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Review of the Spent Fuel Sabotage Aerosol Test Program

Exceptional service in the national interest

Sandia National Laboratories

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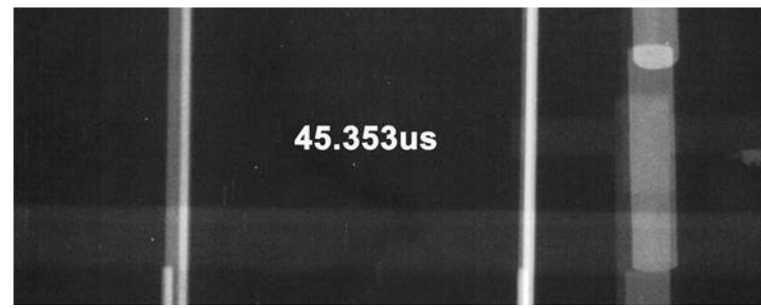

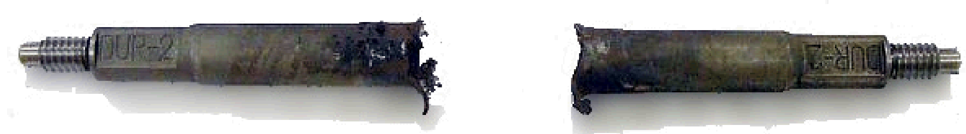

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Motivation

- Spent fuel transport expected to increase dramatically
  - Consolidated storage by 2025
- Need to understand the consequences of an attack on a spent fuel transportation cask
  - How significant would the radionuclide release be?
    - The consequence is proportional to the Release Fraction (RF) of the fuel disrupted
      - RF = Aerosol Mass Generated/Mass of Fuel Disrupted
  - How much fuel can be disrupted inside of a transportation cask?
    - Large-scale transportation cask testing has been conducted using DUO_2 surrogate fuel
  - Spent Fuel Ratio (SFR) is the comparison of the release fraction from spent fuel to the release from DUO_2 surrogate fuel
    - Current estimates inconclusive (SFR ranges from 0.4 to 12)
    - More defensible SFR determination would aid shipping campaign

Background

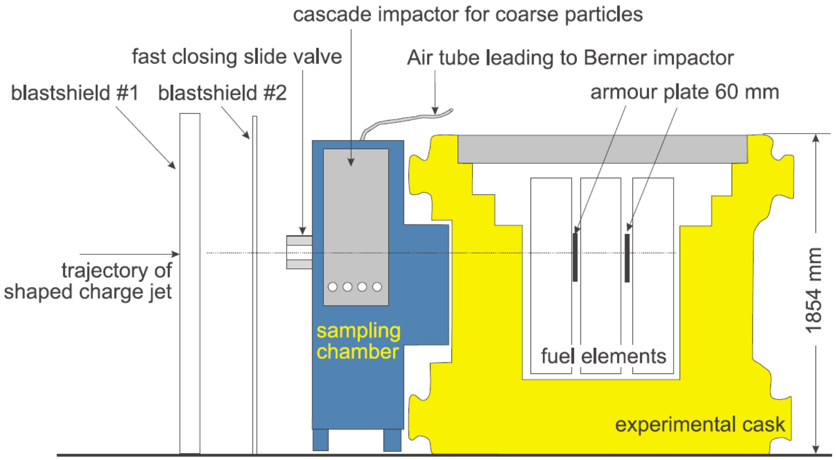
- Surrogate fuel pellets likely aerosolize differently than actual spent fuel
  - Spent fuel pellets are highly fractured
- Data needed to scale release fractions determined from previous large-scale tests conducted with surrogate (DUO_2)
- Spent Fuel Ratio (SFR) quantifies the aerosols produced by a high energy device (HED) acting on spent fuel compared to a surrogate material
  - $SFR = \frac{RF_{\text{Spent Fuel}}}{RF_{\text{Surrogate}}}$, Aerosols AED* $< 10\ \mu m$
  - Enrichment/Enhancement factors
    - Chemically reactive fission products may have enhanced mobility at moderate temperatures ($> 400\ ^\circ C$)
    - Primarily Cs-134 and Cs-137
- Underlying physics highly complex

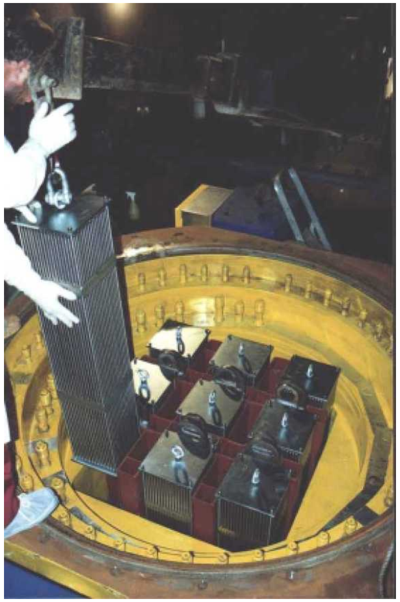
* Aerodynamic Equivalent Diameter (AED)

DUO_2 Tests

- Large scale testing used DUO_2 surrogate fuel pellets
  - DOE/SNL – Early 1980's
    - Obsolete truck cask and ¼-scale tests
  - Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) – Early 1990's
    - Truncated CASTOR IIa with pressurized fuel rods
- Small scale Spent Fuel Ratio (SFR) testing used CeO_2 and DUO_2
  - Funded under DOE Yucca Mountain effort

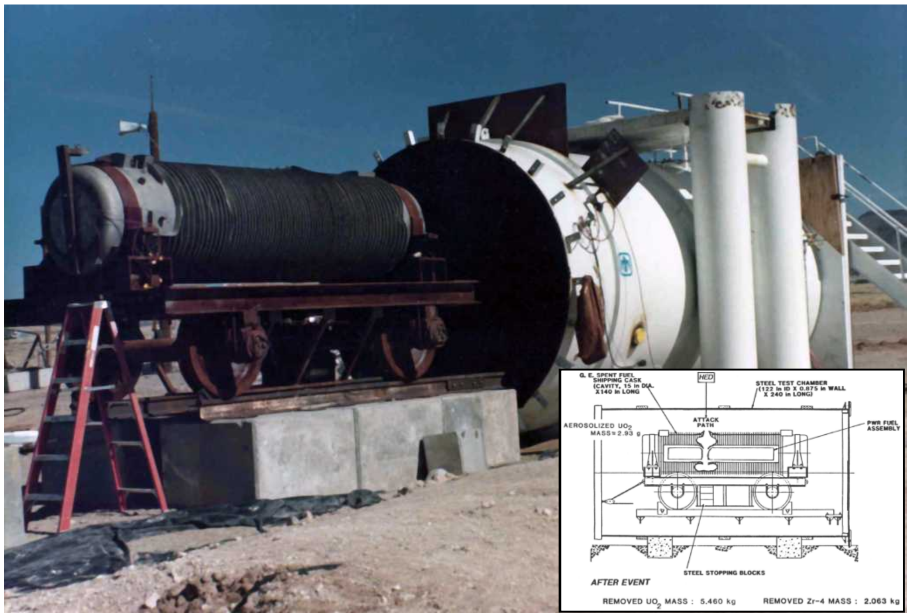
GRS Full-Scale Tests

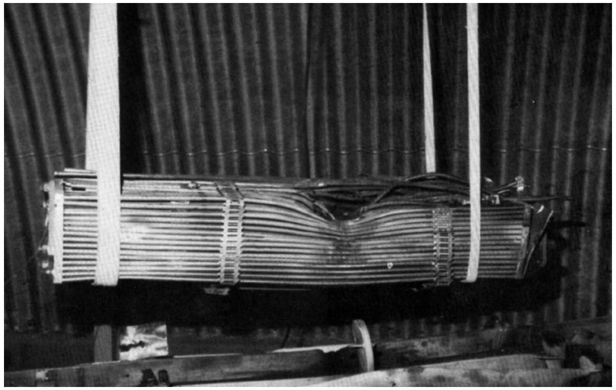




- Pretzsch, G. and Lange, F., "Experimental Determination of UO_2-Release from a Transport Cask for Spent Fuel Elements after Shaped-Charge Attack," GRS-A-2157e
- Full-scale but truncated target
  - 17×17 PWR assemblies with fuel pressurized to 40 bar
  - Cask made of cast iron with ball graphite
- Three attacks on the same cask
  - Two at atmospheric, one at sub-atmospheric (0.8 bar)
  - First two attacks released 1 g for AED < 12.5 µm
  - Third attack (0.8 bar) 0.35 g for AED < 12.5 µm

DOE Large-Scale Testing



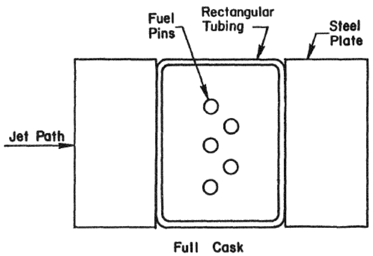


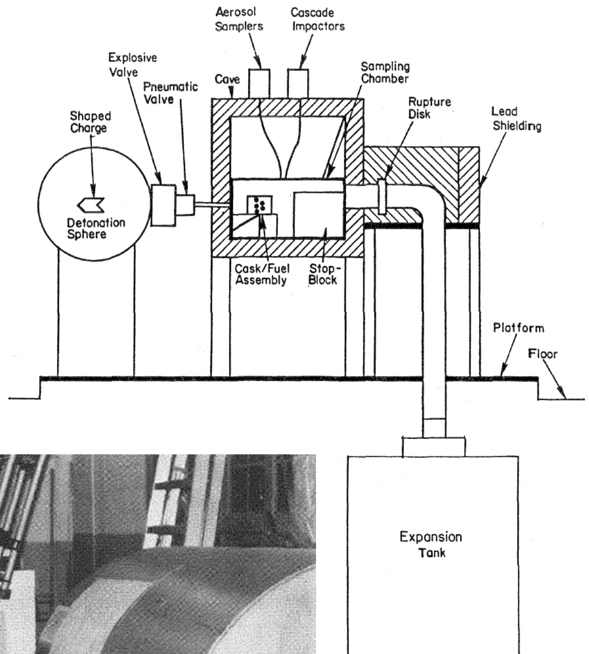
- Sandoval, R.P, et al., “An Assessment of the Safety of Spent Fuel Transportation in Urban Environs,” SAND82-2365
  - Funded by DOE in response to “Urban Study” (DuCharme 1978)
    - Assumed 1 % of cask contents released as respirable aerosol
    - Led to restrictive interim regulations by NRC
- Several ¼ scale tests
  - Simulating wet and dry casks
- One full-scale test of obsolete truck cask
  - 15×15 PWR truncated assembly with DUO_2
    - Fuel unpressurized
    - ~3 g released in “respirable” range

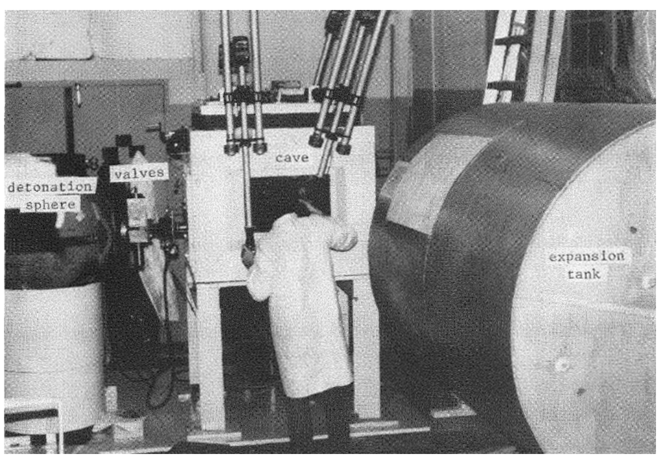
Previous SFR Determination Attempts

- Two parallel attempts in early 1980's to measure the SFR to support transport program
  - BCL – Schmidt funded by NRC
  - INEL – Alvarez funded by DOE
  - Spent fuel and DUO_2 tested with limited success
- Experimental program in 2000's
  - SNL – Molecke funded by DOE/RW
  - Phase 4 (Spent Fuel) uncompleted

Shipping Cask Sabotage Source Term
(Battelle Columbus Laboratories)

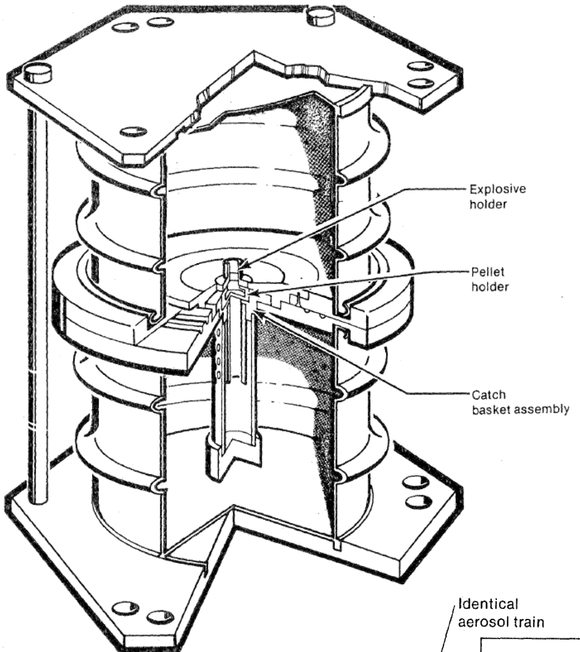


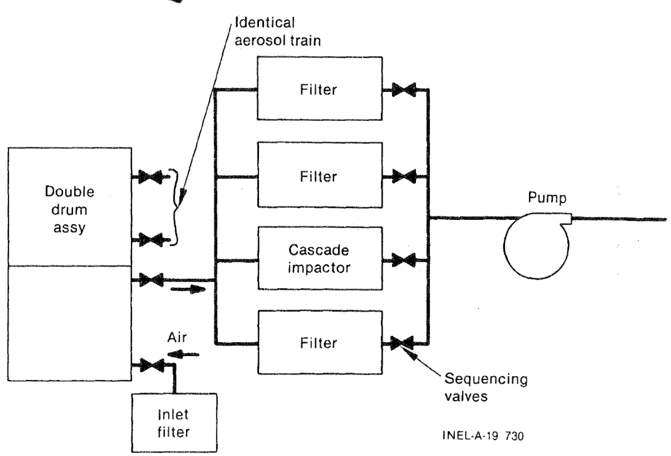




- Schmidt, E.W., et al., “Final Report on Shipping Cask Sabotage Source Term Investigation,” NUREG/CR-2472
- Analysis of BCL results by Sandoval (SAND82-2365) gives SFR = 0.42 to 0.71
- Subsequent review by Luna (SAND99-0963) suggests SFR = 2.5 to 12
  - Limited DUO_2 aerosol cassette data available in BMI-2089
- Experimental uncertainty not quantified

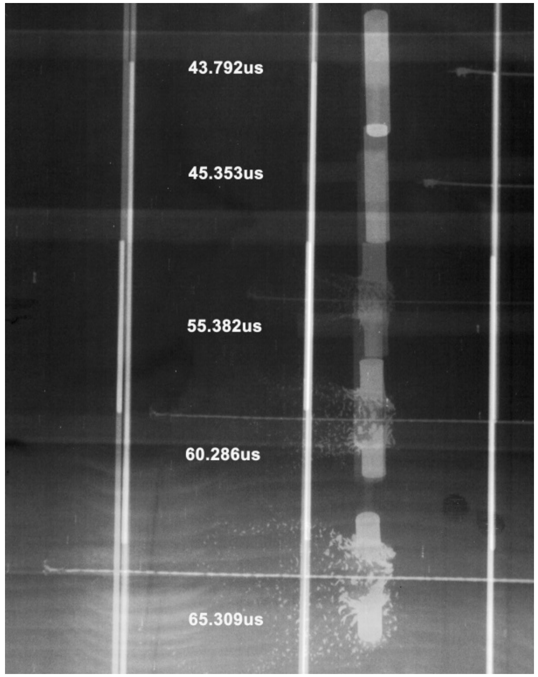
Waste Forms Response Correlation Testing (Idaho National Engineering Laboratory)





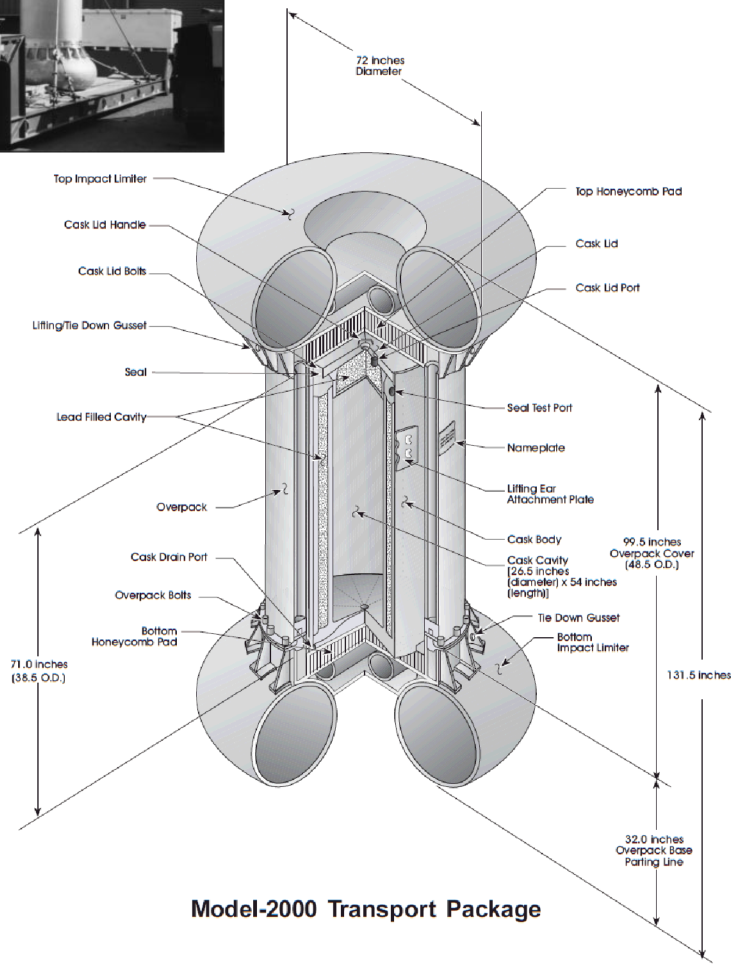
- Alvarez, J.L. and Kaiser, B.B., "Waste Forms Response Project Correlation Testing," EGG-PR-5590
- Relatively small tests
  - CSC (1.1 g explosive mass)
  - Targets (10.4 g)
- SFR reported as 5.6
  - Based on questionable extrapolation of wet sieve data
  - Bulk aerosol measurements give SFR = 0.53
    - Impactor samples were dropped, preventing more accurate analysis
- CSC combustion products in aerosol sample
  - Estimated at 25% of samples
- Experimental uncertainty not quantified

Spent Fuel Sabotage Test Program
(Sandia National Laboratories)



- Molecke, M.A., et al., "Spent Fuel Sabotage Test Program, Characterization of Aerosol Dispersal: Interim Final Report," SAND2007-8070
- Experimental vessel explicitly designed for radioactive disposal after spent fuel testing
  - No spent fuel tested (Phase 4)
- CSC combustion products in aerosol sample
  - Contamination of aerosol samples
  - Introduction of water vapor into sample train
    - Likely caused condensation and therefore undersampling of aerosols
- Experimental uncertainty not quantified in original analysis
  - Later analyzed by Lindgren and Durbin (SAND2009-4484)

Disposal of SNL Test Chambers



Model-2000 Transport Package

- SNL test chambers designed to fit inside GE-2000 transport cask
- Interim storage facility
  - Chamber enclosed within stainless steel overpack for storage
    - Not yet designed
  - Was tentatively set for INL
- Final storage was envisioned at Yucca Mountain
  - Inside 24 in. DOE standardized SNF canisters
- New, viable path for disposal needed for future testing
  - May require complete chamber redesign

Experimental Issues

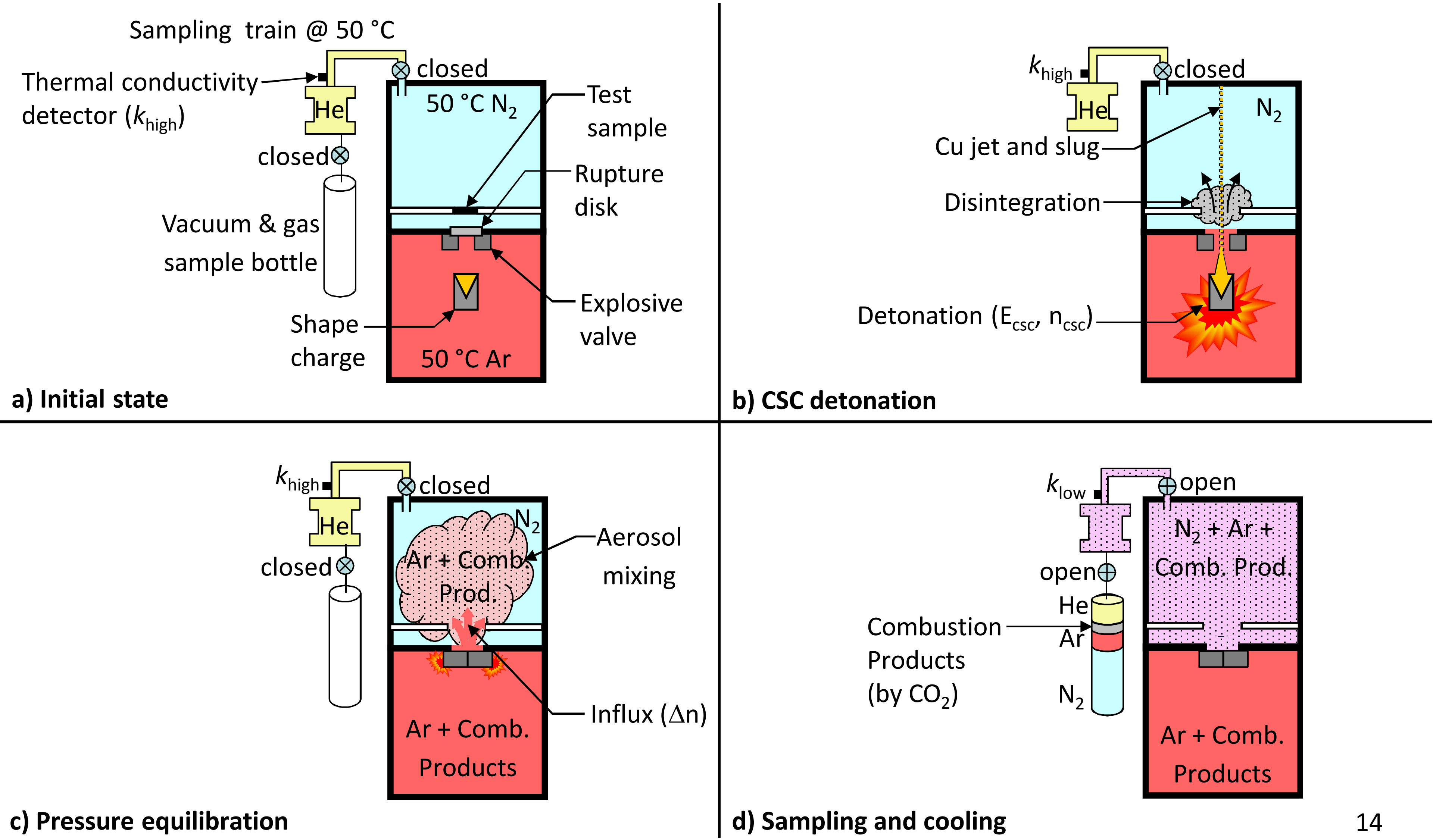
- Combustion product contamination of aerosol sample
  - Carbon particles (soot)
    - Overwhelm aerosol sampling system
  - Water condensation in sampling system
    - Particle loss to walls
  - Pressure and temperature excursions
    - Complicates data interpretation

- Need to carefully quantify experimental uncertainty
  - Statistically significant number of repeat surrogate tests needed
  - Minimize target size (especially spent fuel)

Experimental Improvements

- Reduce target size to single pellet
  - Minimize spent fuel mass and curie load
  - Maintain statistical significance
- Minimize combustion product contamination of aerosol sample
  - Explosive valve isolation
  - Segregated chamber and sample system gases
    - Aerosol sample collection timing mark
    - Combustion product exclusion verification or correction
- Delay sample collection ~20 seconds to allow chamber equilibration
  - Pressure and temperature
- Heat chamber and sample system to above dew point temperature

Sequence of Improved Apparatus



Efficiency through Integrated Testing and Modeling

- Closely coupled experimental and modeling efforts
  - DOE developed shock code (CTH)
  - Predict fragmentation and aerosolization from CSC
- Overall approach similar to SFP
  - Exp design → Pre-test prediction → post-test analysis
  - Use experimental data to validate modeling
    - Not just produce a data point
- Focus more on DUO_2 ceramic targets
  - Homogeneously dispersed decay product surrogates
  - Key for determining enrichment factors
- Determine release as function of characteristic fragment size
  - Parametrically mimic mechanical degradation of spent fuel pellets
- Minimize spent fuel testing

Summary

- Previous efforts have not produced a defendable SFR
  - SFR still needed
  - However, many lessons have been learned
- Moving forward
  - Take the best from each study
    - Explosive valve from BCL study (Schmidt)
      - Minimize combustion gas contamination
    - Single pellet size, small CSC from INL (Alvarez)
      - Well defined disrupted mass and minimize radioactive content (Curies)
    - Design for disposal from SNL (Molecke)
      - Predetermined path
    - Statistical analysis and improved experimental design from SNL (Lindgren and Durbin)
      - Minimize experimental errors and determine statistical uncertainties
  - Closely couple experimental and modeling efforts
    - Validate modeling (not just produce a data point)
    - Predict burnup effects