Chernobyl: How It Happened
The Physics and the Human Factors
Light Water vs. RBMK Reactor

Containment structure
Reactor vessel
Pressurizer
Turbine
Generator
Coolant circulation
Steam generator
Reactor core

Control rods
Radiation shield and containment structure
Steam separator
Steam
Water
Graphite moderator
Fuel rods
Pump

Source: GAO, based on Department of Energy documentation | GAO-15-652

Prof. Michael P. Short
MIT Mesoscale Nuclear Materials Laboratory
Cross Sections (Barns) Give Nuclear Reaction Rates

HE COULDN'T HIT

THE BROAD SIDE OF A BARN

mematic.net
Water and Graphite Slow Down Neutrons…
… and Water Helps Absorb Neutrons, Slowing Fission

![Graph showing neutron absorption and moderation](image)

- Neutrons born here
- Fission happens here
- Moderation

![Diagram of neutron energy and absorption](image)
What Happens When The Water Is Gone?

Prof. Michael P. Short

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Water Helps Absorb Neutrons, Slowing Fission

Prof. Michael P. Short

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Xenon Poisoning and Its Half Life

Half Life: ~9 Hours

Absorption (barns)

Neutron Energy (eV)

Xenon - 131
The Human Factors Which Led to Chernobyl

Prof. Michael P. Short

MIT Mesoscale Nuclear Materials Laboratory
The Energetic Fingerprints of Tiny Amounts of Radiation Damage

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Goal: Verify Historical Uranium Enrichment

• Question to Ask Ourselves:
  – What is the lowest radiation dose that gives useful information?
  • Implications for basic science, reactor safety, and nuclear security

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Goal: Verify Historical Uranium Enrichment

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How much was made?
What was the enrichment?

Alpha radiation will leave a signature in the material that contains UF₆

Grossly simplified centrifuge diagram

U → α + daughter

2³⁵UF₆
2³⁸UF₆
Goal: Verify Historical Uranium Enrichment

Low expected fluences:
- $5 \times 10^9 \text{ } \alpha/\text{cm}^2 = 1 \text{ year of LEU}$
- $1 \times 10^{11} \text{ } \alpha/\text{cm}^2 = 1 \text{ year of 90\% enriched}$

How much was made?

How low can you go?
Focus on Energy Fingerprint of Phase Transformations

- **Wigner energy (defects)** – J/g stored energy
  - 0.1-2.0 J/g for most metals (Snead et al., JNM 2019)
- **Phase transformations** – 100-1000 J/g stored energy
  - If radiation can nucleate phase transformations, measure *these* signals!

Example centrifuge train schematic

- **Al 7075-T6**
- **SS 304**
- **PTFE/PCTFE**

How much was made?
Examine the PTFE (Teflon™) Gaskets First

Radiation breaks chemical bonds, creating the potential for crosslinking to occur.

Cambridge Laboratory for Accelerator Surface Science:
- Irradiated PTFE with 4.5 MeV He$^{2+}$ ions
- Three fluences: $10^{10}$, $10^{11}$, and $10^{12}$ α/cm$^2$

How much was made?

Two bombs worth of UF$_6$ at 5% enrichment

One bomb worth of UF$_6$ at 90% enrichment

Al 7075-T6

PTFE

SS 304
Measuring Radiation Damage using Calorimetry

Output: Heat flow to or from the sample

Heat capacity, phase transformations

Reference Pan

Sample

Net heat conduction

Simplified DSC Schematic

Differential Scanning Calorimetry

How much was made?

TA Instruments Discovery DSC

http://www.tainstruments.com/dt_gallery/discovery-dsc/
How It Works: Measure Differential Heat Flow

Output: Heat flow to or from the sample

Heat capacity, phase transformations

Reference Pan

Sample

Net heat conduction

Simplified DSC Schematic

Differential Scanning Calorimetry

How much was made?
Correct for the “DSC Hook” – Feedback Settling

Output: Heat flow to or from the sample

Reference Pan

Sample

Net heat conduction

Heat capacity, phase transformations

Simplified DSC Schematic

Differential Scanning Calorimetry

How much was made?
Establish Baseline Heat Capacity Outside Data Window

Output: Heat flow to or from the sample

Heat capacity, phase transformations

Net heat conduction

Reference Pan

Sample

Simplified DSC Schematic

Differential Scanning Calorimetry

How much was made?
Measure Heat Gain/Loss During Transformation

Output: Heat flow to or from the sample

Heat capacity, phase transformations

Net heat conduction

How much was made?

Differential Scanning Calorimetry

Simplified DSC Schematic
Output: Heat flow to
or from the sample

Reference Pan
Sample

Net heat conduction

Heat capacity, phase transformations

Differential Scanning Calorimetry

Melting of PTFE

How much was made?
Choose a Baseline for Subtraction

Output: Heat flow to or from the sample

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Simplified DSC Schematic
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- Reference Pan
- Sample
- Heat capacity, phase transformations
- Net heat conduction

Differential Scanning Calorimetry

Melting of PTFE

Construct a Baseline

How much was made?
Extract Parameters of Interest, Repeat!

Output: Heat flow to or from the sample

Differential Scanning Calorimetry

Melting of PTFE

- Melting temperature
- Construct a Baseline
- Enthalpy of melting
DSC of Irradiated PTFE Shows Very Distinct Changes

How much was made?
Confirming Enrichment Levels in Each Sample

What was the enrichment?

Monoenergetic, unidirectional alphas from our accelerator

Monoenergetic, omnidirectional alphas from a UF$_6$ gas
How Do We Effectively Sample in the Field?

- Extract gaskets, etc. from an enrichment plant
- Microtome (cut) into equal, micron-sized thicknesses
- Use DSC on each … but mass is 1000x too small!
  - Need 1mg for DSC, we get 1µg this way
- Switch instruments…

What was the enrichment?

How much was made?
Field Sampling: NanoDSC (Calorimeter on a Chip)

Vapor-deposited Cu on nanoDSC MEMS chip

Image of <500nm thick Cu spot on nanoDSC chip

How much was made?

What was the enrichment?
Improving with FIB Liftout Techniques

How much was made?

What was the enrichment?
3.47x10^{-6} \text{ J} / 28.6624 \text{ J/g} = 121 \text{ ng} \quad 7 \mu m \times (50 \mu m)^2 \times 7.31 \text{ g/cm}^3 = 128 \pm 9 \text{ ng}

Confirmation of In Mass Calibrates the Technique

Test Sample:

- Cu – 10 \mu m
- In – 7 \mu m

How much was made?

What was the enrichment?

(Note: chip not corrected)
We Use Nanocalorimetry to Reliably Measure Radiation Damage in PTFE

Prof. Michael P. Short
MIT Mesoscale Nuclear Materials Laboratory

Slide 30
Microtomed Flash NanoDSC Confirms Alpha Radiation

- NanoDSC confirms DSC data with 1μm slice precision
- Range verification eliminates ability to “spoon” results to fool inspectors
- DSC and nanoDSC absolute measurements agree well
- This is a new, field-ready technique for IAEA inspectors to confirm enrichment activities!
The Energetic Fingerprints of Tiny Amounts of Radiation Damage

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