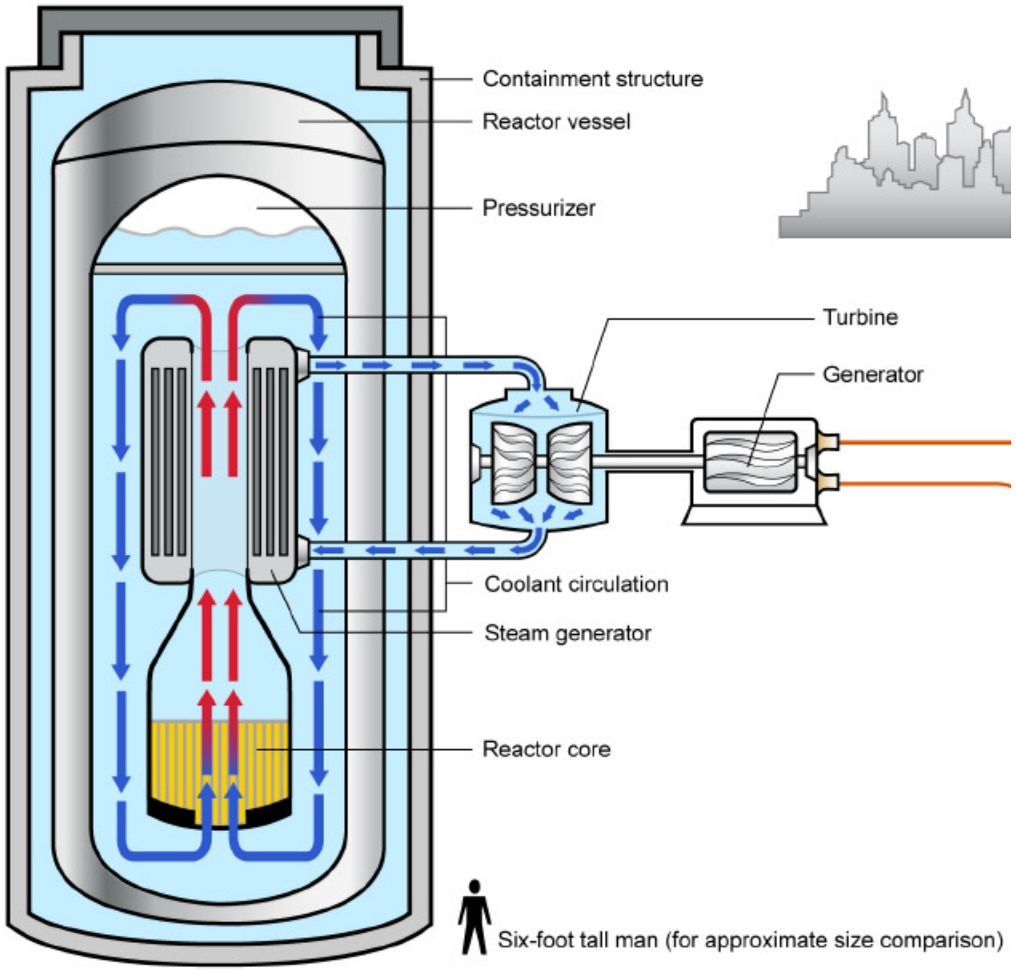
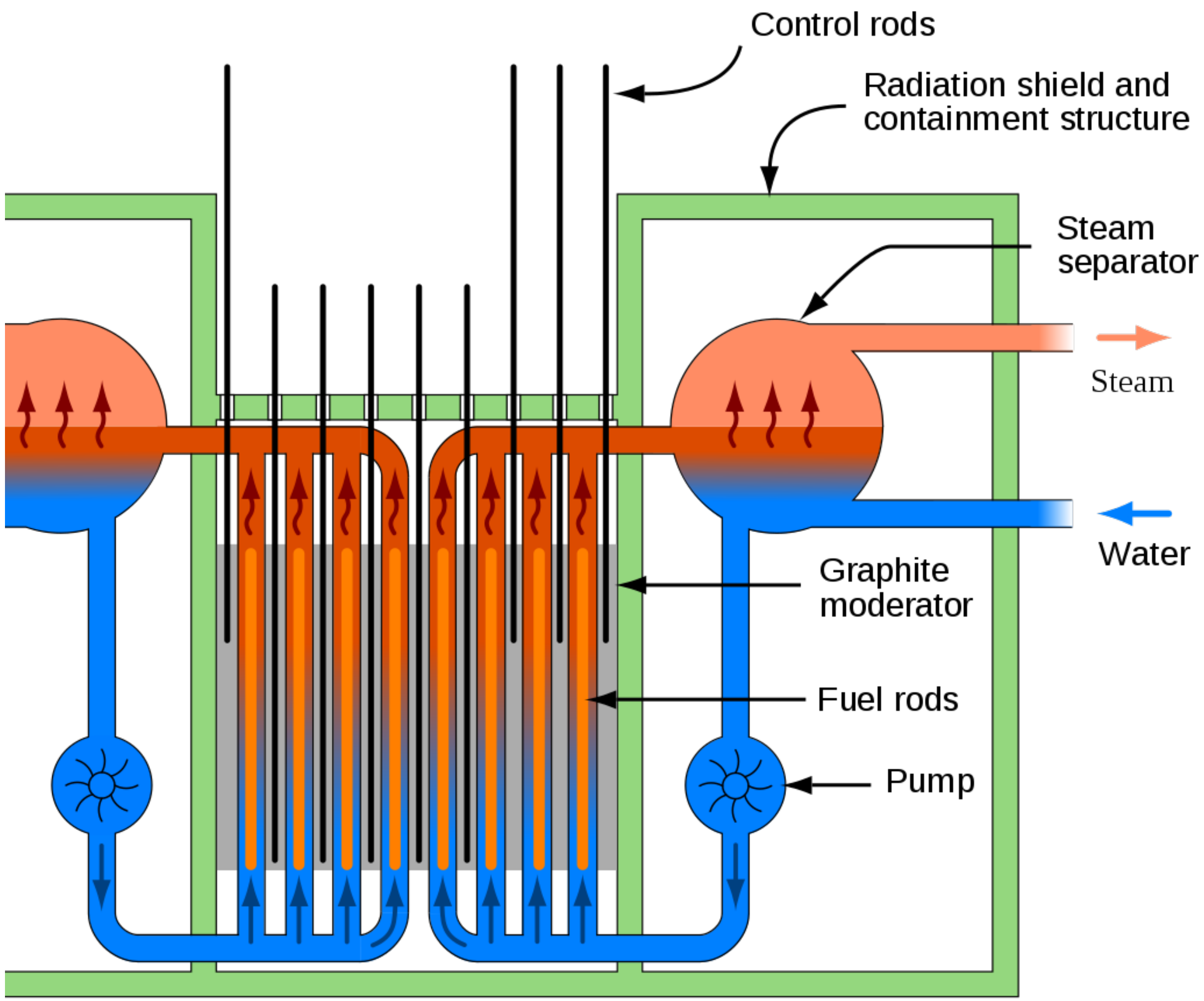
Chernobyl: How It Happened

The Physics
and the Human Factors

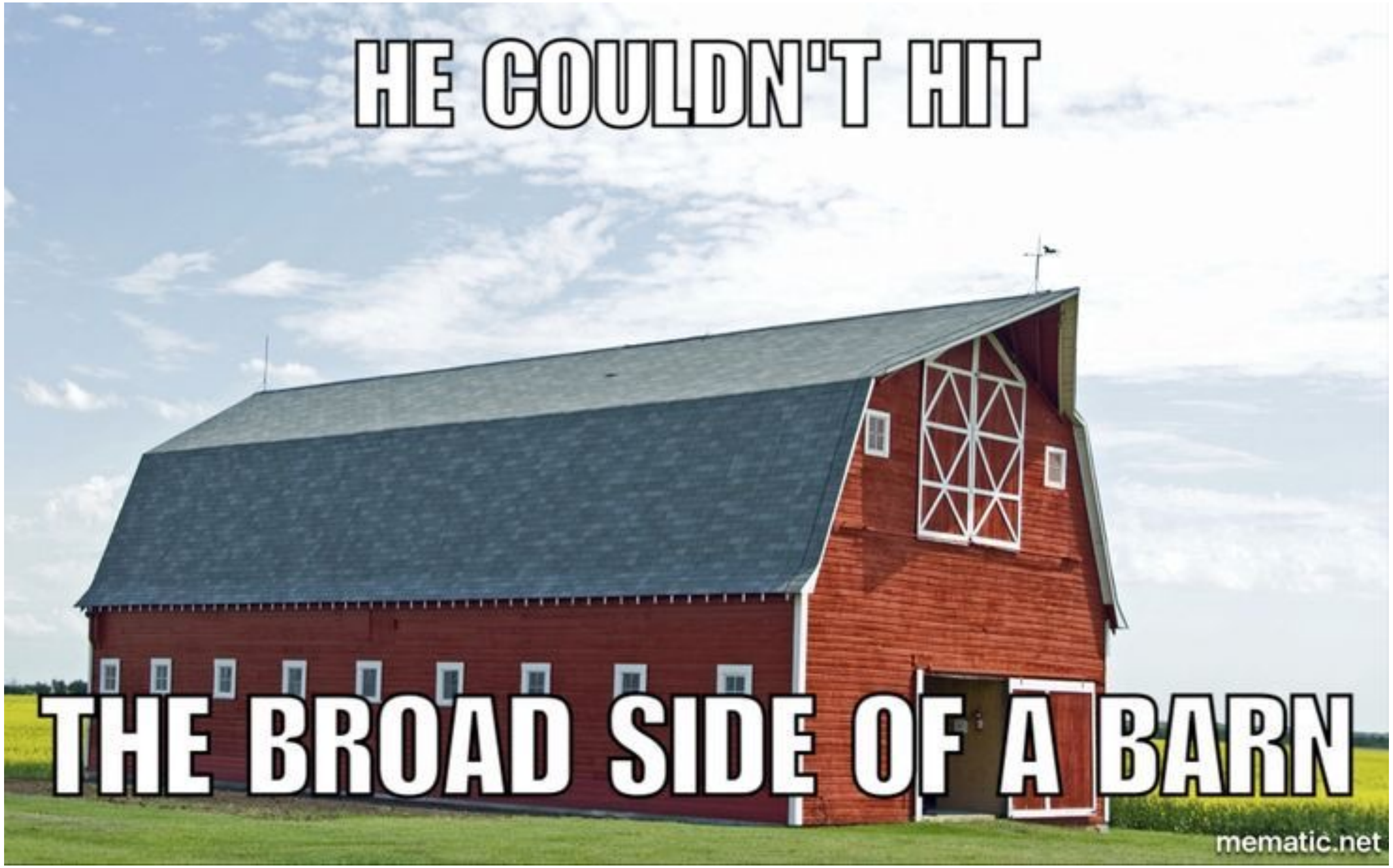
Light Water vs. RBMK Reactor



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

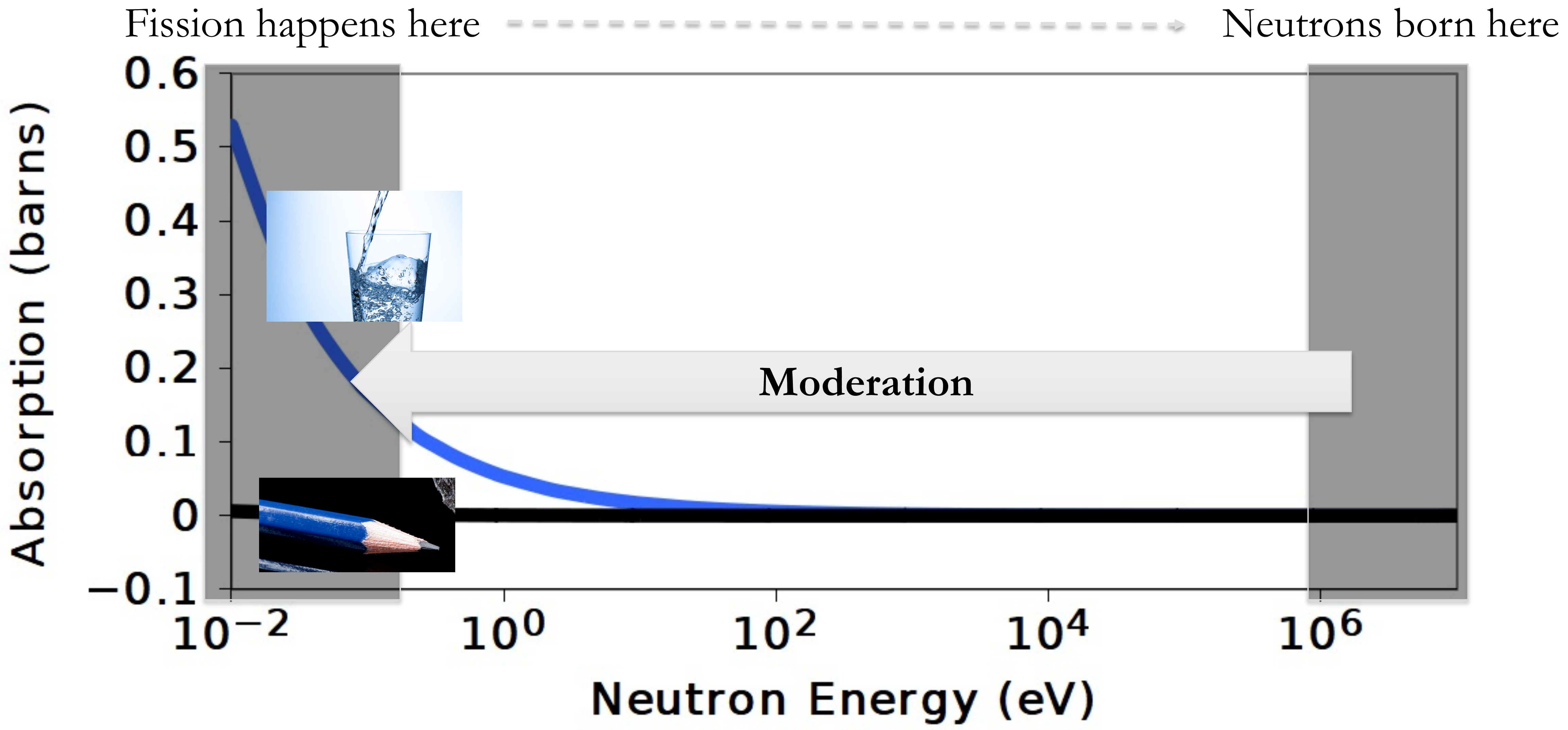


Cross Sections (Barns) Give Nuclear Reaction Rates

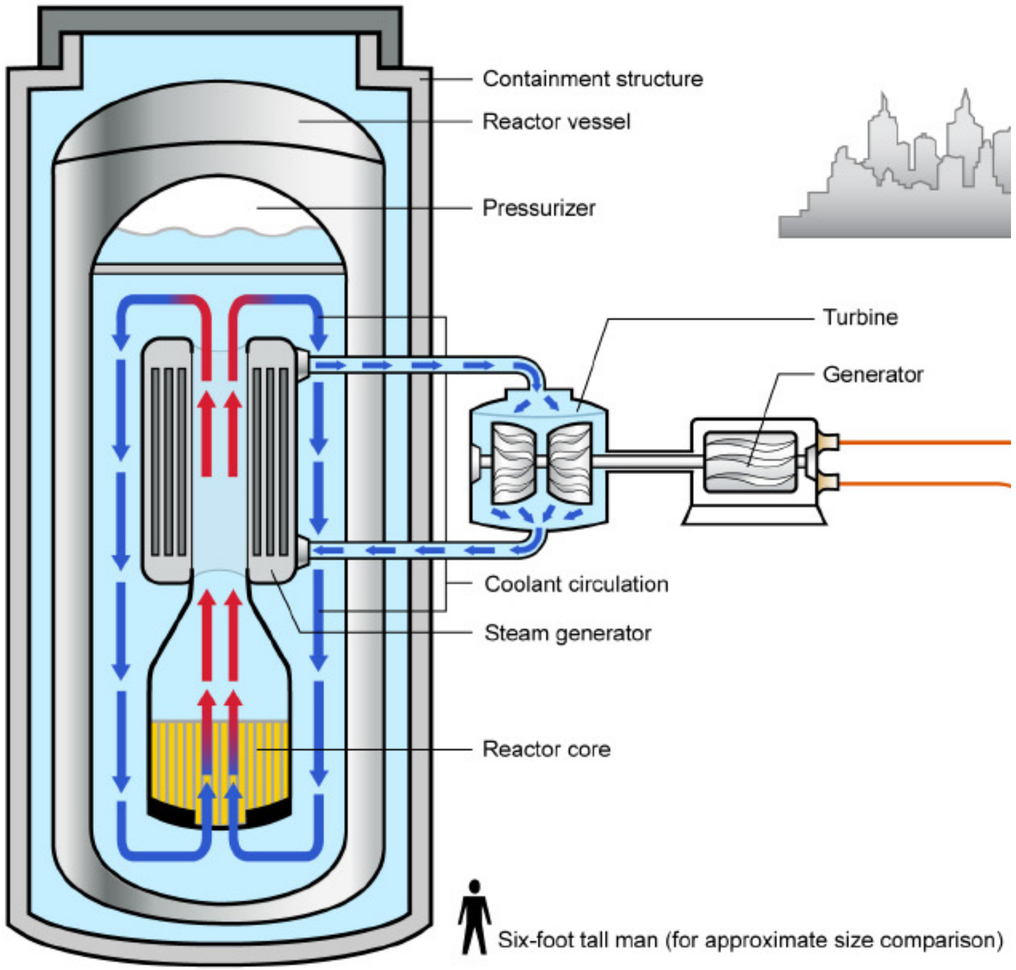


Water and Graphite Slow Down Neutrons…

… and Water Helps Absorb Neutrons, Slowing Fission



What Happens When The Water Is Gone?



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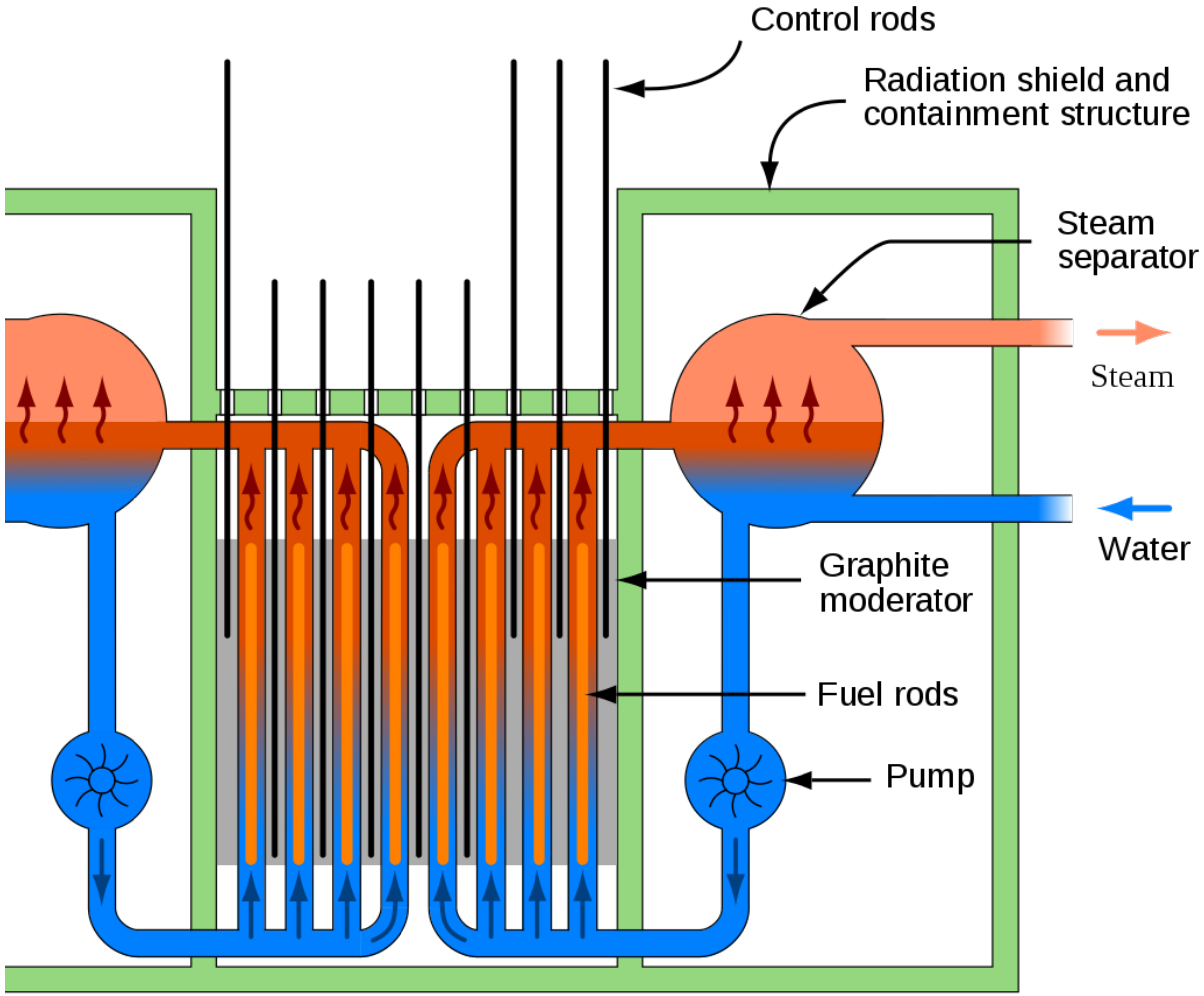
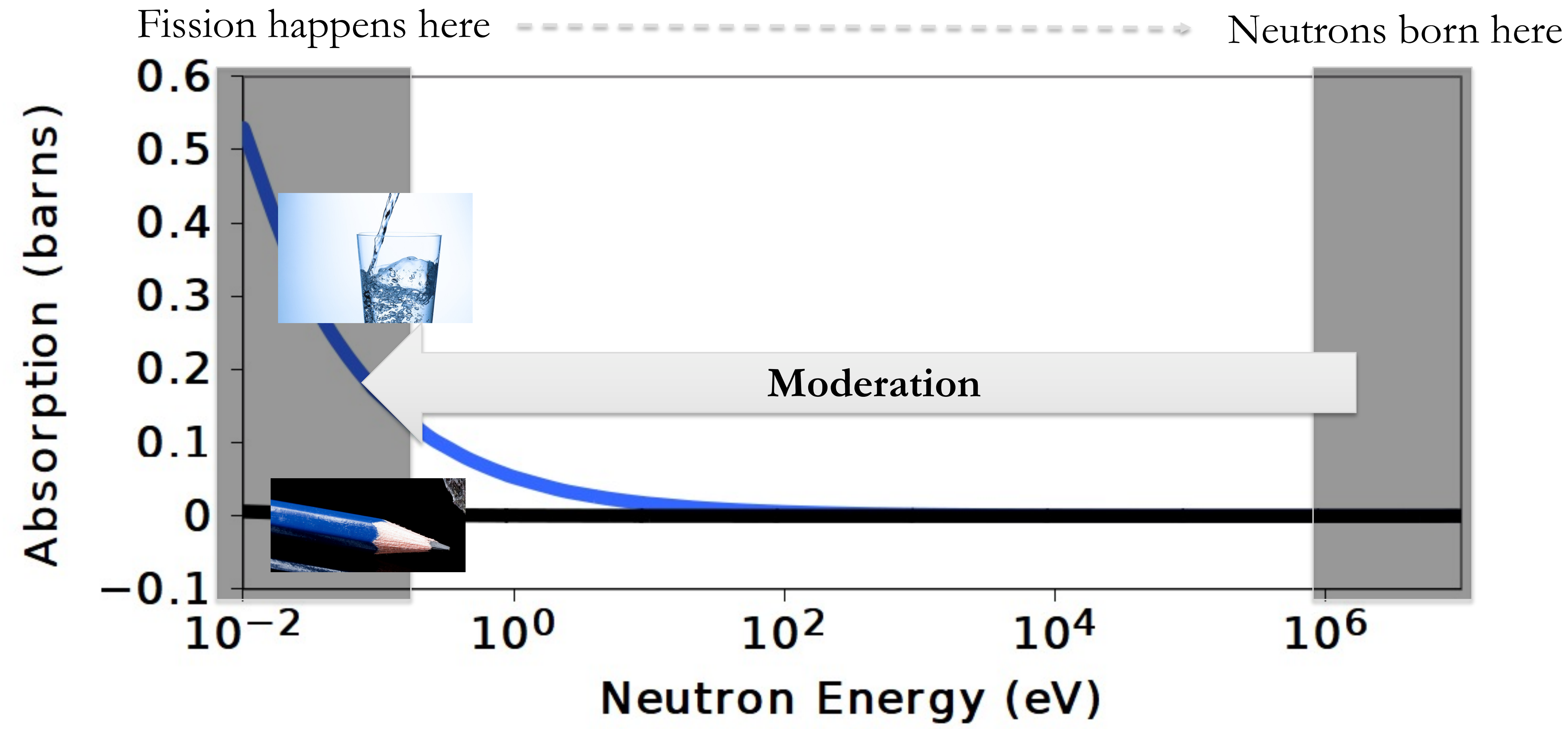
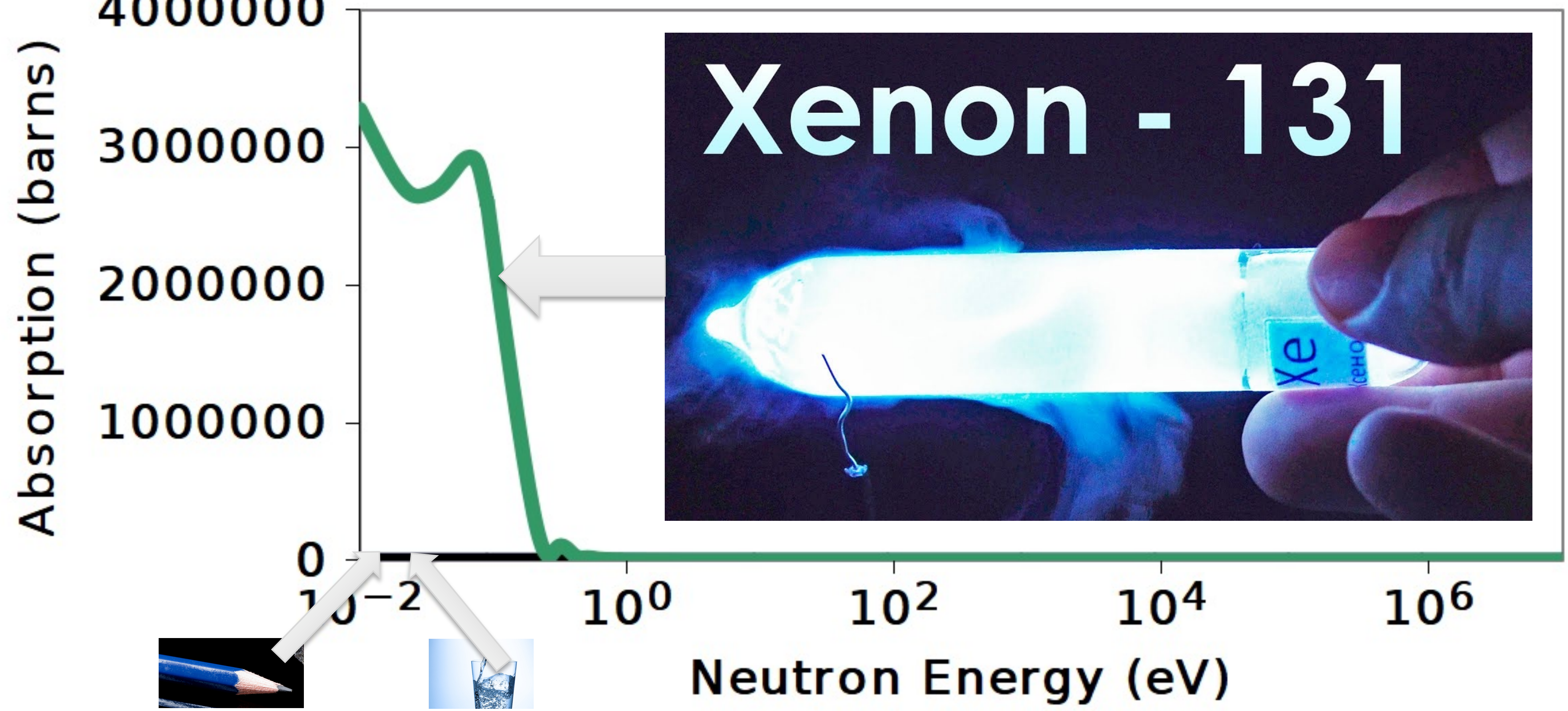


Water Helps Absorb Neutrons, Slowing Fission

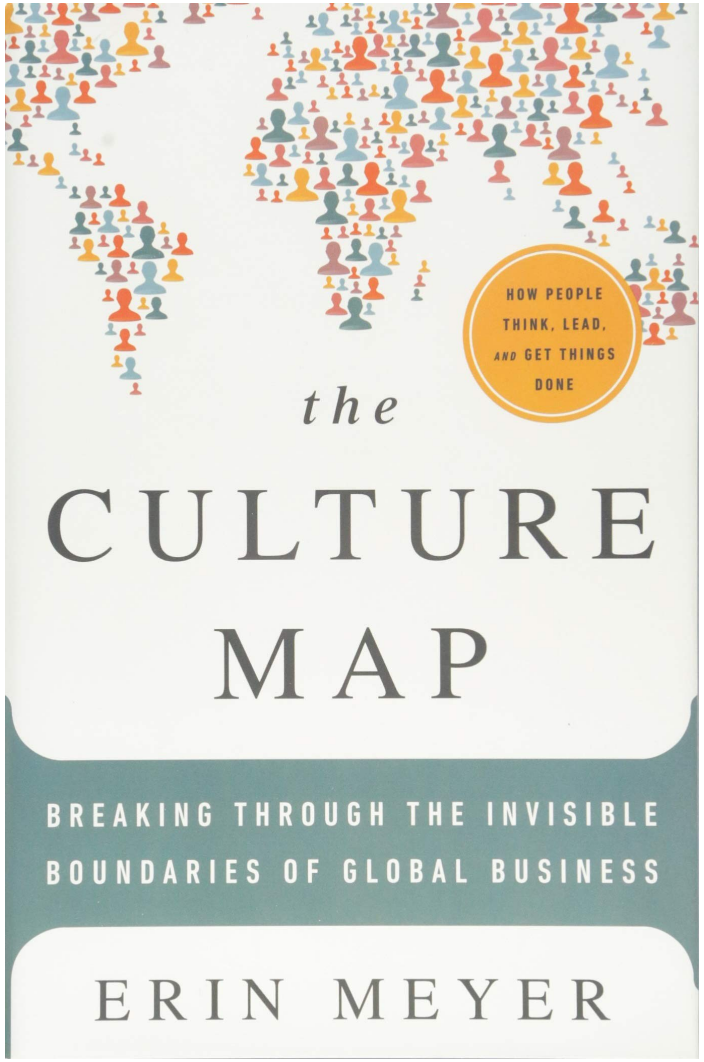


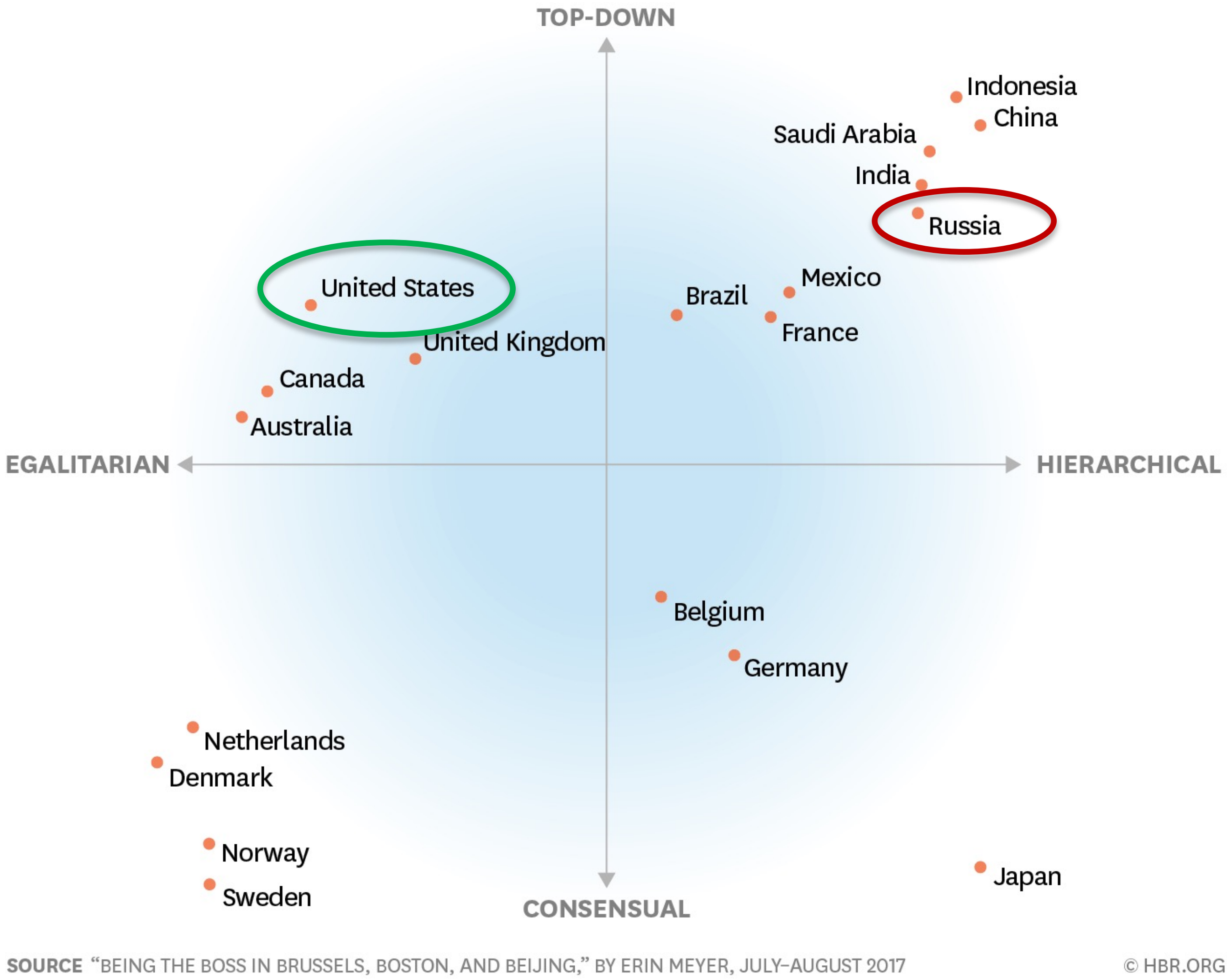
Xenon Poisoning and Its Half Life

Half Life: ~9 Hours



The Human Factors Which Led to Chernobyl





The Energetic Fingerprints of *Tiny* Amounts of Radiation Damage

Rachel Connick[1], Charles Hirst[1], Kangpyo So[1], Penghui Cao[2], R. Scott Kemp[1], Michael P. Short[1]

[1] *Department of Nuclear Science and Engineering, MIT, USA*

[2] *Department of Mechanical Engineering, University of California at Irvine, USA*

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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

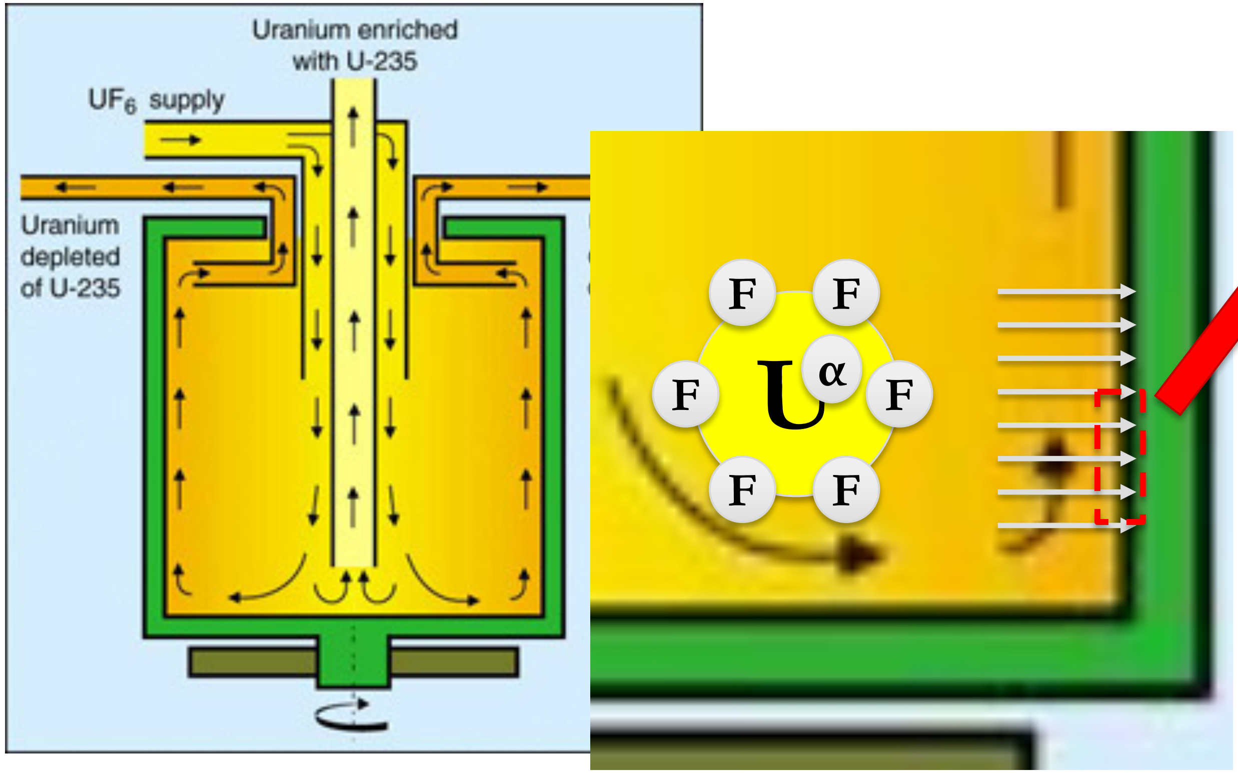
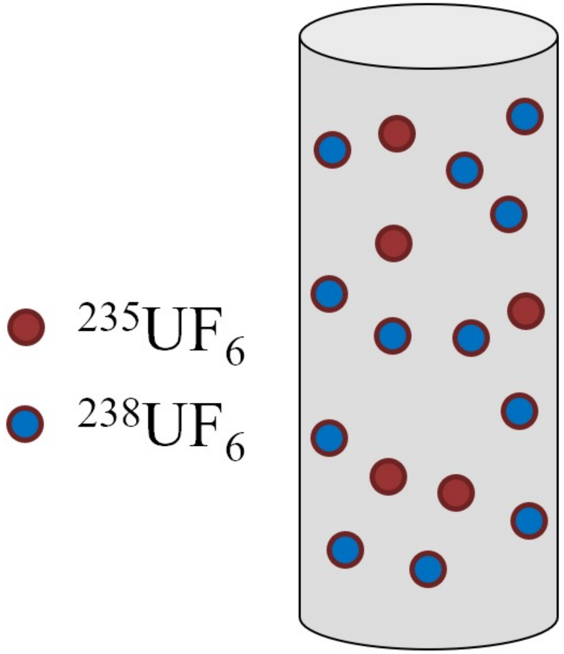
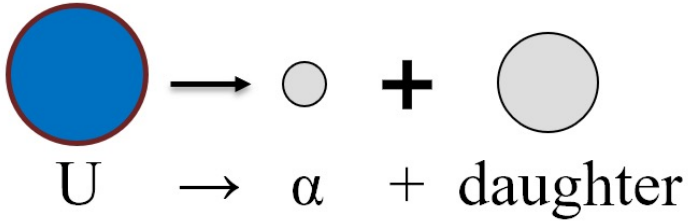


Image: TA Instruments

Goal: Verify Historical Uranium Enrichment



Grossly simplified centrifuge diagram

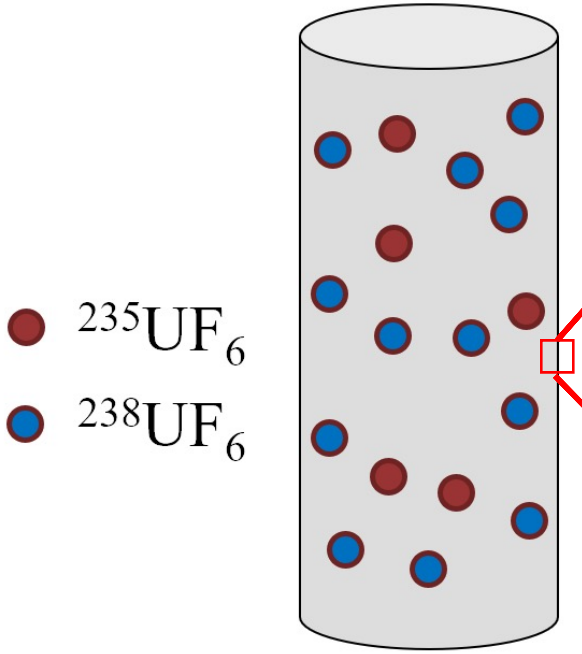


Alpha radiation will leave a signature in the material that contains UF_6

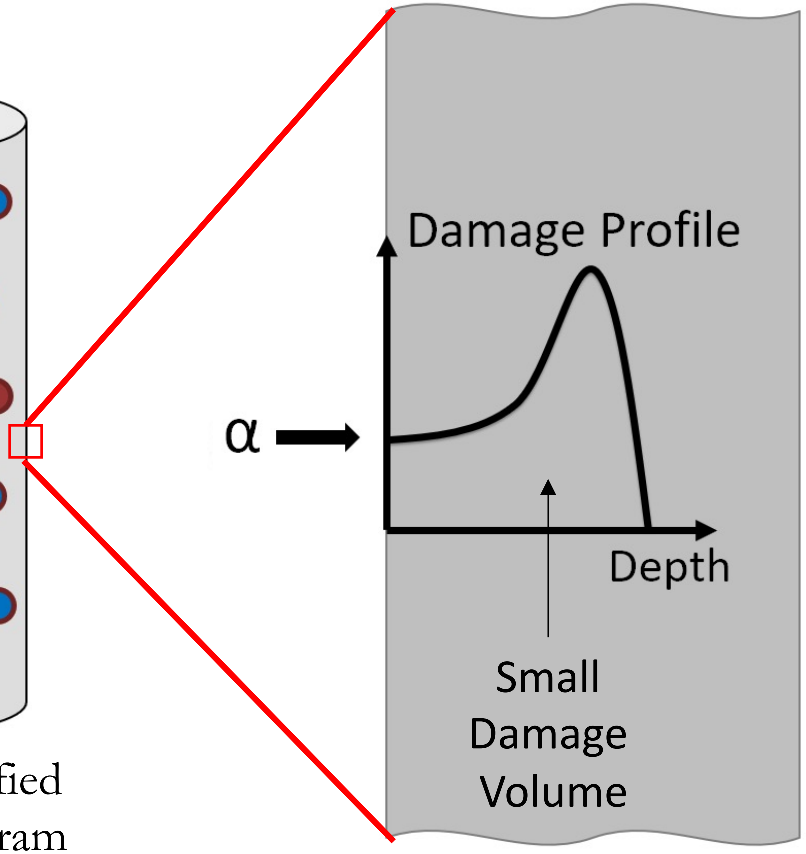
How much was made?

What was the enrichment?

Goal: Verify Historical Uranium Enrichment



Grossly simplified centrifuge diagram



Low expected fluences:

5×10^9 α/cm² = 1 year of LEU

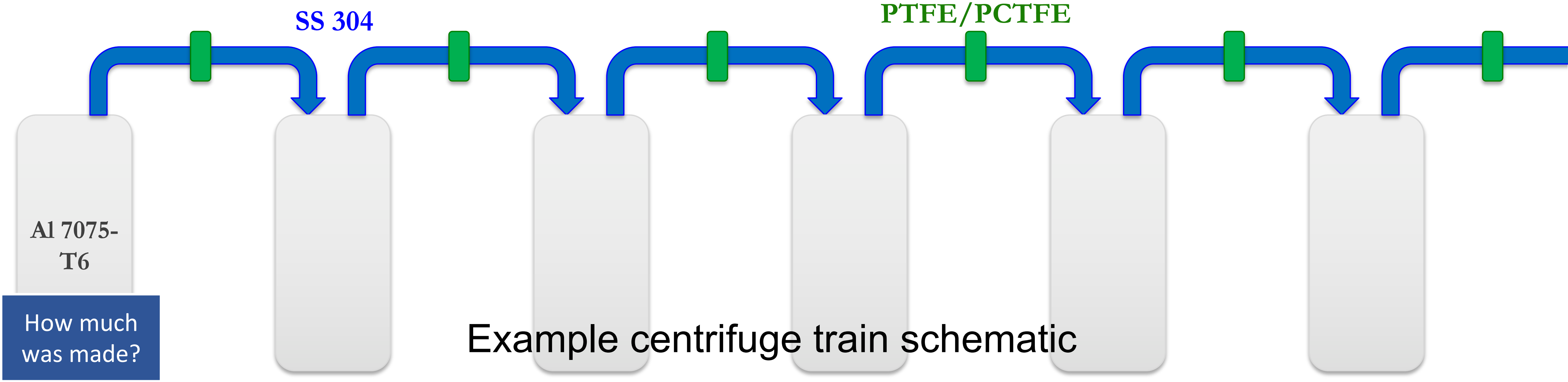
1×10^{11} α/cm² = 1 year of 90% enriched

How low can you go?

How much was made?

Focus on Energy Fingerprint of Phase Transformations

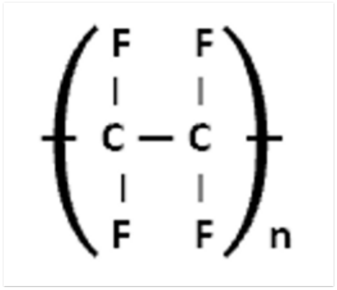
- Wigner energy (defects) – J/g stored energy
  - 0.1-2.0 J/g for most metals (Snead et al., JNM 2019)
- Phase transformations – 100-1000 J/g stored energy
  - If radiation can nucleate phase transformations, measure *these* signals!



Example centrifuge train schematic

Examine the PTFE (Teflon™) Gaskets First

PTFE



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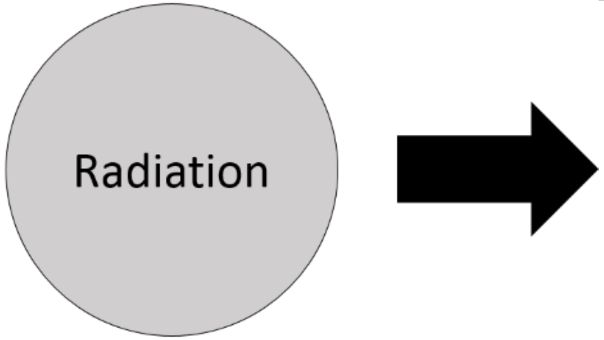
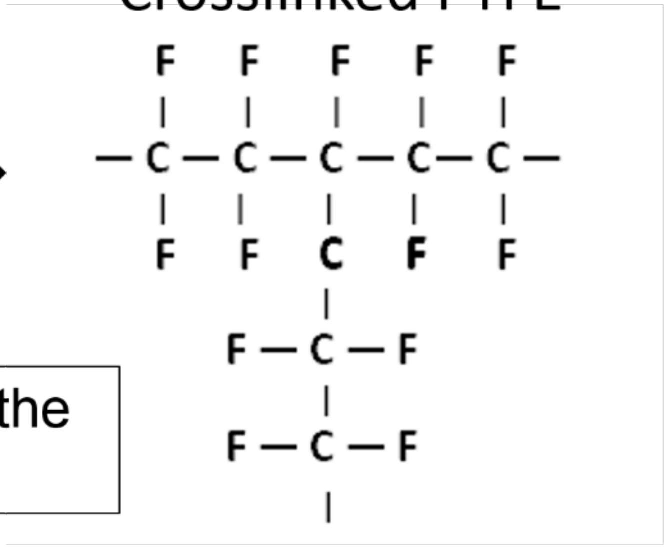


Crosslinked PTFE



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

php

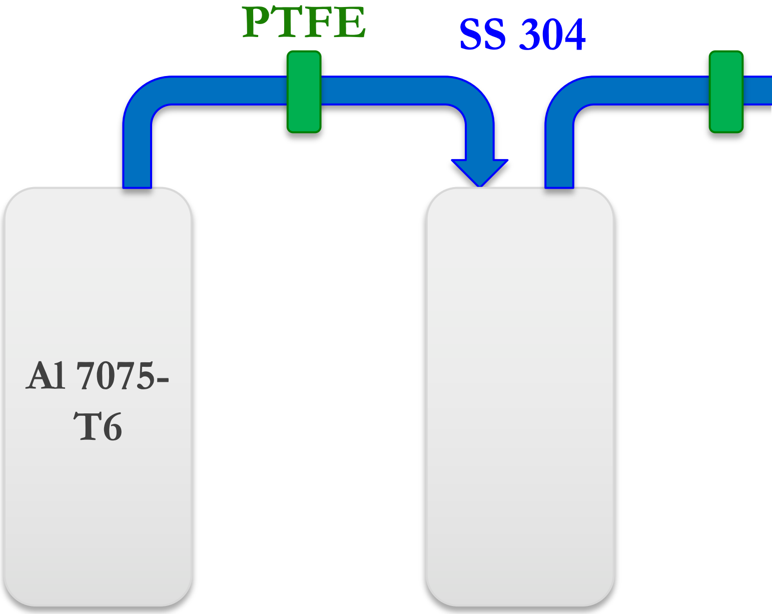
How much was made?

Cambridge **L**aboratory for **A**ccelerator **S**urface **S**cience:

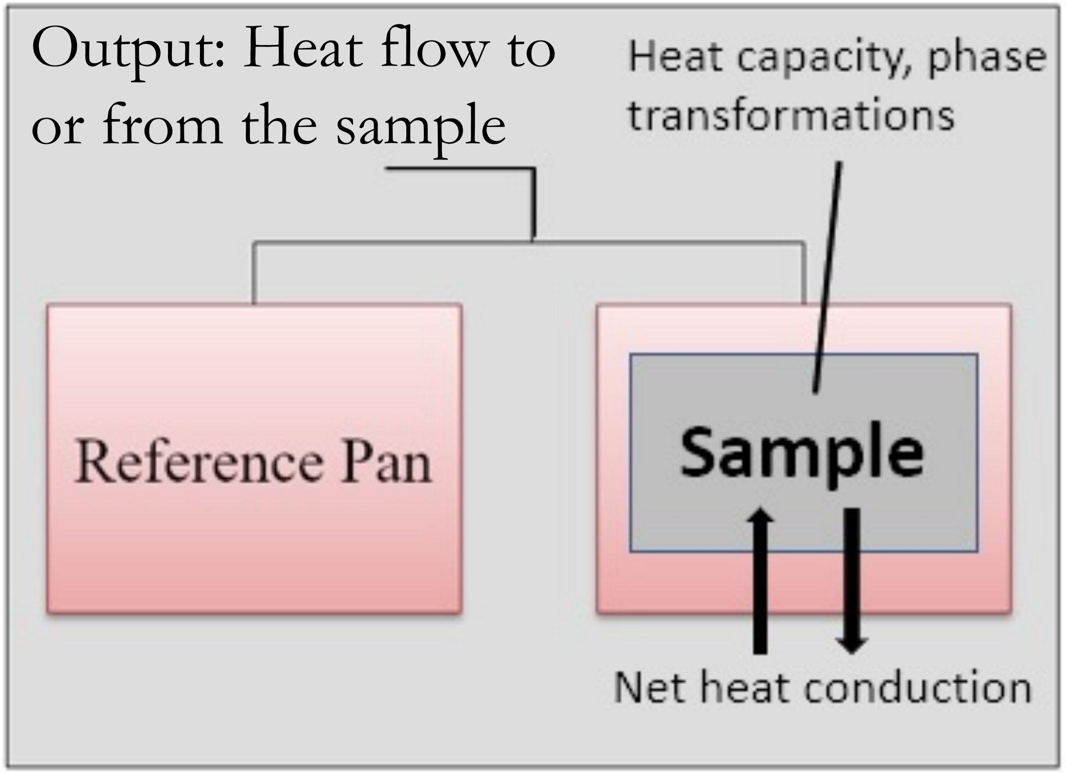
- Irradiated PTFE with 4.5 MeV He^{2+} ions
- Three fluences: 10^{10}, 10^{11}, and 10^{12} α/cm^2

Two bombs worth of UF_6 at 5% enrichment

One bomb worth of UF_6 at 90% enrichment



Measuring Radiation Damage using Calorimetry



Simplified DSC Schematic

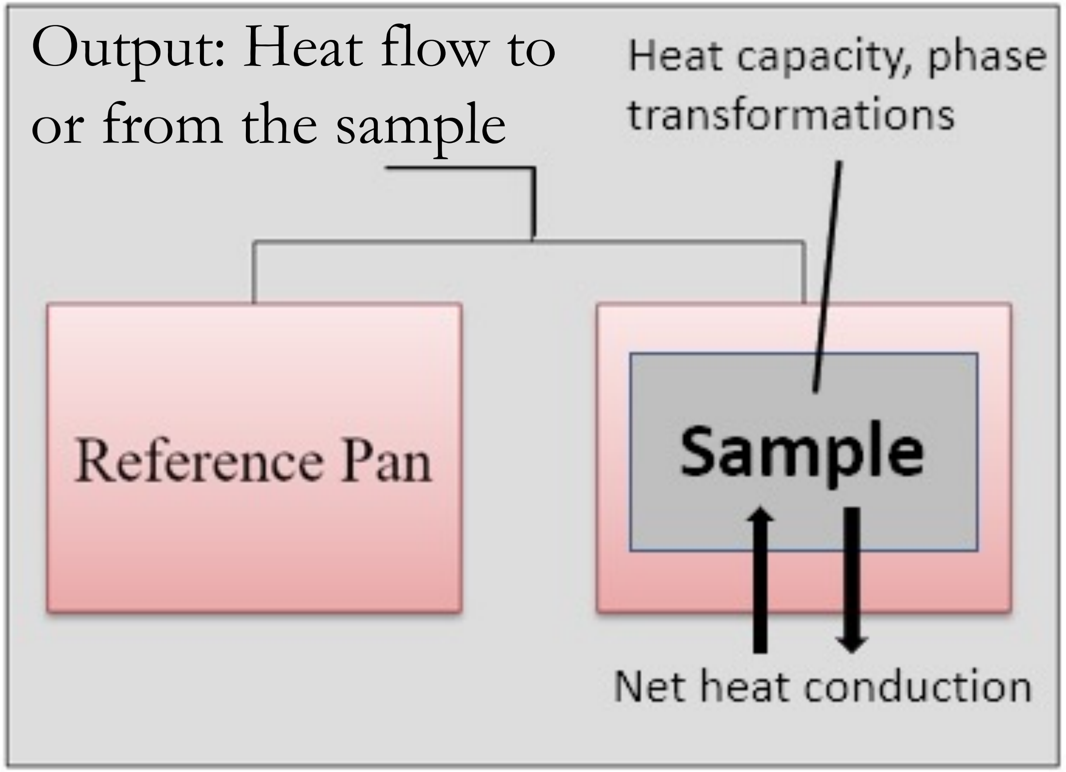
Differential Scanning Calorimetry

How much was made?

TA Instruments Discovery DSC

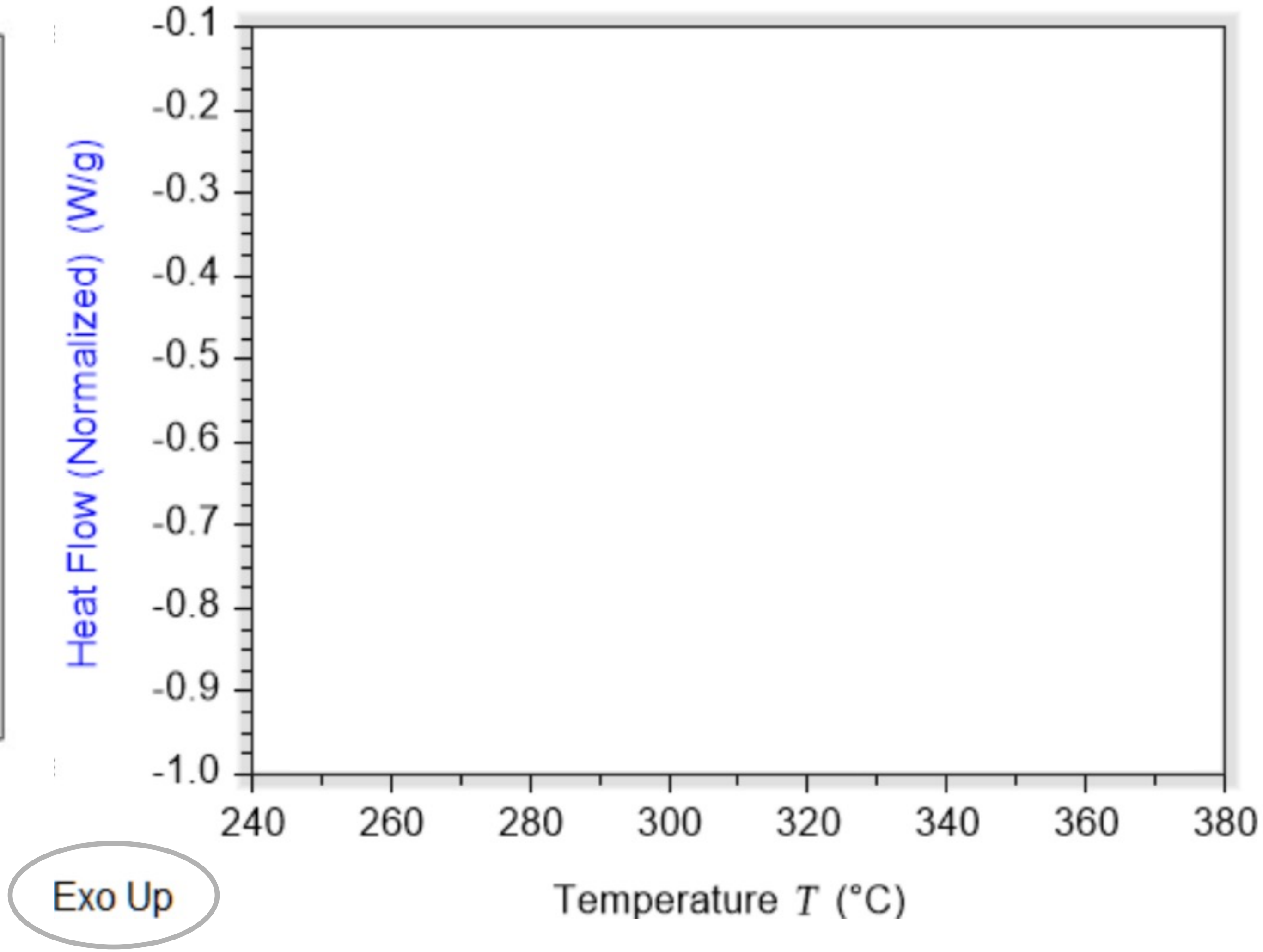
http://www.tainstruments.com/dt_gallery/discovery-dsc/

How It Works: Measure Differential Heat Flow



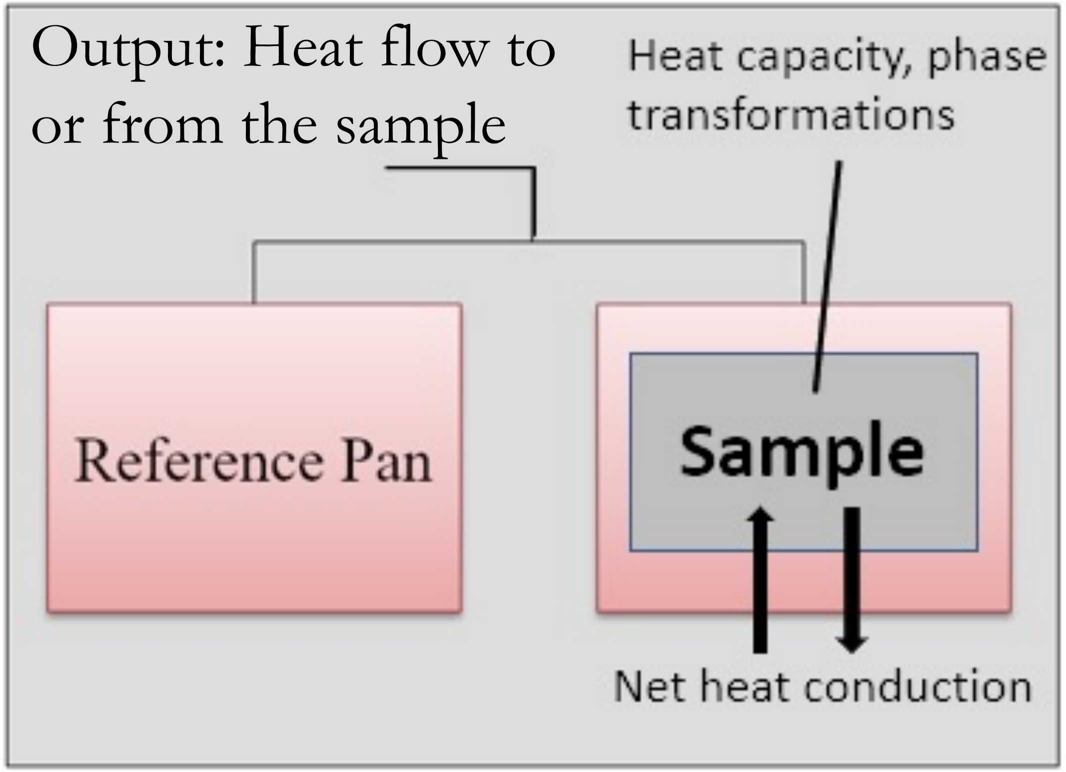
Simplified DSC Schematic

Differential Scanning Calorimetry



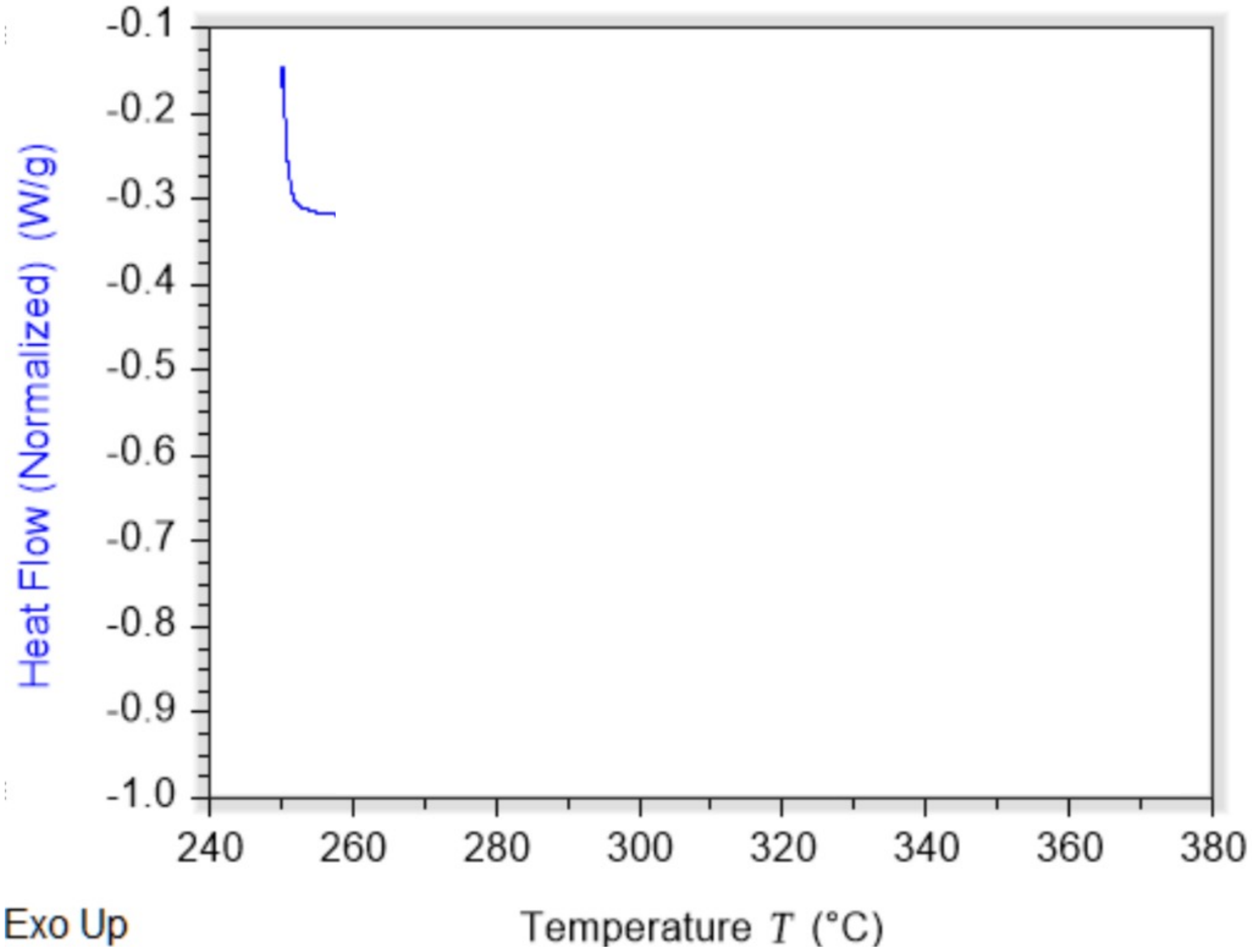
How much was made?

Correct for the "DSC Hook" – Feedback Settling



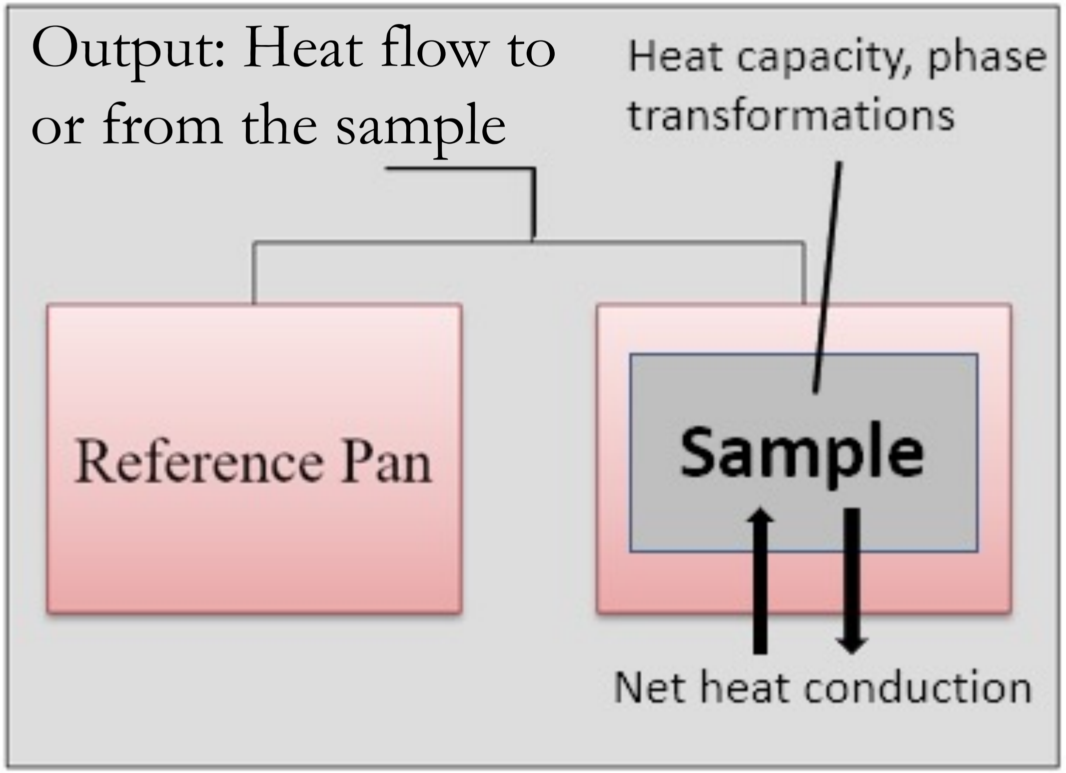
Simplified DSC Schematic

Differential Scanning Calorimetry



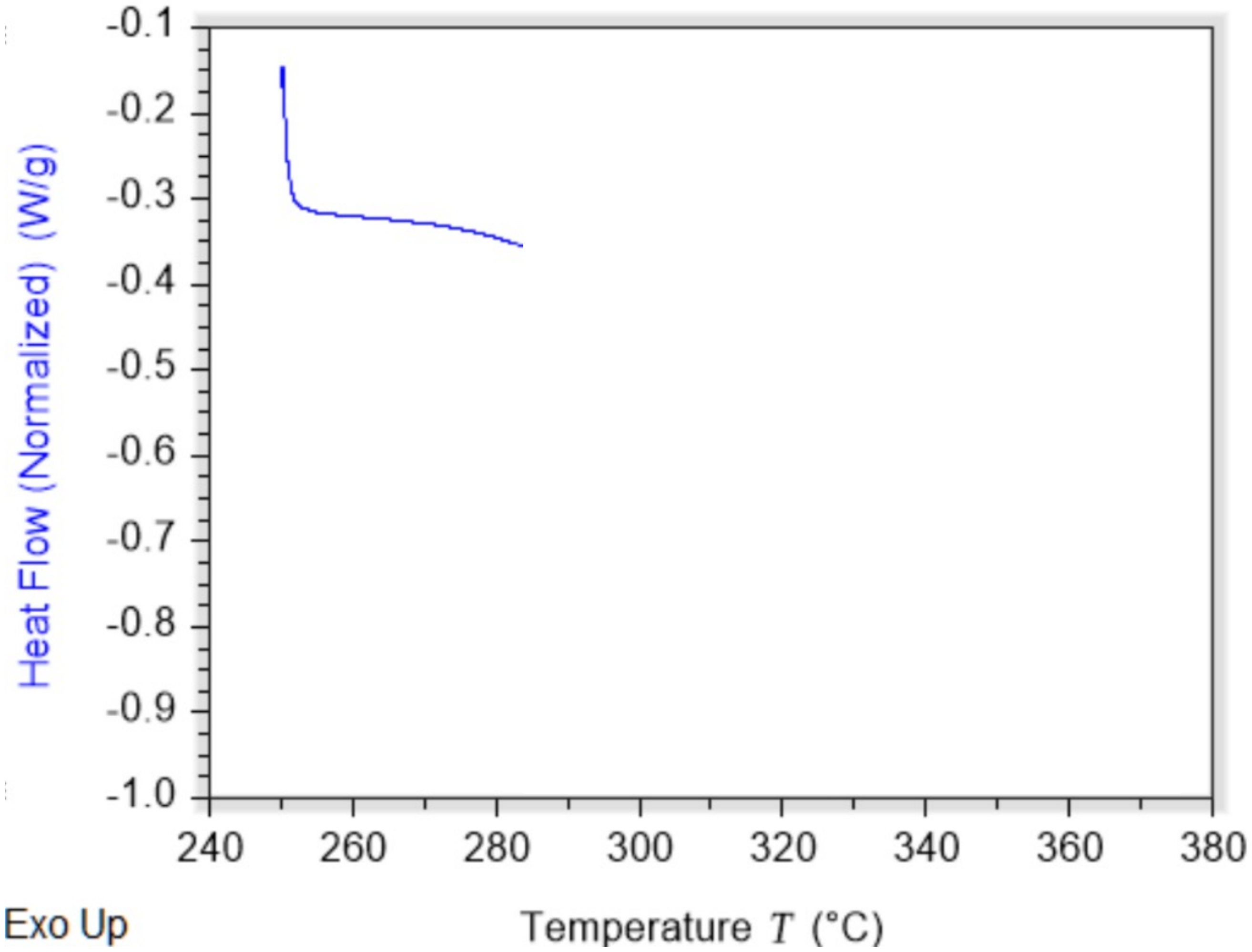
How much was made?

Establish Baseline Heat Capacity Outside Data Window



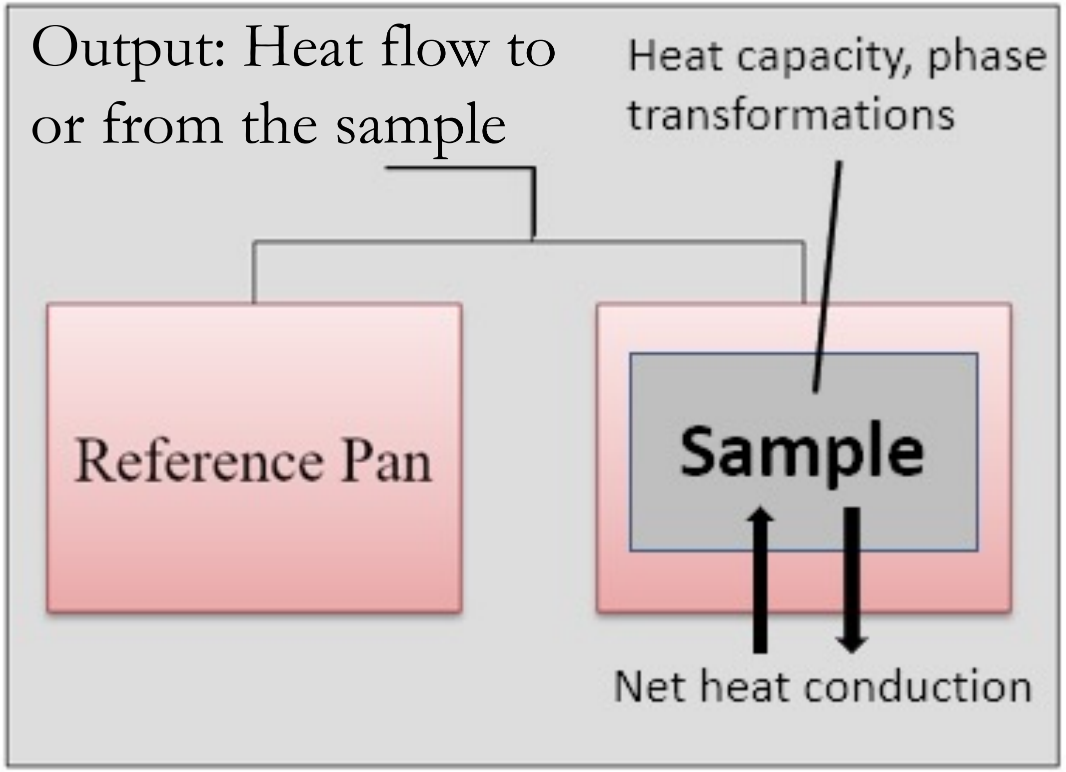
Simplified DSC Schematic

Differential Scanning Calorimetry



How much was made?

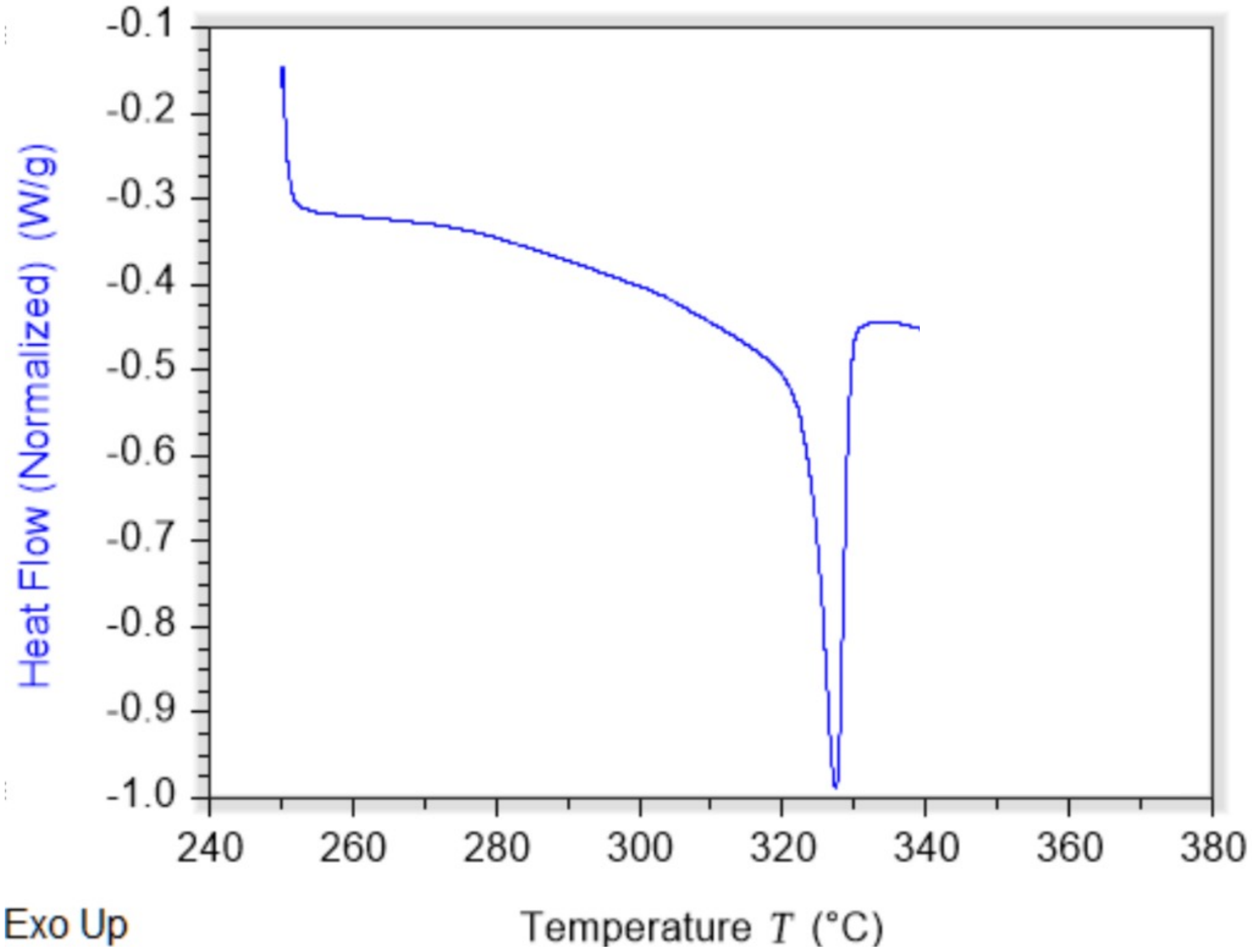
Measure Heat Gain/Loss During Transformation



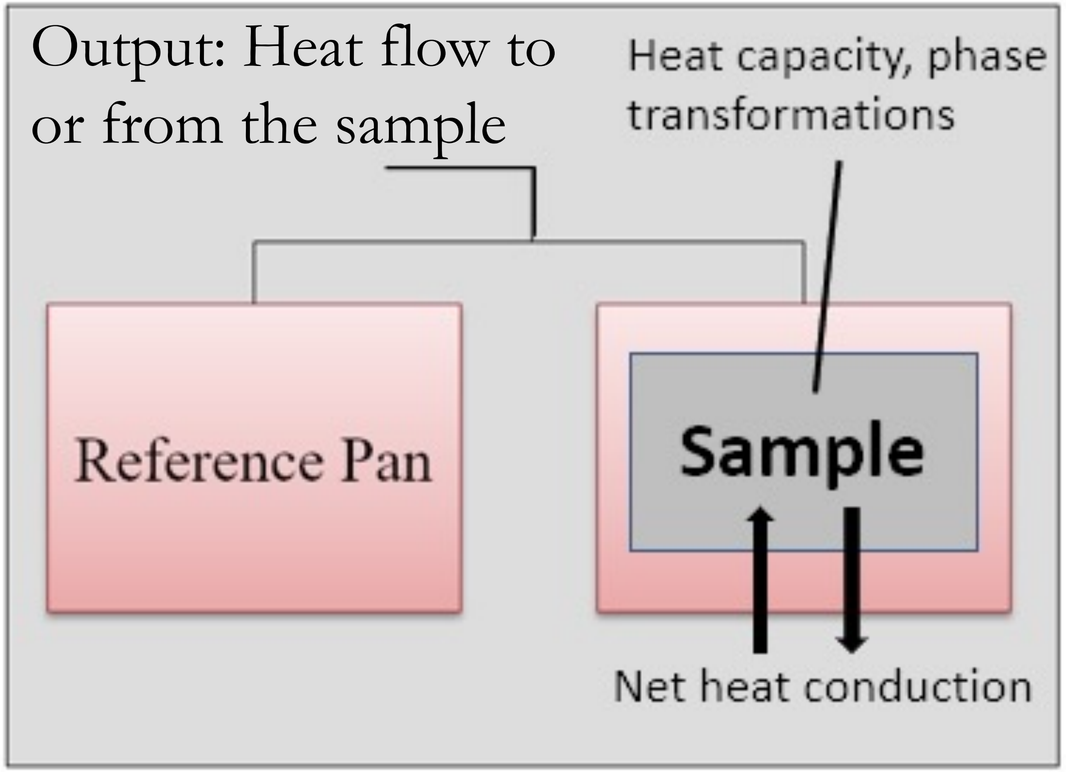
Simplified DSC Schematic

Differential Scanning Calorimetry

How much was made?



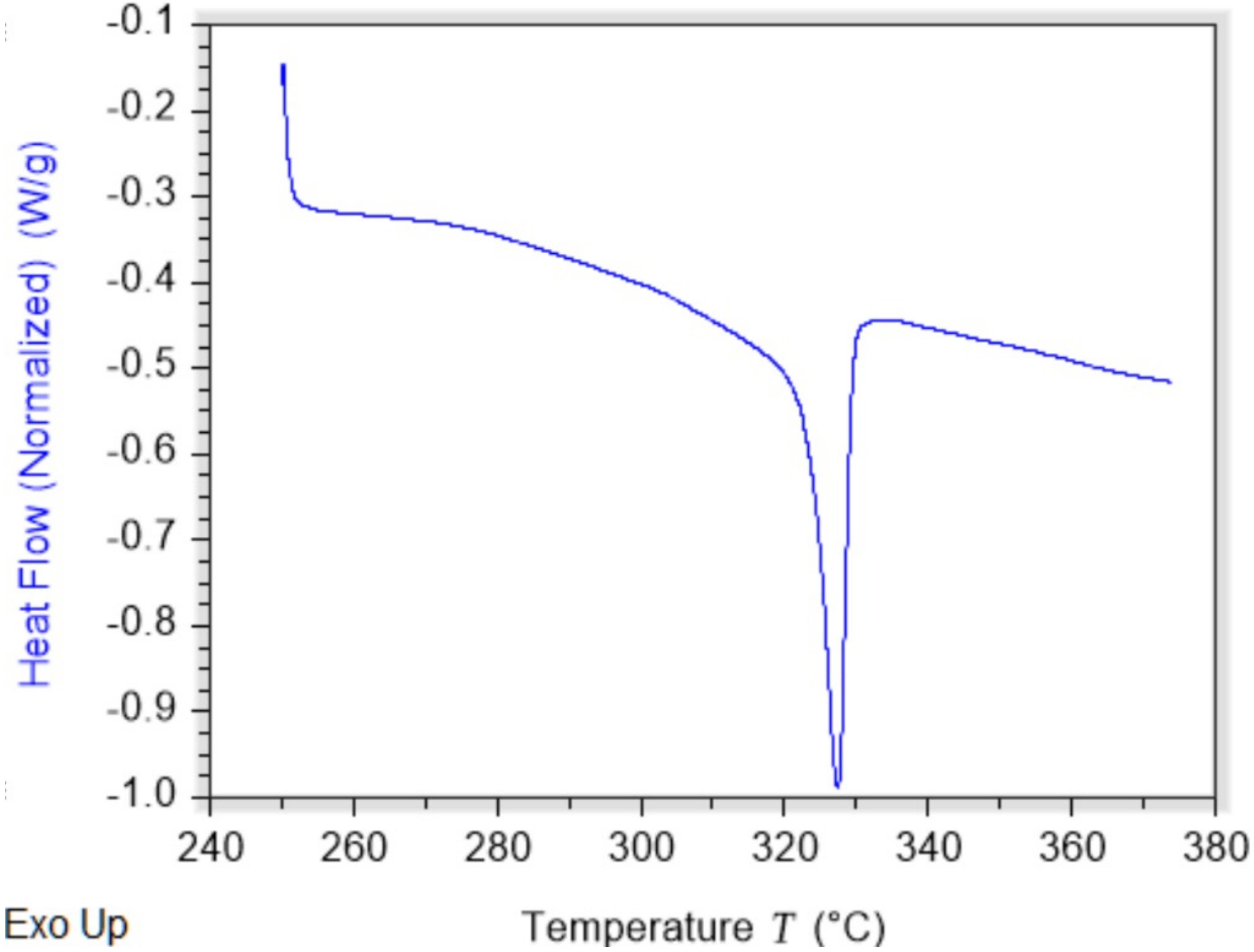
Re-Establish Baseline for Background Subtraction



Simplified DSC Schematic

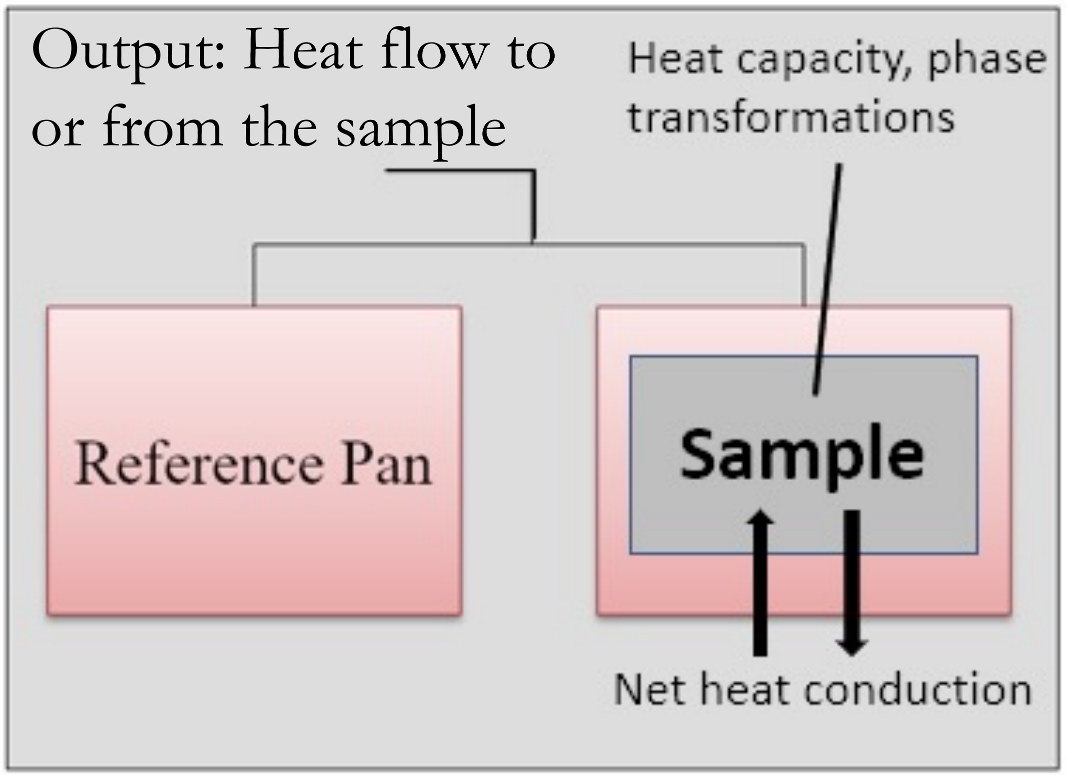
Differential Scanning Calorimetry

Melting of PTFE



How much was made?

Choose a Baseline for Subtraction

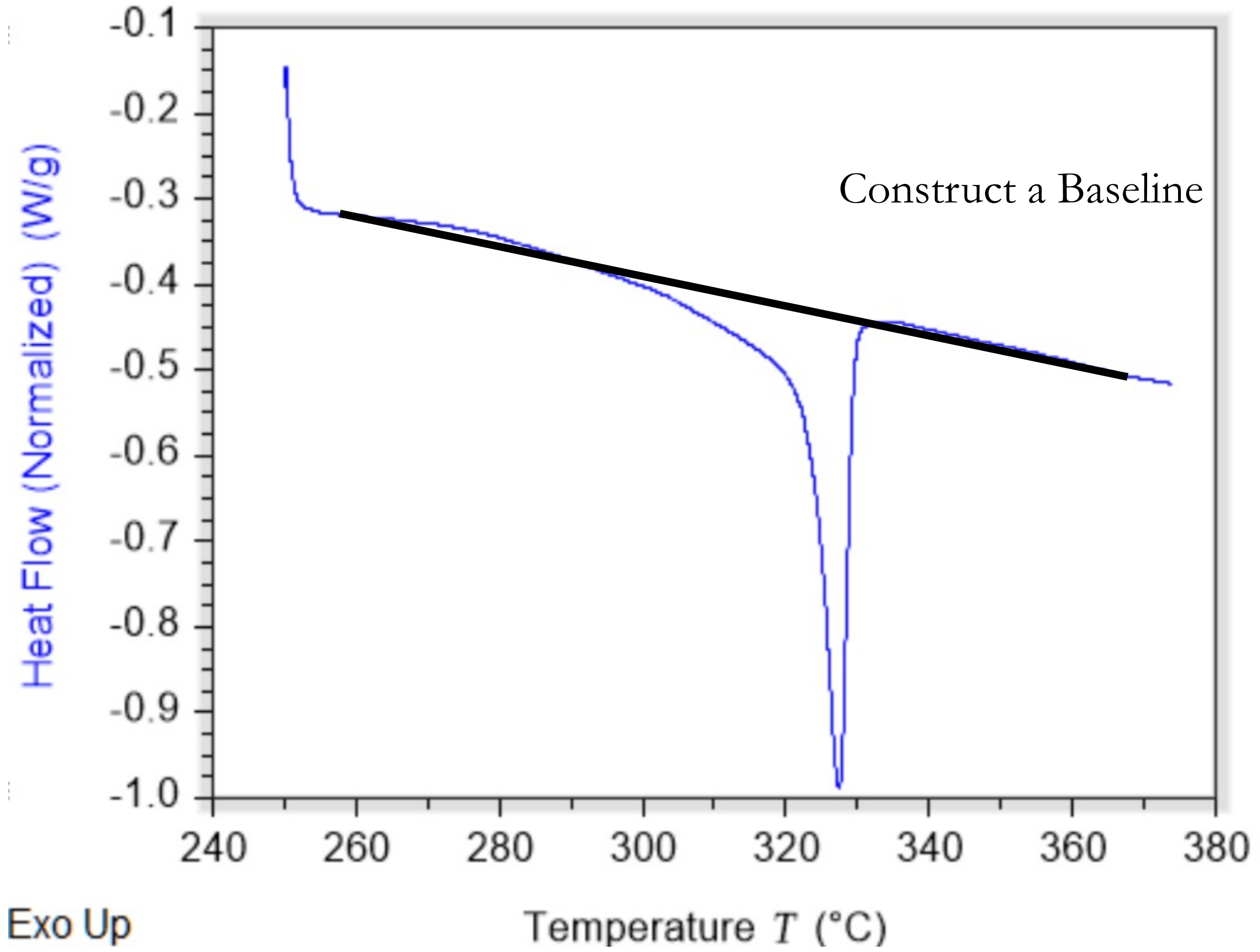


Simplified DSC Schematic

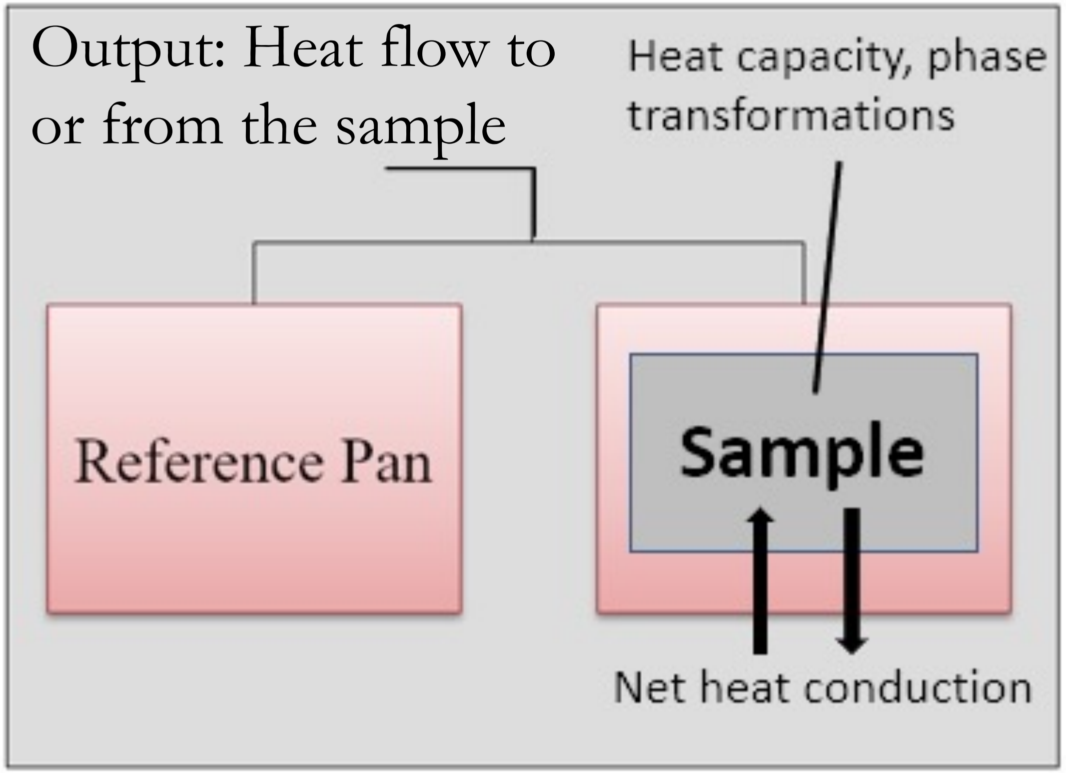
Differential Scanning Calorimetry

How much was made?

Melting of PTFE



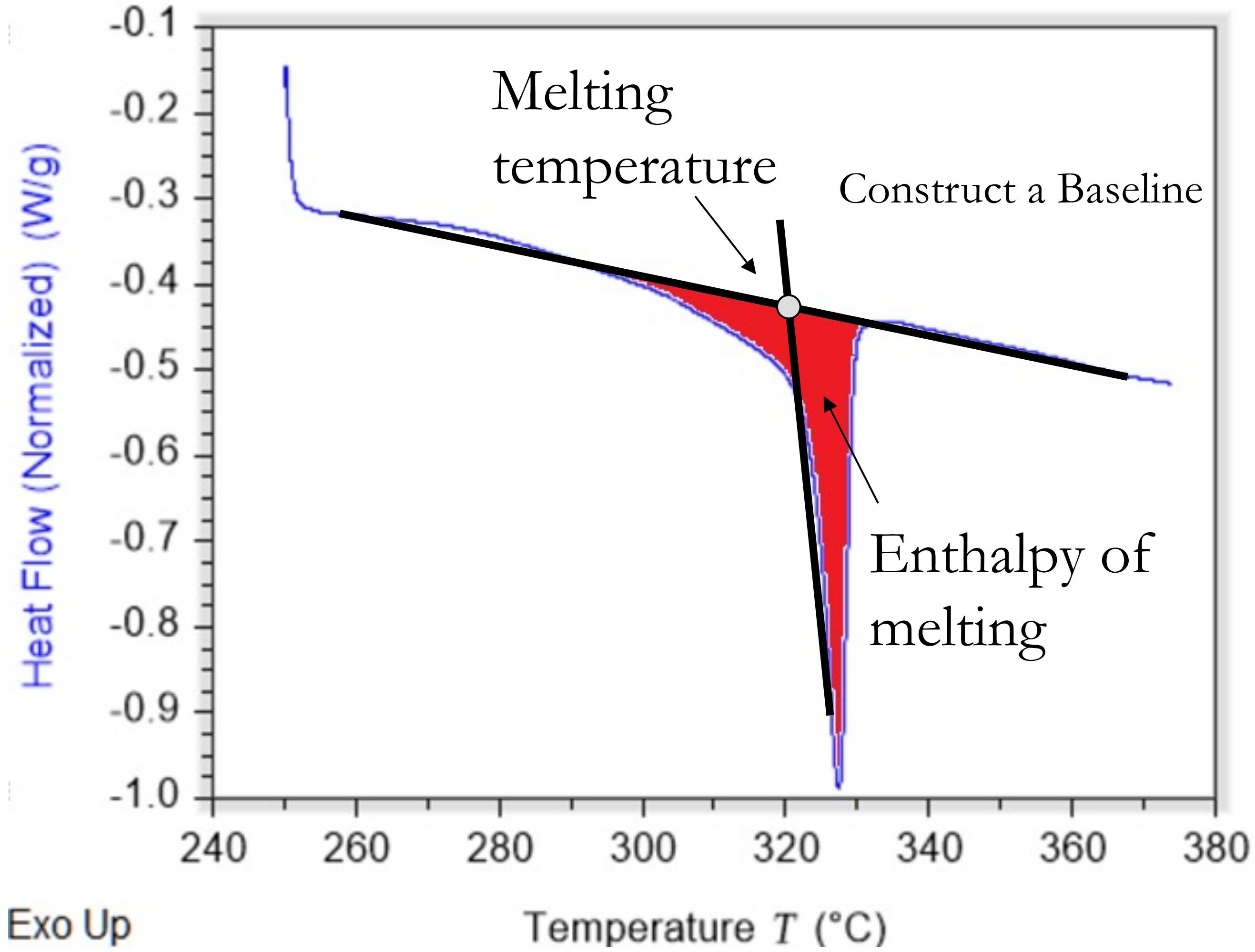
Extract Parameters of Interest, Repeat!



Simplified DSC Schematic

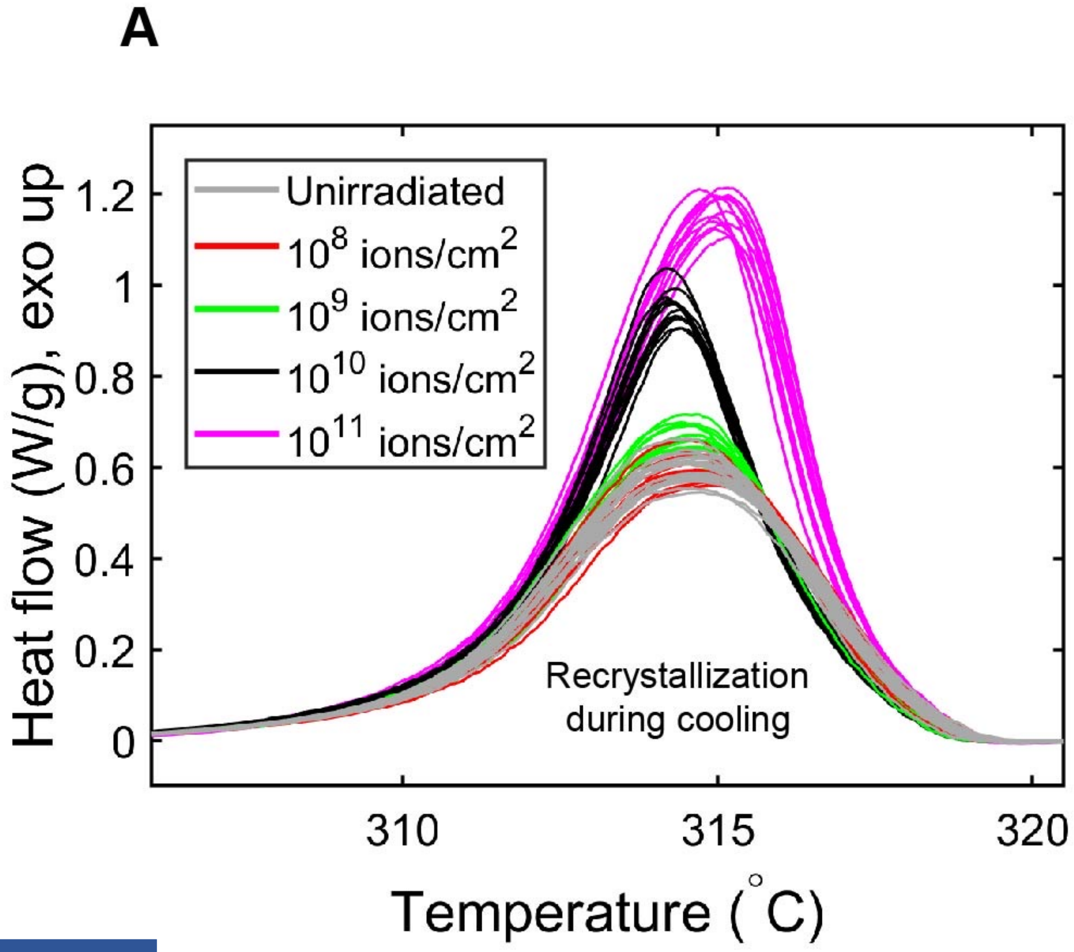
Differential Scanning Calorimetry

Melting of PTFE



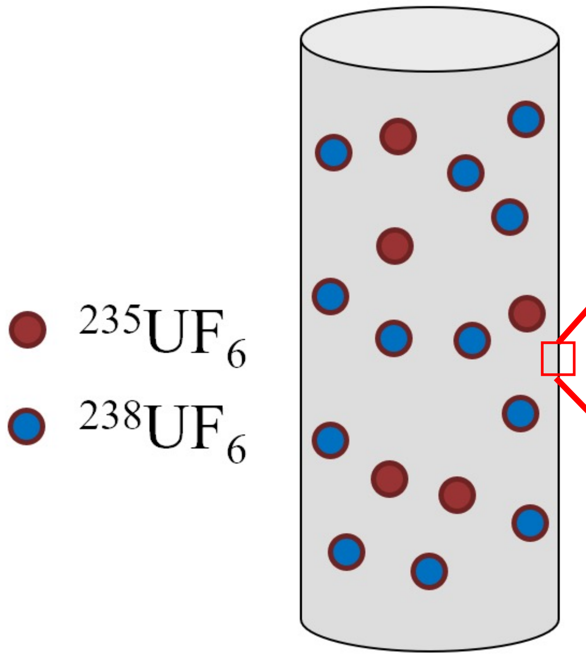
How much was made?

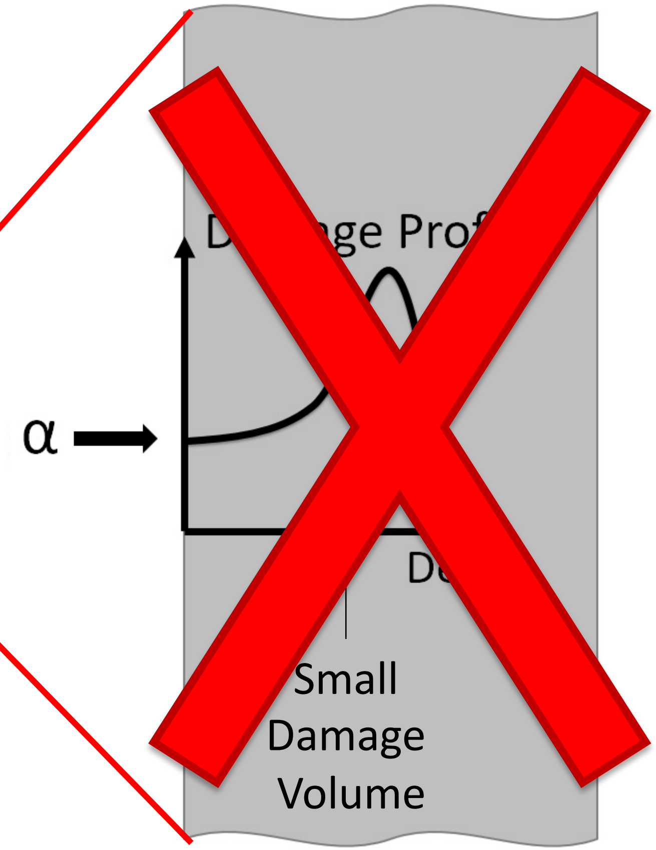
DSC of Irradiated PTFE Shows Very Distinct Changes



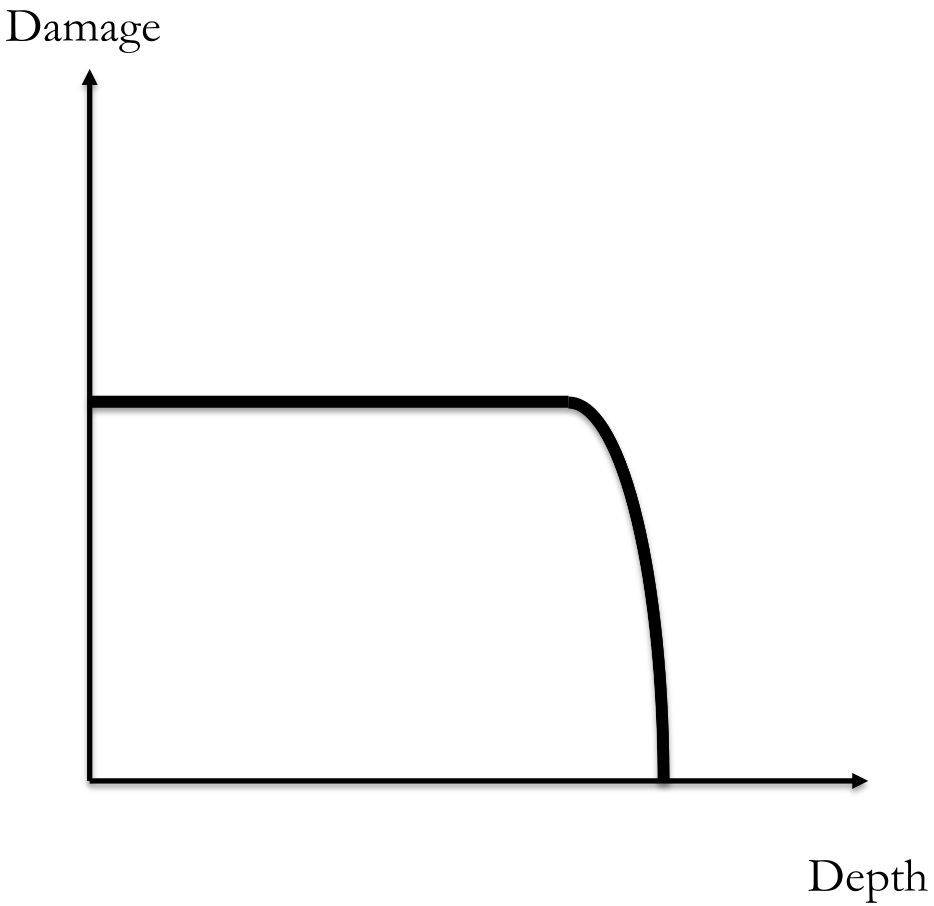
How much was made?

Confirming Enrichment Levels in Each Sample





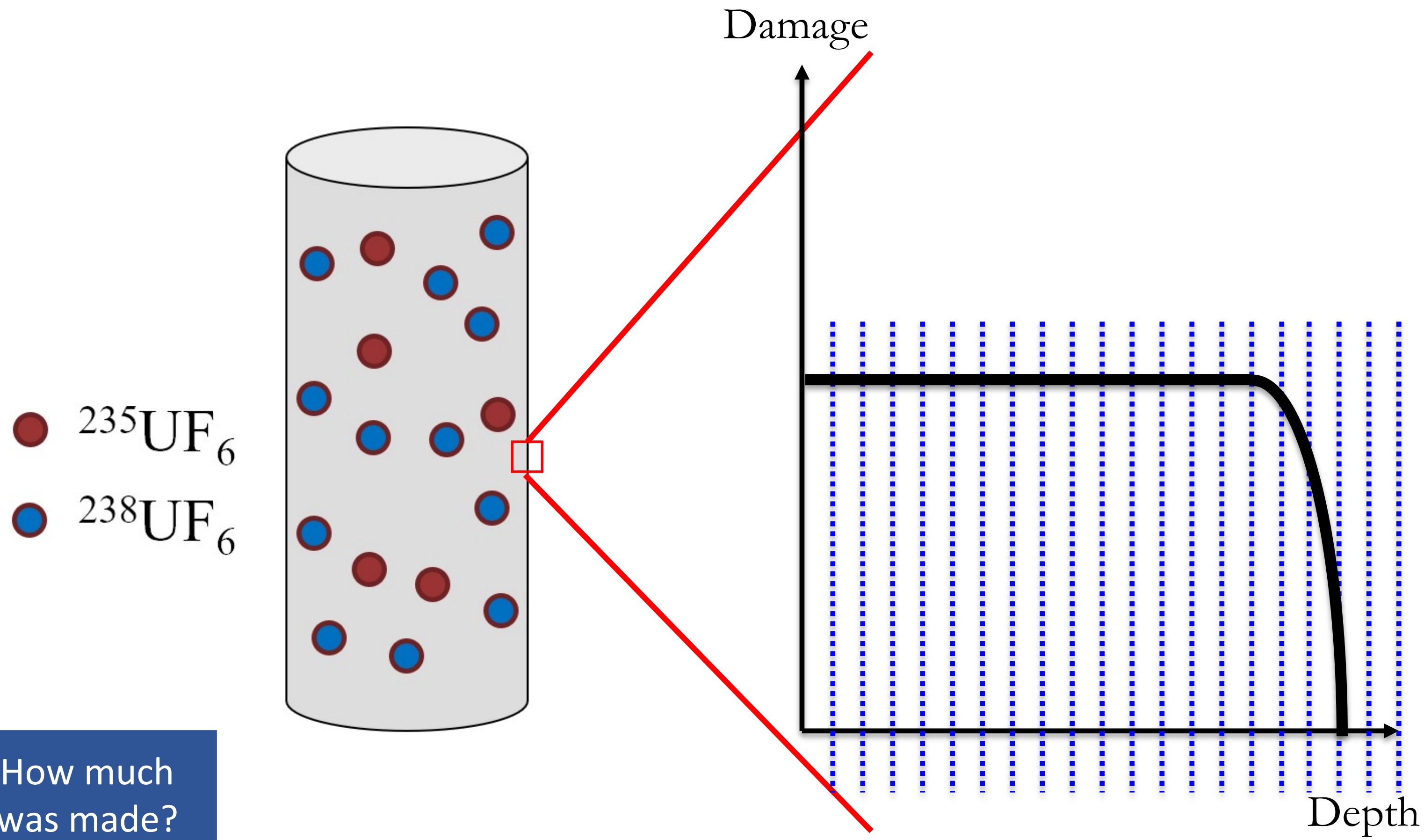
Monoenergetic, <u>uni</u>directional
alphas from our accelerator



Monoenergetic, <u>omni</u>directional
alphas from a UF_6 gas

What was the enrichment?

How Do We Effectively Sample in the Field?



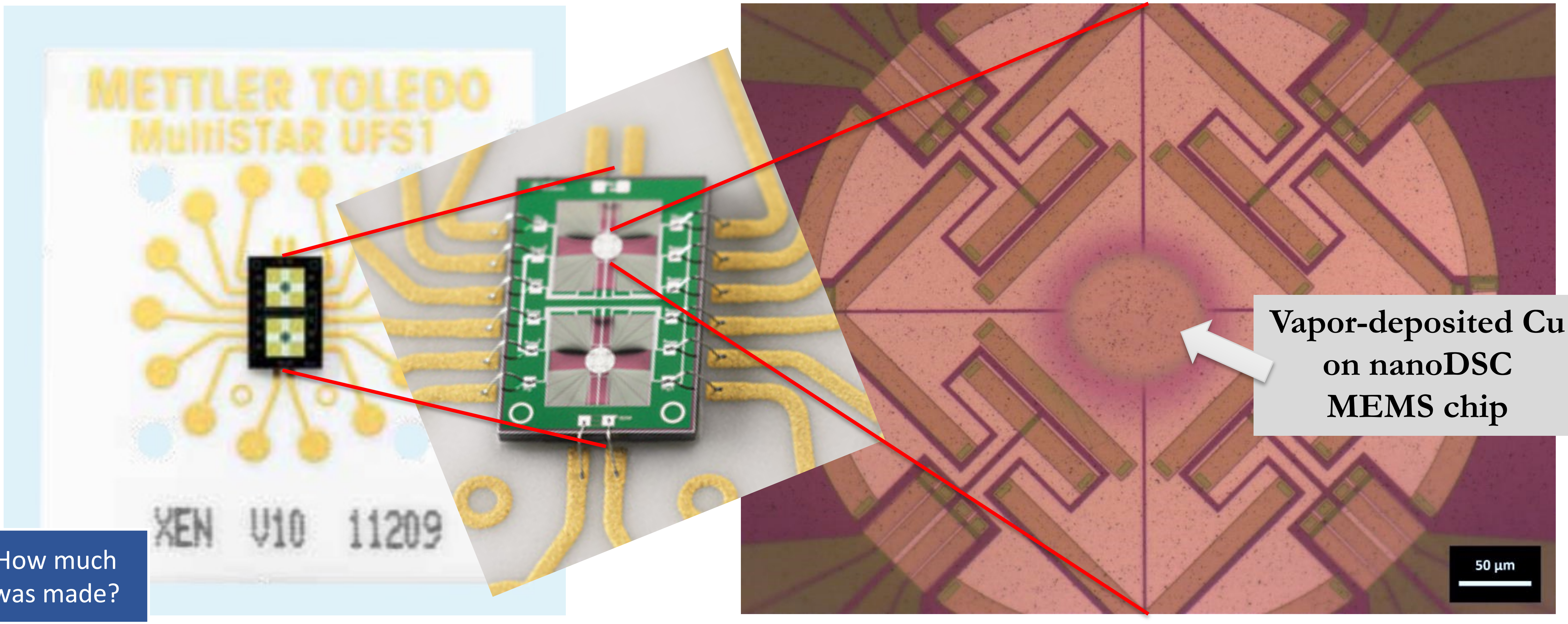
Bienergetic, omnidirectional
alphas from a UF_6 gas

How much was made?

What was the enrichment?

- 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…

Field Sampling: NanoDSC (Calorimeter on a Chip)



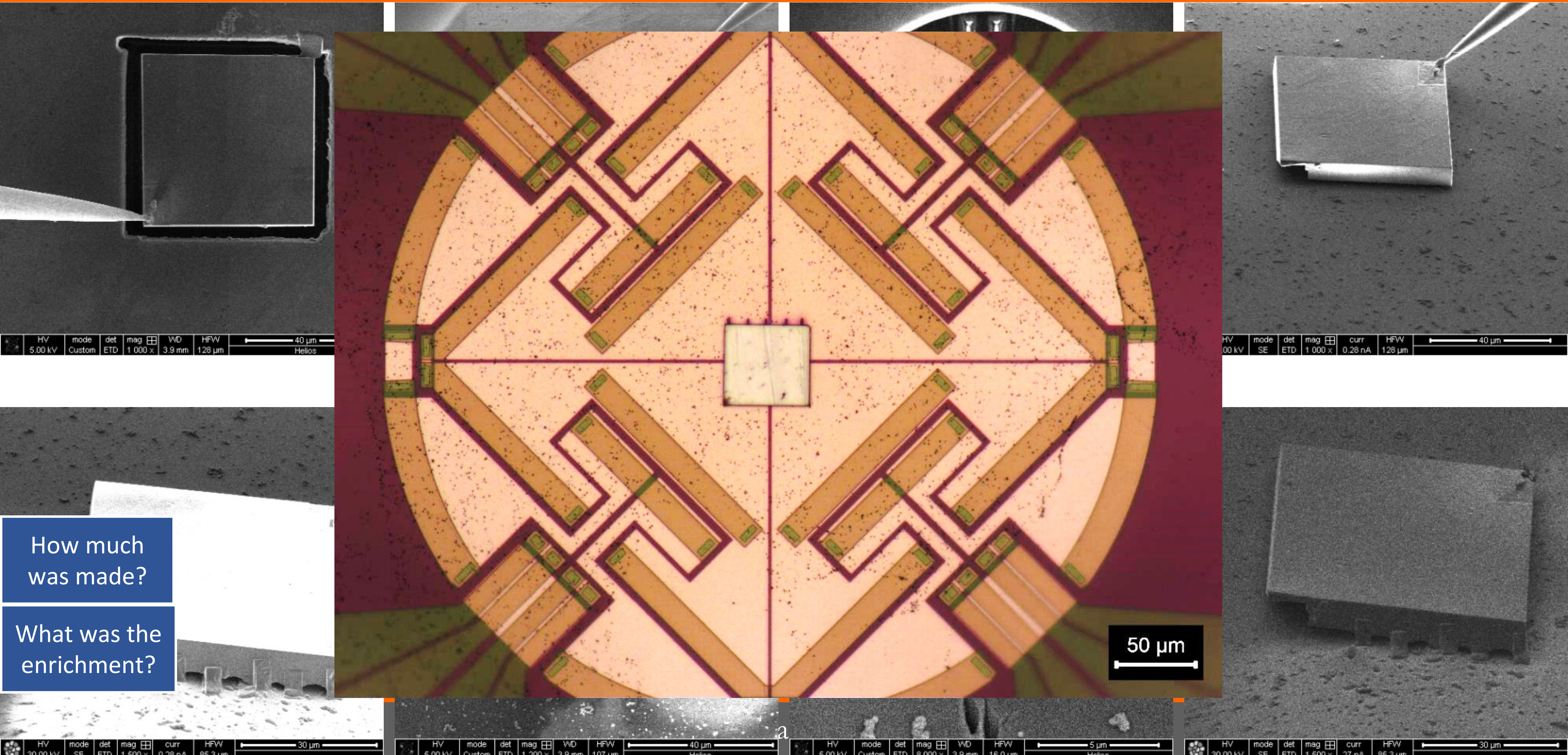
25mm

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?

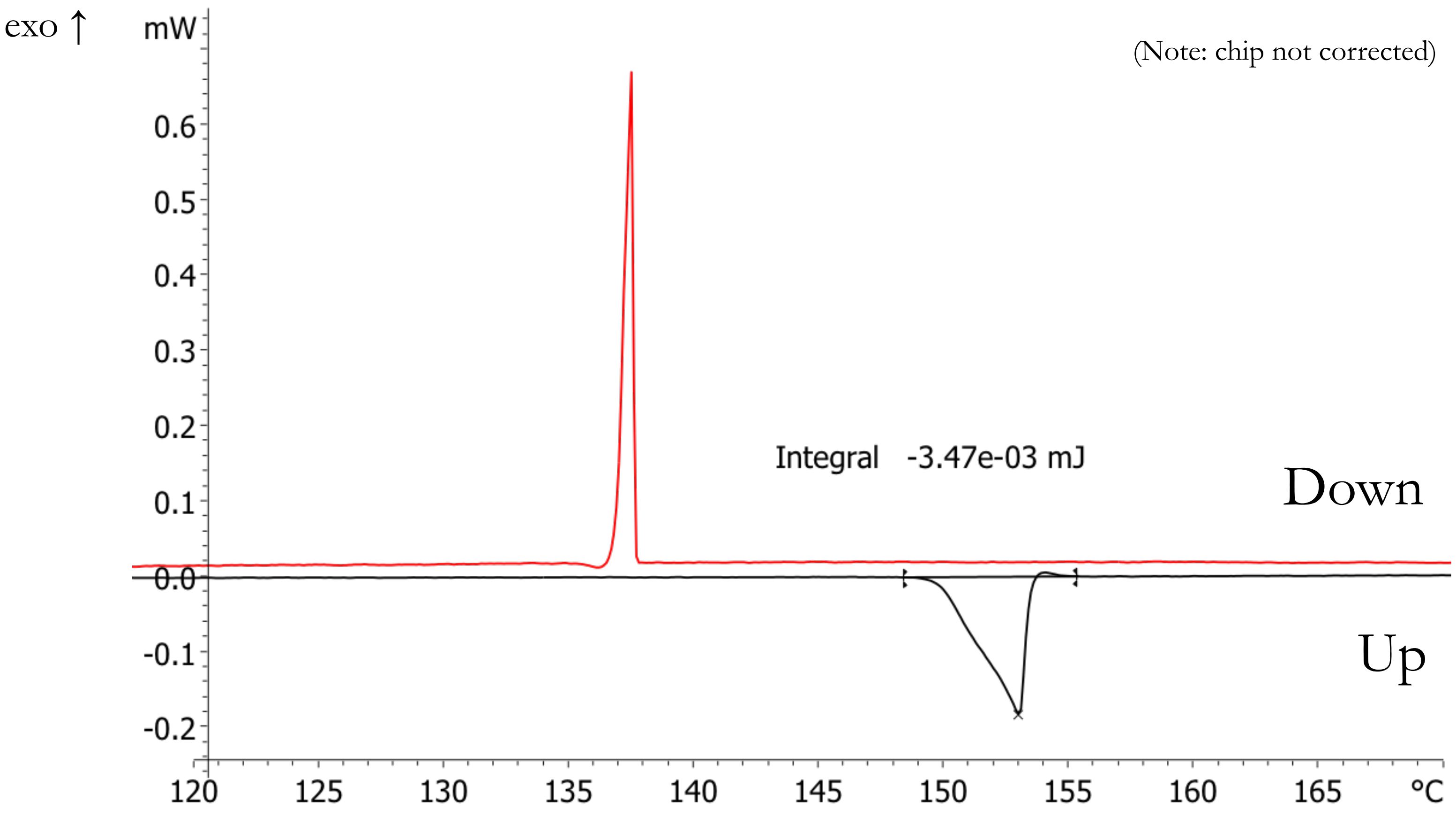
What was the enrichment?

Confirmation of In Mass Calibrates the Technique

$3.47\text{x}10^{-6}\ \text{J} / 28.6624\ \text{J/g} = \mathbf{121ng}$ $\quad 7\mu\text{m}*(50\mu\text{m})^2*7.31\text{g/cm}^3 = \mathbf{128 \pm 9ng}$

Test Sample:

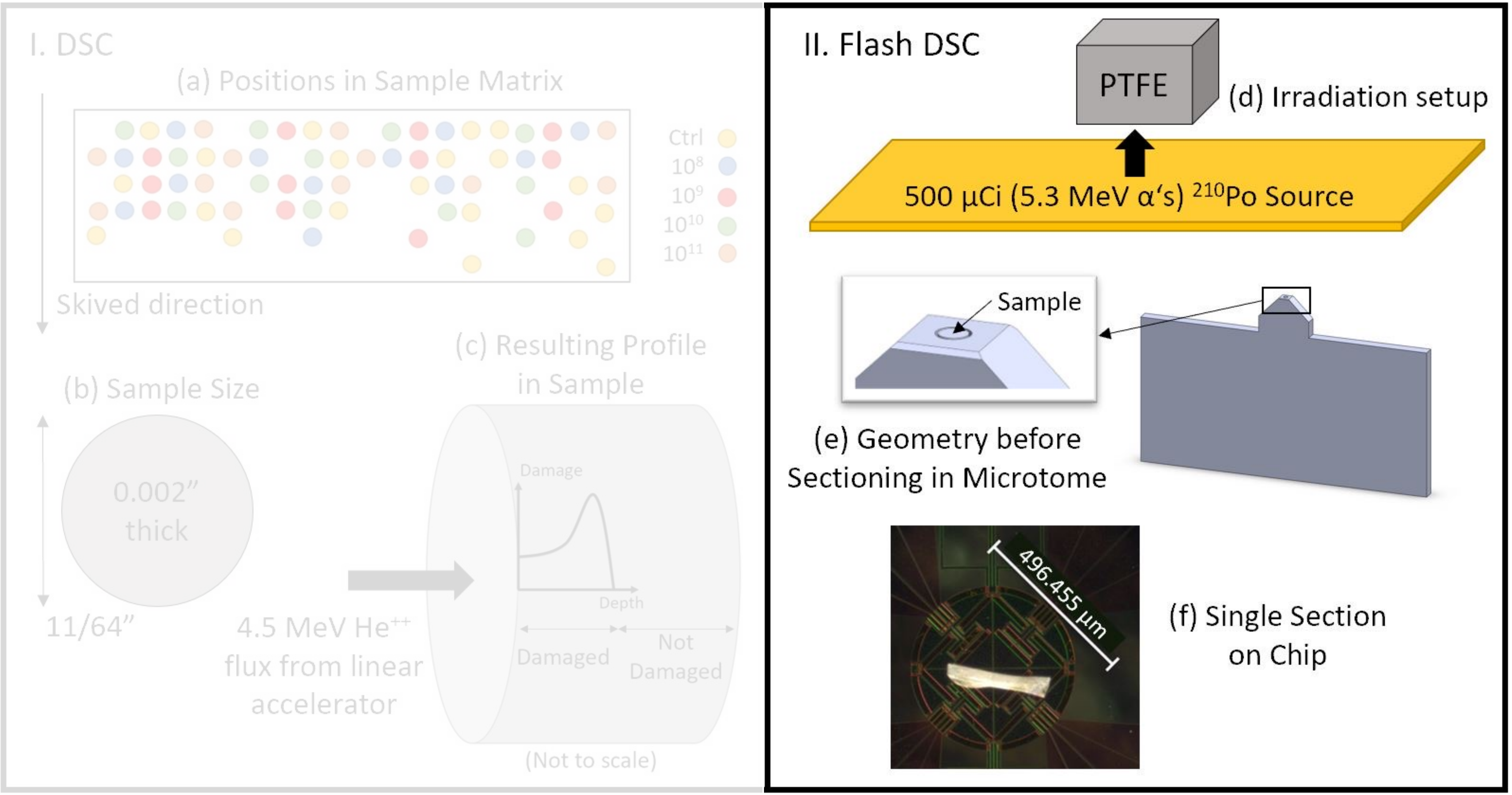
Cu – 10µm
In – 7µm



How much was made?

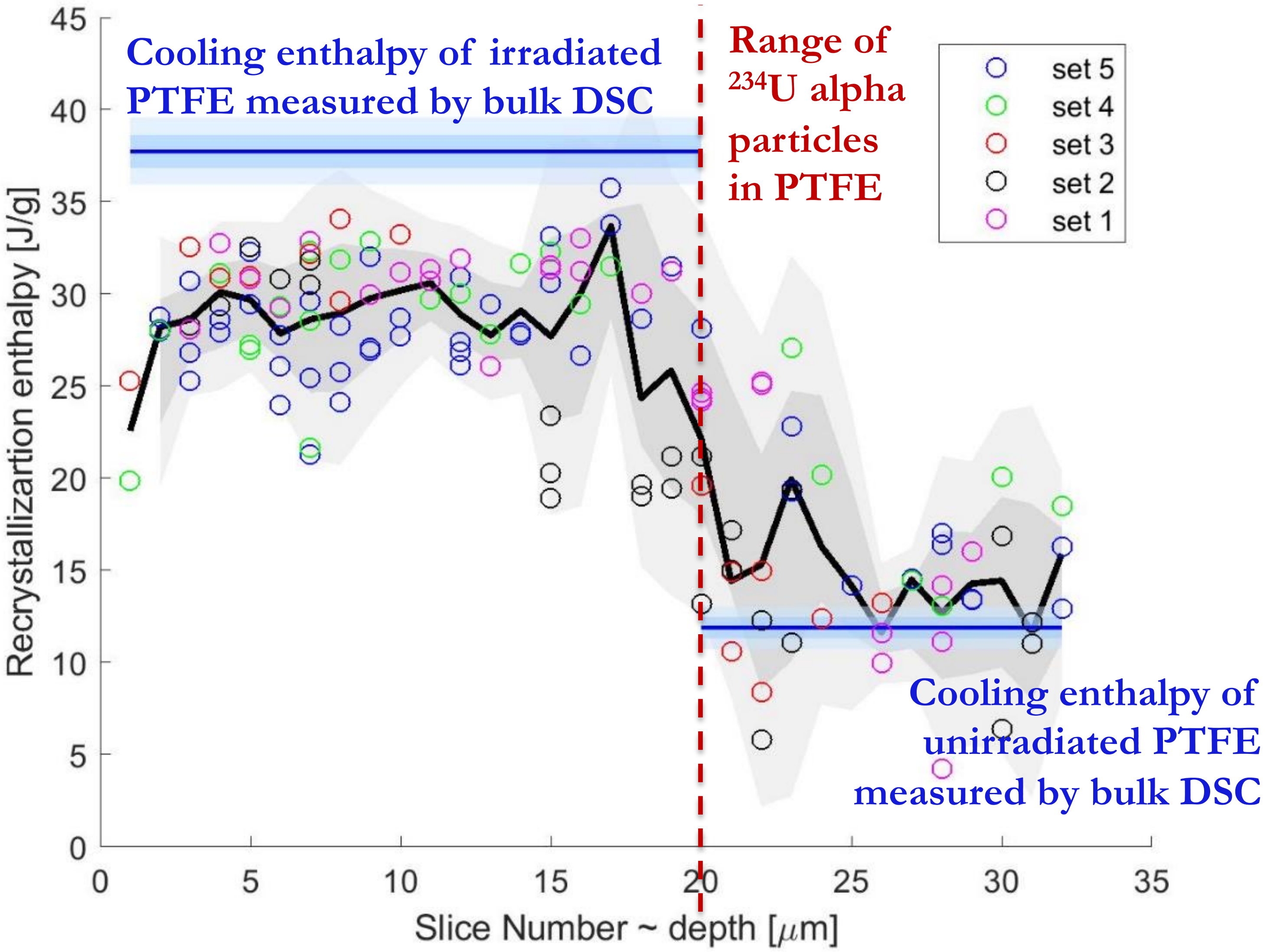
What was the enrichment?

We Use Nanocalorimetry to Reliably Measure Radiation Damage in PTFE



Microtomed Flash NanoDSC Confirms Alpha Radiation

- NanoDSC confirms DSC data with 1μm slice precision
- Range verification eliminates ability to "spoof" 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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