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International Spent Fuel Sabotage Research

KHNP Training Program

Module 5: Packaging and Transportation

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Nuclear Transportation
Potential ACCIDENT Conditions

- STRUCTURAL crash damage
  - Drop, Crush, and Puncture Testing
- THERMAL damage
  - Fire testing
- Computer Modeling of Containment Integrity Results and Predictions
- Regulations and Compliance
  - Code of Federal Regulations: Title 10, PART 71 - Packaging and Transportation of Radioactive Material
- References:
  1. prior modules in this course
  2. www.sandia.gov/tp/SAFE_RAM/TESTING.HTM

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Nuclear Transportation
Potential Terrorist Attack, SABOTAGE

Spent fuel cask truck and rail transport

- **Unlike safety risks for transportation accidents, there is no statistical basis for evaluating consequences of intentional sabotage attack**
- **International concerns on need to quantify materials produced and released (Release Fraction) from credible attack scenarios**
- **Experimental data (source term) and modeling required to assess consequences and risk from sabotage attack**
- **Testing to support transportation safeguards systems and vulnerability assessments**

- **Reference: Molecke, et al., *Spent Fuel Sabotage Test Program, Surrogate and Fission Product Aerosol Results,* SAND2006-5556C, presented at INMM 47th Annual Meeting, Institute of Nuclear Materials Management, July 16-20, 2006, Nashville, TN**

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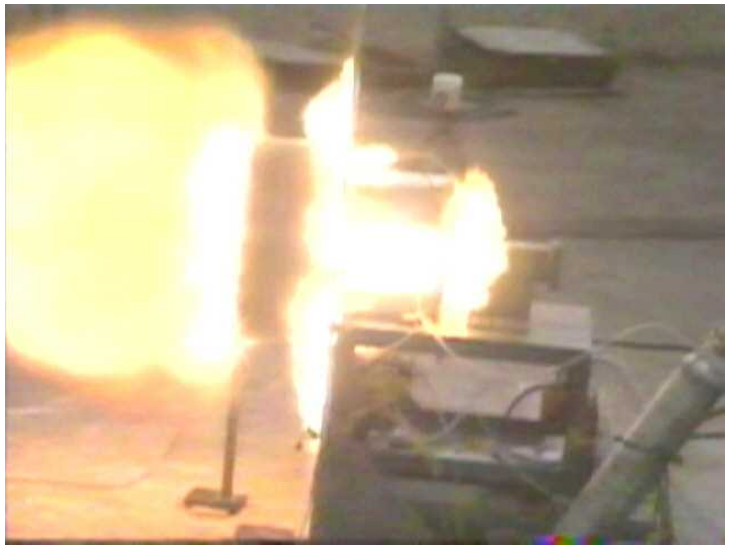
Spent Fuel Sabotage: Aerosol Test Program OVERVIEW

- **SCENARIO: plausible sabotage attack on nuclear transport casks by HEDD-CSC (armor-piercing weapon) …**
- **GOALS-Experimental: Quantify source-term data and analyses on aerosol particles produced from actual SNF and surrogate fuel (CeO_2, DUO_2) single rodlets**
  - **R**espirable **F**ractions & particle distributions (0-10 μm … AED)
  - **E**nrichment **F**actors, volatile fission product enhanced sorption (Cs, Ru, Sr, Eu)
  - **S**pent **F**uel **R**atio, (**SFR** = actual **SNF RF/** surrogate **DUO_2 RF**) …
    - provides bridge to several large-scale surrogate cask tests and consequence modeling; allows scaling
- **Support DOE, NRC, & International WGSTSC assessments**
- **Leverage program testing, modeling, capabilities & benefits over all international WGSTSC participants**



Test 2/3A: HEDD detonation

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International Working Group for Sabotage Concerns of Transport and Storage Casks

Partners and Leveraging:

- **Sandia National Laboratories** (SNL)

TRANSPORTATION Testing	EXPLOSIVE Technologies	Analytical Chemistry
AEROSOL Processes	NUCLEAR Facilities	Ceramics

- **U.S. DOE** (OCRWM & NA): primary funding; Intl. Safeguards
- **U.S. NRC** (RES & NSIR): co-funding support
- **DOE SSO/NNSA** (facilities) & SSA (vulnerability studies)
- **Argonne National Laboratory** (ANL): spent fuel
- **Germany:** Fraunhofer ITEM and GRS, Gesellschaft für Anlagen- und Reaktorsicherheit
- **France:** Institut de Radioprotection et de Surete Nucleaire (IRSN)
- **UK:** Office for Civil Nuclear Security (OCNS)
- **Japan:** (JNES, JAEA; pending)

coop. testing & multinational data sharing, Multilateral Agreement

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WGSTSC Spent Nuclear Fuel Sabotage

Program Objectives & DOE Value Added

- Provide reliable, measured source-term data and technology transfer for credible sabotage consequence modeling & related security studies
- Support evaluations to realistically estimate effects and consequences of sabotage attacks on SNF in particular, hazardous materials, in general
- Provide basis for evaluating appropriate level of physical protection and safeguards requirements, strategies for nuclear materials in use, transport, and storage
- Defensibly assess effectiveness of, and enhancements to, mitigation safeguards and preventative security strategies, implementation, if needed
- Complement DOE efforts to build and sustain strong, collaborative relationships with NRC and International WGSTSC partners to counter nuclear terrorism [data sharing w/ Multilateral Agreement]
- Support (DOE OCRWM) Yucca Mountain Repository transportation sabotage concerns ...

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Spent Nuclear Fuel Sabotage, Dispersal
NRC Regulatory Needs:

- Reliable source-term data, supporting analyses for generation & release (with follow-on modeling) of respirable aerosol particles, atmospheric dispersion
- Help guide and validate technical bases for transport & storage regulations (10 CFR Parts 71, 72, and 73)
- Enhance 20+ yr-old Sandia & others transport cask aerosol data for DOE & NRC Urban studies
- Provide defensible validation of NRC vulnerability studies - enhance old, limited data
- Supplement vulnerability studies performed by NRC in support to Dept. of Homeland Security, in response to terrorism
- Measured data may reduce more speculative anti-nuclear statements about risks associated with nuclear, SNF shipments

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Spent Fuel Sabotage:
Aerosol Test Apparatus

Aerosol-Explosive Test Chamber

Aerosol Apparatus

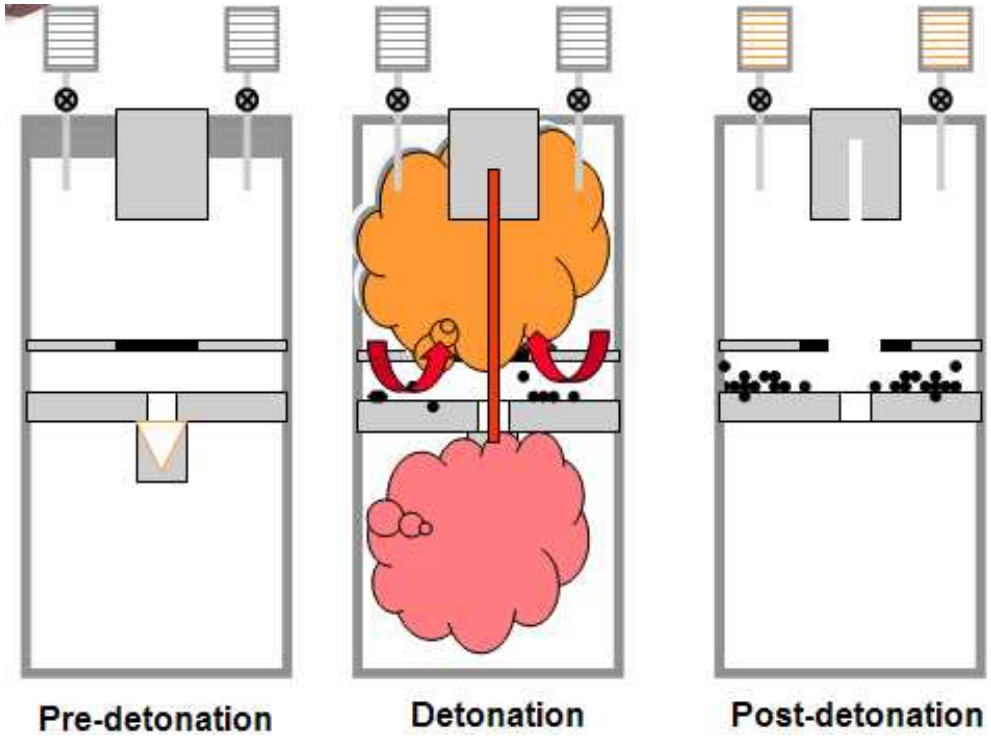
Vertical
TEST CHAMBER:

AEROSOL Chamber

single test RODLET

HEDD & jet

EXPLOSIVE
CONTAINMENT
Chamber



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Spent Fuel Sabotage Aerosol Testing History, A:

- **Small-Scale: DUO_2 and Spent Fuel**
  - Idaho INEL (SNL/DOE) 1982, Alvarez et al.
  - Battelle BCL (NRC) 1982, Schmidt et al.
  - aerosol collection problems, uncertainties ↓
- **Large-Scale Cask: DUO_2 Surrogate**
  - SNL 1980-83, Sandoval et al., full-scale and 1/4 –scale cask tests (single assembly)
  - GRS (Gramat), 1992-94, Pretzsch & Lange, 1/3-length Castor cask tests
- **Spent Fuel Ratio data**
  - SFR range of 0.5 to 12, uncertainties
  - Respirable Fraction uncertainties
  - limited fission product Enrichment Factors

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Spent Fuel Sabotage Aerosol Testing History, B:

- **WGSTSC: Joint Proposal** (2000)
  - more explosive-aerosol testing needed …
  - GRS/SNL aerosol testing plan
  - 3 test phases: glass, DUO_2, Spent Fuel ➘
- **SNL-WGSTSC 4-Phase Testing** (single rodlet)
  - **Phase 1:** glass, CSC (2001-02)
  - **Phase 2:** surrogate CeO_2 (2002-04) & German HLW glass w/ fission product dopants
  - **Phase 2+:** more Cesium F.P. Enrichment Factor studies (2005 & 07 at SNL; 2006 at Fraunhofer)
  - **Phase 3:** DUO_2 tests in SNL Explosive Component Facility (3 in 2005-2006, … 3 remain)
  - **Phase 4:** Spent Fuel rodlets (8), at SNL GIF (2008 … 2010)

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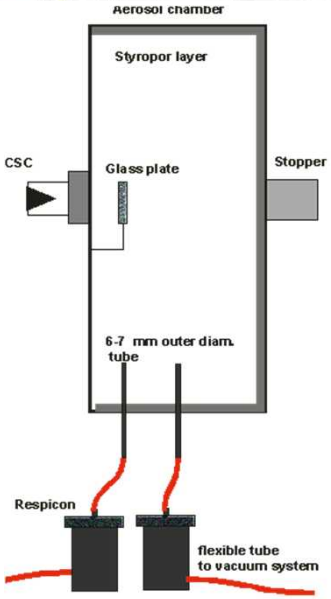
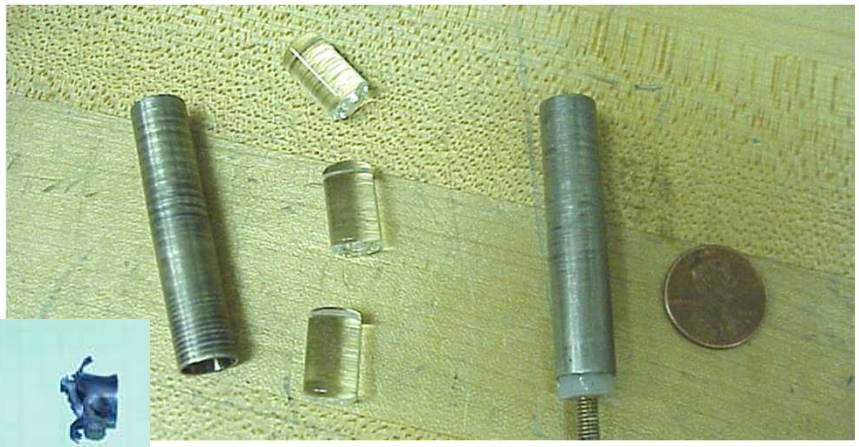
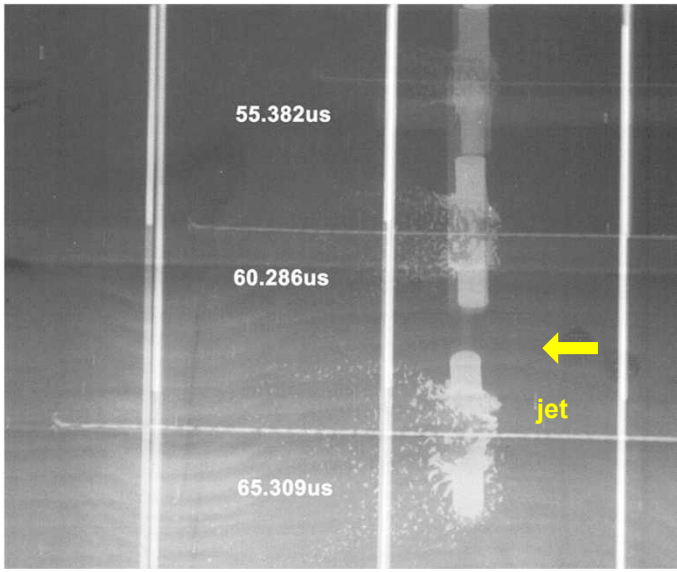
Spent Fuel Sabotage
4-Phase Test Program



Phase 1: Glass, HEDD (2001 - 02)

- HEDD/ CSC evaluation tests
- validate brittle material fracture law (Fraunhofer)
  - leaded-glass plates (4 tests)
  - glass pellets/Zircaloy tube (2 tests)
- aerosol testing at SNL (ECF) & Germany
- development of test apparatus
- results documented
  SAND2005-5873





Flash X-Ray of HEDD jet and glass pellets

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Phase 1 and Phase 2
Test Components

ECF test pad ↑
4 flash X-ray tubes

Test rod in
← aerosol
collection
chamber

← ← HEDD jet

Cerium Oxide ceramic
surrogate pellets,
Zircaloy cladding tube / test rod

Respicon
aerosol particle
← collectors (2)

2003

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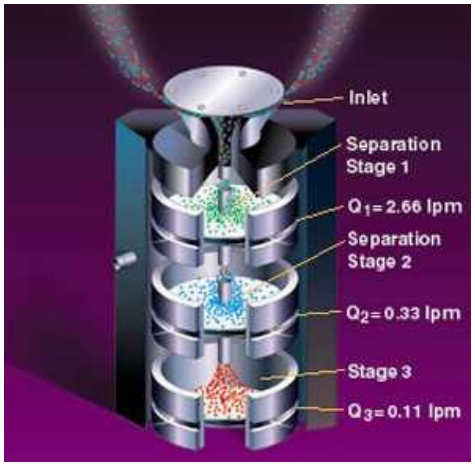
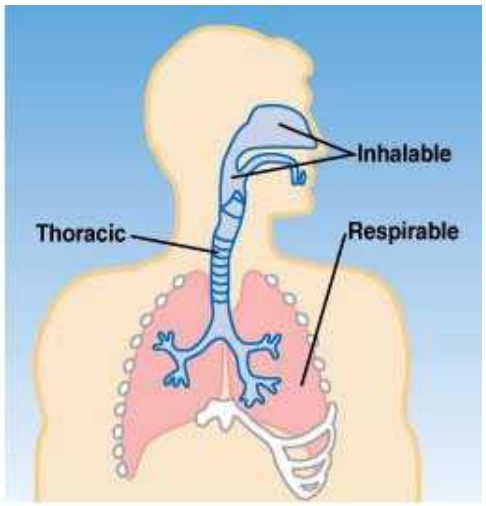
Respirable & Aerosol Particle Collection





RESPICON 3-stage virtual impactor

aerosol particle collection device

Fraunhofer

Aerosolized Particles:

★ **Top:** Respirable fraction, 0 ~ 4 μm AED

★ **Middle:** Thoracic fraction, > 4 ~ 10 μm

- -

Bottom: Inhalable fraction, >10 ~ <100 μm

(*ground shine, fallout …*)

$$AED = GD \times (density)^{1/2}$$

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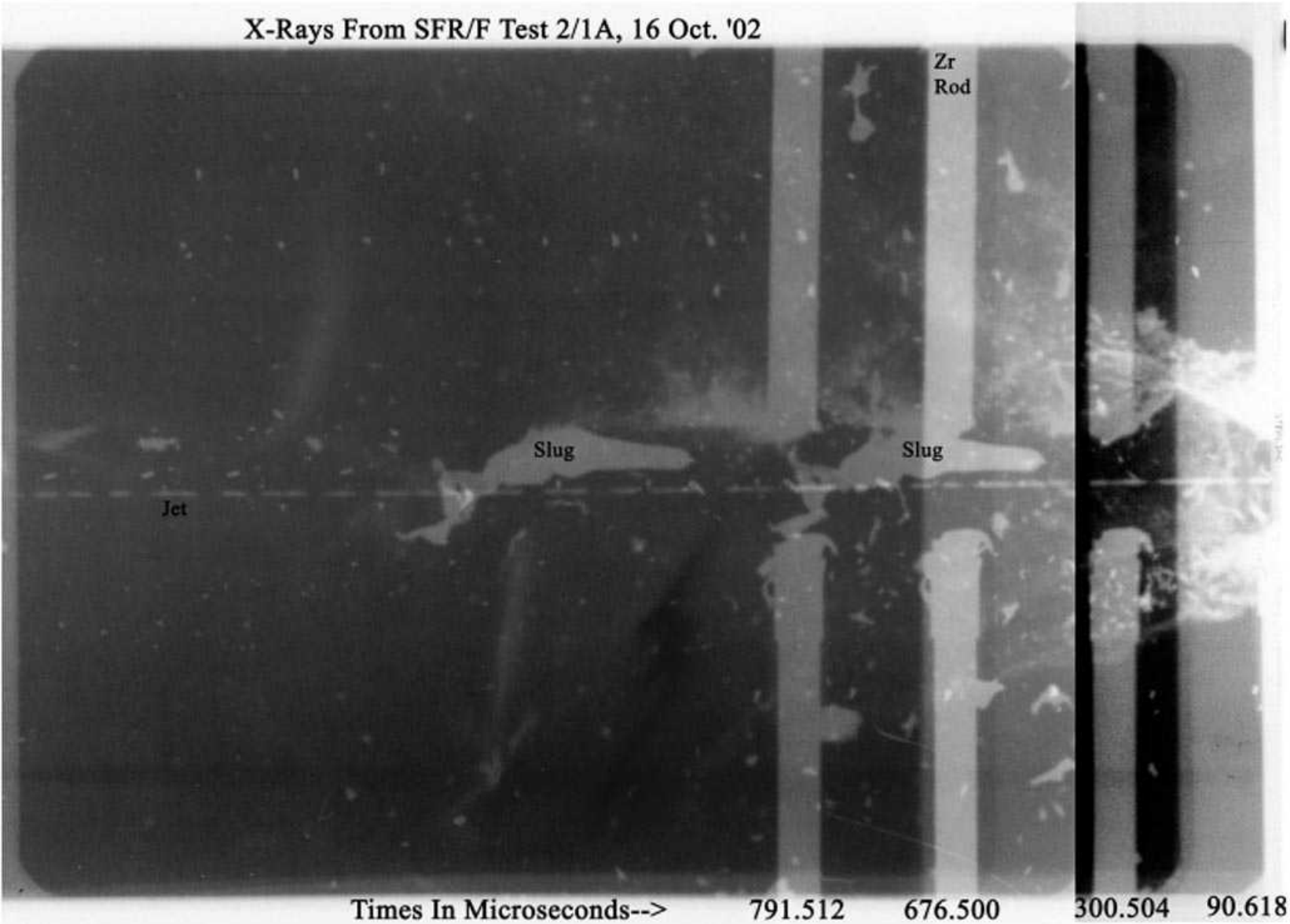
2003

Phase 2 Test # 1A



HEDD jet ←

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Spent Fuel Sabotage
4-Phase Test Program

8/2003 ⬆ ⬇ 2/2004

Phase 2: CeO_2 Pellets (10/2002 - 5/04)

- chemical, ceramic surrogate for UO_2
- 24 explosive- aerosol tests
- 2 with German HLW glass
- test multiple variables at SNL ECF, Explosive Components Facility
- multiple aerosol particle impactors
- Respirable Fractions, distributions, particle chemical analyses by ICP-MS, non-aerosol particle sieving
- *fission product dopants* added (*Cs, Ru, Sr, Eu* Enrichment Factors …)
- *component qualifications & optimizations for Phase 3 and 4*

⬅ 24-32 mm of CeO_2 rodlet "particulated," pellets captured

⬅ SNL- German test cooperation HAW-HLW glass rods

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Explosive-Aerosol Testing
Phase 2 Confinement Progress:

unconfined HEDD detonation, 8/2003 **(video)**

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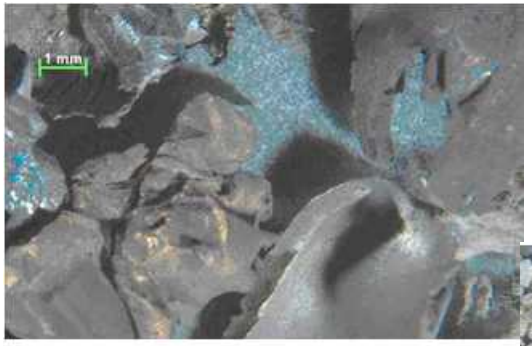
SFR-HEDD Test 2/3A

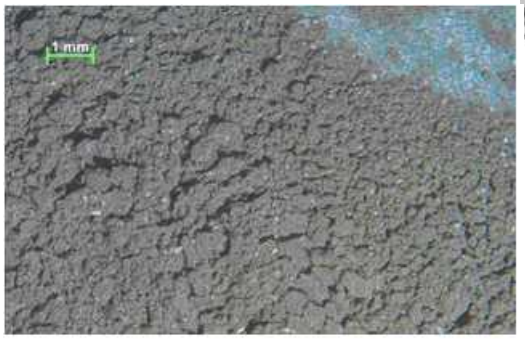
Inside of Aerosol Box:

post-test particles, fragments, & soot for sieving + ICP-MS chem. analyses



Optical Image > 1.00 mm Fraction

> 0.25 mm Fraction



Bottom residue < 0.125 mm / SOOT +

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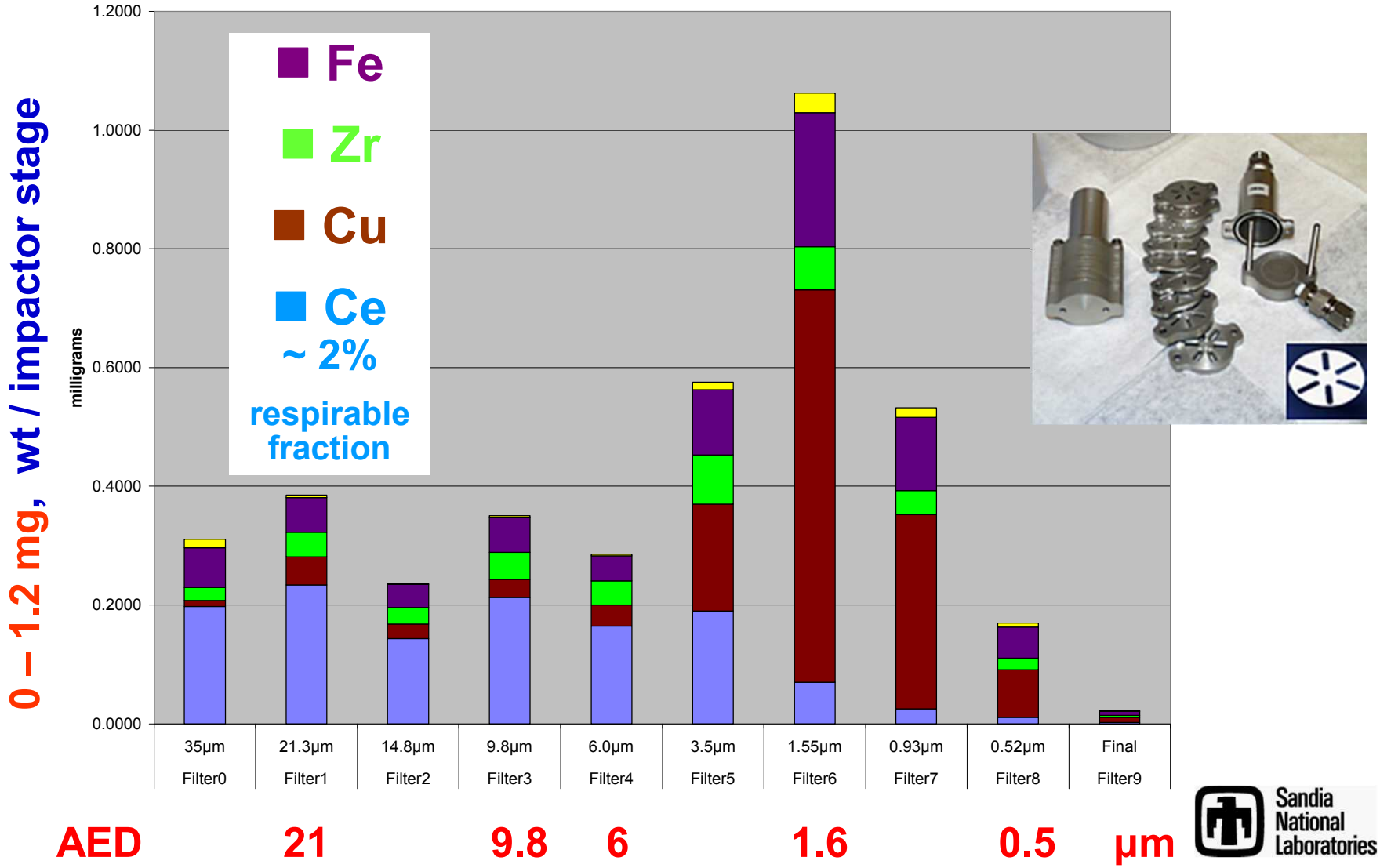
Marple Impactor, Test 2/5G:
Phase 2 Tests, Aerosol Data



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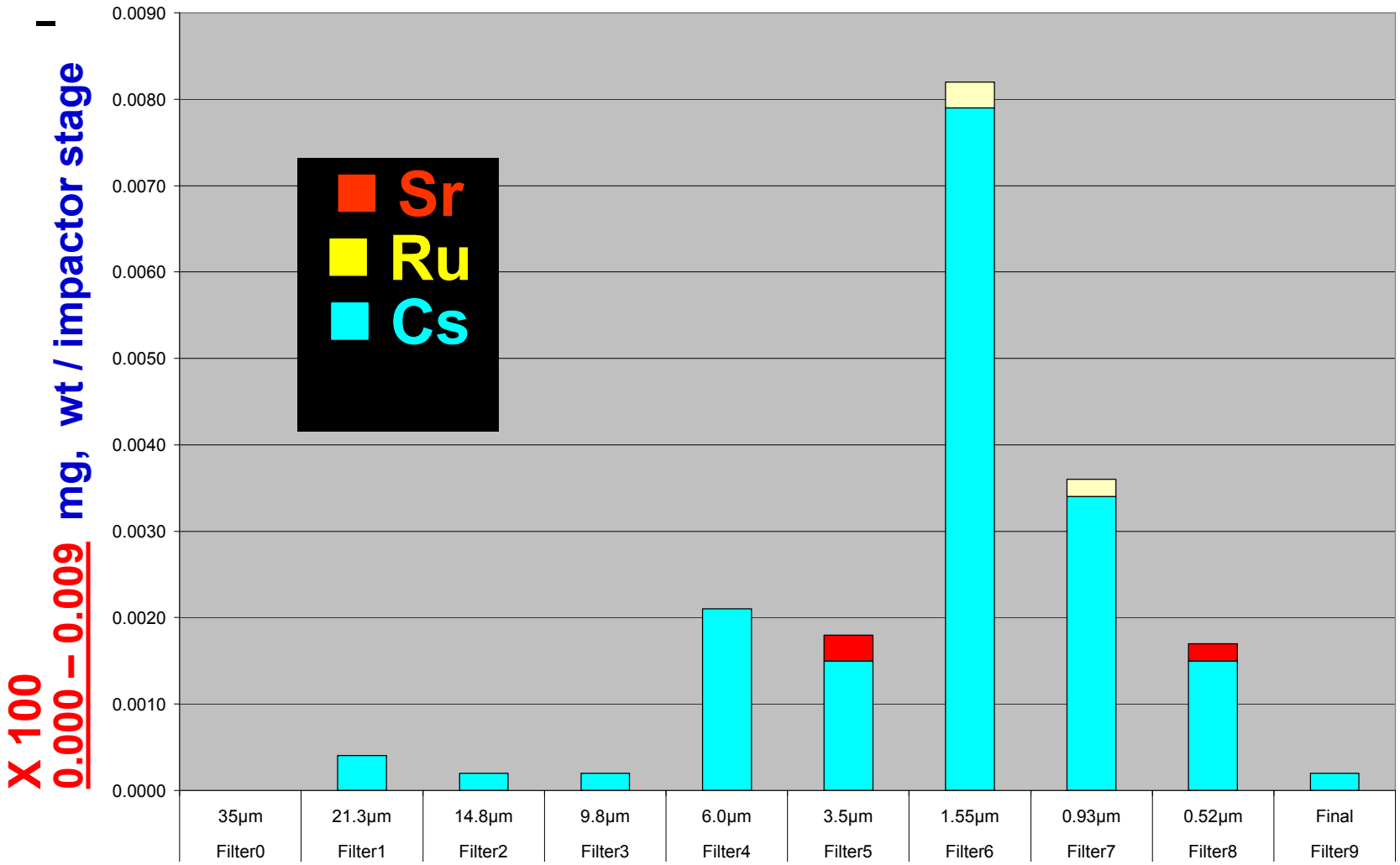
Marple Impactor, Test 2/5G: Volatile Fission Product Enhancement, Aerosol Data



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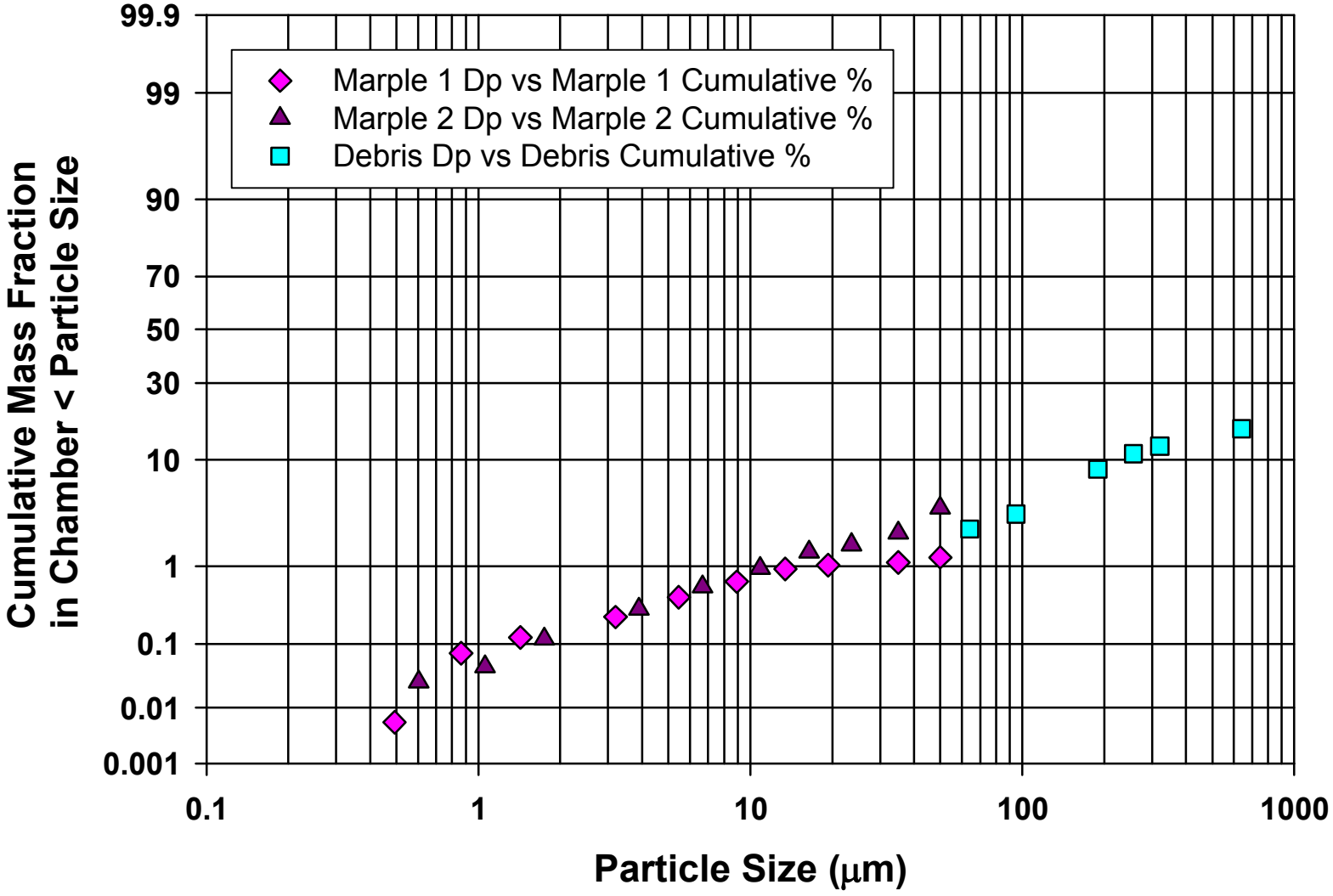
Brittle Material

Cerium Oxide Cumulative Distribution Test 2/8D



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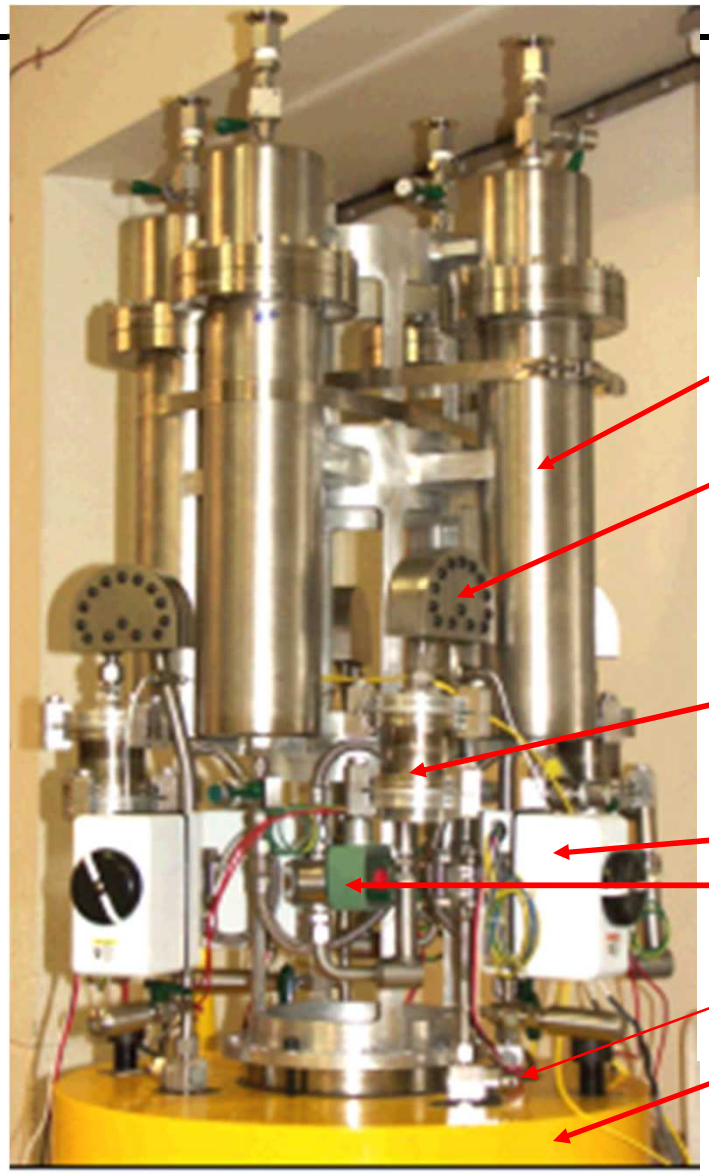
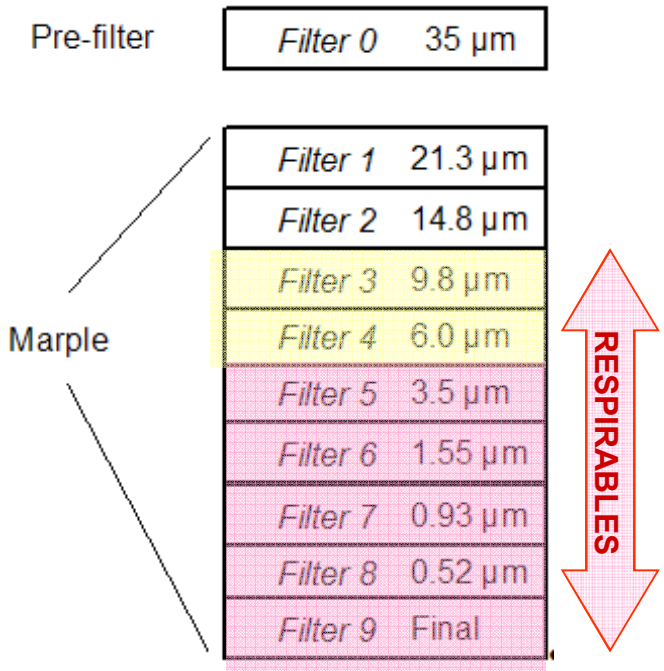
SFR Test Aerosol Particle Collection



4 independent aerosol sampling systems

- vacuum bottle
- Large Particle Separator, LPS * * (~ 30 – 100 µm)
- Marple Impactor (enclosed)
- valves: primary, secondary, manual
- aerosol test chamber



Marple impactor stages
< 0.5 – 20 µm AED

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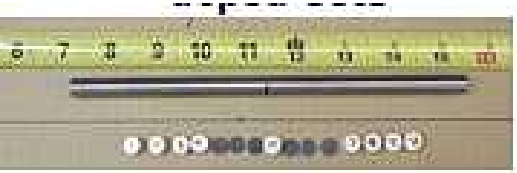
Phase 2+ Fission Product Evaluations
Surrogate CeO_2 & Glass

- **"semi-open" Aerosol Test Chamber: with external CSC (2005 & 2006)**
- **horizontal jet, target rodlet, valved hole, multi-instrumented (T, P) uses same 4 independent aerosol sampling systems**
- **evaluate different types of fission product dopant techniques, w/ CeO_2**
  (Enrichment Factor effects)

real time & slow-motion
video (4 views) ➡



dopant disks, 2/10A, B

doped pellets, 2/10C, D / G, H
(mixed-in, thermally diffused)

9 German doped glass, 2/10E, F

test setup at SNL ECF Gun Site, 7-2005

Laboratories

Phase 2+ Fission Product Evaluations
Surrogate CeO_2 & Glass

- Test 2/10 post-test pictures

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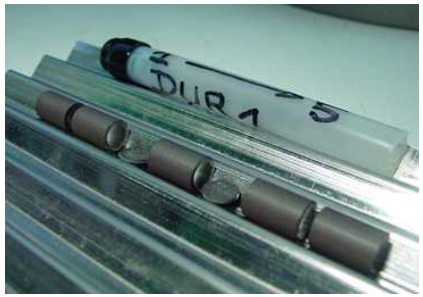
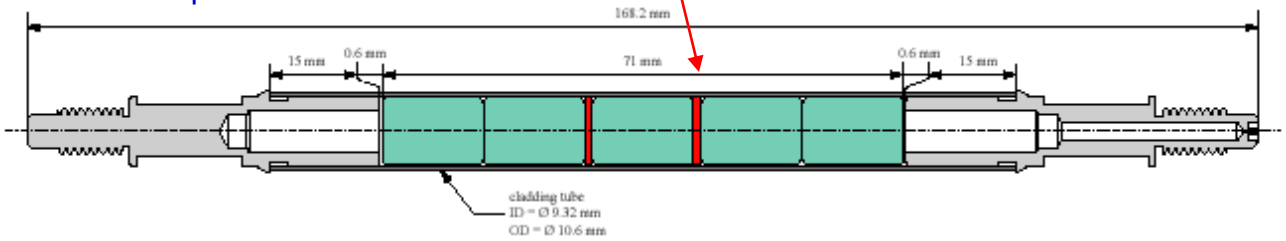
WGSTSC
Spent Fuel Sabotage Aerosol Ratio
4-Phase Test Program:

Phase 3: DUO_2 Surrogate *(current!)*

- vertical explosive-aerosol containment test chamber (reusable)
- test rodlets from France, IRSN
- **variables: FP dopants, P= 1- 40 atm** (plenum), **air/N_2**
- same test conditions as Phase 4
- 6 tests @ SNL ECF
  (10/05, 1/06, 3/06)
  (3 in 2007 … delayed)



plenum



4 aerosol sampling systems

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Advanced Surrogate Phase 3 Test Matrix

Test #	Pressure	Dopant	Variables	ECF Date
Depleted Uranium Oxide Pellets/Rodlets				
3/2 (A) first	1 bar (rodlet)	no	air (aero. chamber)	10-14-2005
3/5 (B) second	40 (He)	no	air	1-12-2006
3/1 (C) third	1	yes	air	3-09-2006
3/3 (D) fourth	1	yes	N_2	
3/4 (E) fifth	40	yes	air	
3/6 (F) sixth	40	yes	N_2	

@ SNL Explosive Components Facility (ECF)

IRSN

post-test

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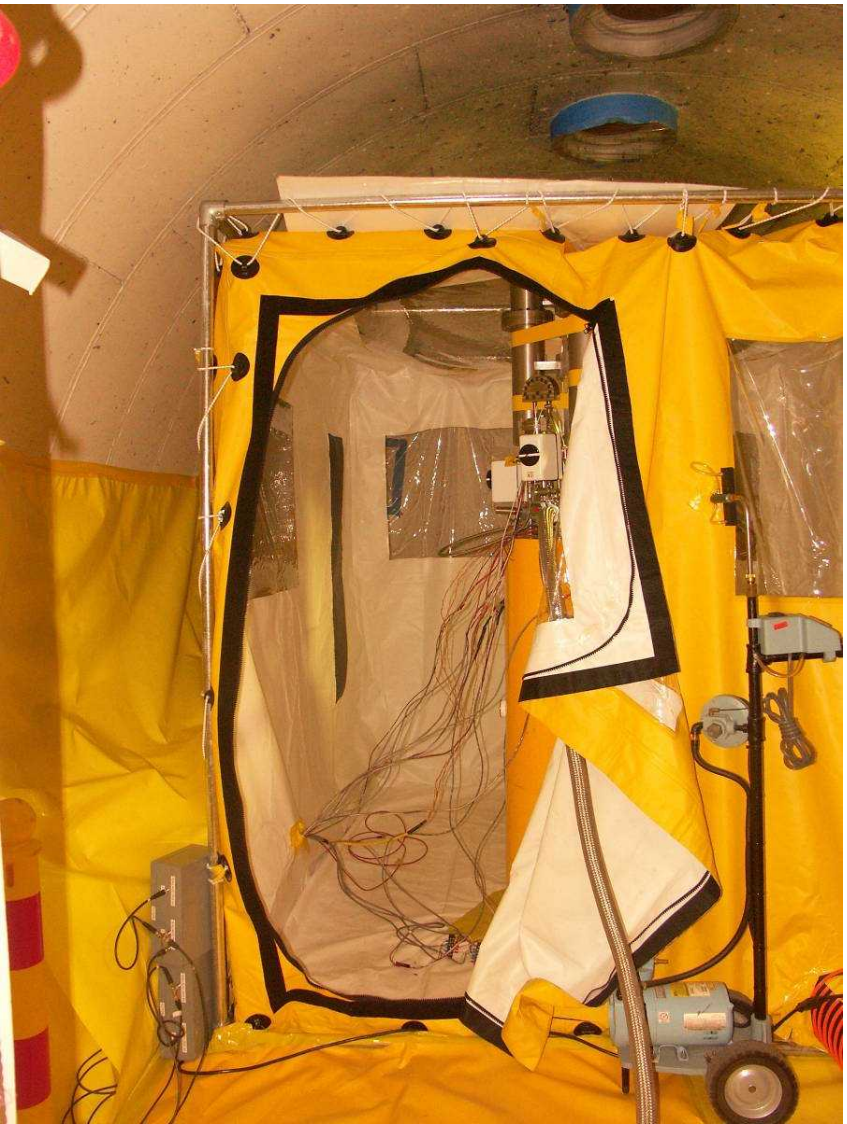
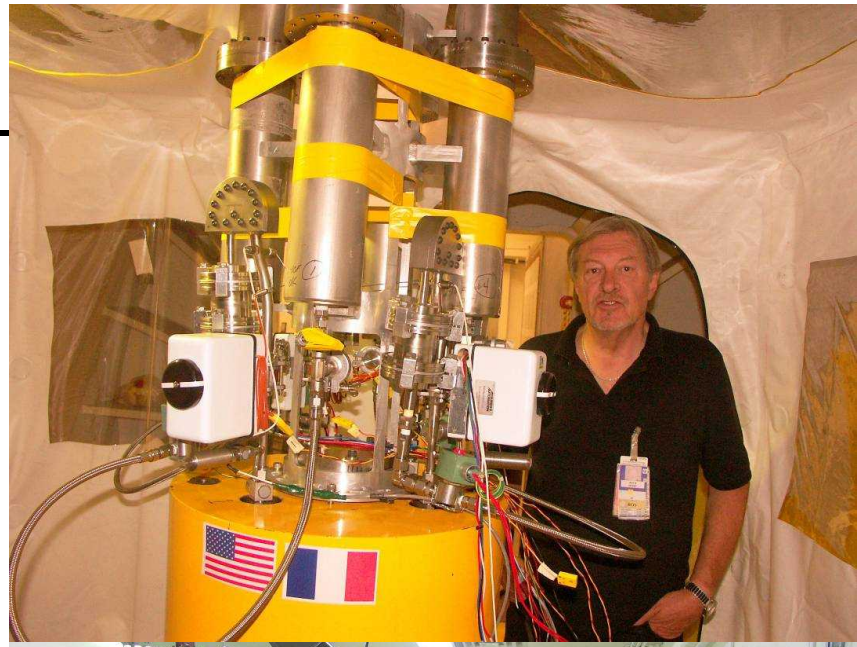
Phase 3 DUO_2 Test at
SNL Explosive Components Facility

test chamber and secondary enclosure
within large blast chamber





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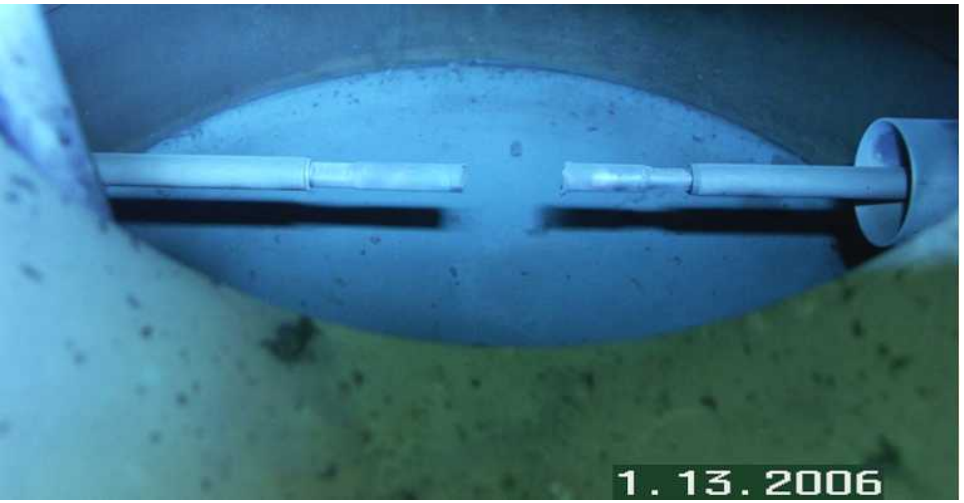
Phase 3 DUO_2 Test
Post-test Disassembly



contamination during aerosol apparatus removal and within glovebox:
at or below detectable levels

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Review of Current Spent Fuel Surrogate Aerosol Test Results

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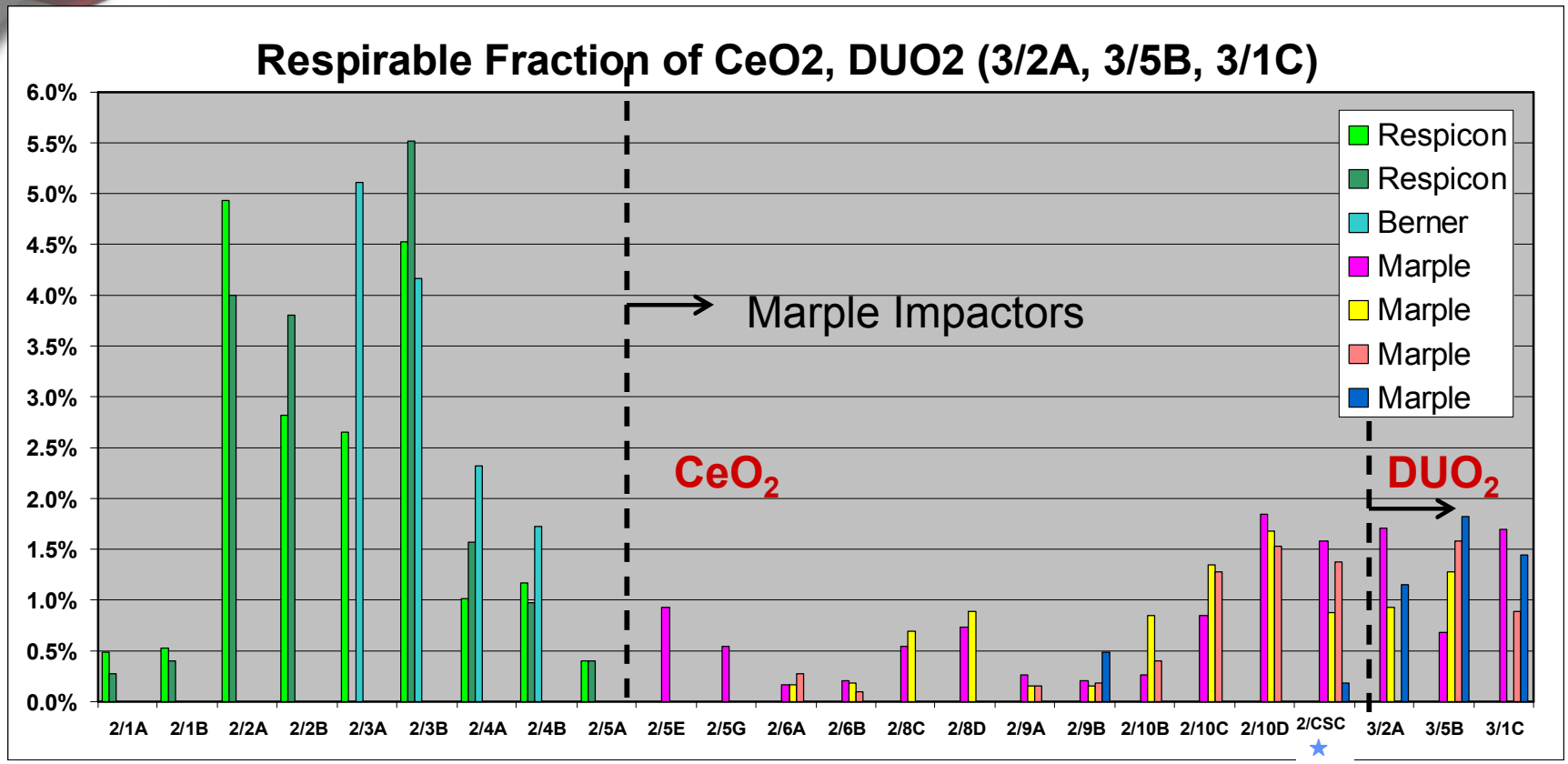
Ce and DU RF's: Phase 2, 2+, 3

(5/16/07)



- CeO_2 RF = 0.68 ± 0.25 % ave., Marple Impactors (99% confidence interval)
- CeO_2 RF = 1.34 ± 0.56 % ave., all data, old & Marple (99% confidence interval)
- DUO_2 RF = 1.32 ± 0.32 % (preliminary, **99% confidence interval**) (3 of 6 tests analyzed)

Ce and DU RF's comparable but RF for DU may be higher based on Marple data

★ **5 % RF conservatively estimated for UO_2,** YMP EIS (Luna, 1999)
(➡ reduced consequences!)

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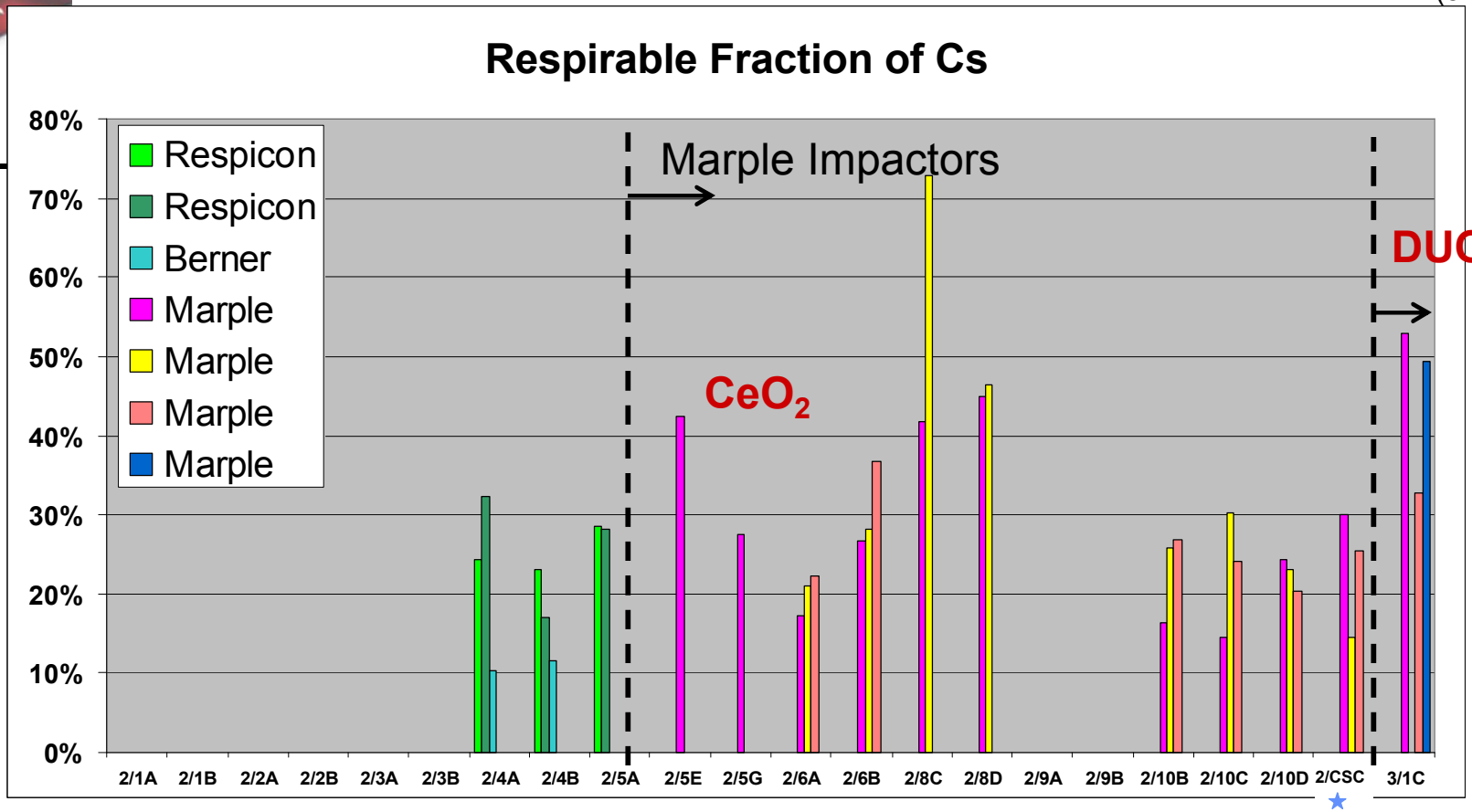
CESIUM Respirable Fraction: Phase 2, 2+, 3

(5/16/07)



- **Cs RF = 29.3 ± 7.6 % ave., Marple Impactors Ce tests (99% confidence interval)**
- **Cs RF = 27.5 ± 6.1 % ave., all data, old & Marple Ce tests (99% confidence interval)**
- **Cs RF = 45.0 ± 16 % ave., Marple Impactors DU tests** (preliminary, **99% confidence interval)** (1 of 4 tests analyzed)
- **Cesium definitely enriched compared to base, with good detectability**

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Other Fission Product Dopant Respirable Fractions: Phase 2+ Test Results

- **Ruthenium Respirable Fraction** (volatile)
  - **RF is 3.6 ± 1.7 % of dispersed mass based on all data** (99% confidence interval)
  - **RF is 5.0 ± 2.2 % of dispersed mass based on Marple data** (99% confidence interval)
  - **Enrichment Factor in smaller sizes seen, EF = 16 ± 7 …**
    - EF range due to detectability levels
    - low concentrations, uncertainties in doped pellets
- **Europium Respirable Fraction** (non-volatile)
  - **detected at ~ 2X background, but interference from fiberglass substrate**
  - **not enough information yet for RF, EF estimates** (RF ~ 7.5 ± 5.9)

- **Zr (Zircaloy-4 cladding) RF = 1.3 ± 0.3%** from Phase 2, 2+, 3 tests)

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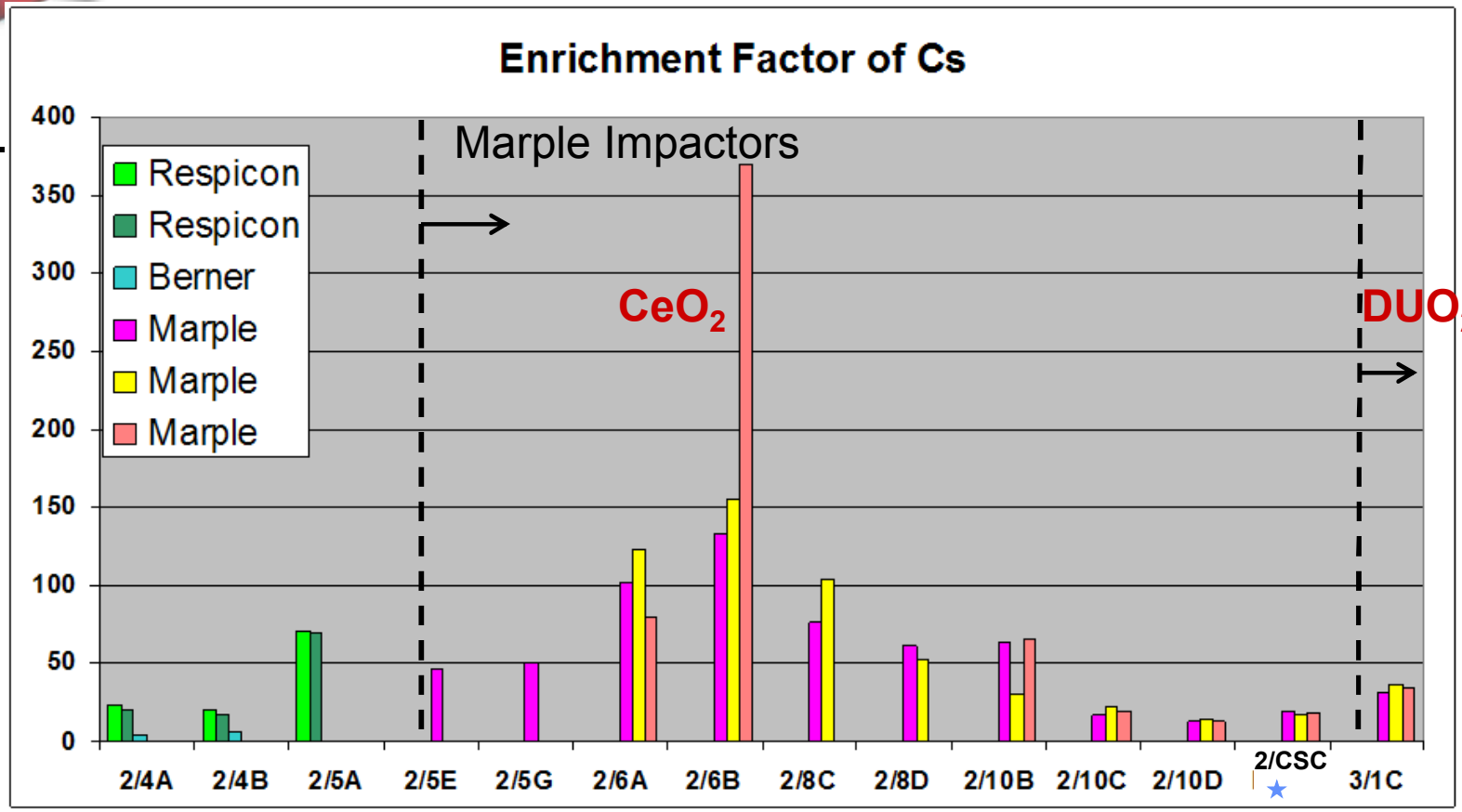
CESIUM Enrichment Factor: Phase 2, 2+, 3

(5/16/07)



- Enrichment Factor, EF = RF_{FP} / RF_{matrix} (integrated, 0-10 µm AED)
- Cs EF = 69 ± 45 ave., Marple Impactors Ce tests (99% confidence interval)
- Cs EF = 59 ± 34 ave., all data, old & Marple Ce tests (99% confidence interval)
- Cs EF = 34 ± 4 ave., Marple Impactors DU tests (preliminary, 99% confidence interval)
  (1 of 4 tests analyzed)

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Cesium Differential Enrichment Factor

- Enrichment Factor computed as a function of particle size at each size class from material collected in LPS and Impactor
- Cs EF falls from ~ 100 at < 1 μm to < 10 at ~ 10 μm (next slide)
- observed increase in CS EF above 10 μm
- data for DUO_2 test 3-1C not as pronounced – flatter curve

- Mass distribution has increase above 10 μm - in most cases

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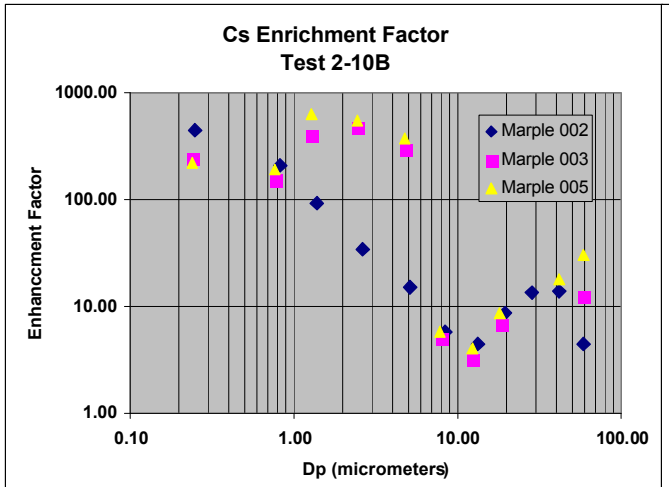
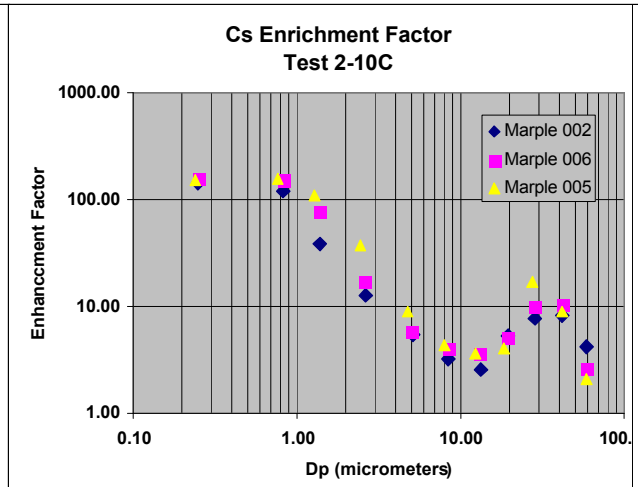
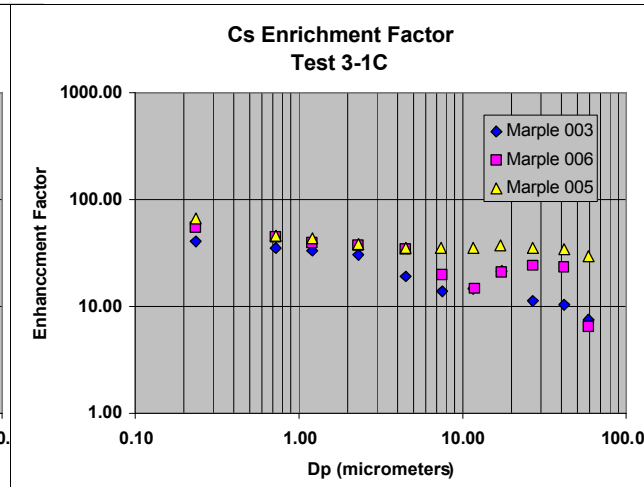
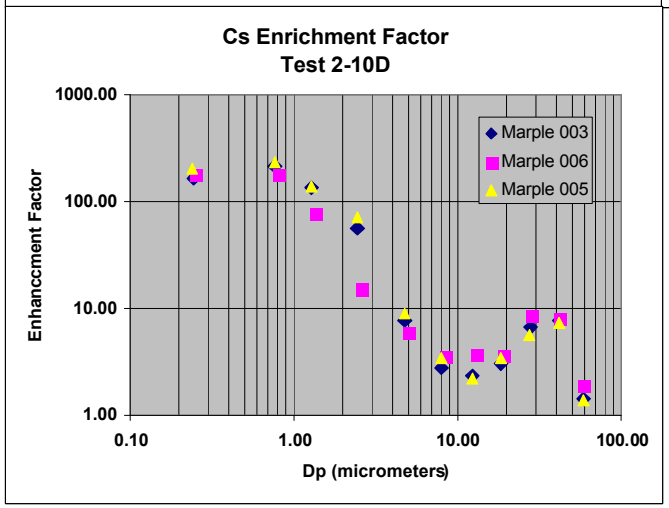
Phase 2+ and 3Tests
Differential Cesium EF

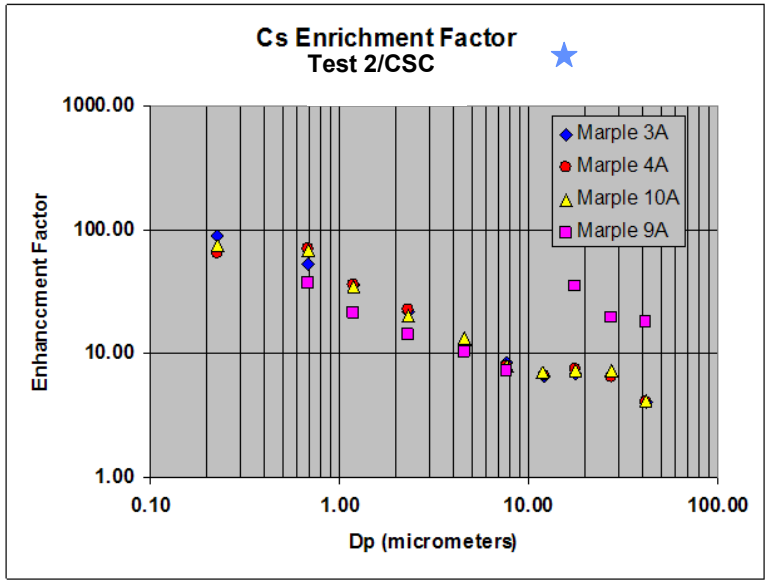
(5/16/07)











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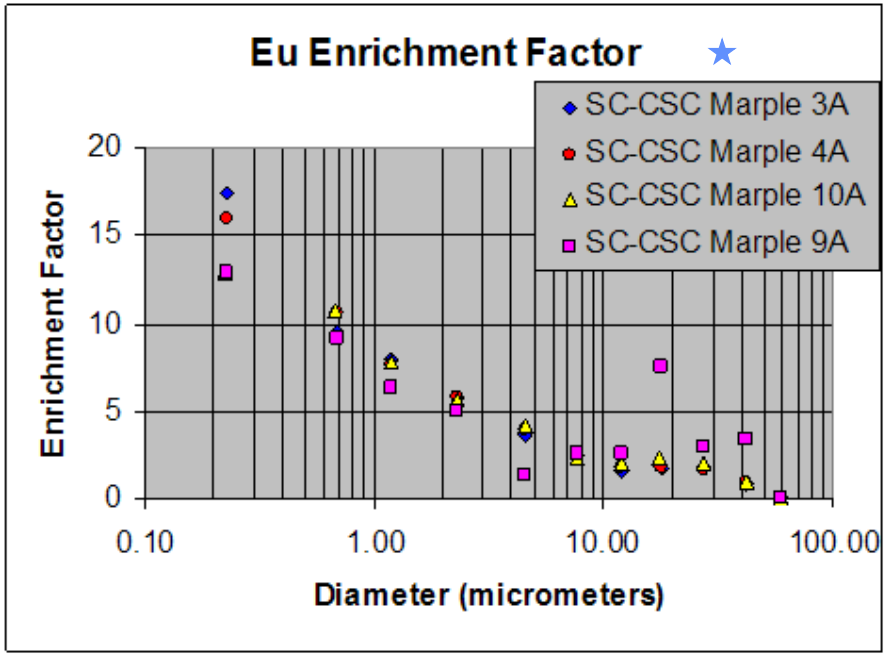
(5/16/07)

Test 2/CSC
Europium Differential EF



- data for strontium RF and EF still being evaluated
- chemical analysis for ruthenium aerosols in progress at GEL Lab

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Aerosol Sampling
Technical Issues, Uncertainties - A

- Particle deposition observed on inside of sampling tubes
  - thermophoretic particle deposition occurs on cooler surfaces
  - diffusiophoretic particle deposition occurs on surfaces that water condenses on
  - turbulence … can enhance particle deposition
- Rapidly changing temperatures and pressure in Phase 2, 2+, 3 test chambers variations in sampling efficiencies, volumetric flow
- Current, <u>preliminary</u> Respirable Fraction (RF) Values may be underestimated by a factor of ~ 2
- Enhancement Factor is a ratio of RF's, uncertainties ~ cancel

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Aerosol Sampling
Technical Issues, Uncertainties - B

- **Resolutions:**

1. **further laboratory aerosol apparatus calibration tests (ongoing) can minimize levels of uncertainties**

2. **complementary testing, in 50 m^3 chamber, test 2/CSC, 3/07**
3. **test 2/CSC results, with chamber Efficiency Multipliers included, tend to indicate that RF values (from other tests) may have uncertainty/underestimation factor of < 2**

4. **lab completion & RF value finalizations … by 9/07**

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NRC RES-Cooperative
Test 2/CSC

- **Spent Fuel Sabotage and Explosive Dissemination Surrogate Test** with **Depts. 6417** (explo. dispersion) + **6765** (transportation), **2554** (aerosol) **cooperation**
- **single test in 50** (48.6) **m^3 aerosol chamber @ SNL, 8 March 2007**
  - eliminates pressure variation during sampling and effects on flow
  - minimizes sampling inlet and sampling tube deposition effects
  - significant dilution of explosive-soot effects
  - target: Phase 2/2+ CeO_2 pellets, Zr-4 tube, with 8 FP dopant disks
  - same CSC and stand-off as Phase 2, Phase 3 vertical chamber tests

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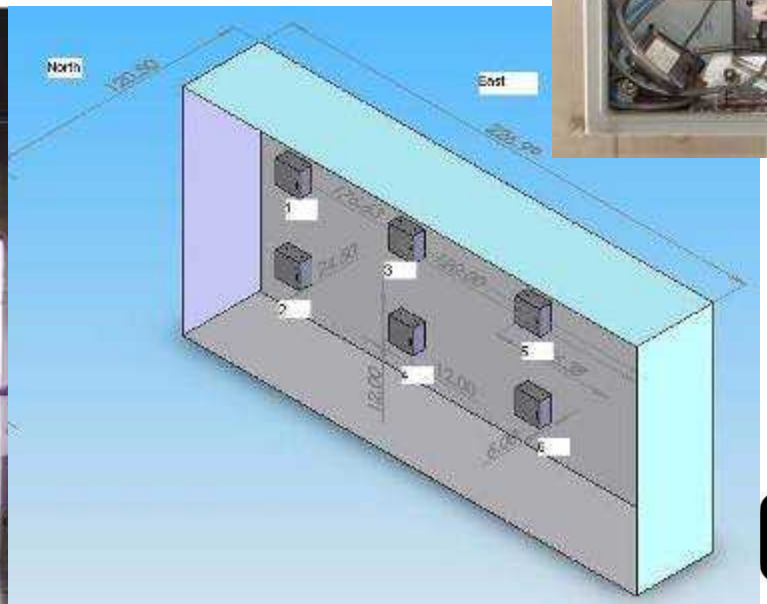
NRC RES-Cooperative
Test 2/CSC

- **Aerosol sampling:**
  - 8 Marple cascade impactors, 12 inline total mass samplers, 2 cyclones, 4 fans (to promote mixing); 12 thermocouples, 1 pressure transducer
  - sampling over longer time (0-15 min, 0-30 min, 15-30 min), with more uniform concentration of smaller particles
  - post-test vacuuming of particles on chamber floor and walls
  - post-test ICP-MS chemical analyses of aerosols



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Current Aerosol Results and Conclusions

- On Sampling
  - Respirable particles are sampled with high efficiency
    - respirable Fractions are accurately determined
    - larger particles have lower but characterized efficiencies
    - sampling uncertainty w/ respect to sample line losses being resolved
- On Enrichment
  - Enrichment of elemental species would require
    - phase change with vapor nucleation/condensation, fragmentation
    - and/or native distribution of material smaller than matrix (CeO_2 or UO_2) fragments
  - Small particle mode arising from soot formation provides condensation sites for vapor and/or nucleation particles
    - soot and Cu and Cs distributions are correlated
  - Materials that are more uniformly distributed in the matrix may behave differently than the same materials located at discrete points in or adjacent to the matrix - - <u>but test results inconclusive</u>

WGSTSC
Spent Fuel Sabotage Aerosol Ratio
4-Phase Test Program:

Phase 4: Spent Fuel Rodlets

- explosive - aerosol testing, with actual SNF
- needed for SFR determination
- U.S. PWR spent fuel rodlet segments, characterization and fabrication at Argonne National Laboratory

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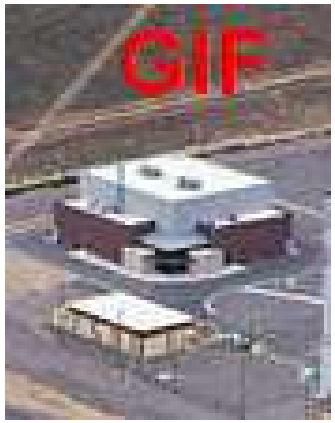
w/ high & low-mid burn-up:
4 - H.B. Robinson, 72 GWd/MTU
4 - Surry, 38 GWd/MTU

(~ same rodlet design as Phase 3)

- *8* tests @ SNL GIF (… 2009)
- now* 1-Atm internal; air or N_2 in test chamber
- wt. & γ @ SNL + post-test particle ICP/MS @ ANL



- SNL GIF feasibility study, 8/2002
- DOE SSO approved GIF DSA & SER, 6/2007

- post-test SNF test chambers to INL, in GE 2000 cask (temp. storage, then YM)

- ➡ (CONTINGENCIES …)

2 of 8 test chambers fabricated
(one-time use only)

WGSTSC
Spent Fuel Sabotage Aerosol Ratio
4-Phase Test Program:

Test Phase 4: Actual Spent Fuel (PWR) Rodlets		
Test #	Pressure ^	Variables
4/1	~ 44 bar (rod plenum)	H.B. Robinson, high-burnup, ~72 GWd/MTU
4/2	~ 44 (He)	Air (in aerosol chamber)
4/3	~ 44	N_2
4/4	~ 44	N_2
4/5	~ 33 bar	Surry, low-med burnup, ~38 GWd/MTU
4/6	~ 33 (He)	Air
4/7	~ 33	N_2
4/8	~ 33	N_2

^ modified to 1 bar He (2006)

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Sandia Tech Area-V Facilities

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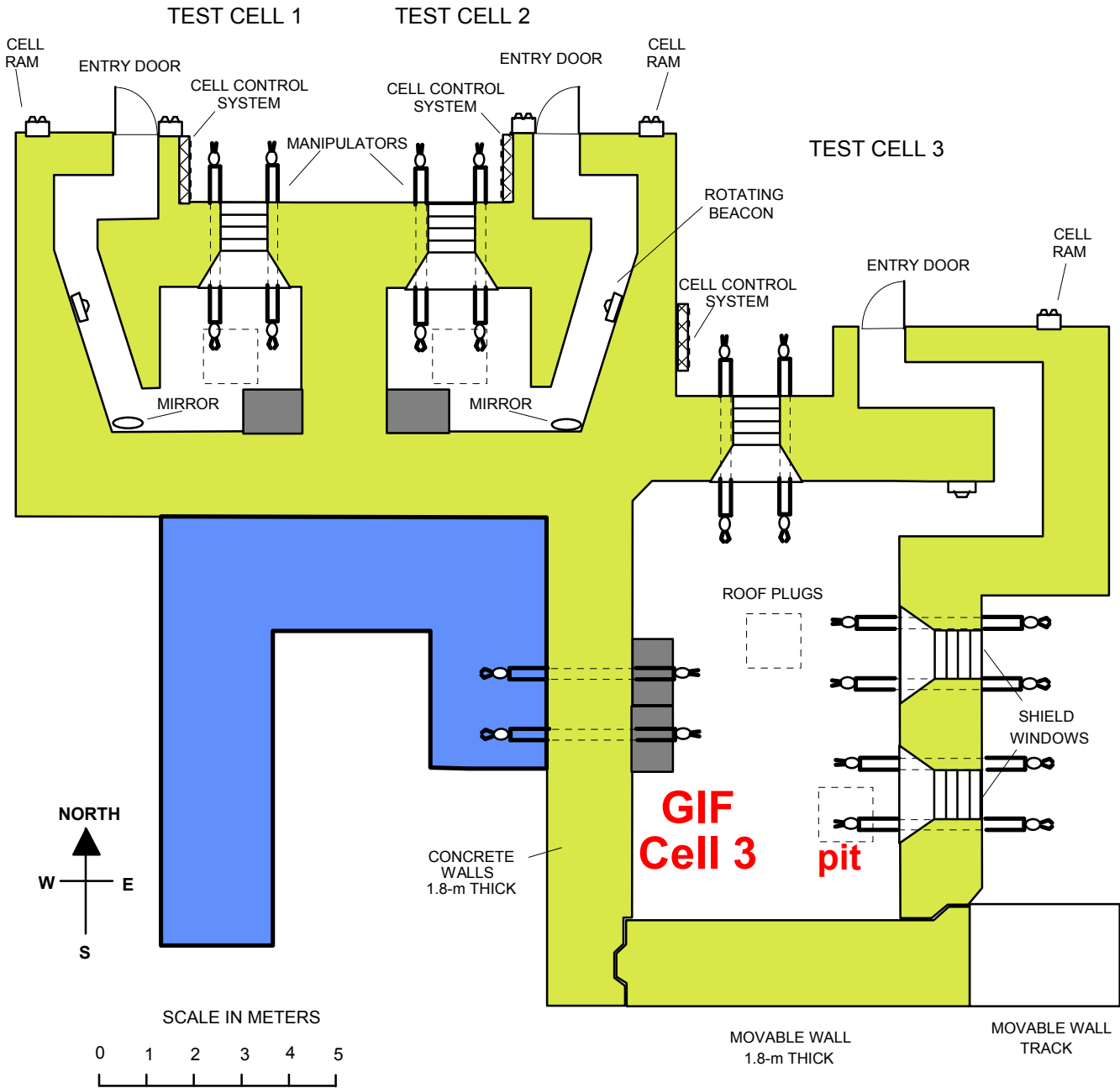

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GIF Cell 3

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Spent Fuel Sabotage
Phase 4 Test Completion

- **Plan to:**
  - perform 8 Phase 4 spent fuel tests in GIF, 2008 - 2010
  - perform aerosol particle analyses, at SNL & ANL, 2009-10
  - clean-up GIF, put post-test chambers in GIF storage, 2010
  - perform supporting modeling studies at SNL, w/ WGSTSC
  - technical and NUREG reports, to come

- **Contingencies being addressed:**
  - all schedules dependant on future adequate funding
  - successful Yucca Mountain Repository license application
  - ANL completion of spent fuel rodlet fabrication
  - DOE RW & EM agreements on post-test shipment and storage of SNL test chambers at INL
  - other minor issues

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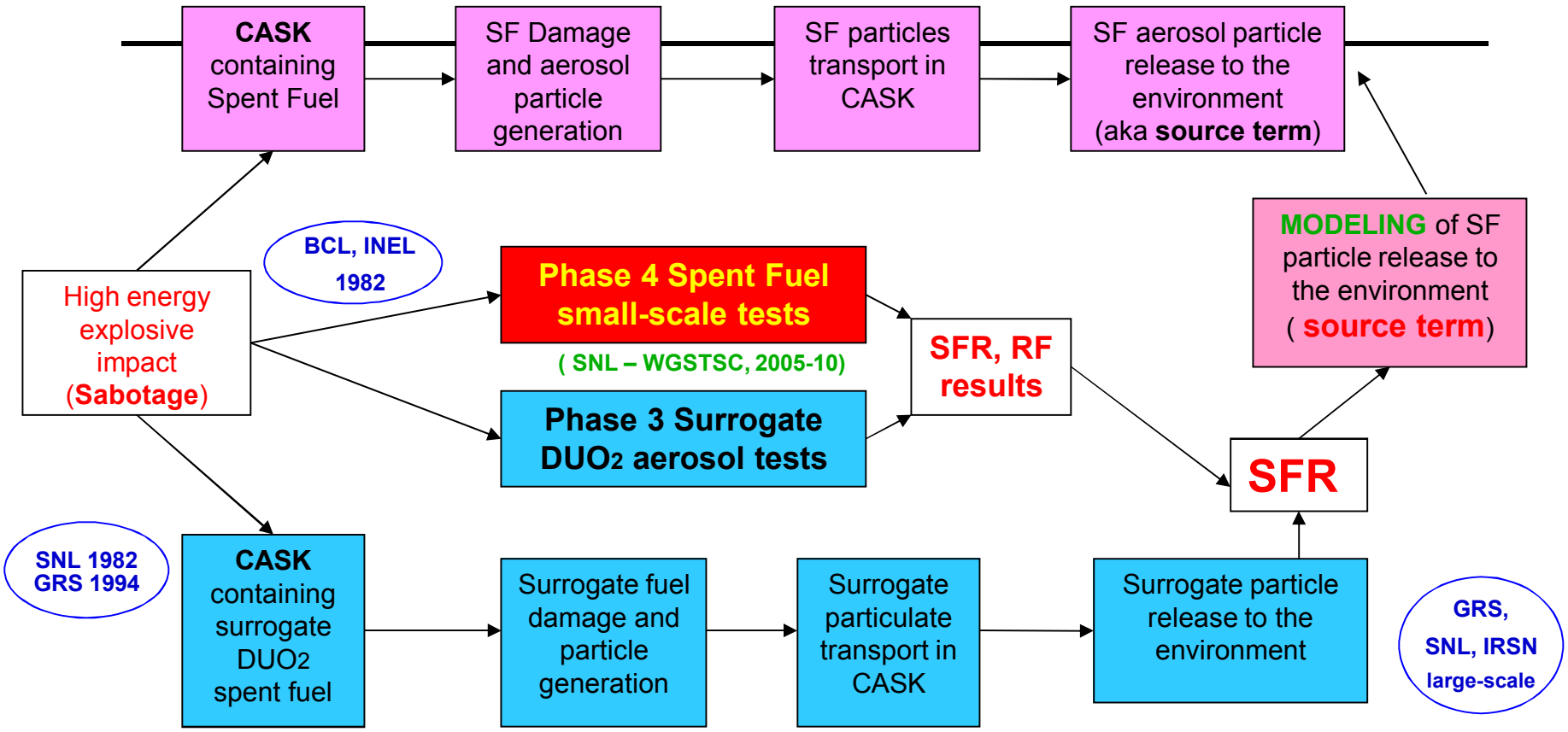
Spent Fuel Sabotage
WGSTSC Program Progressions

1. from small-scale, simplified rodlet testing focus (now)
2. to planned large, cask-scale WGSTSC surrogate testing (by GRS in Germany, with IRSN)
3. to primary, continuing modeling follow-on analyses by all WGSTSC partners
4. informal Memorandum of Understanding (MOU) and formal Multilateral Agreement (MLA) between parties to allow sharing of classified information, in process now
5. interactive test and modeling cooperation continues

(2008 ➡➡)

Testing + Data Use and Modeling Correlations



TEST DATA + MODELING: tie
small-scale SNF & intermediate surrogate results
to Spent Nuclear Fuel CASK release consequences

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Spent Fuel Sabotage Data Applications

- Source-term data to be used for modeling of radiological dispersal hazards and consequences, atmospheric dispersion, vulnerability assessments, support for multiple governmental and regulatory agency needs
- Provide basis for parametric evaluations, other scenarios

- Parallel modeling efforts (Sandia: NRC, DOE; WGSTSC; others)
  - near-field aerosol dispersion
  - computational fluid dynamics; transport cask relevant
    - MELCOR, CTH Hydrocode, SCAP, CSC Jet
    - Similar French (SPH) and German modeling …
    - RADTRAN modeling studies
  - effects of cask hole size, internal P & T on blow-out releases; rod bundle fragmentation vs. deformation studies
  - test program results tie to vulnerability program studies …

- Other international follow-on modeling and consequence assessments relevant to transportation safety and repository evaluations …

GRS IRSN Sandia National Laboratories

Modeling
Technical Issues to Consider …

- **Generation Mechanisms**
  - Direct Fragmentation
    - Material phase changes: Melting, Vaporization
    - Enrichment
  - Gap Blow down
    - Dependent on actual rod internal rod configuration and available material and composition
    - Entrainment
- **Transport Mechanisms**
  - From Point of Generation to Bundle Boundary
  - From Bundle Boundary to Cask Breach
- **Energy Relationships**
  - Specific Energy Input
  - Particle Material Distribution
  - Respirable Fraction (RF) and Enrichment Factors (EF)
- **Matrix Dependence**
  - Cerium Oxide, other surrogates
  - Depleted Uranium Oxide
  - Spent Fuel (UO2)
  - Other fuels (TRIGA, MOX, etc.)
- **Scale Effects**
  - Single (short) Fuel Rod – Data From Current Test Program
  - Fuel Rod Bundles – historical Data and Future German (w/ US, France) Tests

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