U.S. DEPARTMENT OF ENERGY

Nuclear Energy

# IRP: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks: Functions and Requirements PSU, UIUC, USC


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NEUP Nuclear Energy University Programs

U.S. Department of Energy

UFD Meeting, 9-11 June 2015, Las Vegas, NV

# IRP: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks: Functions and Requirements
# PSU, UIUC, USC

- **Overall Goal: develop and demonstrate robotic multi-sensor inspection systems for monitoring dry cask storage canister (detection of cracks and detection of SCC-inducing salts) and concrete overpack (microcracks)**

Hope Creek ISFSI

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- **Canister Types: sensing systems for welded stainless canisters, delivery system for MPC/HI-STORM, steel-clad and exposed concrete overpack**
- **Access: LIBS via optical fiber and multiple EMAT heads will be delivered via the HI-STORM ventilation system**
- **Size Constraints: robotic multi-sensor system will navigate to and operate in gap between full-length guide channels in HI-STORM overpack**
- **Operational Implementation: robotic multi-sensor system will be operated from outside the cask and follow ALARA**

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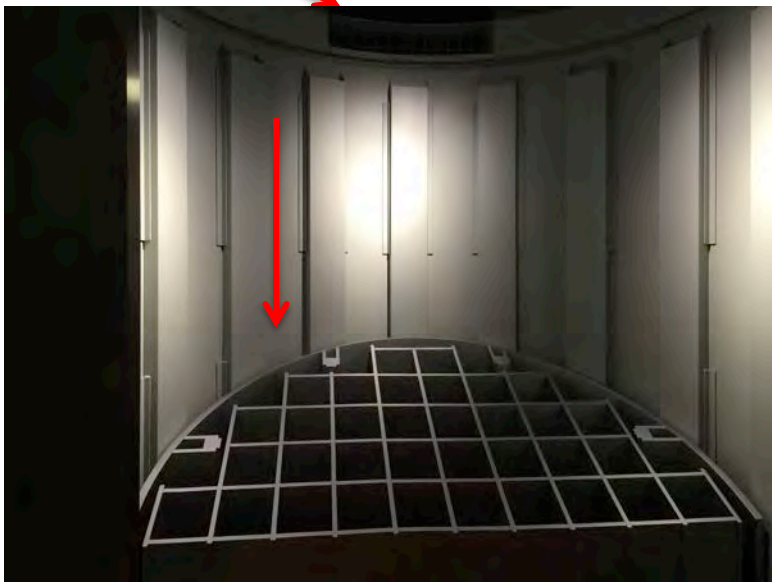
**HI-STORM**

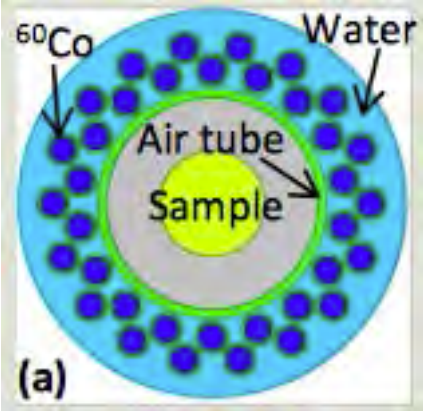
**Access point**



**travel down plenum between guide channels**

# IRP: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks: Functions and Requirements PSU, UIUC, USC

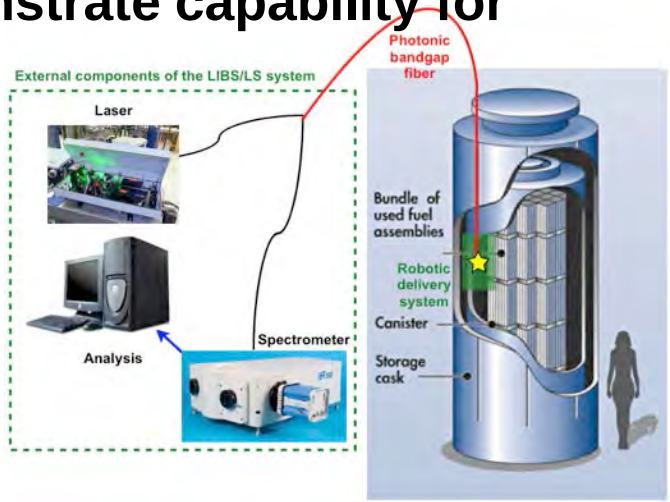
- **Environmental Requirements: the electronics and materials of the sensing equipment will survive 250 F (with an ultimate goal of 350 F) with a gamma dose of 2.7 x $10^4$ Rad/h (270 Gy/h) for at least a few hours; the time to perform partial and full monitoring of the welds will be estimated**
- **Environmental Requirements: modeling effort will use COBRA-SFS and MCNP6.1 to calculate temperature and radiation field at various locations inside and on the cask surface**
- **Environmental Requirements: the robotic system will be designed to not damage the cask surfaces and be retrievable with a tether**
- **Material Compatibility: organic materials, cobalt, and Teflon will be avoided**




Gamma-ray irradiation at Penn State RSEC

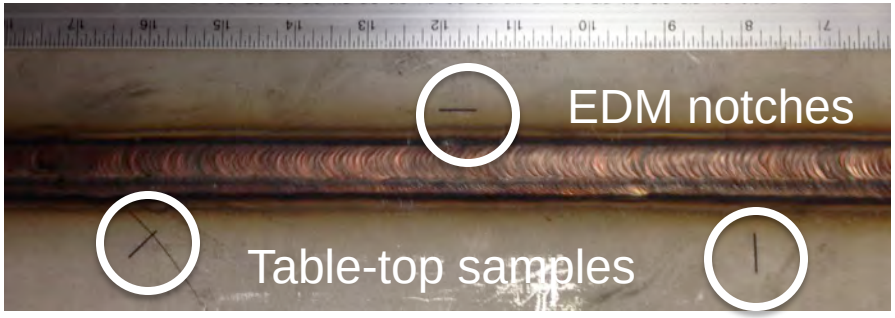
# IRP: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks: Functions and Requirements PSU, UIUC, USC

- **Localization: the robotic system will be able to trace its position to within 2” (50 mm)**
- **Measurements: LIBS Detection of deposited salts; demonstrate ability to detect 0.05-10 g/m$^2$ of NaCl deposited on stainless steel; quantitative benchmarking will be performed and detection limits explored**
- **Measurements: ultrasound detection of cracks in canister; arbitrarily oriented semi-elliptical cracks 0.21x0.42” (5x10 mm); start with EDM notches and later demonstrate capability for realistic stress corrosion cracks**
- **Measurements: noncontact ultrasound monitoring of exposed concrete overpack for microcracking; steel-clad concrete will also be inspected for voids and major disbonds**



# IRP: Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks: Functions and Requirements
# PSU, UIUC, USC

- **Measurements: radiation detection and temperature measurement for calibration of the models will be performed as part of the multi-sensor robotic system**
- **Data Acquisition and Management: DAQ system located outside the cask will acquire, process, and fuse data from the sensing systems; open file formats will facilitate collaboration in analysis of results**
- **Validation: systems will be demonstrated first on table-top experiments and later tried on partial and full mockups; the sensitivity of the robotic and sensing systems both to radiation and to thermal/humidity conditions will be demonstrated separately**
- **Validation: reproducibility of results will be demonstrated**



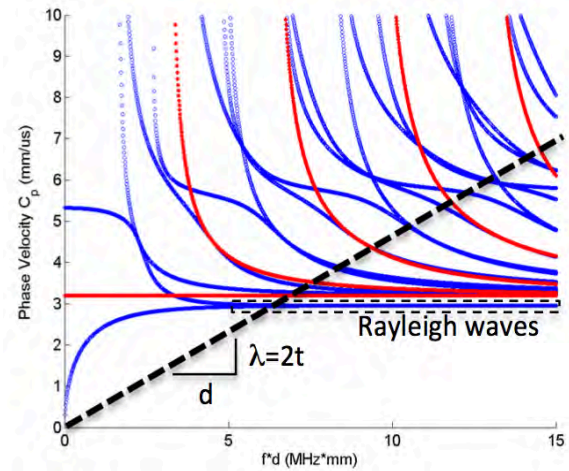
# Canister NDI

Melody Strayer, Chad Lani, Hwanjeong Cho, Sungho Choi, Cliff Lissenden

Matt Lindsay, Owen Malinowski, Jason Van Velsor

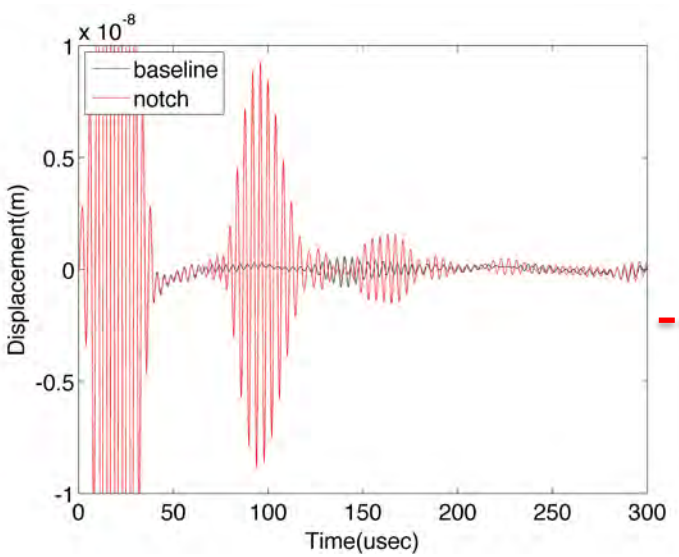
# Guided waves (SH type) provide capabilities for detecting stress corrosion cracks in HAZ of weld

- Guided waves have proven capabilities (Rose, 1999 & 2014)
  - ✓ Detecting defects in plate, pipes ,etc
  - ✓ Applicable for structures with limited accessibility
- FE simulations show utility for detecting cracks in HAZ




**SCC:**

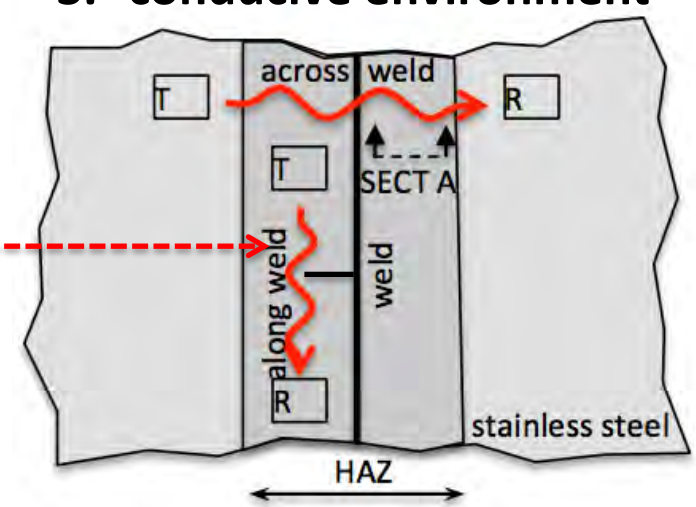
1. **susceptibility**
2. **tensile stress**
3. **conducive environment**



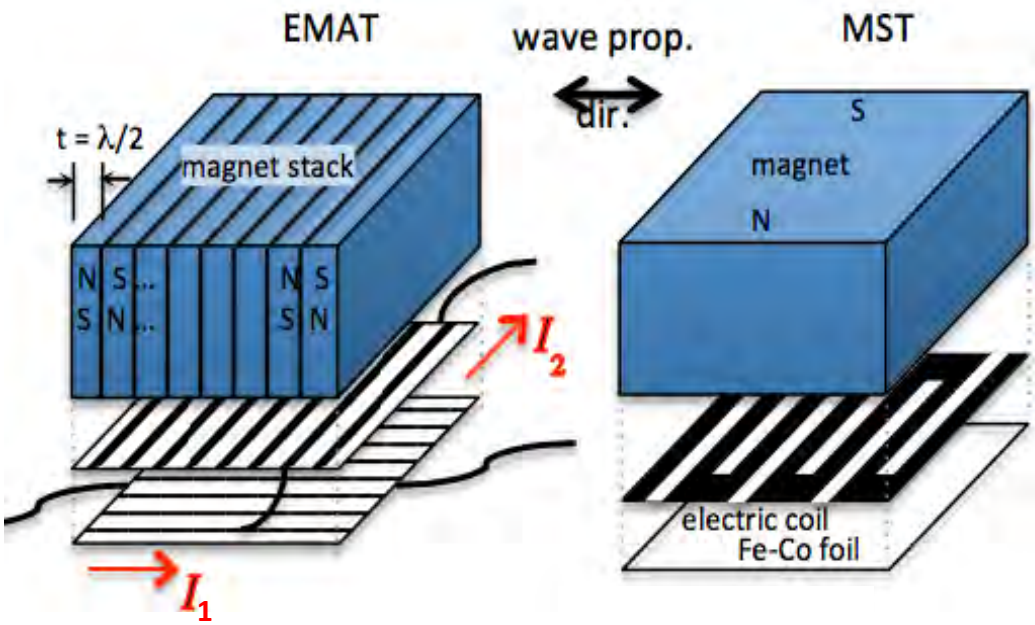

**Wave Paths:**

1. **along weld**
2. **across weld**
3. **oblique**

Pulse-Echo



# Compact EMAT (and MST) transducers are being developed for robotic delivery in harsh environment

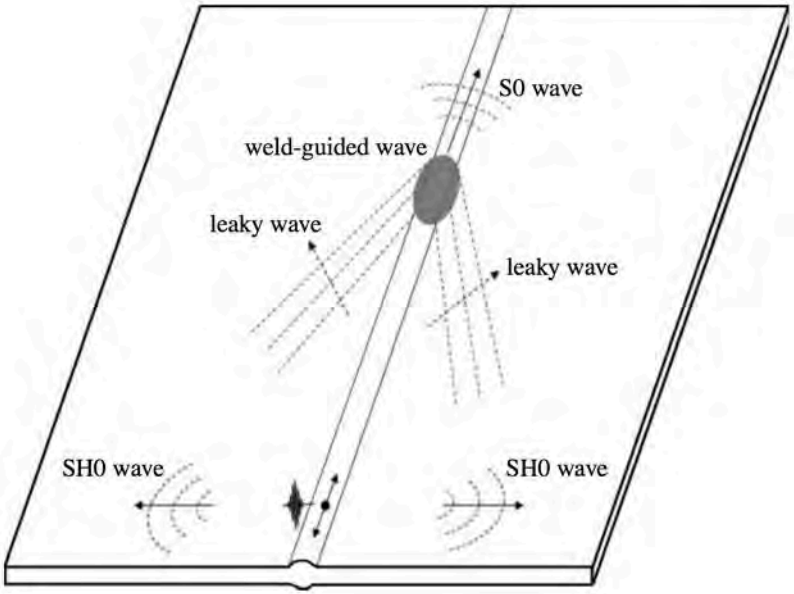


**EMATs: need to be more compact**

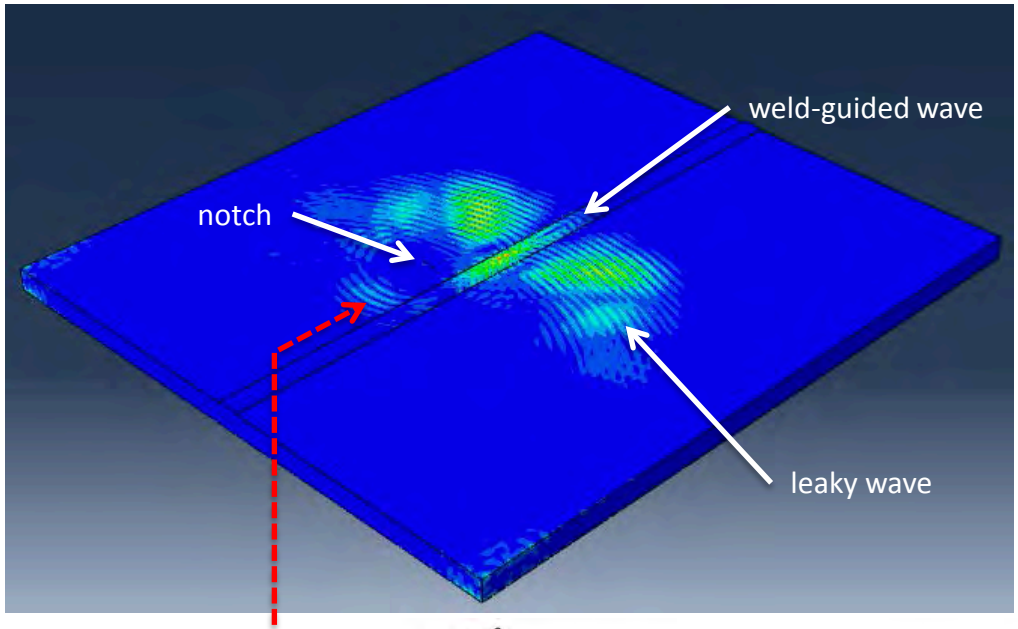
- EMAT and MST are under consideration
  - ✓ Neither need couplant – applicable for high-temp.
  - ✓ Will make selection based on SNR, Sensitivity, etc

- Prototype compact EMAT transducers are under lab-scale functional assessments
  - ✓ Tailored for high temperature / high gamma radiant application
  - ✓ Center frequency is at 0.25 MHz, polarized for shear horizontal waves

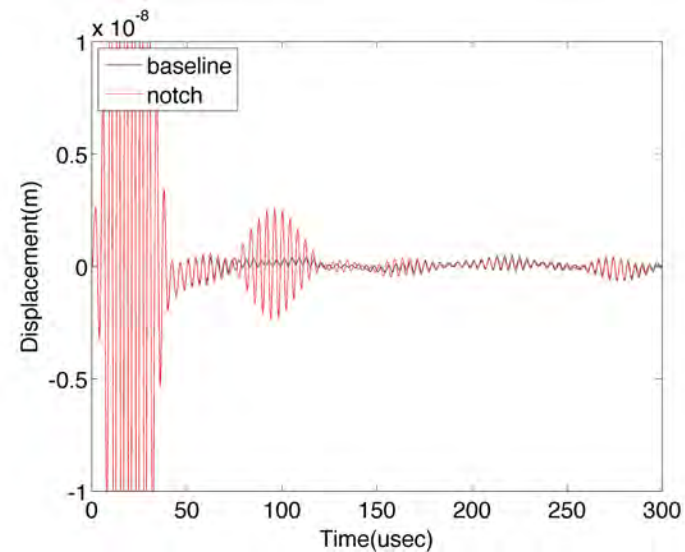
# “Weld-guided wave” shows potential for detecting cracks in weld HAZ




From : Fan and Lowe (2009)



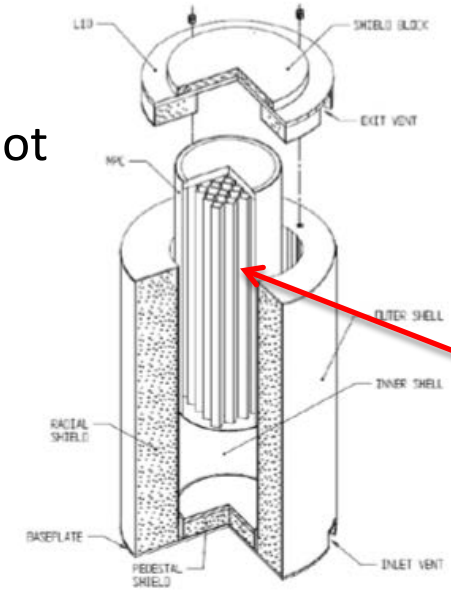

Pulse-Echo



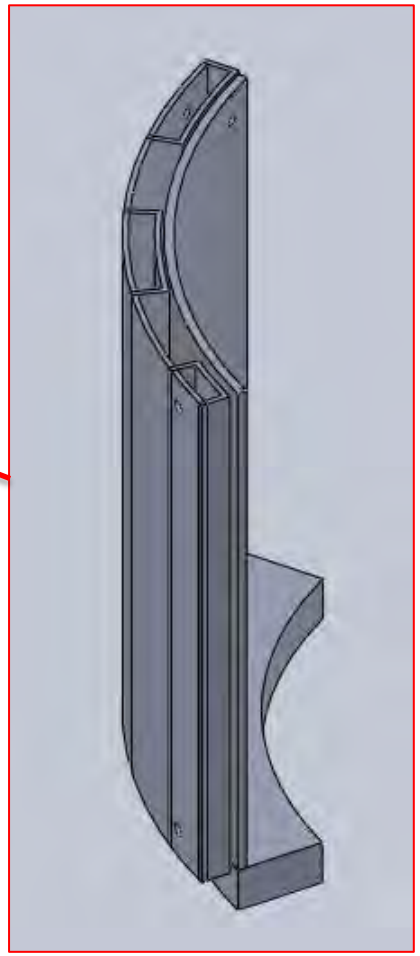

- “Shear weld-guided wave” exist in weld (Fan and Lowe, 2009)
- FE simulations show great potential of weld-guided wave for detecting cracks in HAZ as well as weld

# A lab-scale mock-up of HI-STORM 100 is under development

- Realistic lab-scale mock-up will serve as a test bed for robot/sensing systems
  - ✓ Delivery/retrievability tests for robot
  - ✓ EMAT measurements
  - ✓ Chlorine concentration measurements test
  - ✓ Temperature measurement
- Will be equipped with a heating system to evaluate robustness of the delivery/sensing systems




Holtec HI-STORM (Meyer et al, 2013)



Mock-up design (in progress)

# IRP Progress Update: Surface Characterization and T&R Measurements

**Lu Chen, Brendan Sporer,**
**Ishak Johnson, Igor Jovanovic**

**The Pennsylvania State University**
**www.mne.psu.edu/IJ**

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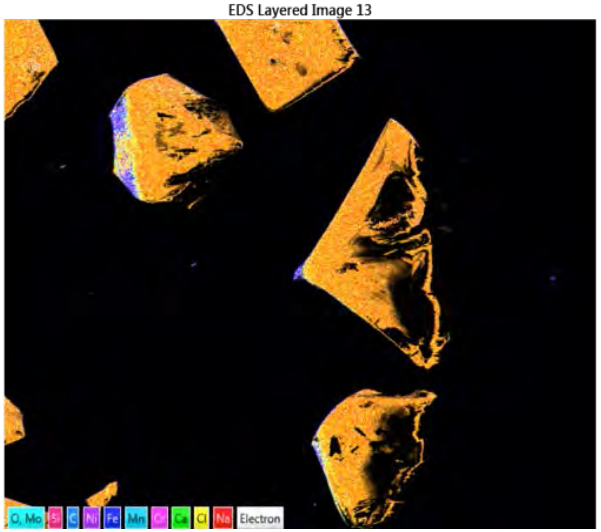
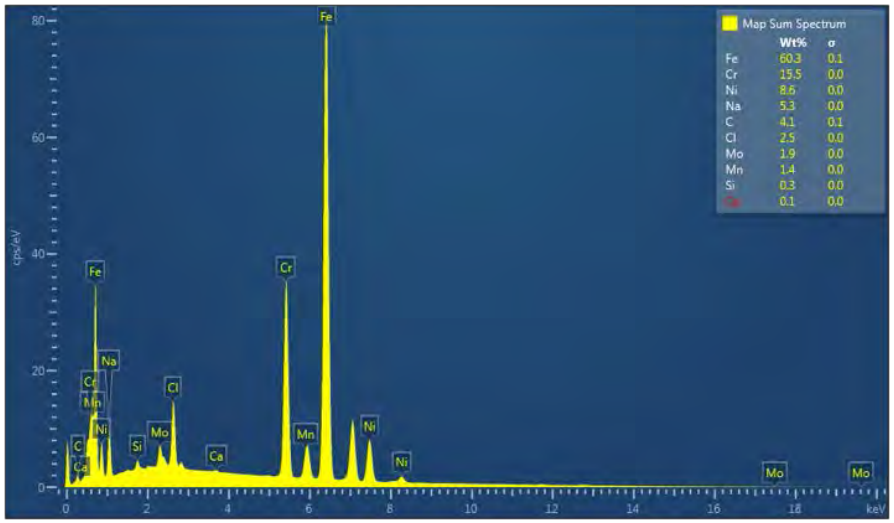
**June 1, 2015**

# Elemental composition analysis

- **Sample coupons are created from NaCl solution dropping on top of stainless steel coupon**
- **Solution molarities are between 0.01 M to 5M corresponding to estimated 0.6 g/m$^2$ to 300 g/m$^2$**
- **Samples are mapped using EDS/SEM technique**
- **Highly nonuniform distribution of deposits suggests that a scanning measurement will be required to draw conclusions on salt areal concentration**

**Figure: Droplet of solution on SS coupon**




**Figures: EDS scan(left) and spectrum (right) of residual 0.01 M NaCl solution on stainless steel coupon**

# Elemental composition analysis

- **LIBS set up has been adapted for the experiment**
- **LabView software for LIBS measurements has been adapted**

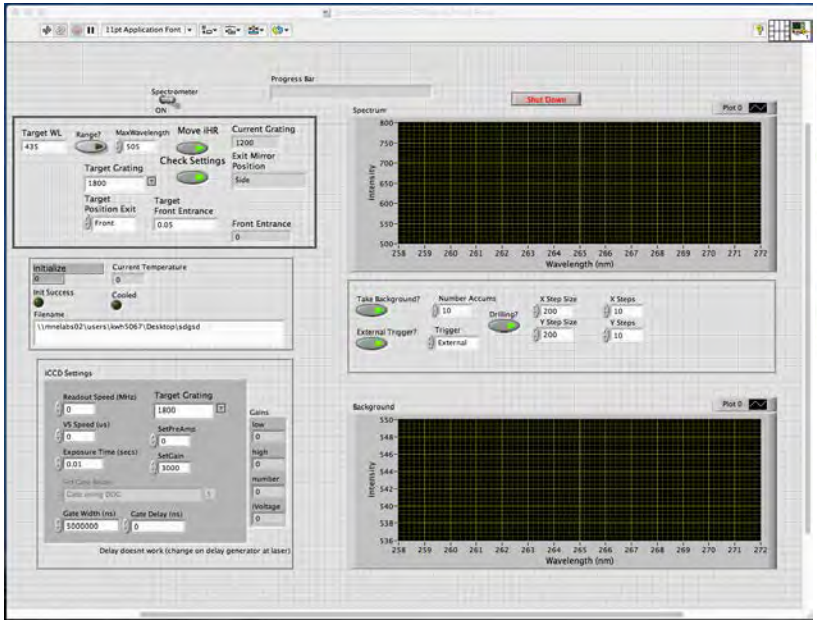
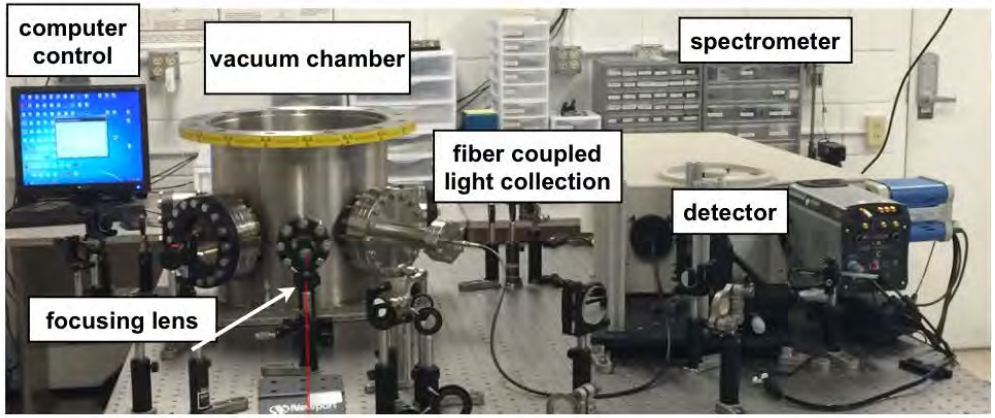



**Figure: LabView command interface**




**Loan from LANL: Echelle spectrometer Oct 2014–**

**Figure: Detail of current free-space coupling for spectral analysis**

# Temperature and radiation sensing

- **Radiation sensing:**
  - **Canberra RGR-100 detector purchased**
  - **Preliminary experiments examine the detector using Co-60 source**
  - **Additional vendors contacted regarding alternative detectors**
- **Thermocouple comparisons are in progress**

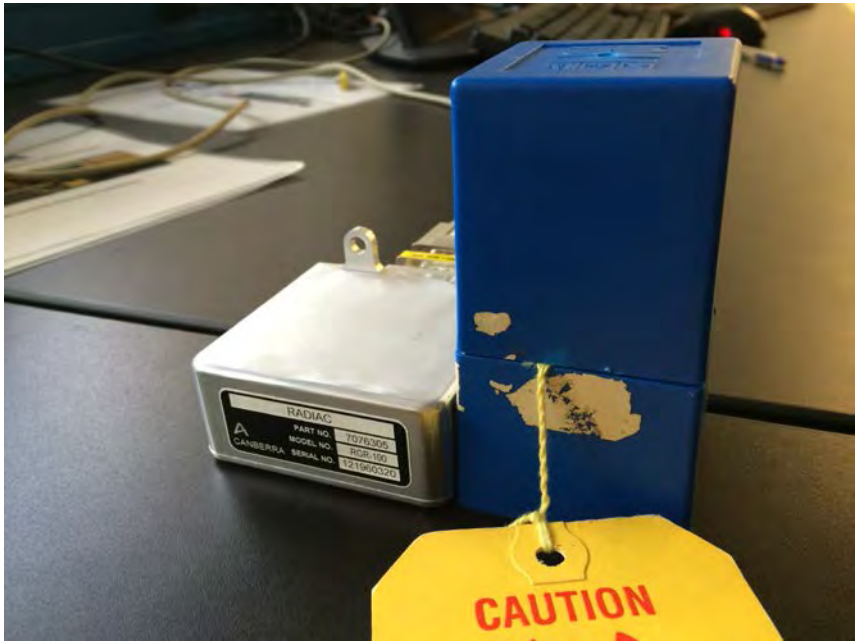



**Figure: Testing detector with Co-60 source**

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 0000 | 00:19:43 | +23.5 | 0014 | A:** | 6.65uG/h | .003uG | .003uG | 6.65uG/h |
| 0001 | 00:19:47 | +23.4 | 0016 | A:** | 7.75uG/h | .008uG | .008uG | 7.75uG/h |
| 0002 | 00:19:49 | +23.4 | 0013 | A:** | 6.91uG/h | .011uG | .011uG | 6.07uG/h |
| 0003 | 00:19:51 | +23.4 | 0008 | A:** | 5.31uG/h | .013uG | .013uG | 3.71uG/h |
| 0004 | 00:19:53 | +23.4 | 0014 | A:** | 5.62uG/h | .017uG | .017uG | 6.54uG/h |
| 0005 | 00:19:55 | +23.4 | 0012 | A:** | 5.61uG/h | .020uG | .020uG | 5.59uG/h |
| 0006 | 00:19:57 | +23.4 | 0010 | A:** | 5.37uG/h | .022uG | .022uG | 4.65uG/h |
| 0007 | 00:19:59 | +23.4 | 0021 | A:** | 6.50uG/h | .028uG | .028uG | 9.89uG/h |
| 0008 | 00:20:01 | +23.4 | 0018 | A:** | 6.74uG/h | .032uG | .032uG | 8.45uG/h |
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**Figure: Data template of RGR-100 detector**

# IRP Progress Update: Robotic Delivery System

**Bobby Leary, Karl Reichard, Sean Brennan**

**The Pennsylvania State University**

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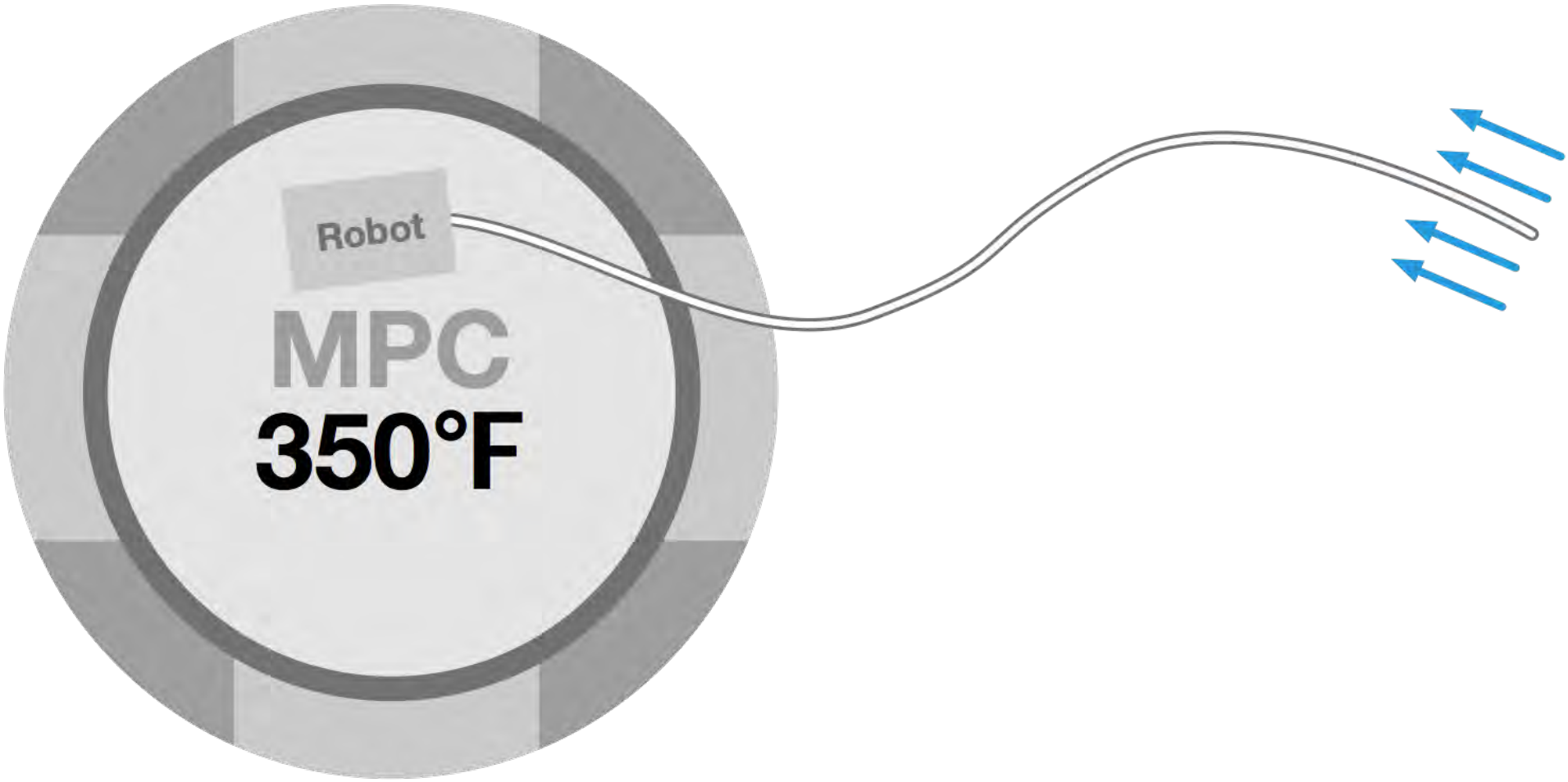
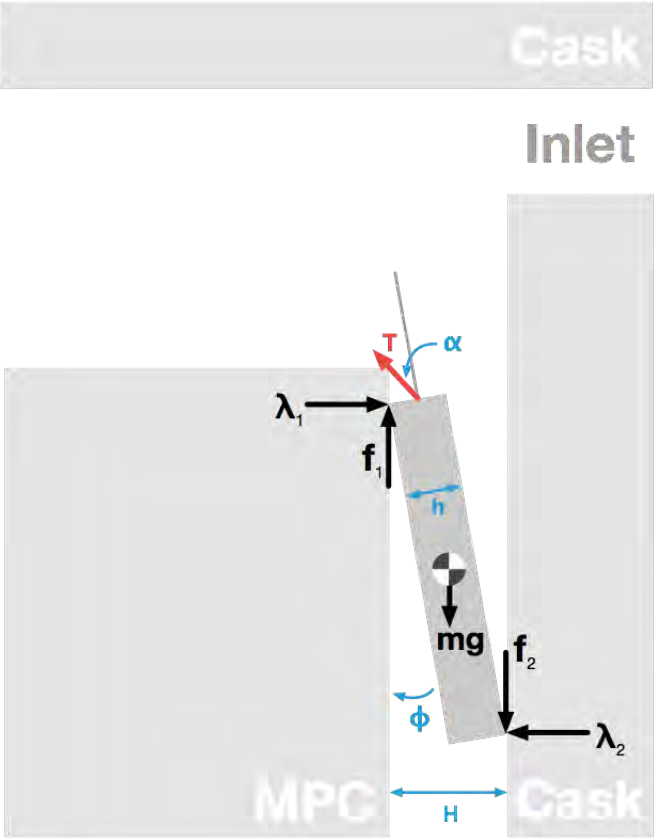
**June 1, 2015**

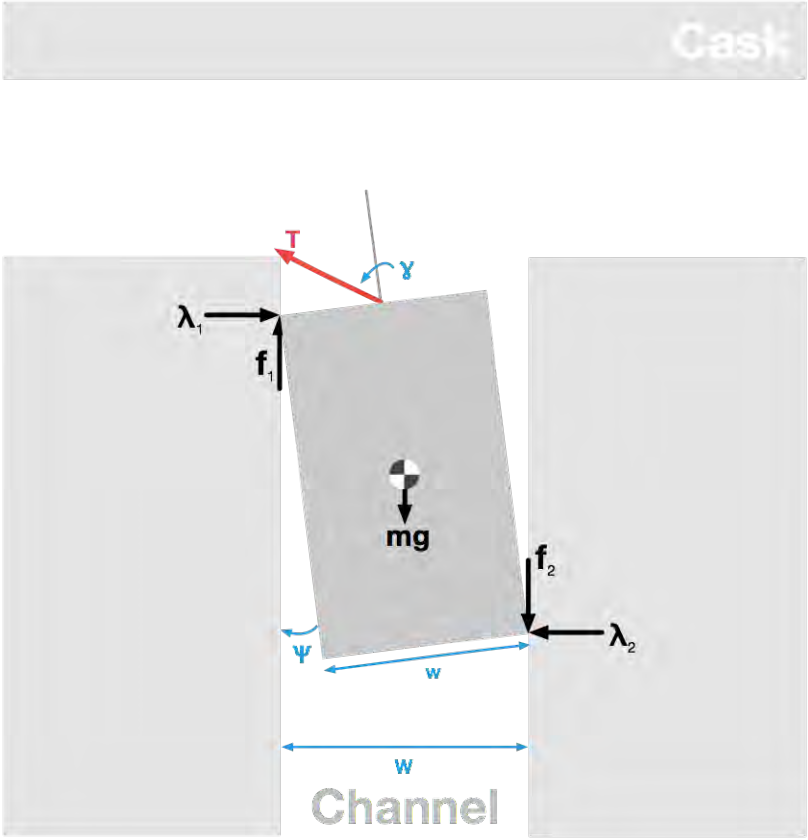
The maximum temperature within the cask is 350°F, but most off-the-shelf robotics supplies can only withstand temperatures up to 140°F.



In the event of actuator failure, passive removal can result in wedging or jamming of the robot with a channel.

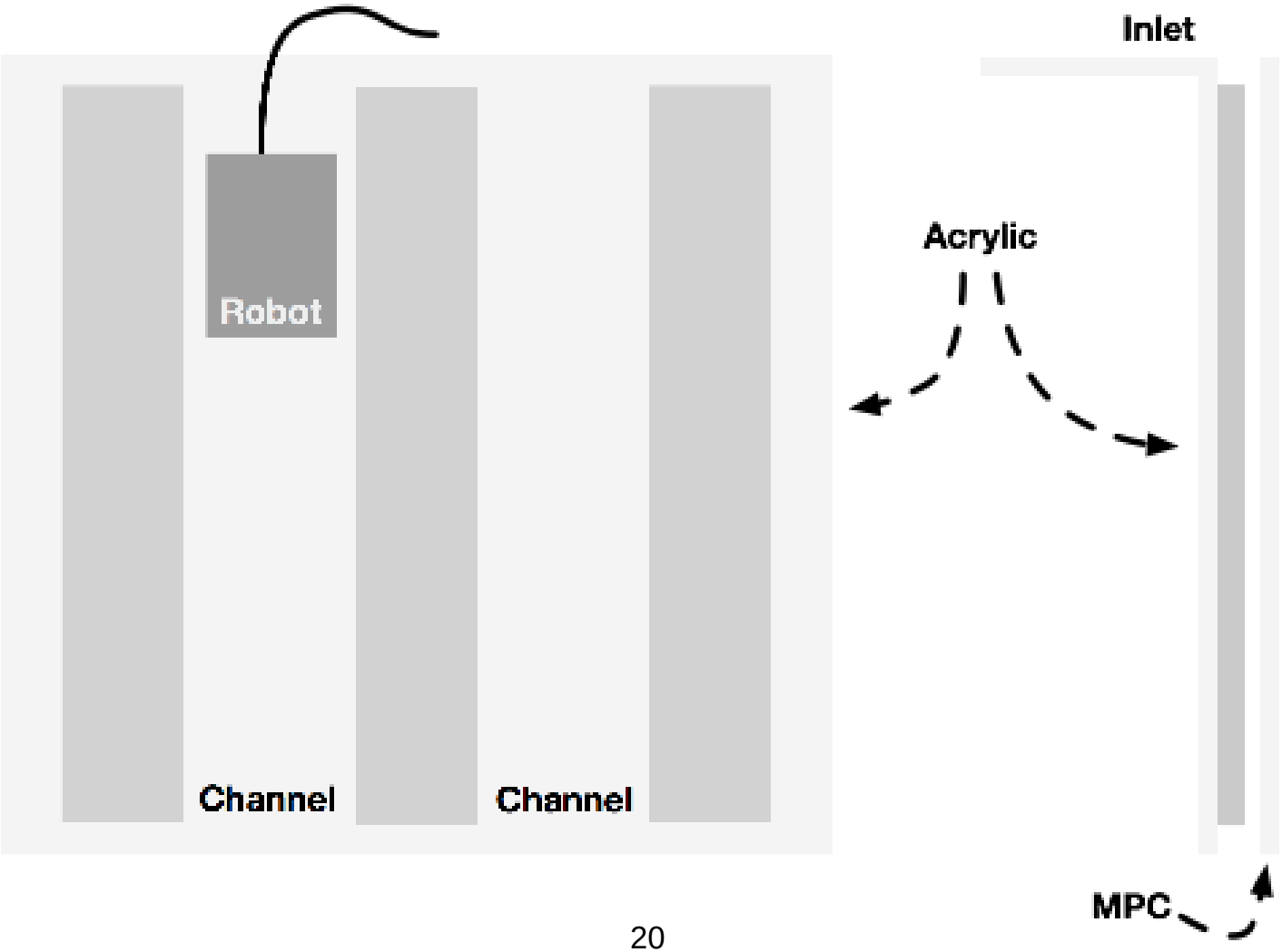



Case 1




Case 2

To help with testing the wedging and jamming analysis, transparent mockups of each restrictive case are being designed.

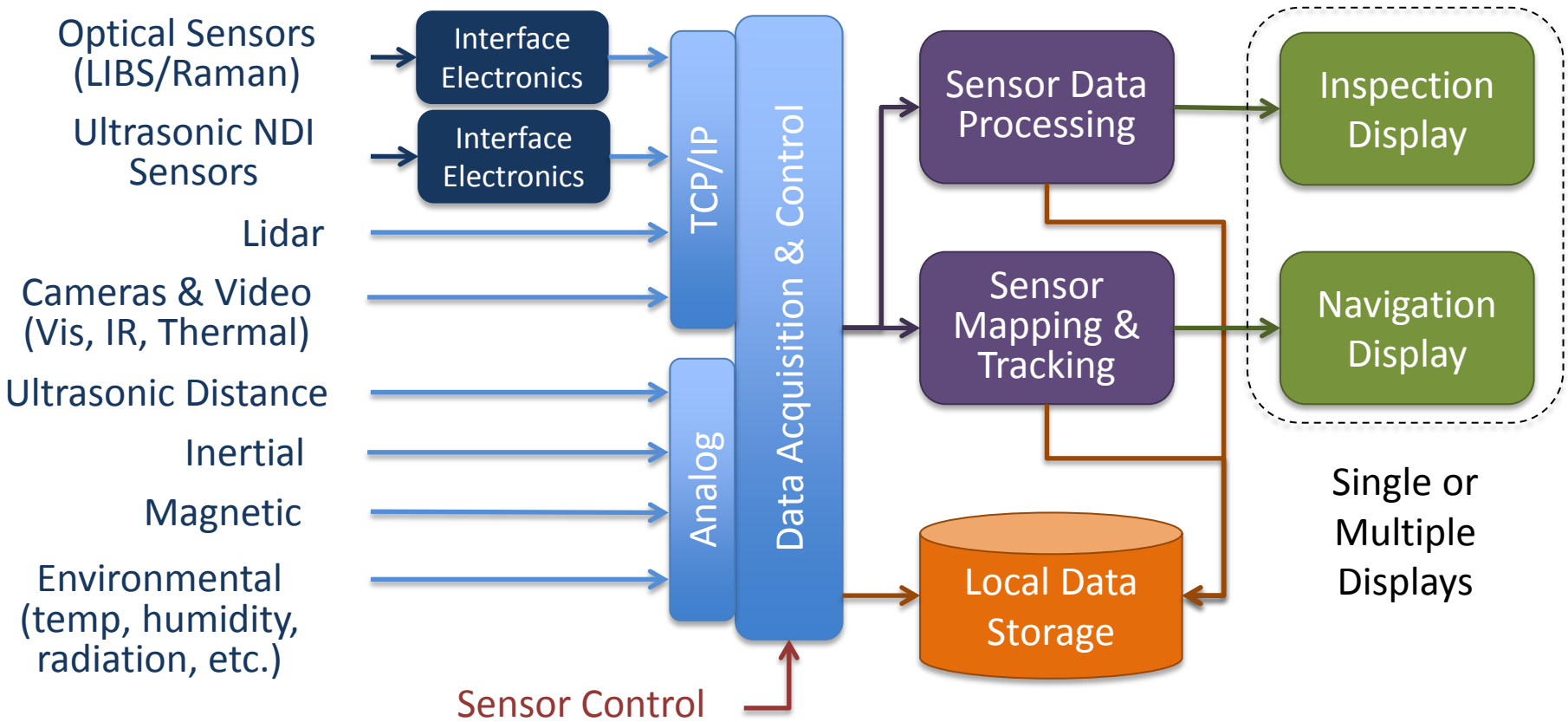


# Multi-Sensor Inspection and Robotic Systems for Dry Storage Casks
# *Task 6 - Data Analysis, Management and Security*

## Advisory Board Kickoff Meeting

Karl Reichard, PhD
The Applied Research Laboratory
The Pennsylvania State University

# Data Collection and Processing System Concept




- Identify sensor interfaces and data bandwidth requirements
- Conduct cost benefit analysis for inclusion of sensors to allow final sensor down select
- Procure and assemble hardware for the data collection and processing system

# Current Work

- 5 Subsystems Requiring Sensor Data Collection
  - Robotic Delivery System
  - EMAT / Ultrasonic Sensing
  - LIBS Measurement
  - Temp & Rad Measurement
  - External Concrete Inspection System
- Approach
  - Treat each system as separate from a data acquisition standpoint
  - Each subsystem may have unique data collection requirements so a single common data acquisition system may not be feasible
  - May need to fuse data for operator to guide sensor placement

# Current Work

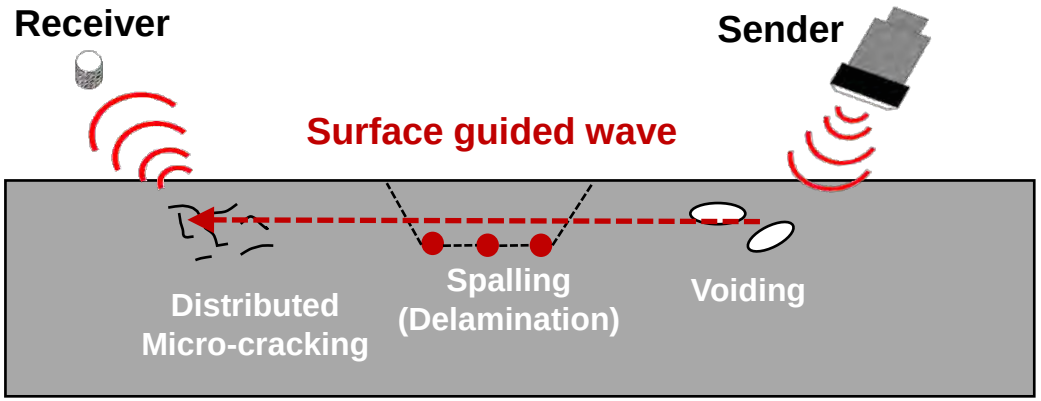
- Data Management
  - Don’t try to force all data collection through single data acquisition system
  - Focus on commonality of data formats to facilitate post measurement analysis
  - Create single database structure to manage data, even if there are some differences in data formats / meta data collected with primary measurements
  - Currently working on identifying sensors (primary and secondary), sample rates and data formats from each subsystem

# Current Work

- Impact on Sensor Delivery System (Robot)
  - Power requirements for sensors – will be provided from a supply external to the cask, so minimal impact on robot
  - Cabling - this is the big driver for the robot design. Cables will have strength and bend radius properties that can have an effect on insertion and extraction of the robot delivery system
  - Gathering data on cabling requirements, then include cabling properties in ongoing insertion/retrieval simulations

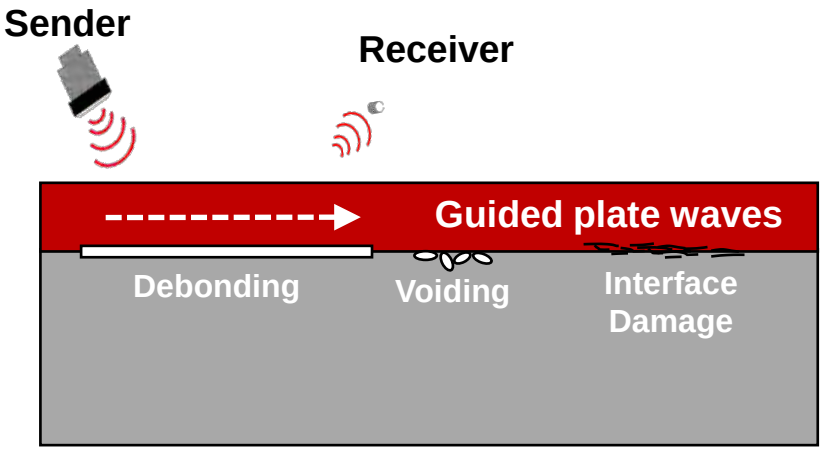
# Damage Types and Detection Approaches

## Horizontal Systems




- Surface guided wave approach: forward- and back-scatter configurations
- Ultrasonic waves interact with sub-surface concrete damage
- Contactless sensing enables rapid scanning

## Vertical Systems




- Guided plate wave approach: leaky wave propagation in steel liner
- Configuration enables inspection of underlying concrete and back side of steel liner
- Contactless sensing enables rapid scanning



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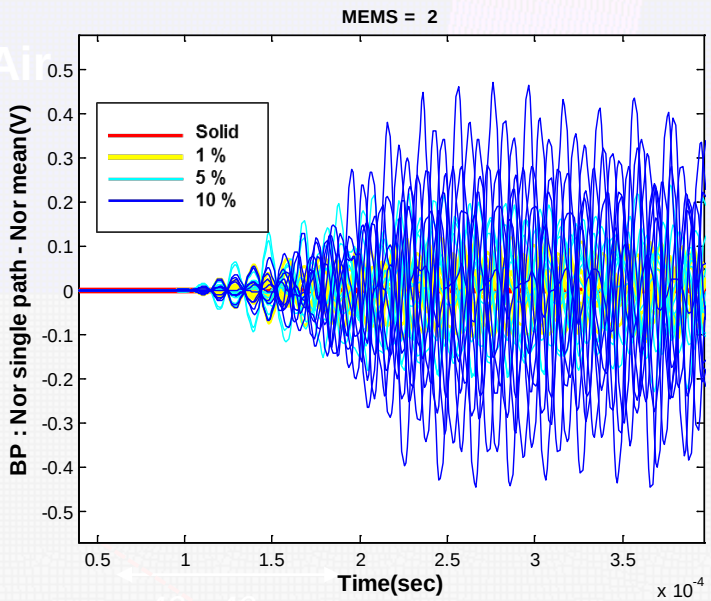
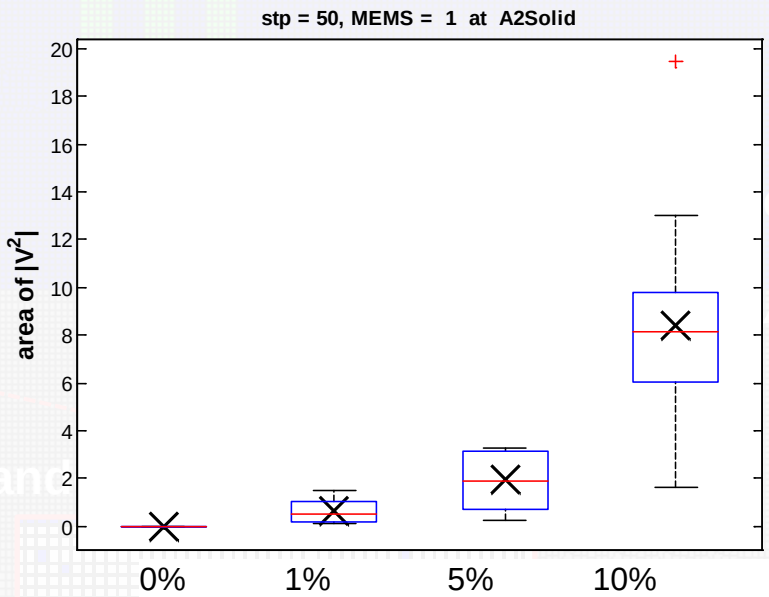
# Research Progress (1) – Horizontal System

**Finite element simulation of wave scatter caused by distributed cracking in concrete**




**Results from a range of simulated internal crack contents (0 to 10% by volume) show that back scatter wave energy increases monotonically as the cracking content increases.**



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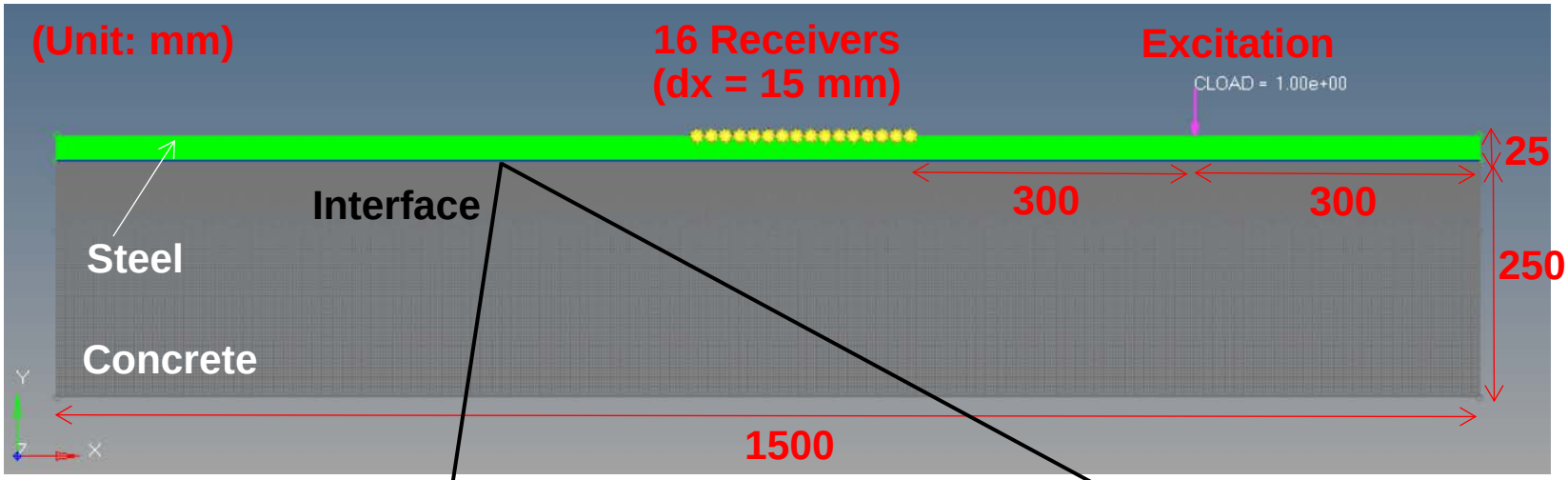
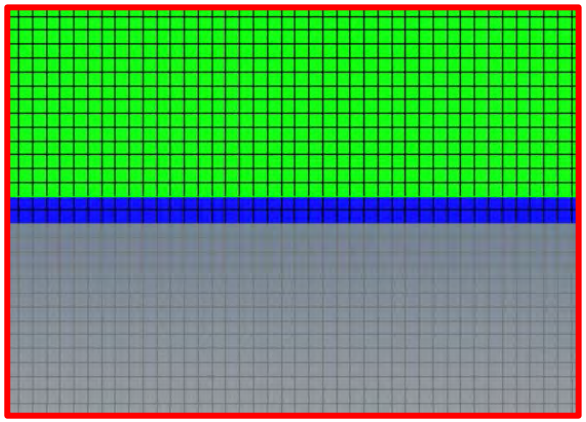
# Research Progress (2) – Vertical System

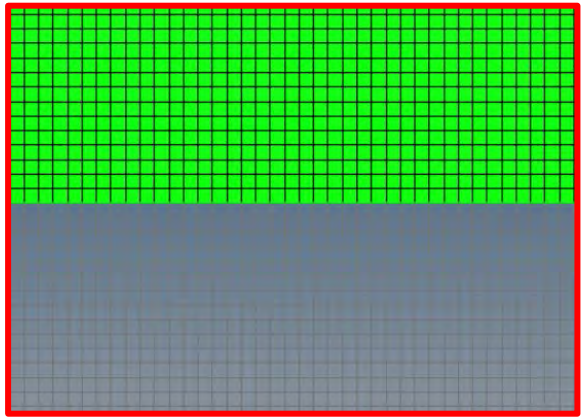
**Finite element simulation model for wave propagation in steel liner bonded and disbonded to concrete underlying substrate**




**Disbonded**



**Bonded**





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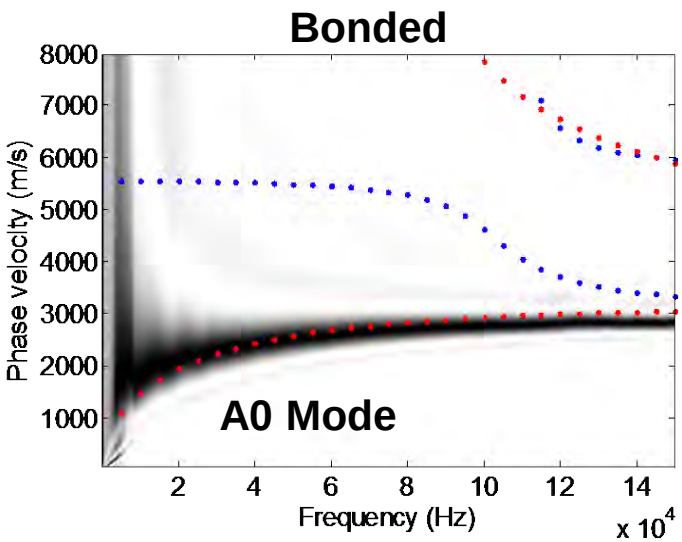
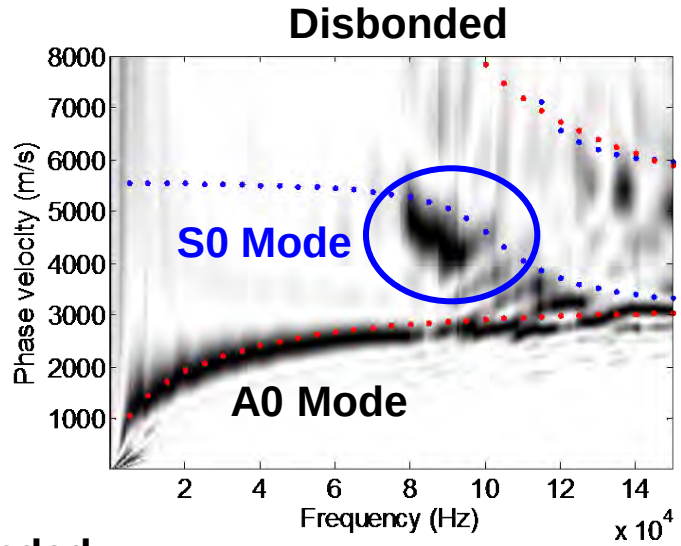
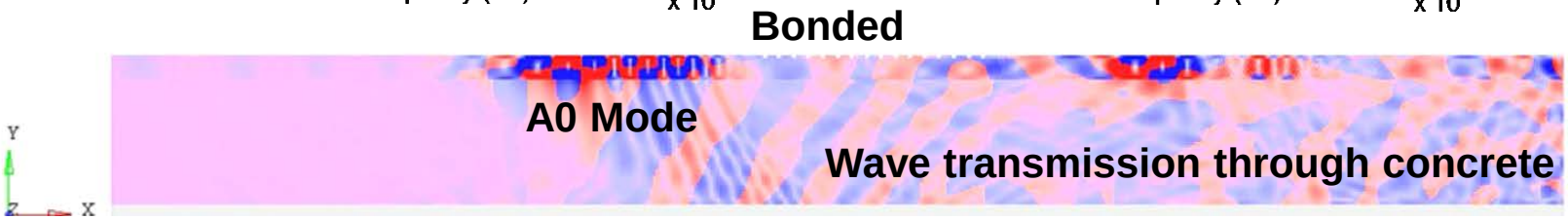
# Research Progress (2) – Vertical System

**FE simulation data presented in MASW phase velocity map (top) and cross-sectional distribution of Von Mises stress (bottom) at a given time instance. Only S0 and A0 modes generated at 50 kHz; distinction between bonded and disbonded cases seen.**



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# Radiation Dose and Thermal Assessment of Used Fuel Canisters

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Charles R. Priest

Kyle Singer

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Nuclear Engineering

# Radiaton Dose and Thermal Analysis

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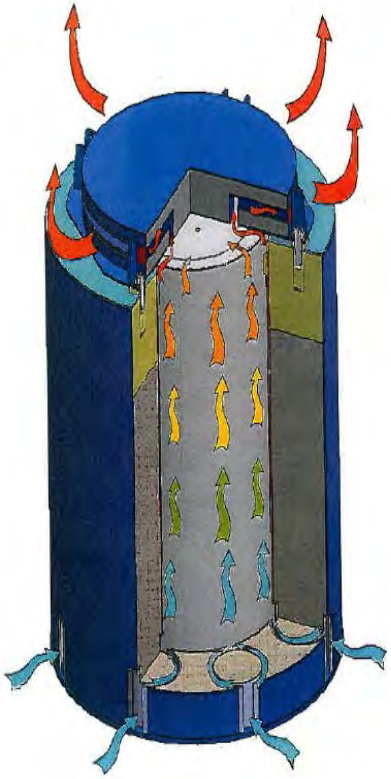
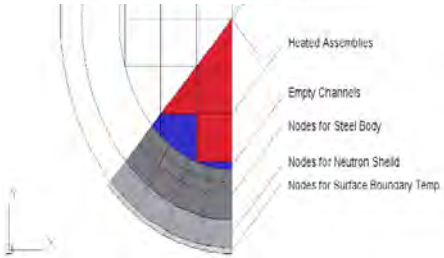
Nuclear Engineering

- Developing or utilizing:
  - State-of-the-art tools for radiation transport and dose calculation and thermal analysis
  - Detailed cask models to include detailed fuel and basket structures
- Collaboration:
  - ORNL - Centralized Used Fuel Resource for Information Exchange (http://curie.ornl.gov/)
- Detailed HiStorm100 model for thermal analysis
  - Modified version of COBRA-SFS – Approvals granted through ORNL-CURIE
- USC developing a detailed model of HiStorm100 for radiation transport and dose calculation.
  - MCNP (LANL developer) for radiation transport and dose calculation
- USC updating current version of COBRA-SFS (PNNL developer) to Fortran95
  - Cobra-SFS subchannel code for thermal analysis
- USC Beta user for SCALE-6.2 (ORNL developer) for source generation (source neutrons and photons from decay of used fuel)





# Radiation Transport and Dose Calculation

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Nuclear Engineering

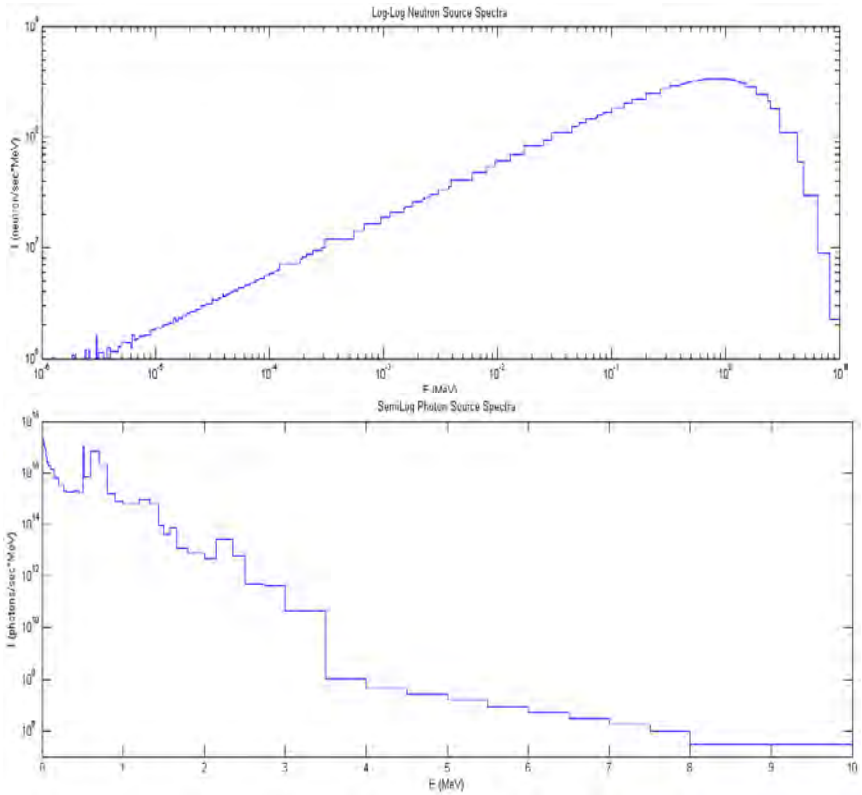
## Computational Tools

- MCNP 6.1
- SCALE 6.1
  - ORIGEN-ARP

## Output Information

- Transported neutron spectra, MPC, Overpack
- Transported photon spectra, MPC, Overpack
- activation in annulus
- dose from activated instrumentation
- Electronics damage → Si damage, defined by dose
- Site specific dosimetry, vent entrance

$$\frac{d}{dt}N_{Co^{60}} = \sigma_{c(E)}\emptyset_{(E)}\,N_{Co^{59}} - \lambda_{Co^{60}}\,N_{Co^{60}}$$

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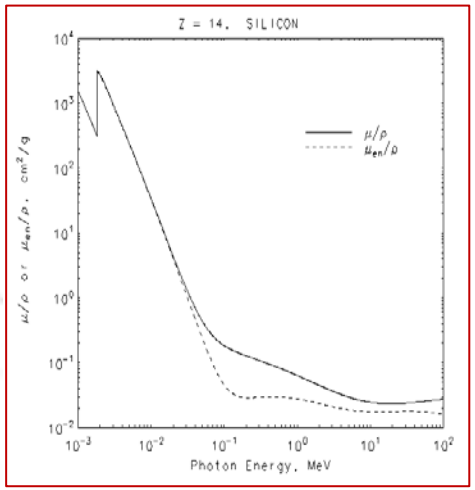
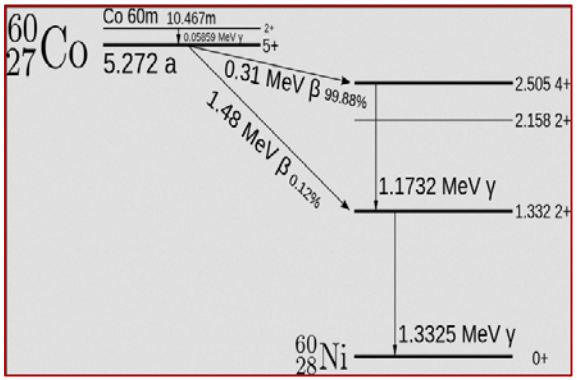



## Current Tasks

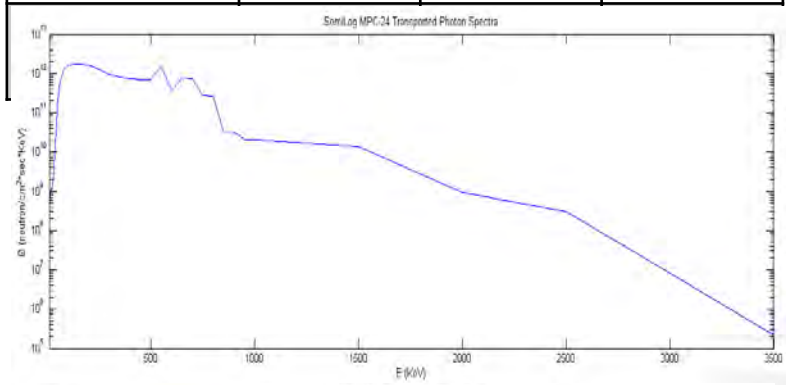
- Parallel development of assorted Overpack, MPC models
- Tool package development, listed outputs
- Literature investigation, methods for quantifying electronics damage under mixed species radiation fields
- Fine treatment of output data in terms of space and energy
- Fine treatment of geometry, use of publicly available resources for evaluation

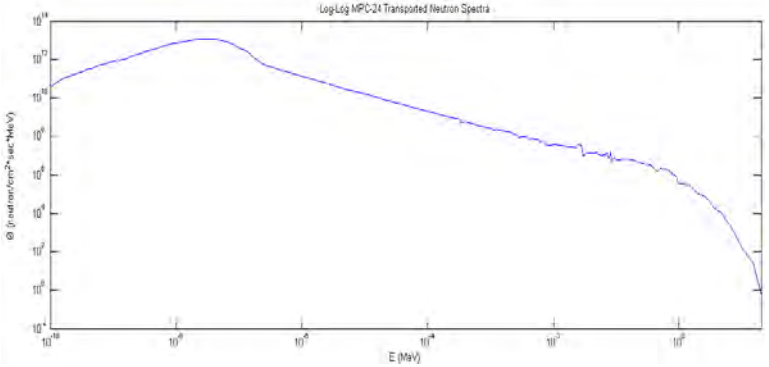
# Cask Modeling and Dose

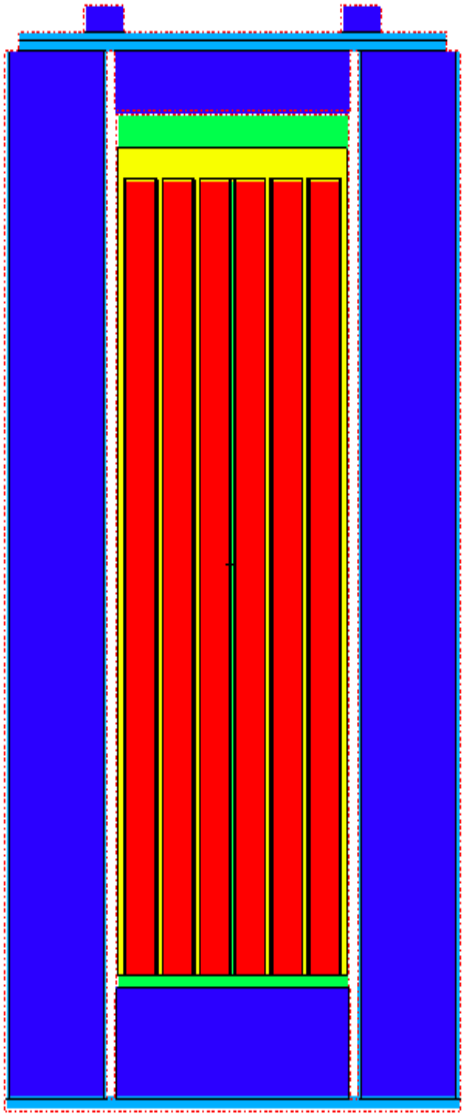
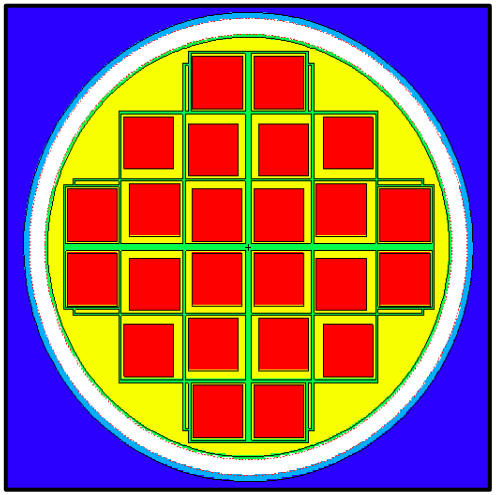
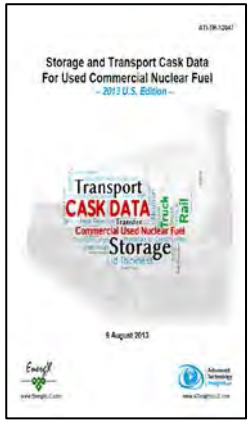
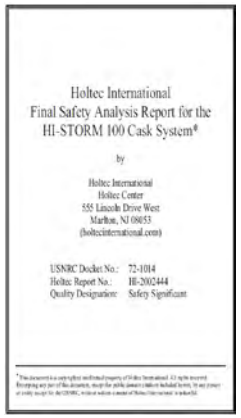
**Design Process, Variations**

- Holtec HI-STORM 100 family
  - Current focus, MPC-24 design

| Overpack | 24 Assembly | 32 Assembly | 68 Assembly |
|---|---|---|---|
| HI-STORM 100 | MPC-24 | MPC-32 | MPC-68 |
| HI-STORM 100S | MPC-24E | MPC-32F | MPC-68F |




**Geometry: HI-STORM 100, MPC-24**