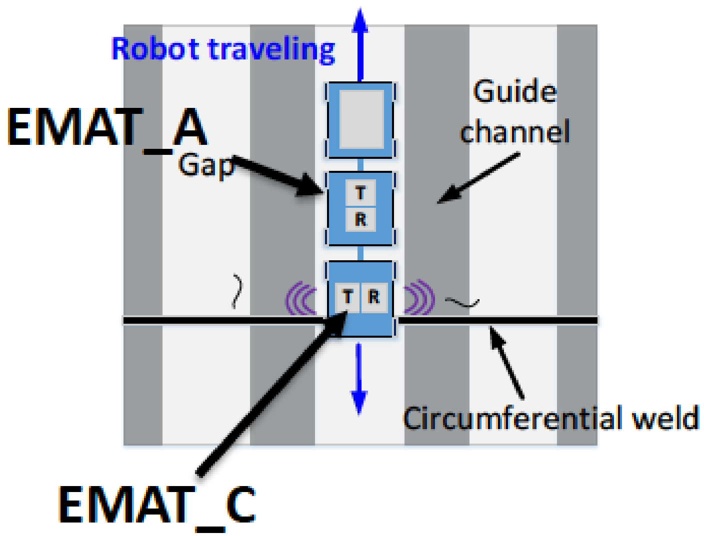




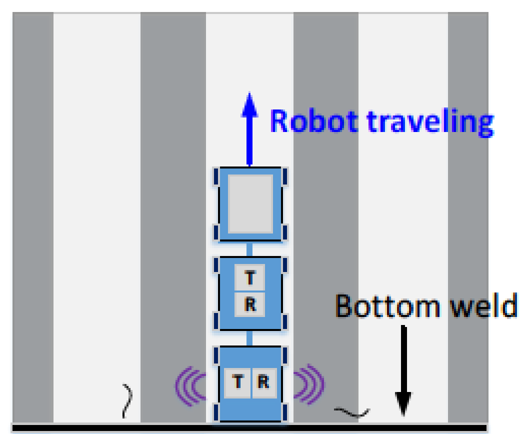


SH wave based NDI of weld HAZ using EMATs on sensor cars enables inspection of all welds.

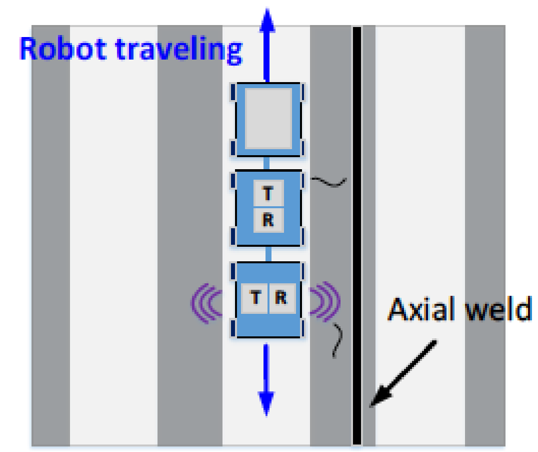
Circumferential weld inspection



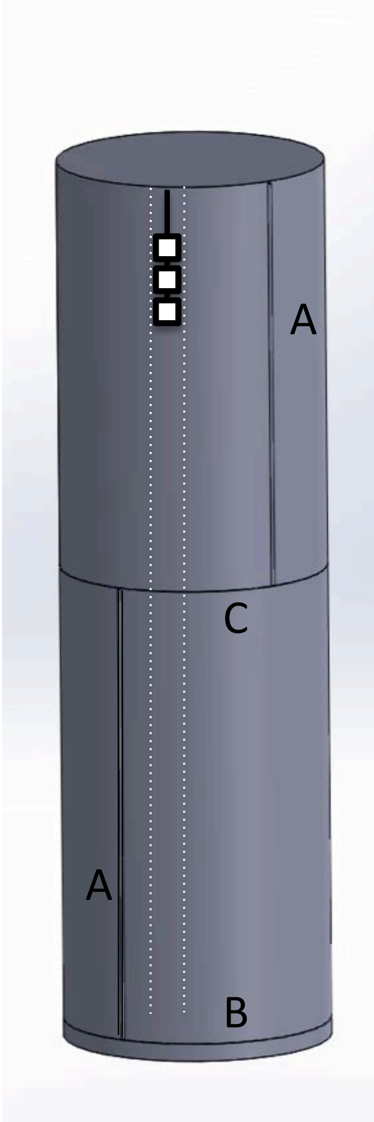
Bottom weld inspection



Axial weld inspection



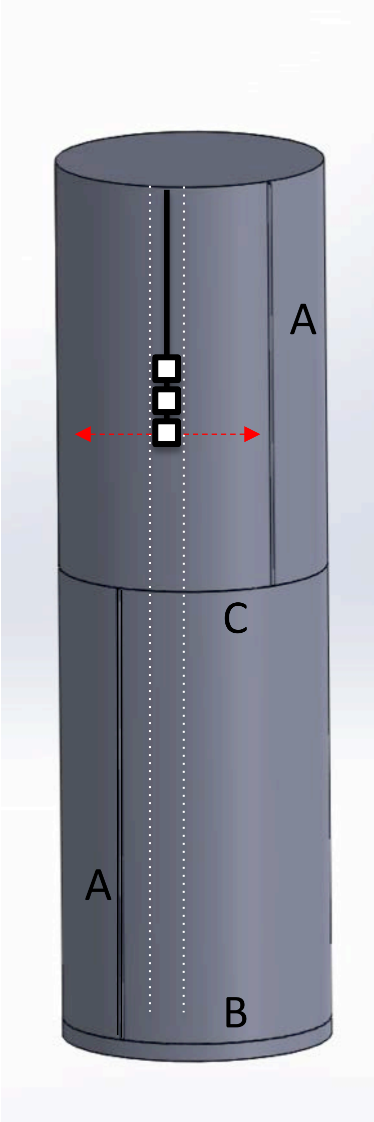
PennState



A = axial weld
B = bottom weld
C = circumferential weld

Canister NDI Methodology

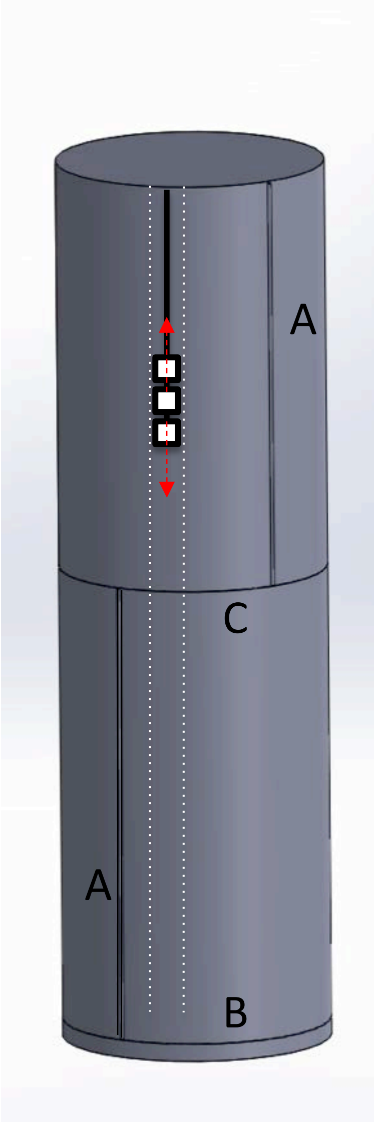
1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
B = bottom weld
C = circumferential weld

Canister NDI Methodology

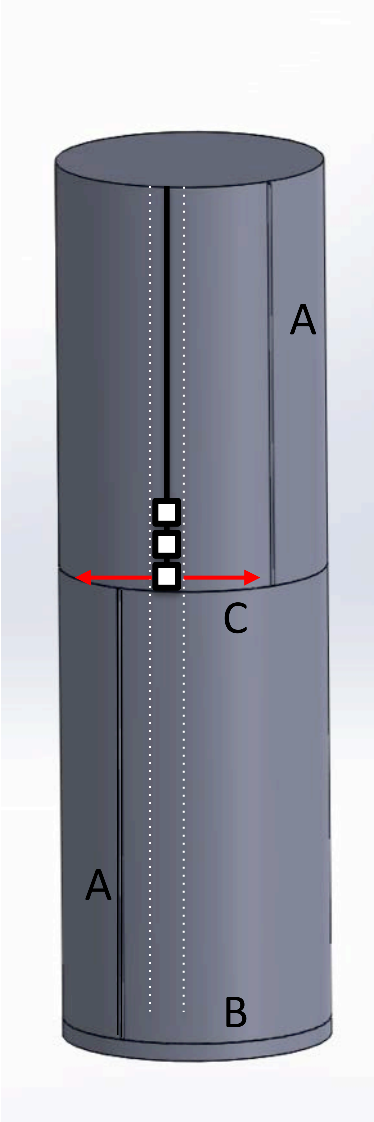
1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
B = bottom weld
C = circumferential weld

Canister NDI Methodology

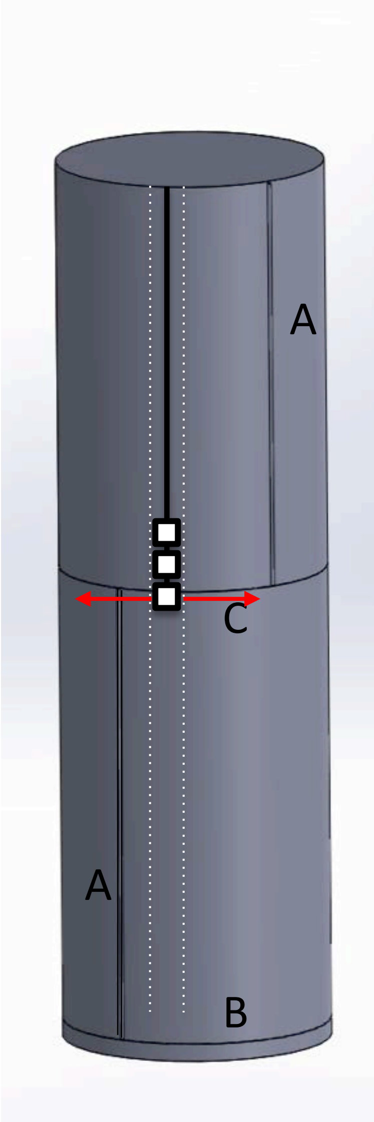
1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
B = bottom weld
C = circumferential weld

Canister NDI Methodology

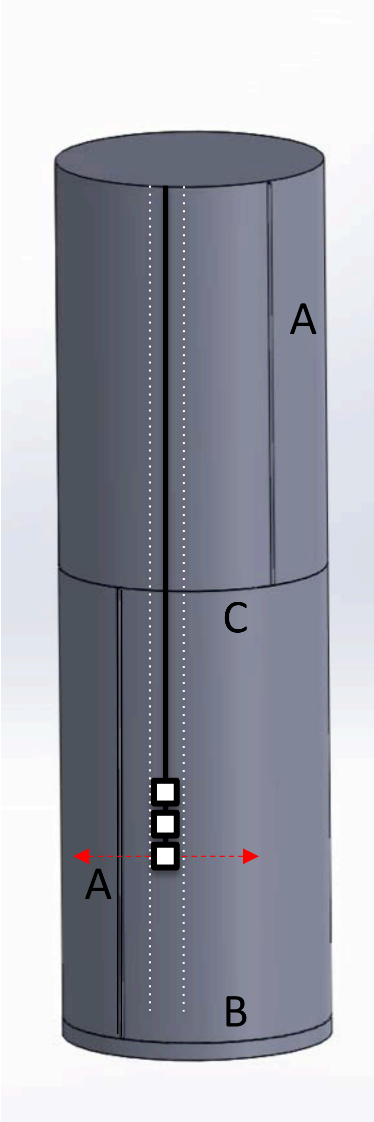
1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
B = bottom weld
C = circumferential weld

Canister NDI Methodology

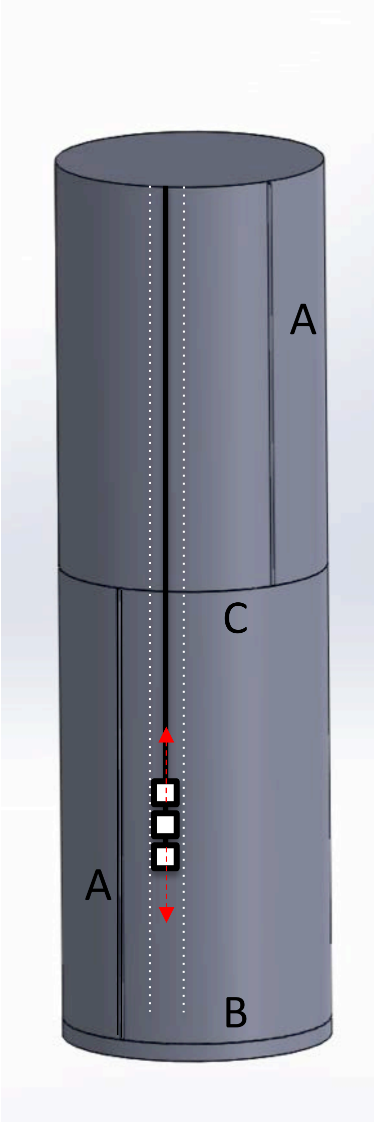
1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
B = bottom weld
C = circumferential weld

Canister NDI Methodology

1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
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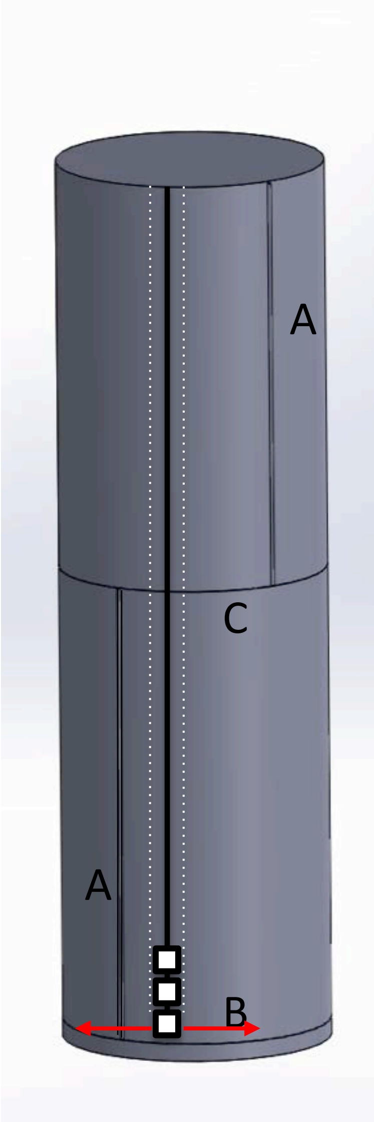
C = circumferential weld

Canister NDI Methodology

1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
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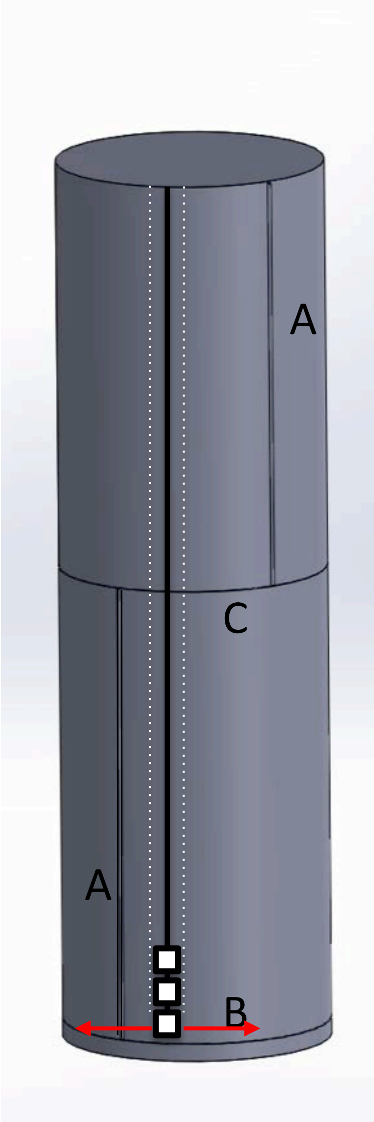
C = circumferential weld

Canister NDI Methodology

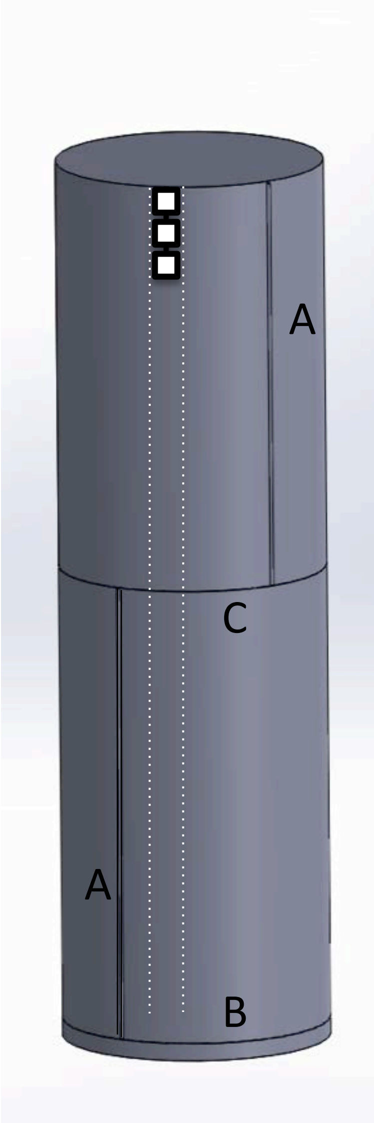
1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
B = bottom weld
C = circumferential weld

Canister NDI Methodology

1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
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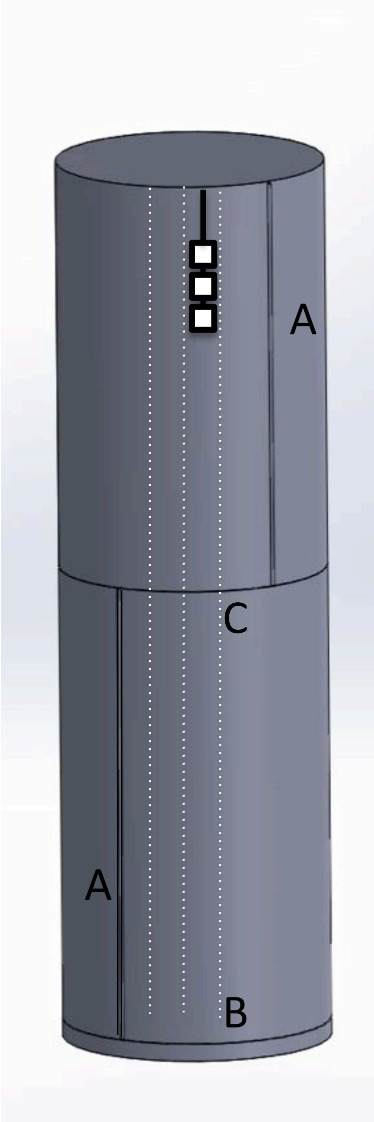
C = circumferential weld

Canister NDI Methodology

1. Launch sensor cars from canister lid into gap 1
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected



A = axial weld
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C = circumferential weld

Canister NDI Methodology

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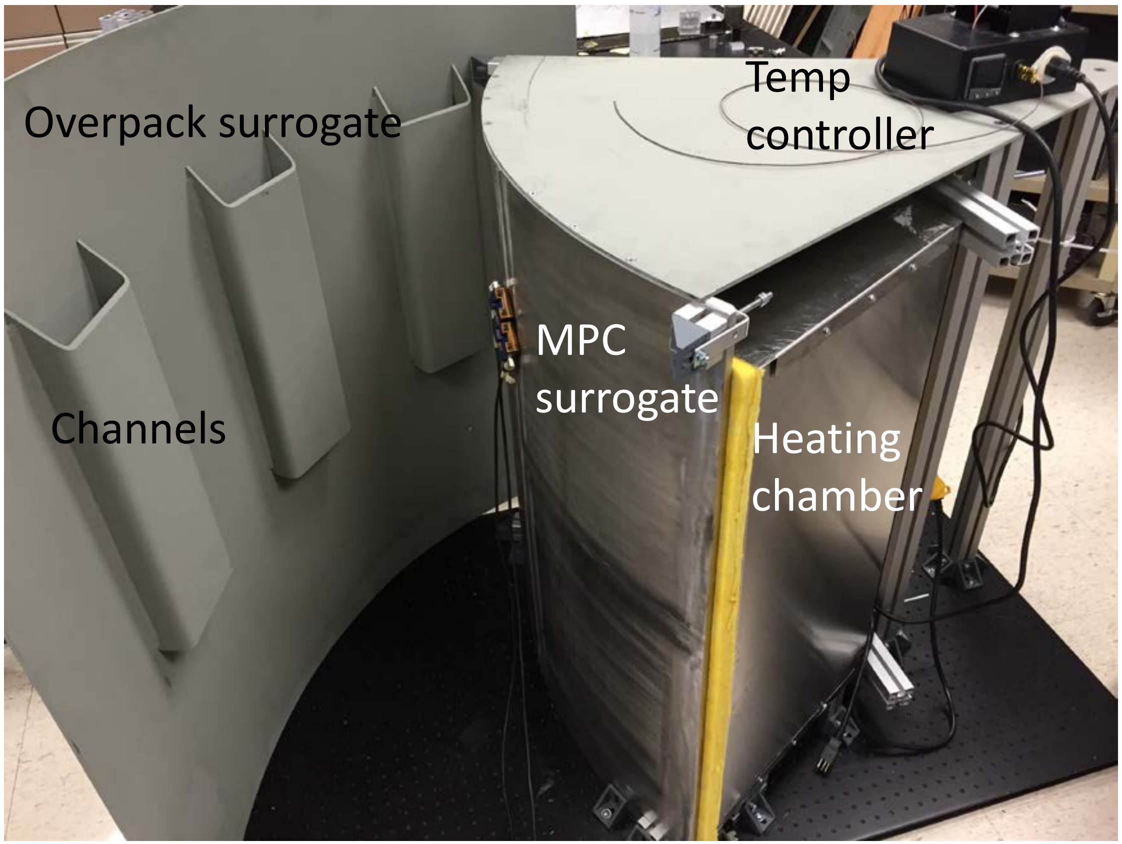
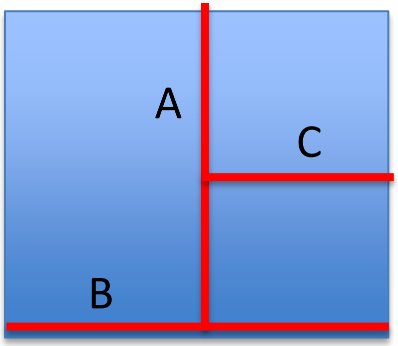
2. Stop and ping to locate welds C & A
3. Lower cars to weld C
4. Inspect HAZ above weld C while stopped
5. Inspect HAZ below weld C while stopped
6. Lower sensor cars
7. Stop and ping to locate welds B & A
8. Lower sensor cars to weld B
9. Inspect HAZ above weld B while stopped
10. If weld A is adjacent to gap 1 then inspect it while sensor cars are being raised
11. Withdraw sensor cars back onto canister lid
12. Re-position and launch sensor cars into gap 2
13. Inspect welds C and B
14. Traverse all 16 gaps in this fashion
15. Four of the 16 times the sensor cars are withdrawn the HAZ of a weld A will be inspected

HI-STORM 100S mockup has been fabricated and setup in the Penn State lab.



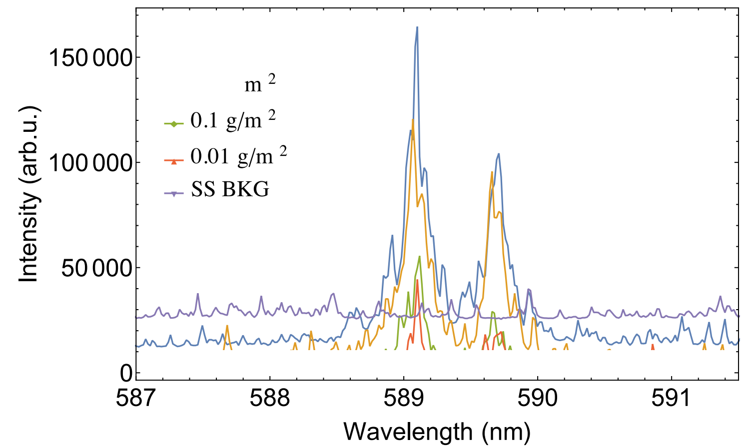
Features

- Authentic welds: axial, circumferential, bottom
- Weld triple point
- Realistic geometric
- Variable non-concentricity
- Elevated temperatures
- Robot delivered sensing



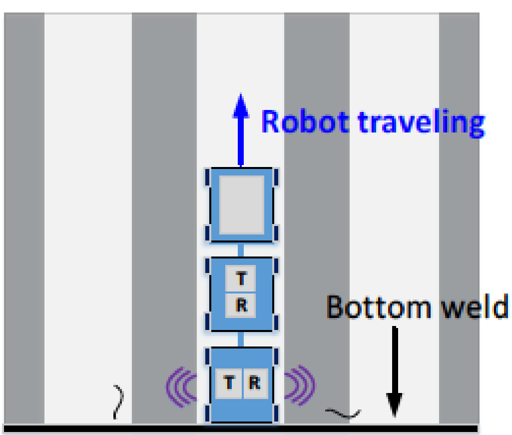
In conclusion, multi-sensor inspection and robotic system development for dry storage casks is progressing well.

Robotic delivery for HI-STORM 100S: command center, delivery arm, sensor cars



Fiber-delivered LIBS measurements of Na detection limit of 0.005 g/m^2

Bottom weld inspection



SH wave based crack detection in HAZ using noncontact EMATs

THANKS!

QUESTIONS?

PennState

Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks

U.S. DEPARTMENT OF ENERGY
Nuclear Energy

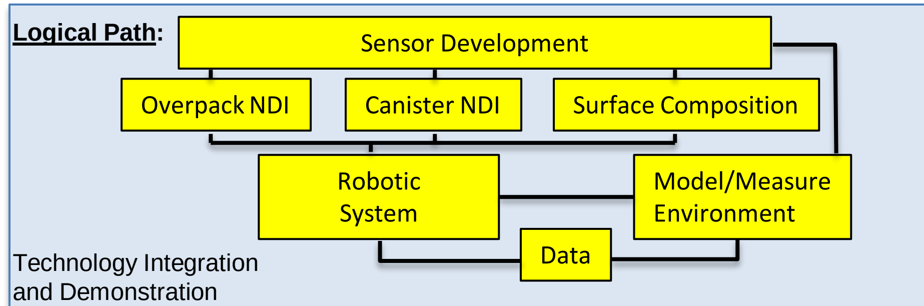
OVERVIEW

Purpose: Develop sensors, monitoring methodologies, and a delivery system to ensure safe dry storage of used nuclear fuel. A robotic device and new sensing systems are proposed to monitor for conditions conducive to stress corrosion cracking and inspect for cracks within dry storage casks. The multi-sensor inspection robotic system will be designed to access the canister surface through the ventilation system of the overpack.

Objectives:. The robotic system will enable a broad range of measurements to be made through a common, multi-sensor interface for characterization and inspection methods, including: surface sampling via laser induced breakdown spectroscopy (LIBS) delivered by optical fiber, nondestructive inspection using linear and nonlinear ultrasonics, ultrasonic surface waves for the concrete overpack, and environmental sensing – temperature, relative humidity, ionizing radiation.

IMPACT

Logical Path:

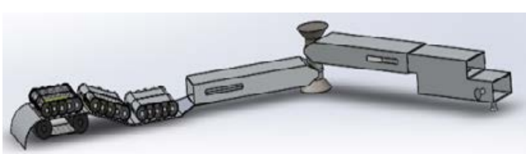


Outcomes: Robotic system to traverse the dry storage casks ventilation system with sensors to measure temperature, radiation, surface composition, and damage. LIBS and EMAT sensors to characterize surface composition (chlorides) and cracking (especially stress corrosion cracks). System to be demonstrated on industry-provided mockup of Holtec HI-STORM storage cask.

DETAILS

Principal Investigator: Cliff Lissenden
Institution: Penn State
Collaborators: UIUC, USC, ORNL, PNNL, EPRI, Holtec
Duration: 36 months
Total Funding Level: $3,000,000
TPOC: Steve Marschman
Federal Manager: JC de la Garza
Workscope: IRP-FC-1

PICSNE Workpackage #:
NU-14-PA-PSU_-0401-01
Project 14-7356
DE-NE0008266



Delivery arm concept to launch sensor cars from lid into gap between guide channels in cask

RESULTS

Results and Accomplishments: Milestone M1 LIBS salt detection and:
H Song and JS Popovics, 2016, "Hidden disbond detection in spent nuclear fuel storage systems using air-coupled ultrasonics," SPIE proceedings 9803-111.

Na I emission spectrum from sea salt (0.01-1 g/m^2 Cl) on stainless steel using 10m-fiber coupled LIBS setup with 8 mJ laser energy detects salt on stainless steel.