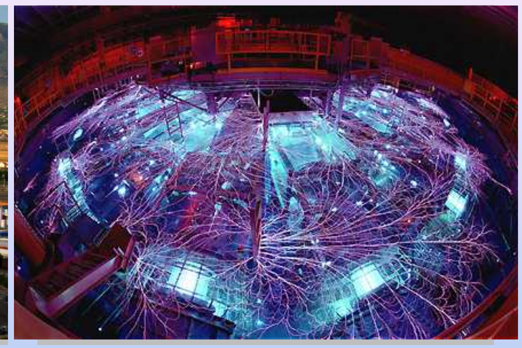
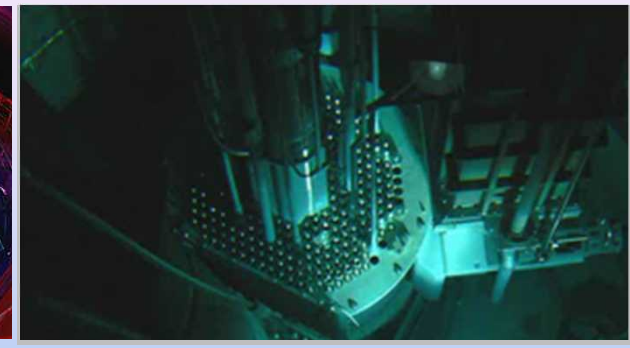
SAND2016-1527PE

Exceptional service in the national interest





Nuclear Criticality Safety & The 1999 Accident in Tokai-Mura, Japan

Ronald Allen Knief

Criticality Accident

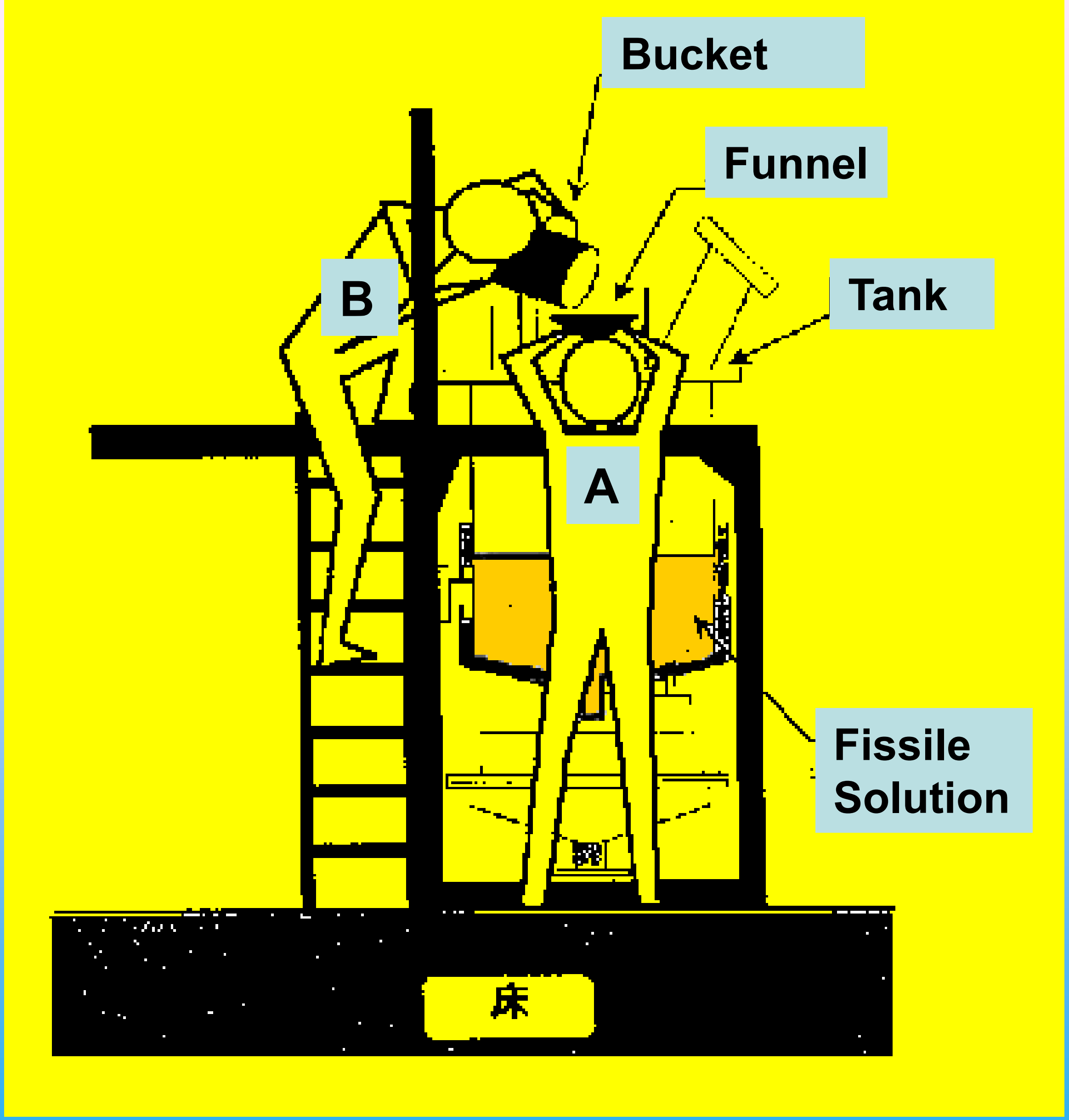
Process Criticality Accident Example

Tokai-Mura, Japan

Uranium Solution

in a Large Tank

Accident Scene



Criticality Accident

- Prevention of Consequences
  - Avoid a Criticality Accident

    or

  - Protect Personnel from the Consequences

Practice Nuclear Criticality Safety

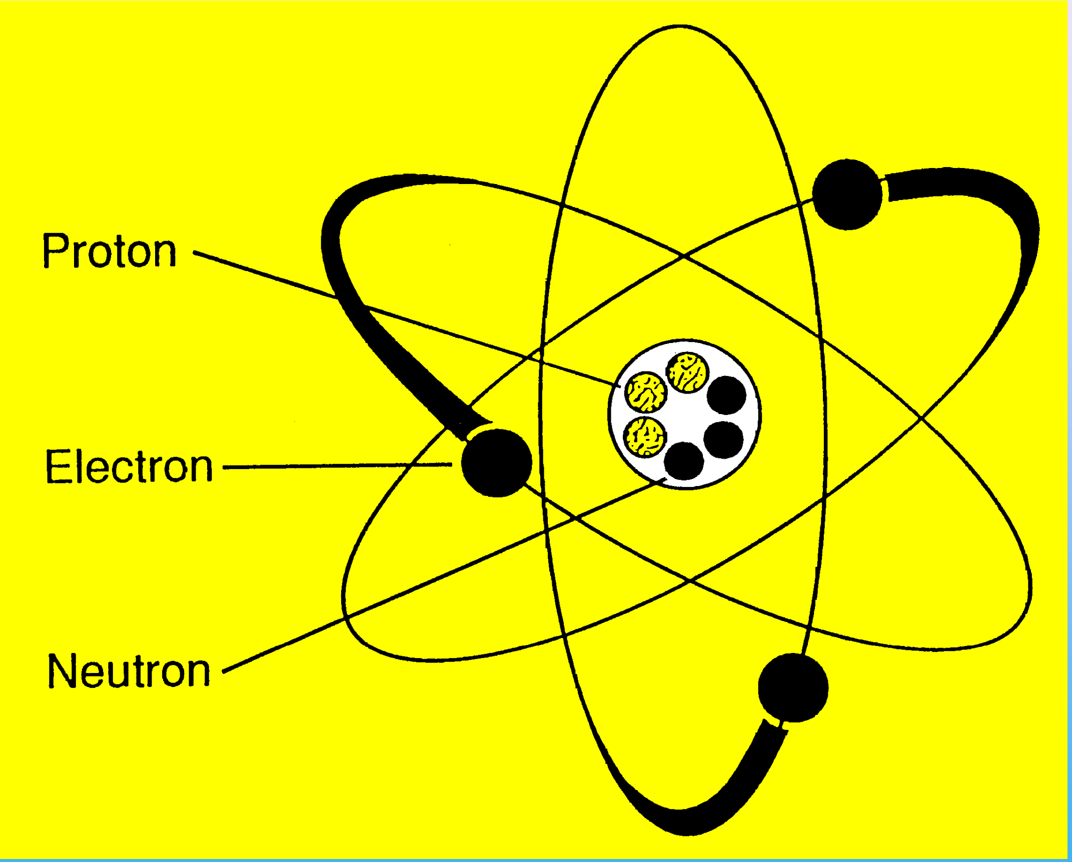
NUCLEAR

CRITICALITY

SAFETY

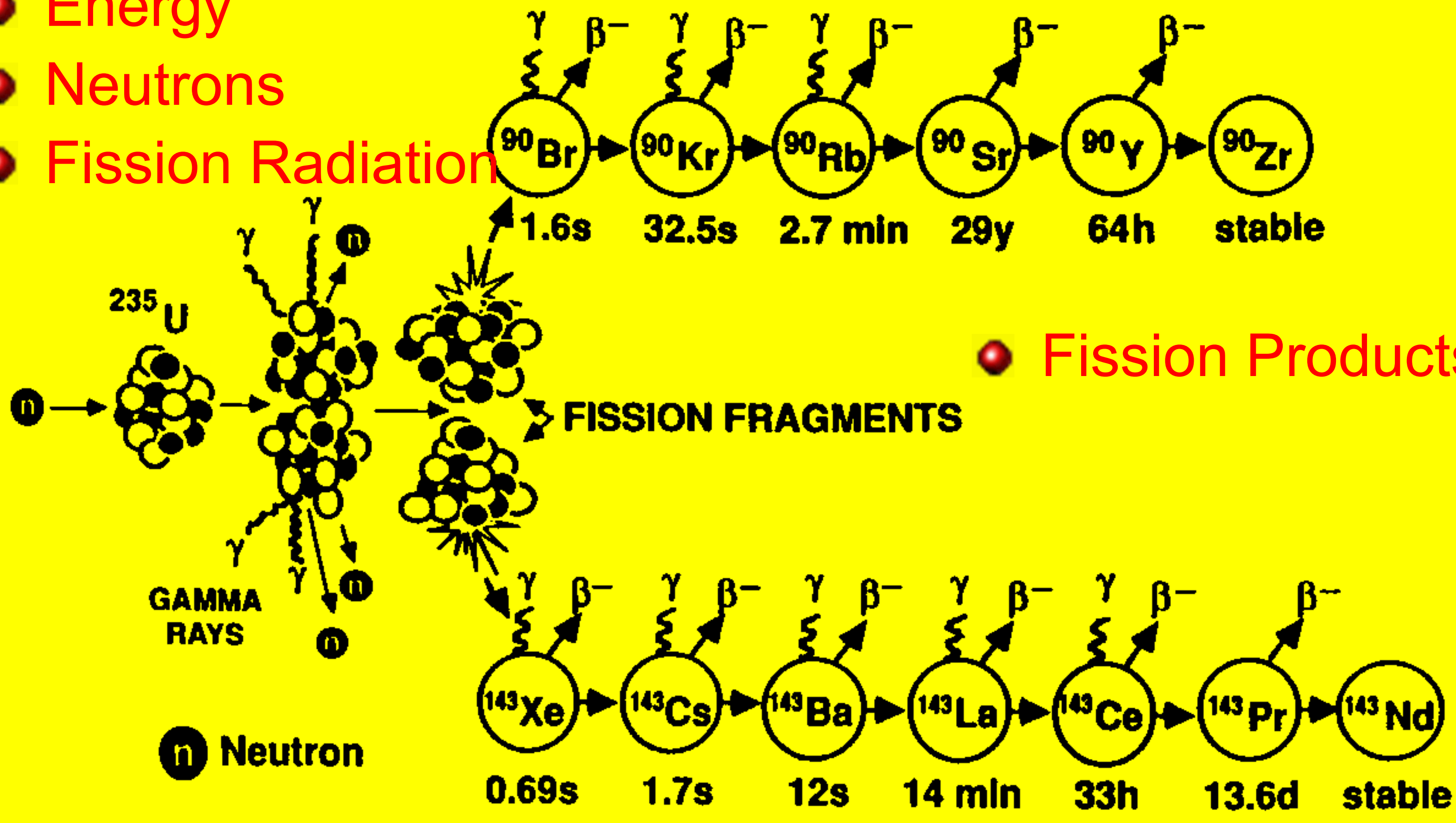
Atom

- Electrons
- Nucleus
  - Proton
  - Neutron



Nuclear Fission

- Energy
- Neutrons
- Fission Radiation



- Fission Products

Nuclear Fission

- Major Fissionable Species
  - Fissile ^{235}U ^{233}U ^{239}Pu ^{241}Pu
  - Threshold ^{232}Th ^{238}U ^{240}Pu
- Major Fertile Species

^{232}Th ^{238}U ^{240}Pu

NUCLEAR

CRITICALITY

SAFETY

Neutron Balance

$Production \leftrightarrow Losses$

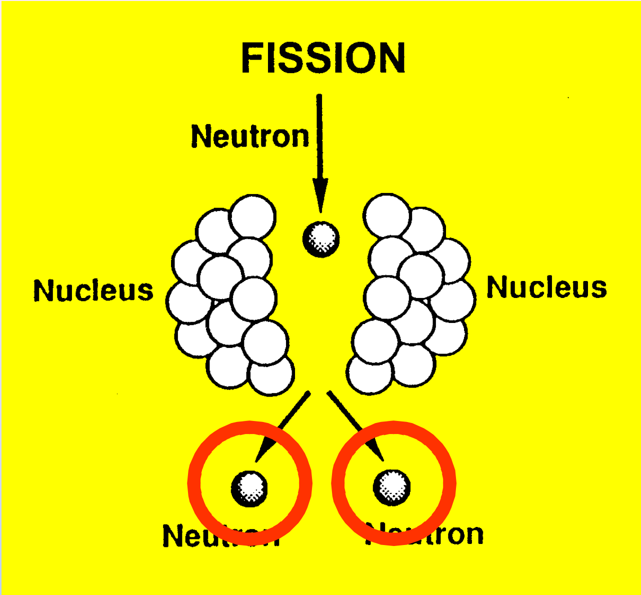
$Production \leftrightarrow Absorption +$
$Leakage$

+ *Moderation* Effect

Effective Multiplication Factor

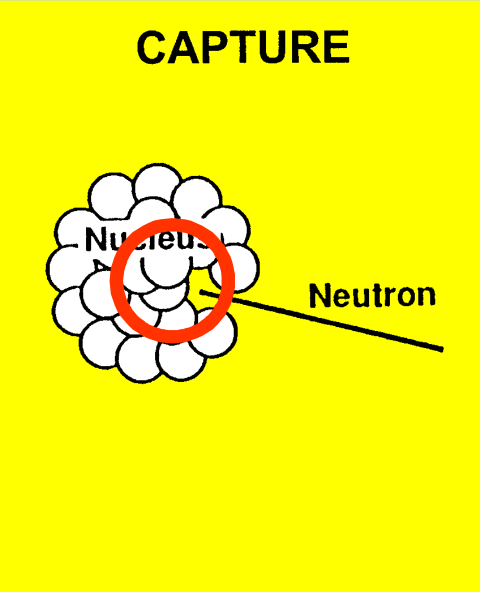
$$k_{eff} = k = \frac{\text{Production}}{\text{Absorption + Leakage}}$$

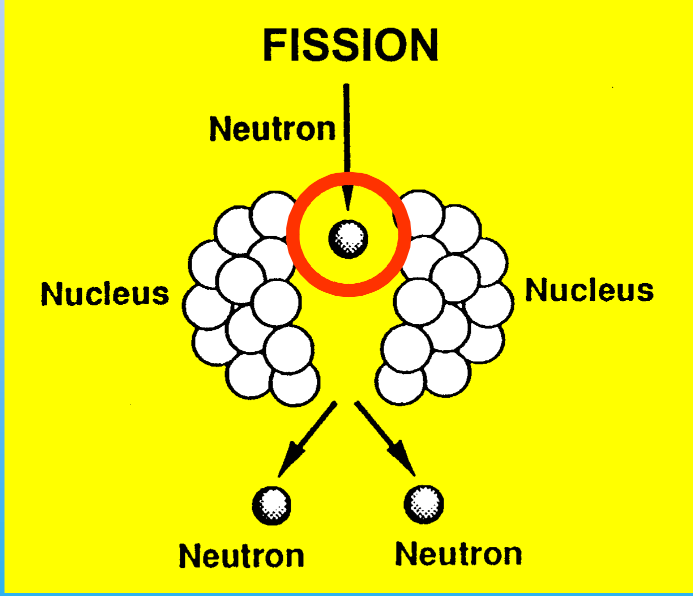
Nuclear Reactions



PRODUCTION

ABSORPTION





Effective Multiplication Factor

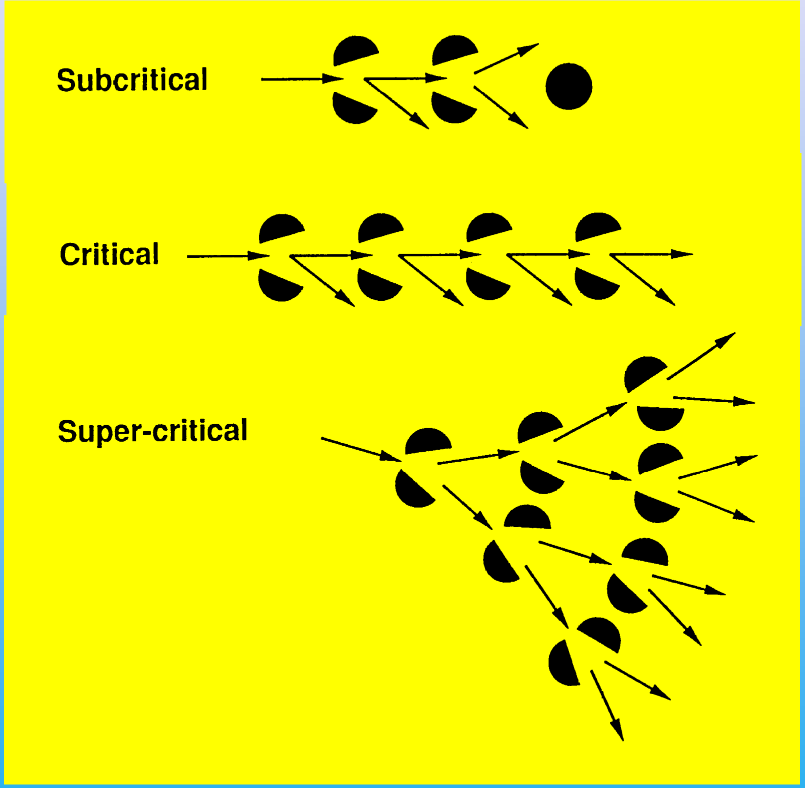
$$k_{eff} = k = \frac{\text{Production}}{\text{Absorption + Leakage}}$$

$k_{eff} < 1$ Subcritical

$k_{eff} = 1$ Critical

$k_{eff} > 1$ Supercritical

Fission "Generations"



Reactor

- Power Reactor →
  Startup/Shutdown/Steady-State
- Some Research Reactors →
  Also Pulse
- Adjustments Required
  - Account for Feedback Effects & Power Fluctuations
  - Control Rod Motion for Critical

Fuel Facility or D&D

- Subcritical
- No Required Adjustment
  - Current Configuration Subcritical
  - Confirm That Proposed Changes Will Be Subcritical
- Calculations
  - Multiplication Factor (k_{eff})

Nuclear Criticality Safety

$$k_{eff} < 1$$

- Not Merely Calculated or Computed
- *Must Account for ALL:*
  - *Uncertainties in Experimental Data and Calculations*
  - *Scenarios*
    - *Normal*
    - *Anticipated Abnormal*
    - *Credible Accident*

NUCLEAR

CRITICALITY

SAFETY

Definitions

Prevention or termination of inadvertent nuclear chain reactions in non-reactor environments

– Standard ANSI/ANS-16.1
  (Predecessor to ANSI/ANS-8.1)

Protection against the consequences of an inadvertent nuclear chain reaction, preferably by prevention of the reaction

– Standard ANSI/ANS-8.1-1998

Definition

The art and science of *not* building a nuclear reactor without shielding, coolant, and control

The art and science of *not* building a nuclear reactor . . .

. . . *anywhere you don't want one ! ! !*

Neutron Balance

- CONTROL STRATEGY BASIS
  - Terms
    - Production
    - Absorption
    - Leakage
  - Inter-Relationship Effects
    - Enrichment
    - Moderation

Enrichment

- Uranium Isotopic Content

Depleted (DU) 0.2-0.35 wt% ^{235}U

Natural 0.7 wt% ^{235}U

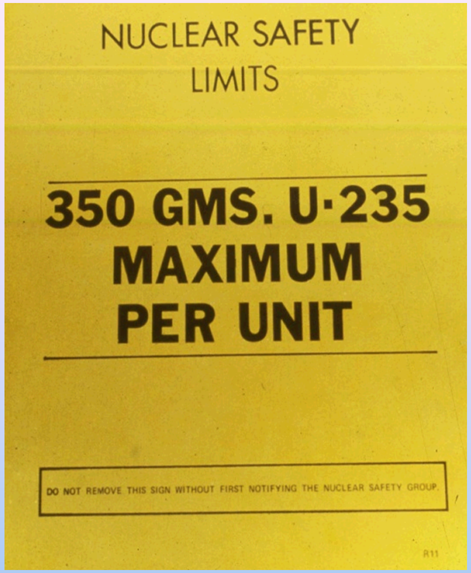
Low Enrichment (LEU) 1-6 wt% ^{235}U

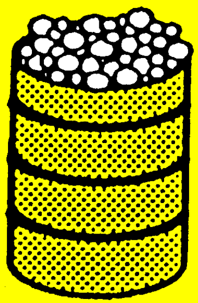
Intermediate Enrichment

High Enrichment (HEU) >90+ wt% ^{235}U

Production

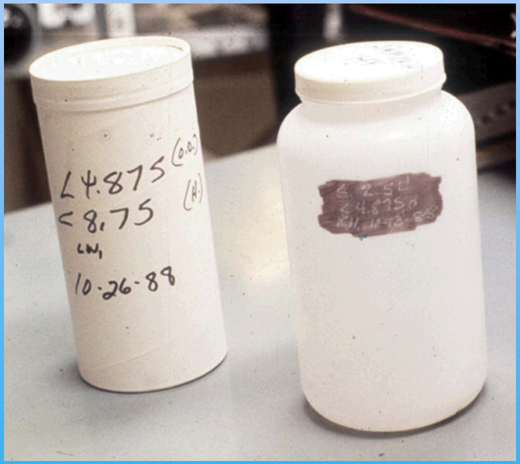
- MASS CONTROL
  - *"Safe Mass"*
- VOLUME CONTROL
  - *"Safe Volume*





1.4 wt% ^{235}U

≥90 wt% ^{235}U
(1 gallon/4 litres)

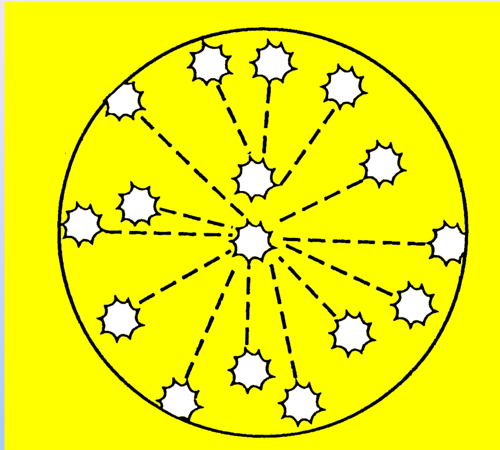


Absorption

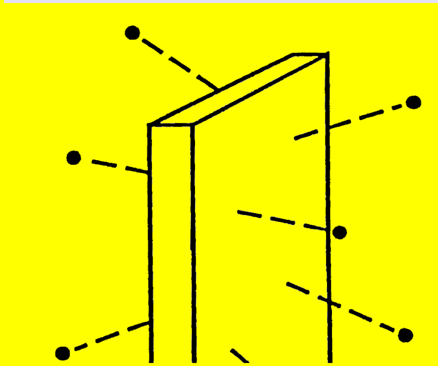
- Emphasis on Non-Fission Absorption [Capture]
  - Threshold Fissioning Materials (Lower Enrichment)
  - Structural & Other Materials
  - "Neutron Poisons"
    - Borosilicate glass Raschig rings
    - Soluble boric acid

Leakage

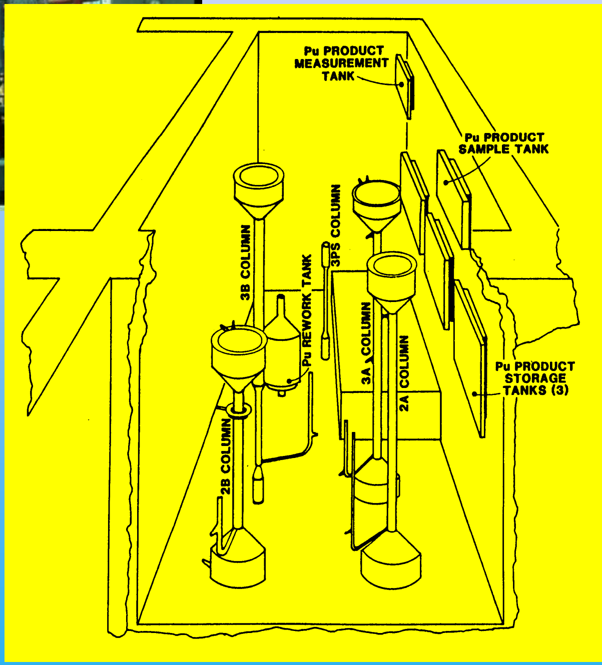
- GEOMETRY



Few Neutrons Leak from Given Volume as a Sphere

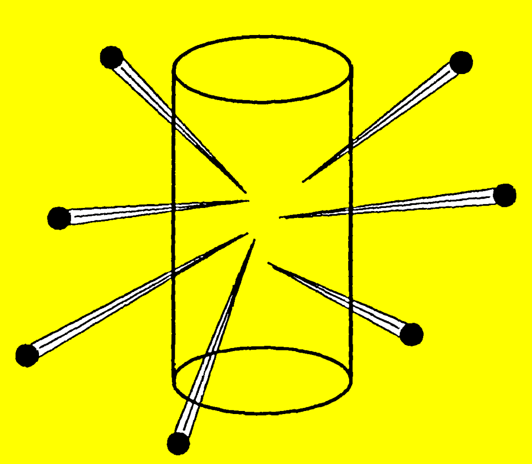


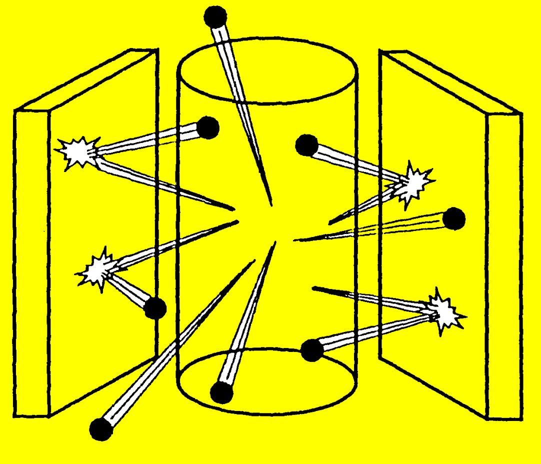
More Neutrons Leak from Same Volume as a Slab



Leakage

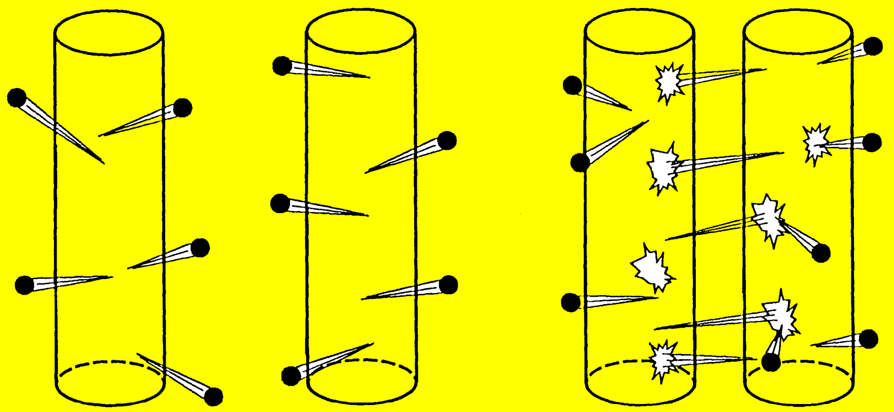
- GEOMETRY
- REFLECTION


No Reflection


Reflection

Leakage

- GEOMETRY
- REFLECTION
- SEPARATION/SPACING



When two containers are widely separated, few neutrons escaping from one will hit the other.

When two containers are placed close to each other, neutrons escaping from each will be more likely to hit the other.

Neutron Balance

- Moderation Change Effects:
  - Production Term
  - Absorption Term
  - Leakage Term

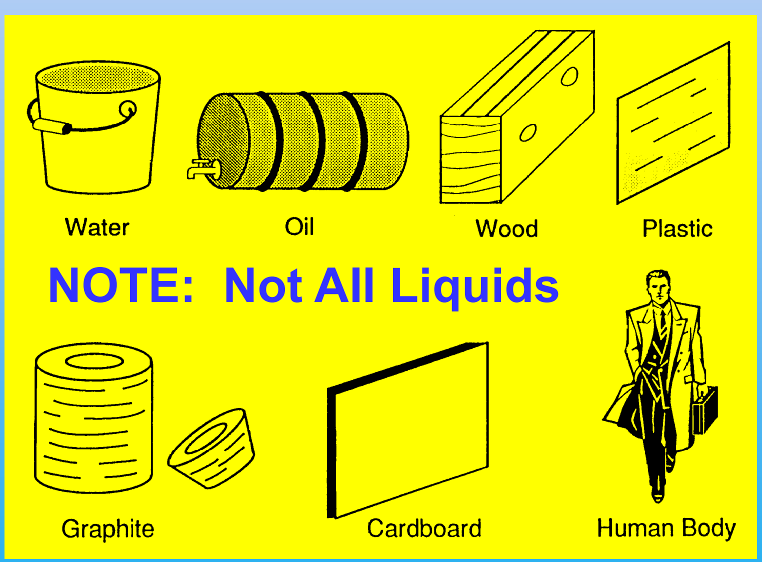
Production Term and Absorption Term: Fission & Capture Increase w/ Decreasing Neutron Energy

Leakage Term: Leakage Increases w/ Decreasing Material Density

Moderation

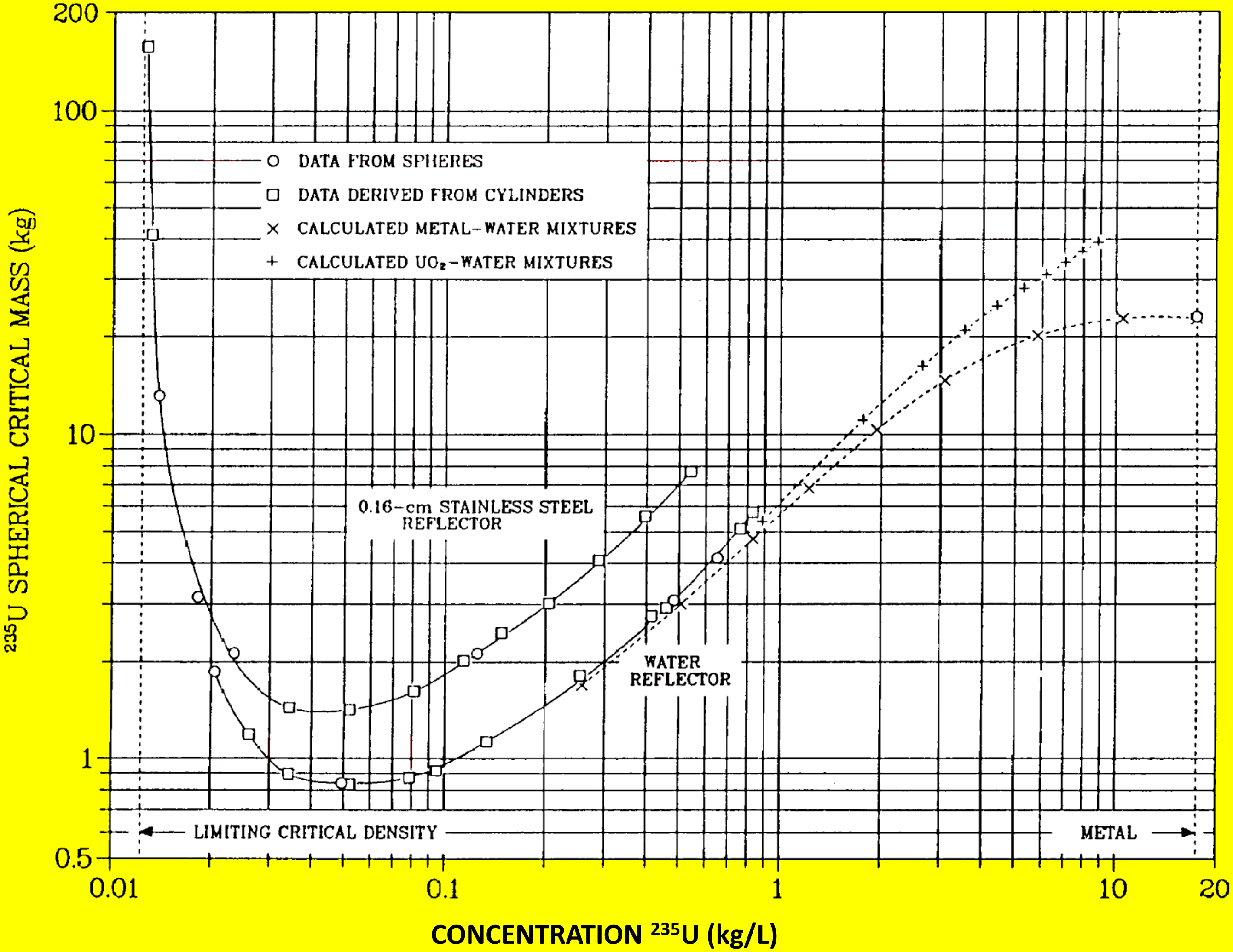
- MODERATOR
  - Low-Mass-Number Materials
    - Scatter Neutrons
    - Reduce Neutron Energies Effectively
    - Change Reaction Probabilities
  - Examples
    - Water Oil Wood
    - Plastic Cardboard
    - Human Body Graphite

Major NCS Focus



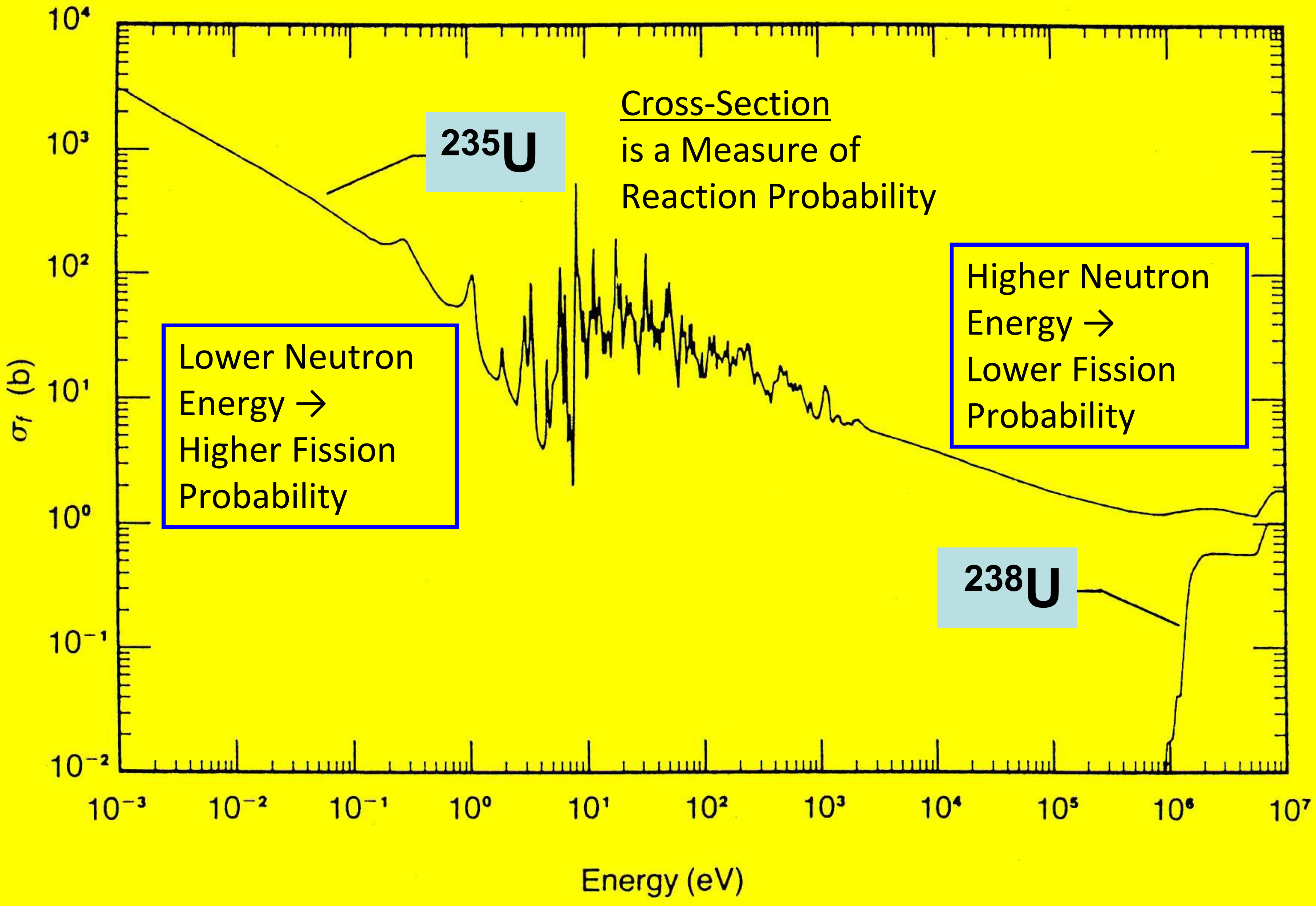
^{235}U CRITICAL MASS VS. CONCENTRATION

Sandia National Laboratories

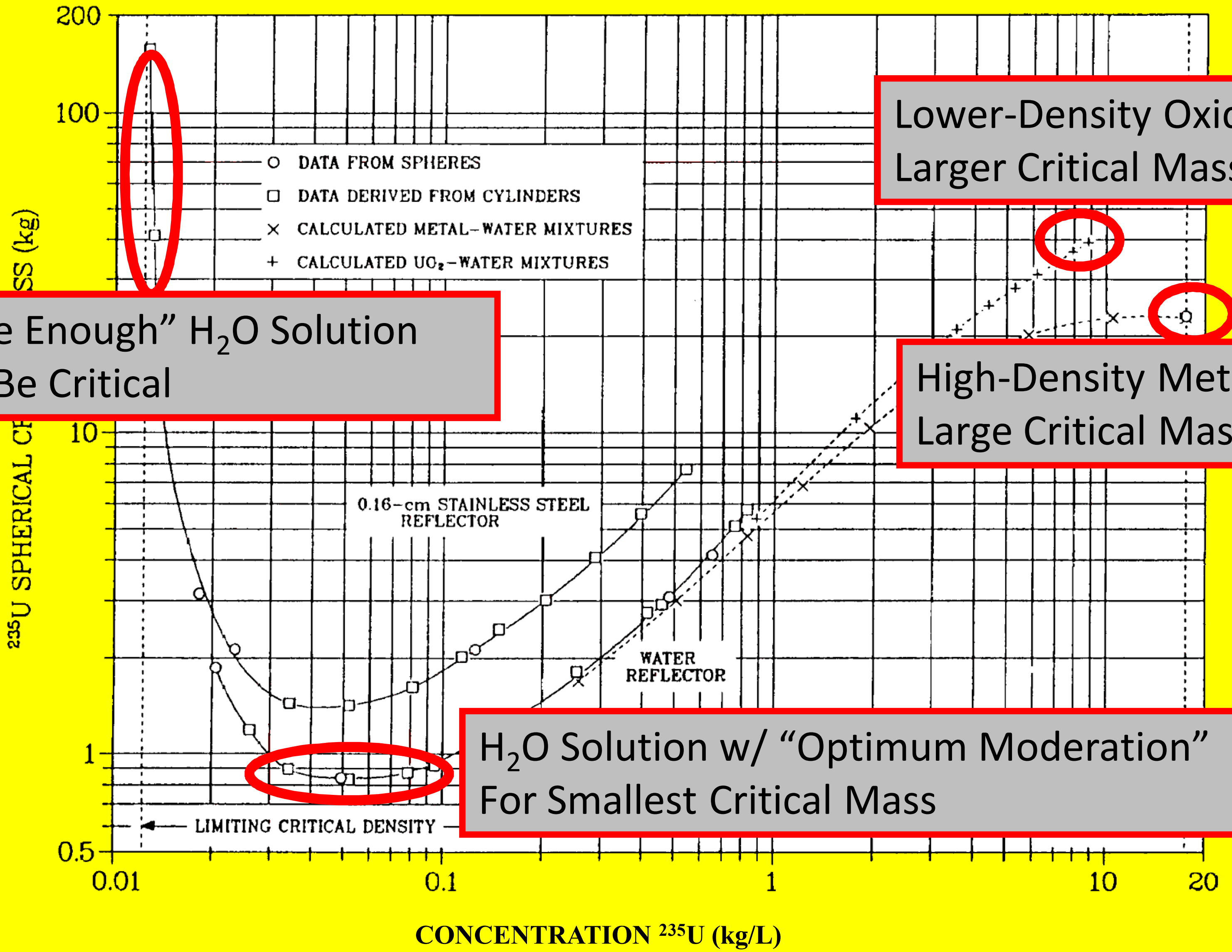


LA-10860 (1986)

Uranium Fission Cross Sections

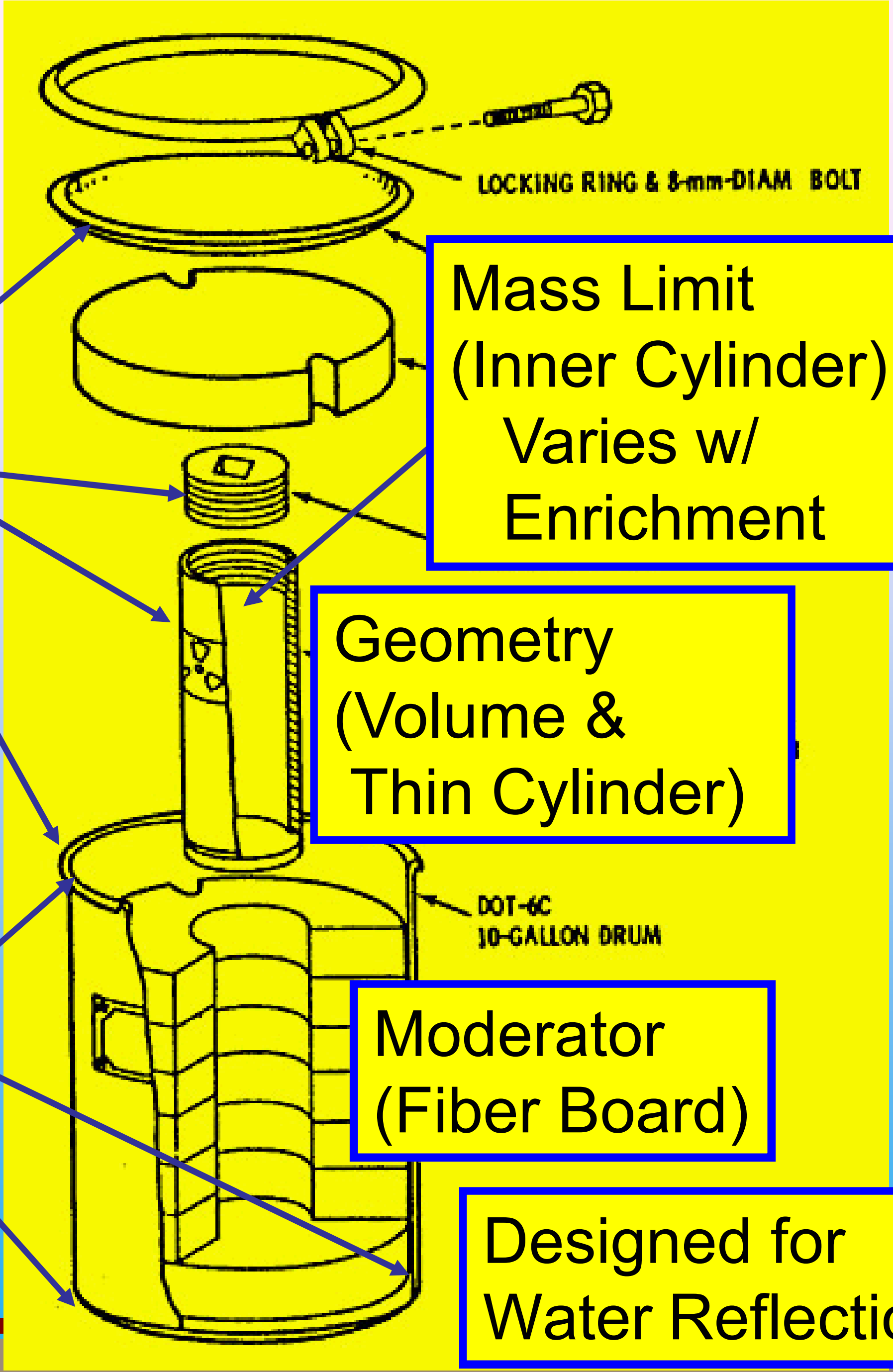


^{235}U CRITICAL MASS VS. CONCENTRATION



LA-10860 (1986)

Interaction



Absorber (Steel)

Mass Limit (Inner Cylinder) Varies w/ Enrichment

Geometry (Volume & Thin Cylinder)

Spacing (Drum Size)

Moderator (Fiber Board)

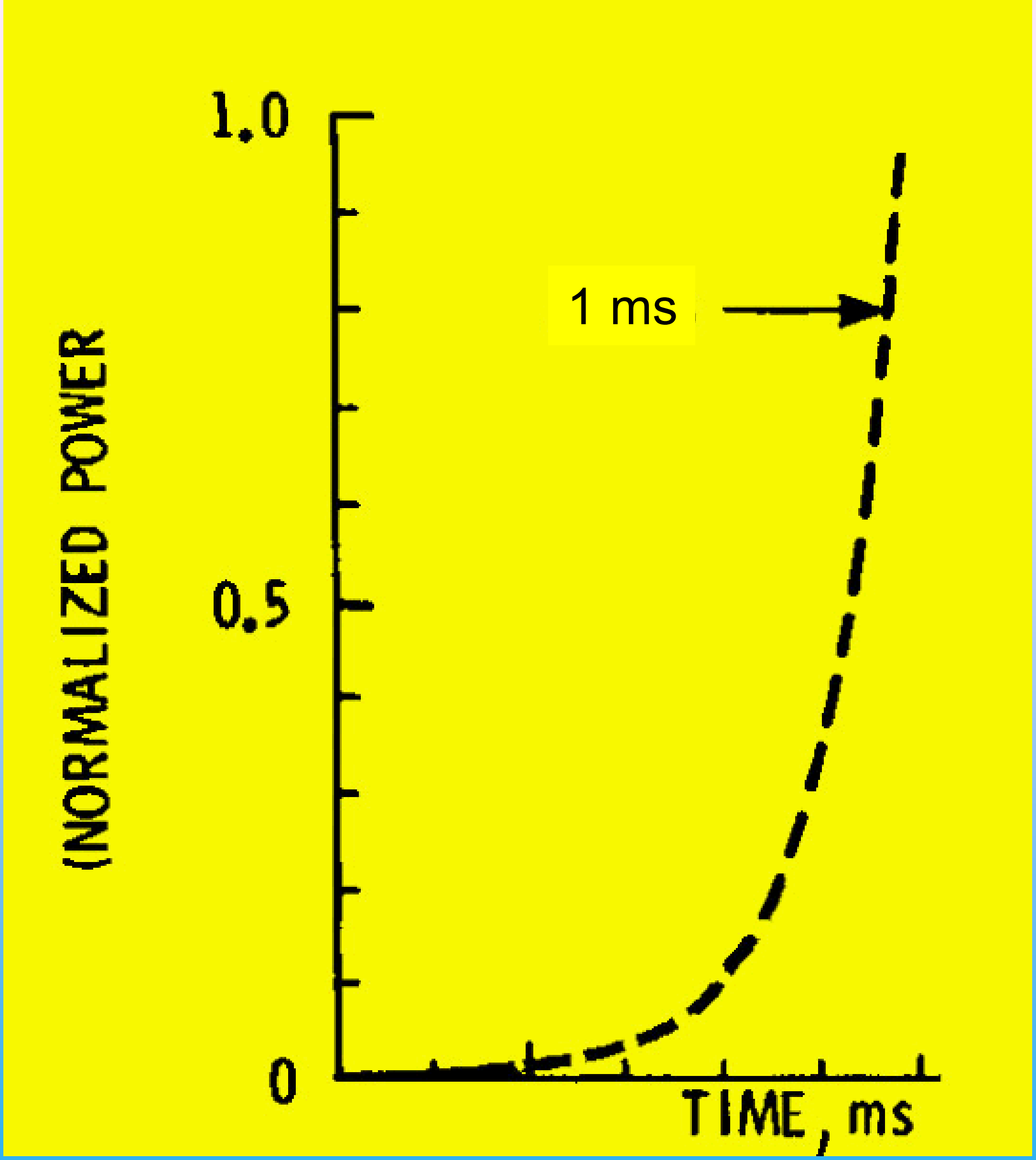
Designed for Water Reflection

Nuclear Criticality Safety

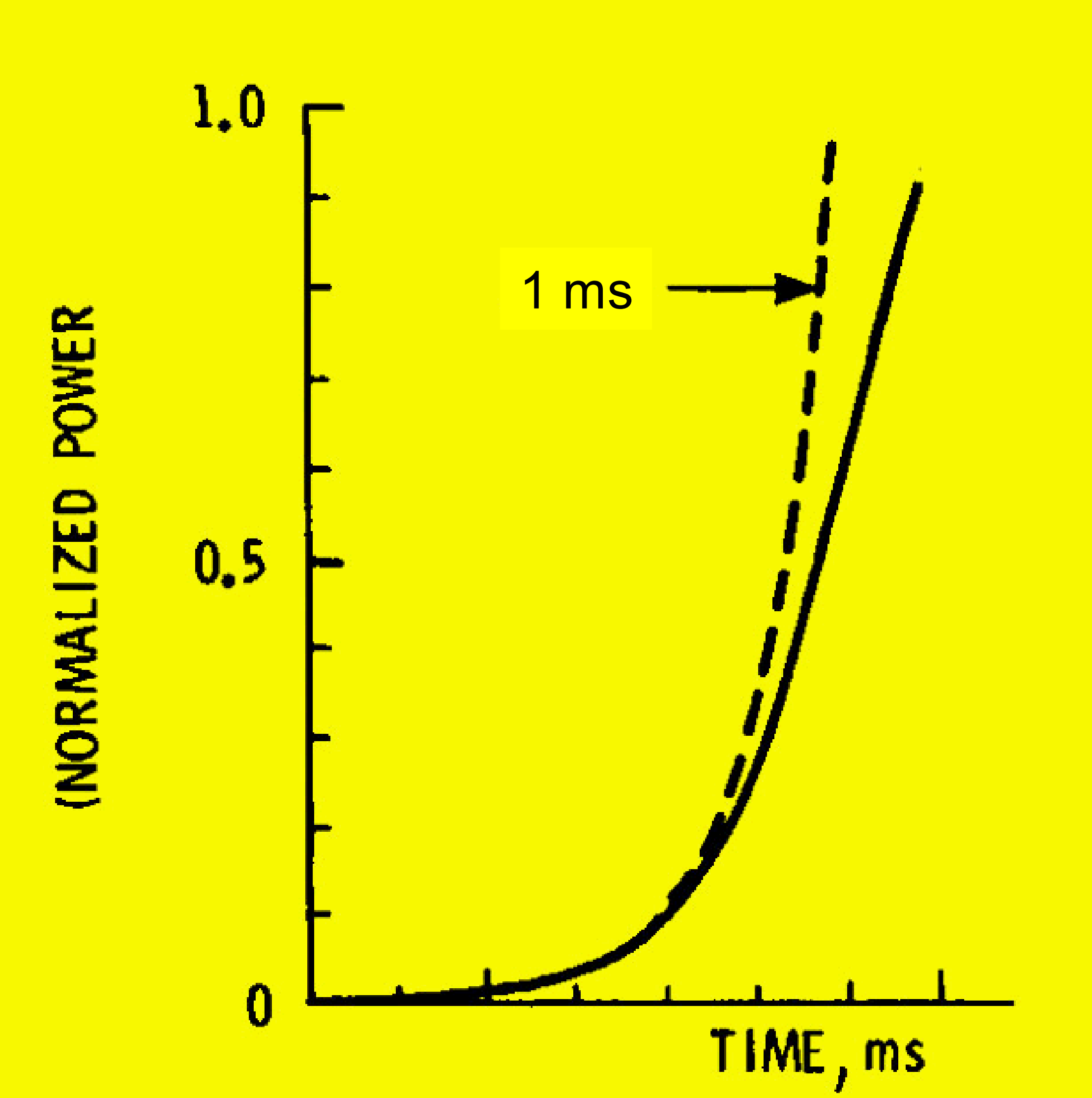
- ELEMENTS
  - Neutron Physics — *Experiments & Computational Methods*
  - Engineering — *Components, Systems & Structures – Physical Controls*
  - Administration — *Rules, Procedures & Practices – Administrative Controls*

Supercritical Excursion (Pulse)

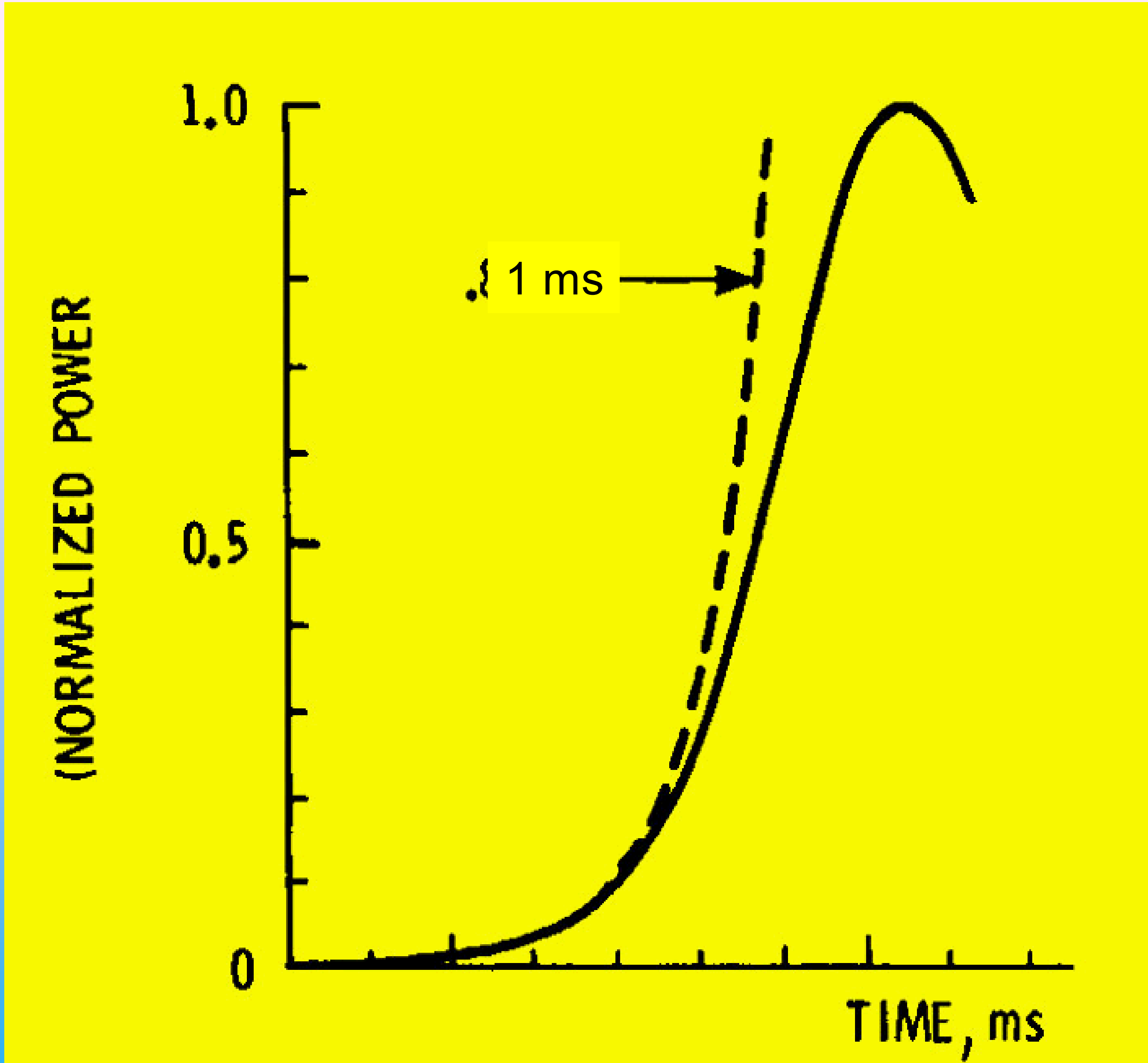
- Paradigm
  - Sandia National Laboratories Annular Core Research Reactor [ACRR])
    - Sequence Initiation (Unrecoverable)
    - Prompt Supercritical Pulse
    - Parameters

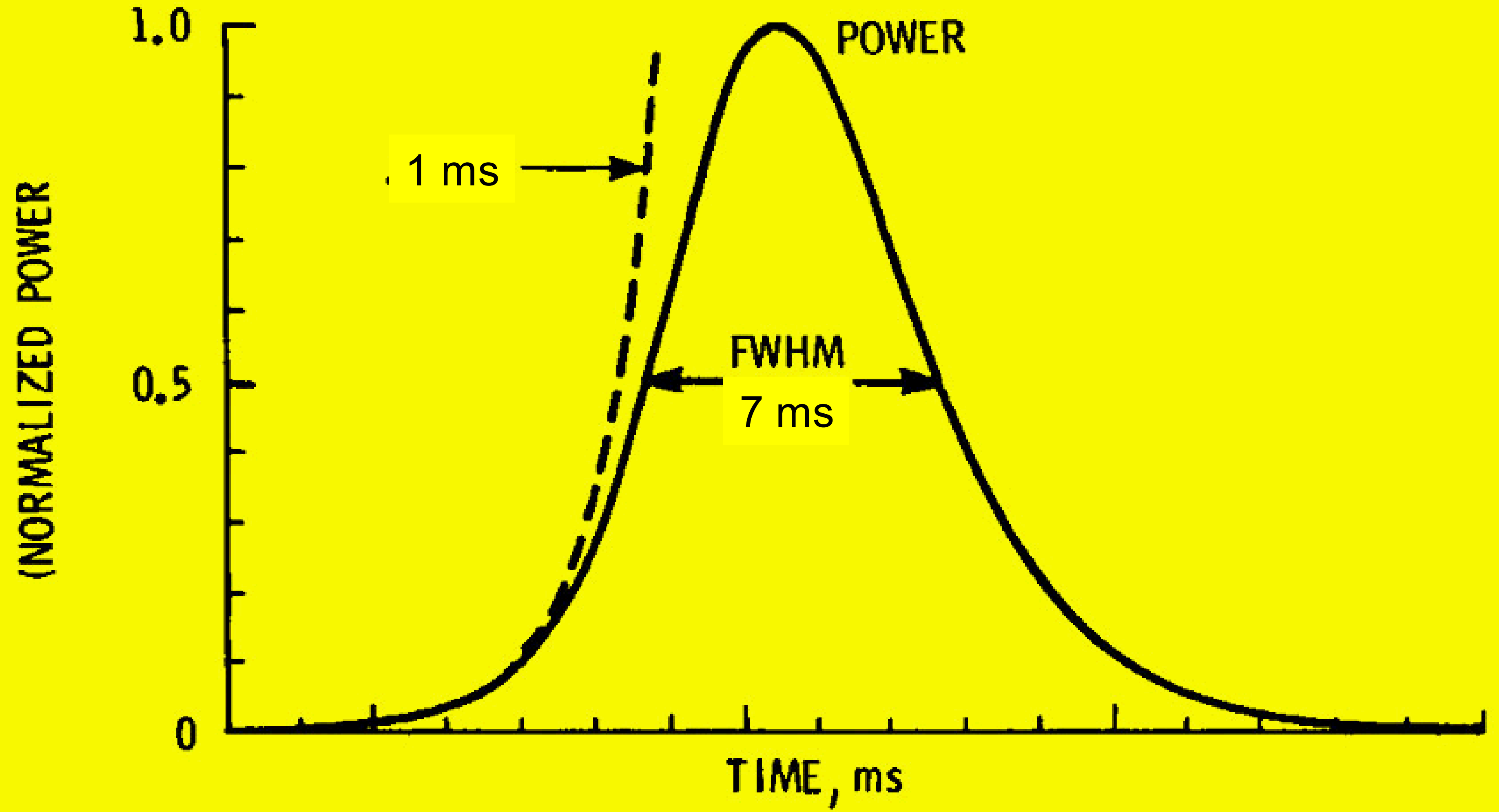


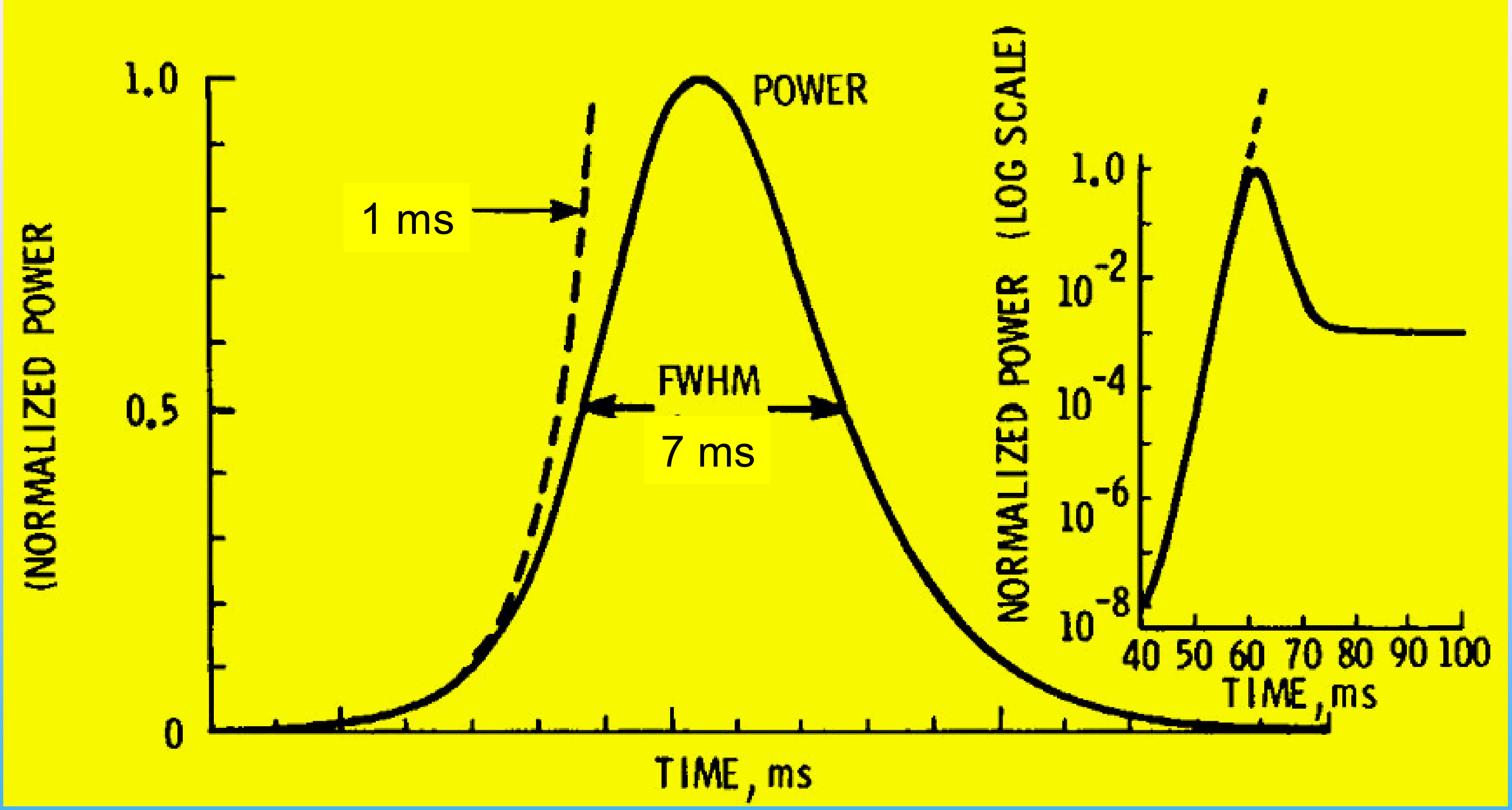
1.0
0.5
0
(NORMALIZED POWER
1 ms
TIME, ms


1.0
0.5
0
(NORMALIZED POWER)
1 ms
TIME, ms

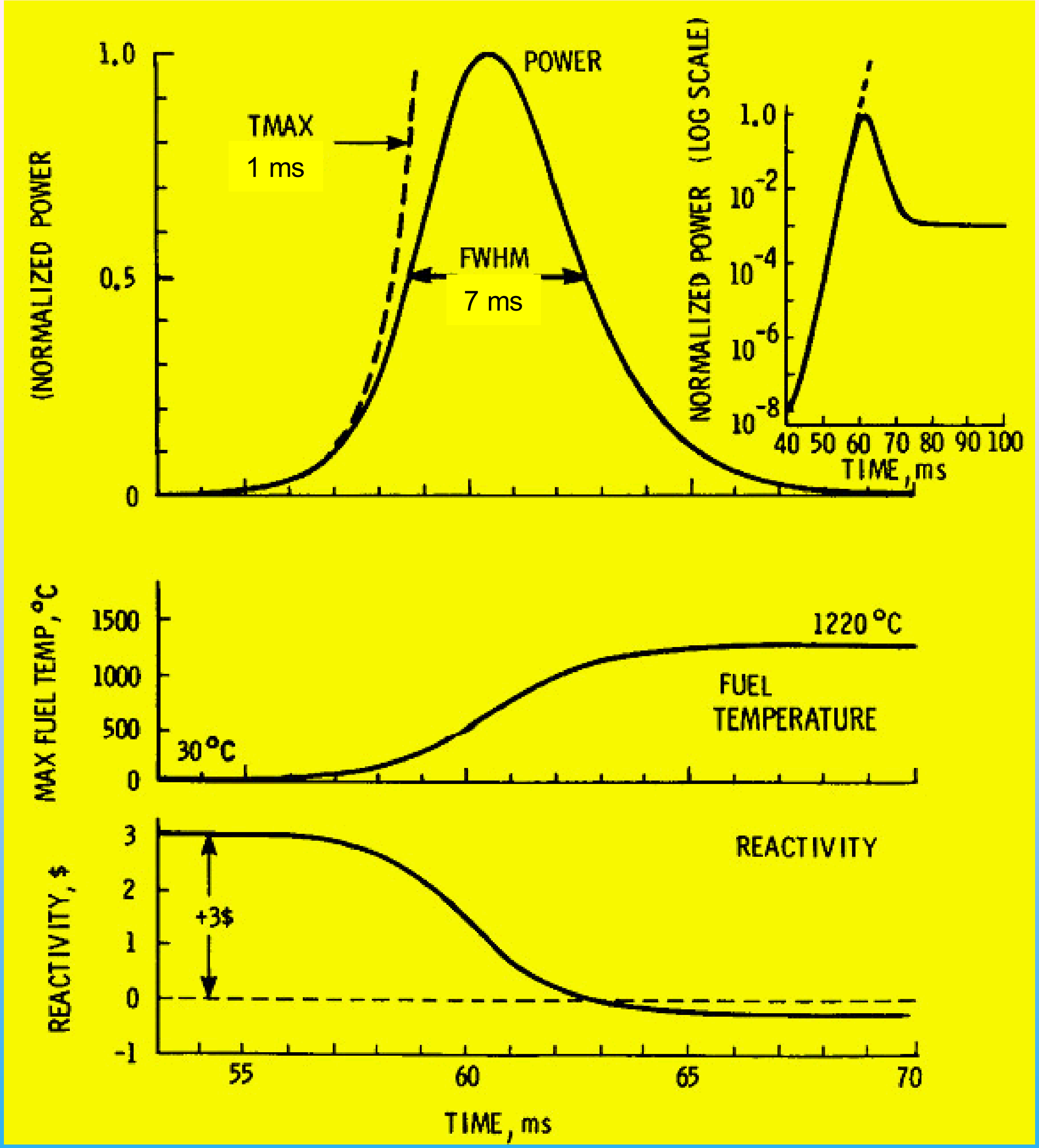
Sandia National Laboratories




1.0
0.5
0
(NORMALIZED POWER
POWER
1 ms
FWHM
7 ms
TIME, ms



1.0
0.5
0
(NORMALIZED POWER
TIME, ms
POWER
1 ms
FWHM
7 ms
NORMALIZED POWER (LOG SCALE)
1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
40 50 60 70 80 90 100
TIME, ms



Initial Period 1 ms

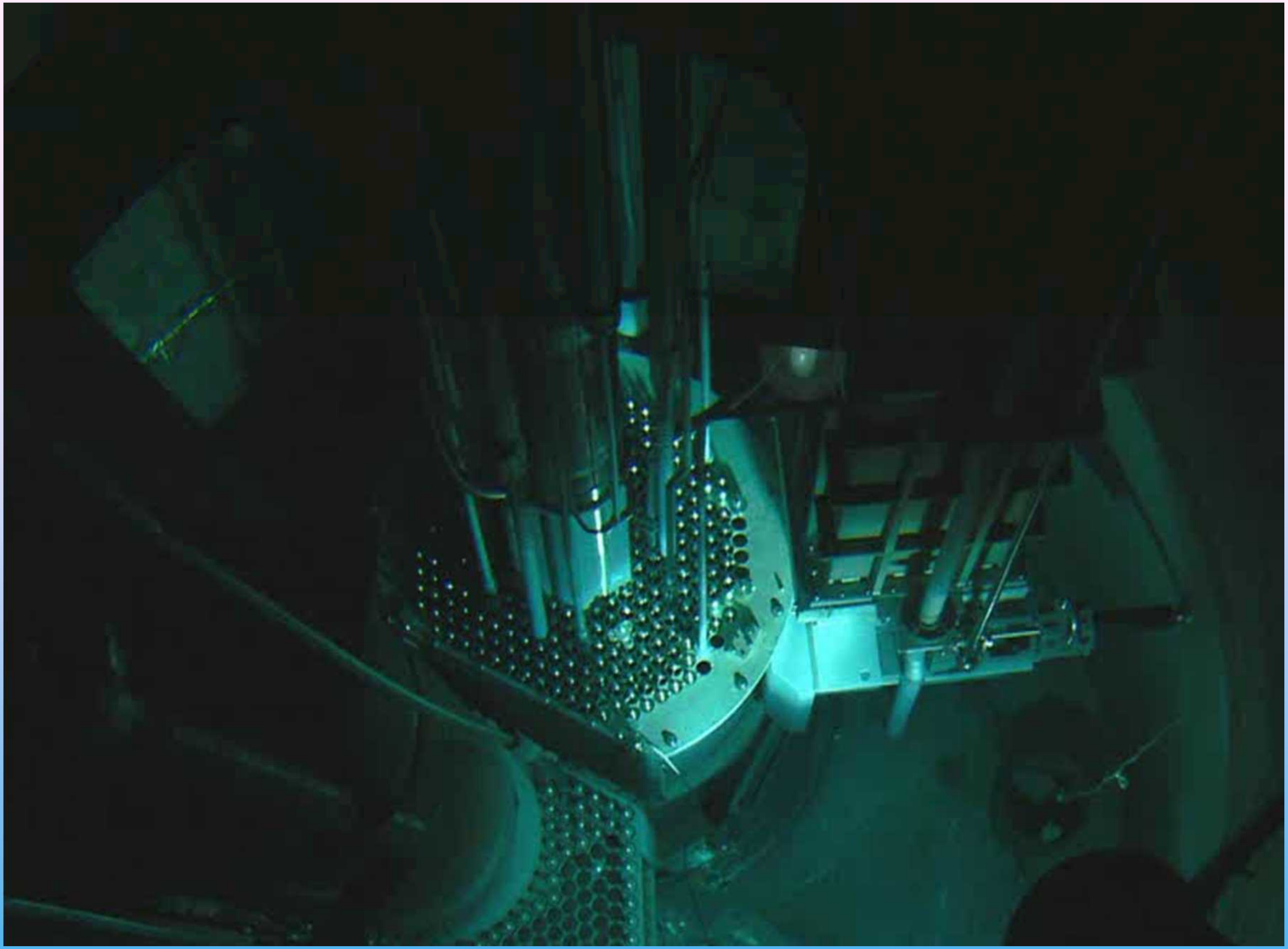
Maximum Power

35,000 MWth

Pulse Width 7ms

Fuel Temperature Rises

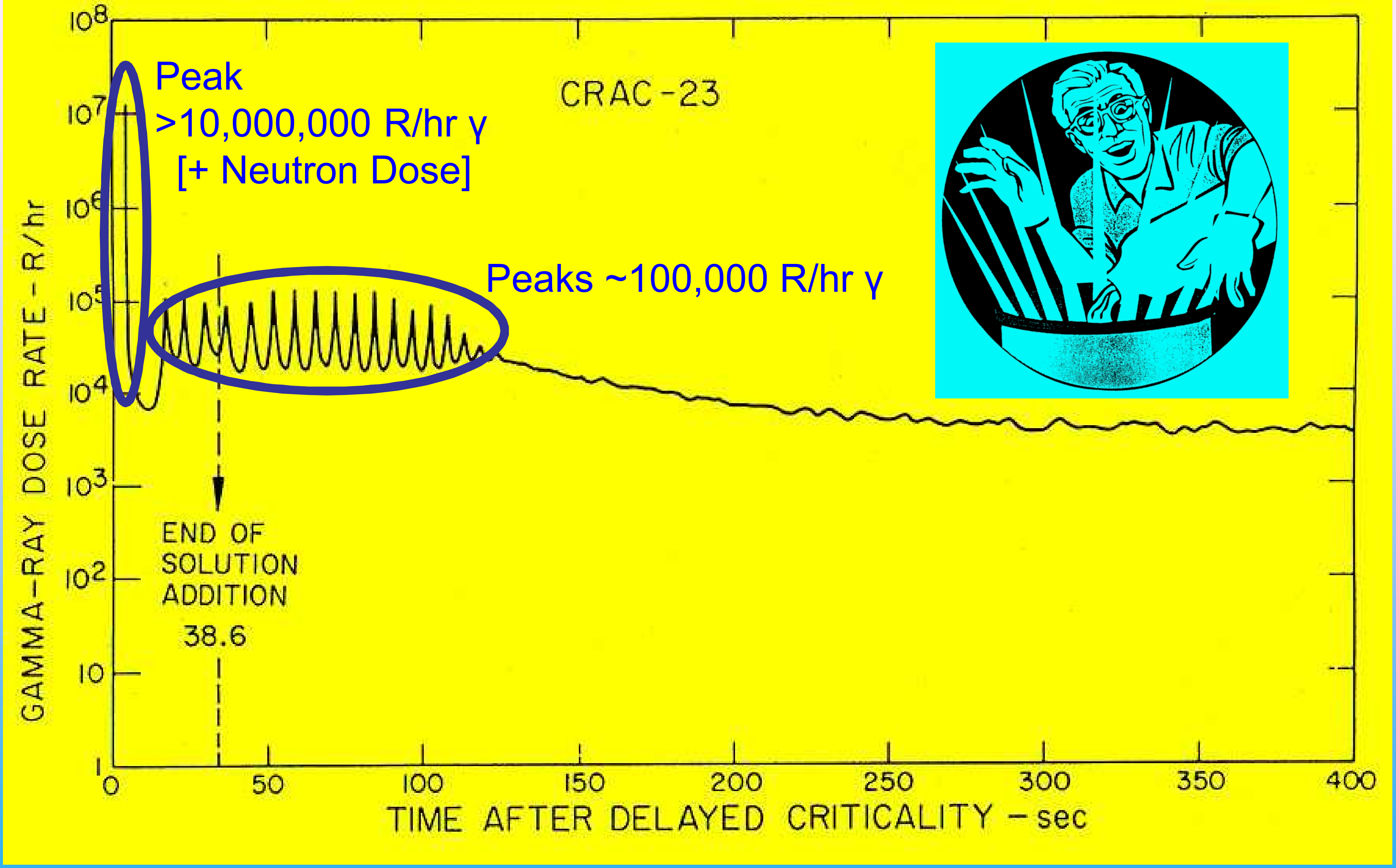
Multiplication (Reactivity) Falls



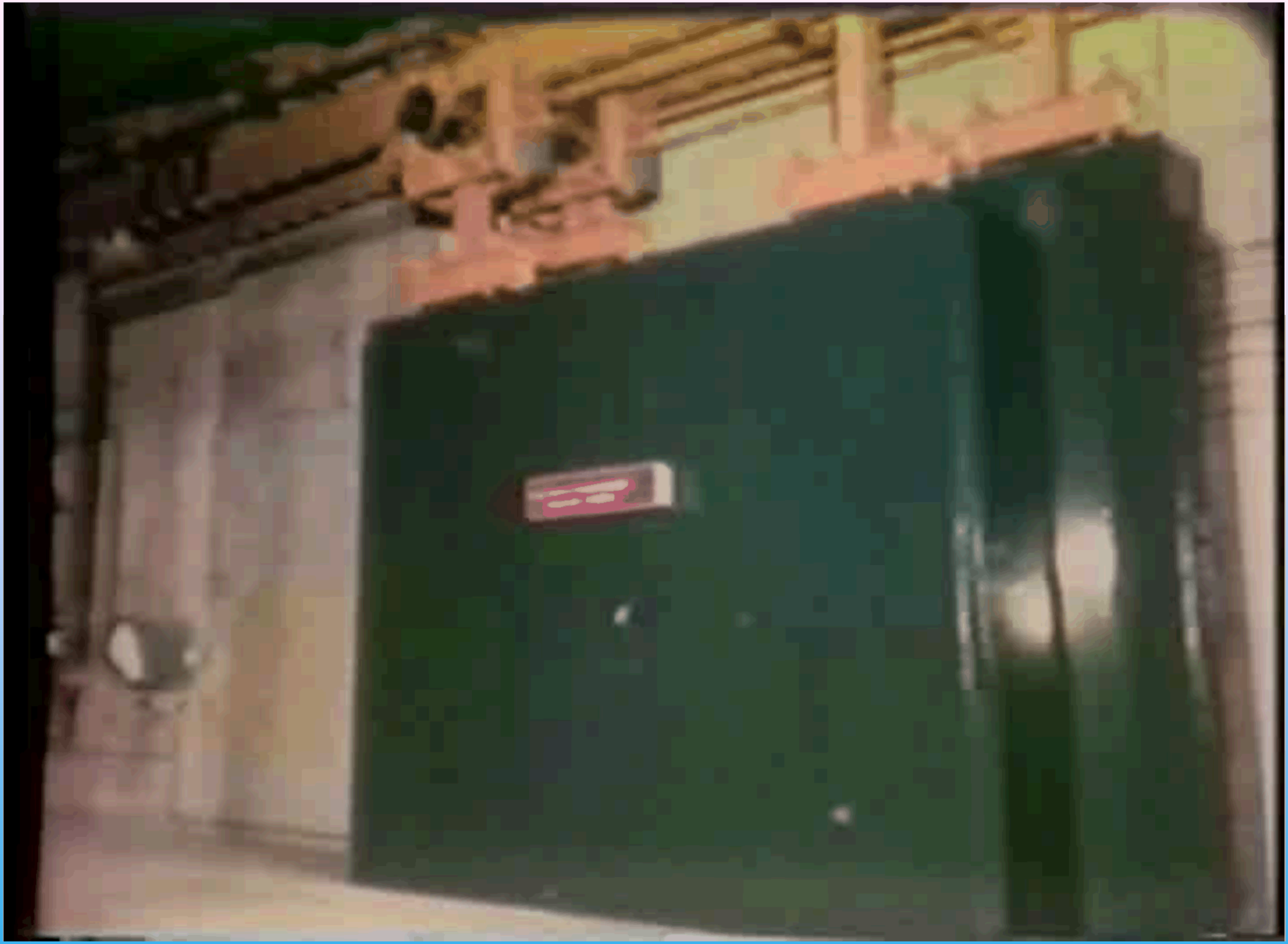
10,000th Pulse
https://www.youtube.com/watch?v=pa0Fmcv83nw

Supercritical Excursion (Pulse)

- Criticality Accidents
  - Similarities To ACRR Pulse
    - Initiation
    - Initial Pulse
    - Temperature Feedback
  - Likely Differences – French “CRAC” Experiments
    - Time Scale
    - Solution Response
    - Multiple Pulsing (“Ringing”)

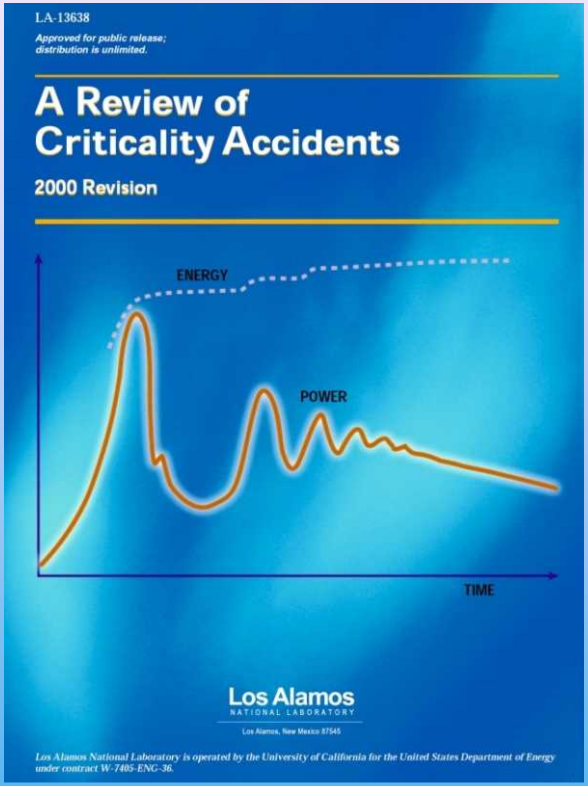


Peak
>10,000,000 R/hr γ
[+ Neutron Dose]
CRAC-23
Peaks ~100,000 R/hr γ
END OF
SOLUTION
ADDITION
38.6
GAMMA-RAY DOSE RATE - R/hr
TIME AFTER DELAYED CRITICALITY - sec



Historical Criticality Accidents

- Definitive reference: LA-13638 (McLaughlin, et al.)
  - Reactors
  - Critical-Measurement Facilities
  - Processing Plants
- Lessons learned focus



http://ncsp.llnl.gov/basic_ref/la-13638.pdf

Process Criticality Accident

Tokai-Mura, Japan

September 30, 1999

Uranyl(18.8) Nitrate Solution

in Precipitation Vessel

Tokai-Mura

September 30, 1999

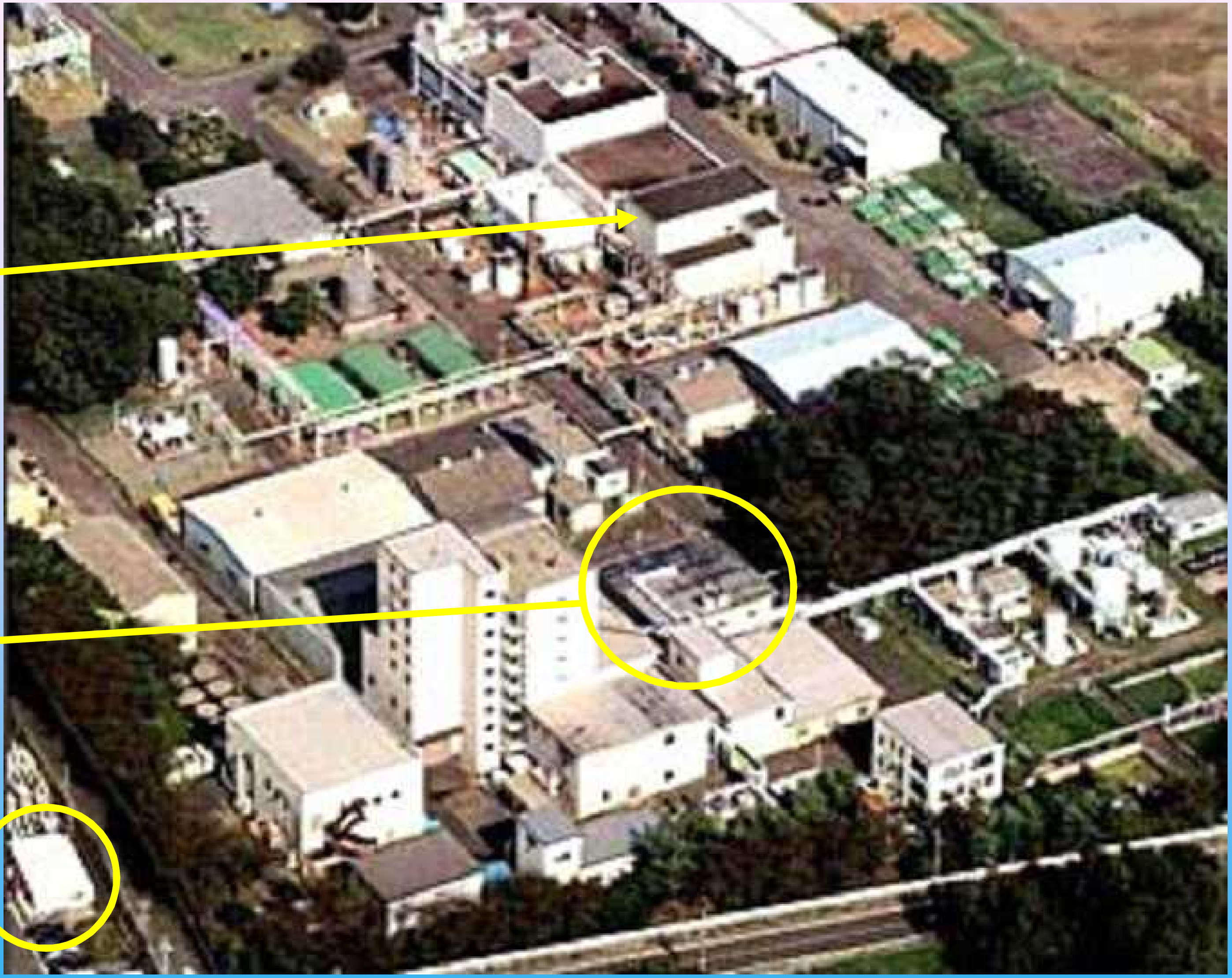
- JCO Facility
  - Tokai-Mura, Japan
  - 140 km north of Tokyo
  - Site w/ several uranium processing plants
  - Congested area; Public close-in

JCO Tokai Site – Aerial View

Fuel Fabrication Buildings

Conversion Building

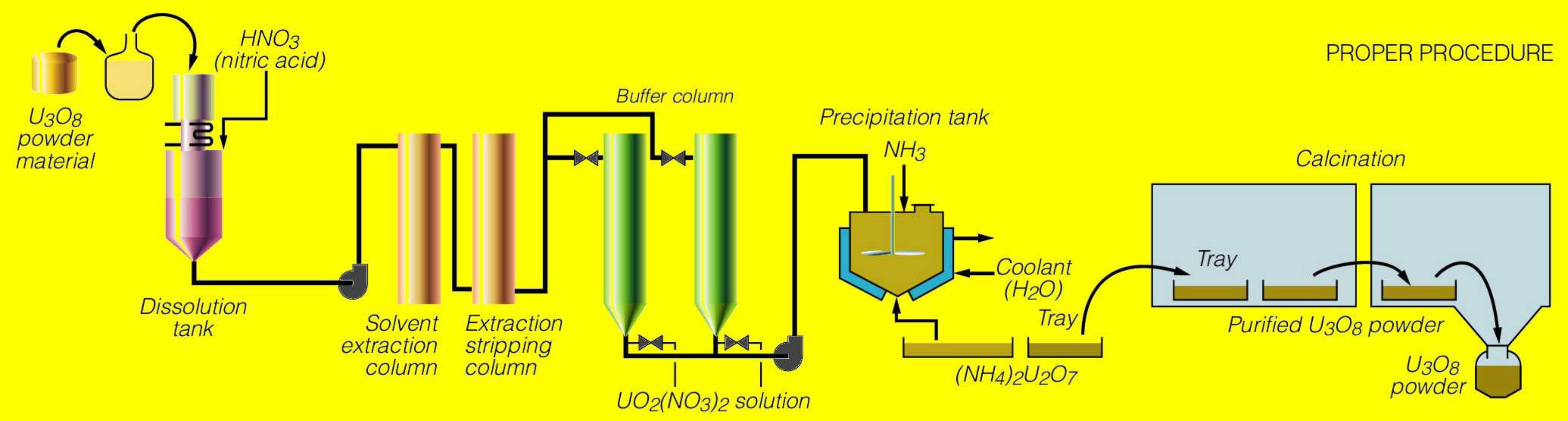
Construction Office (Off-Site)



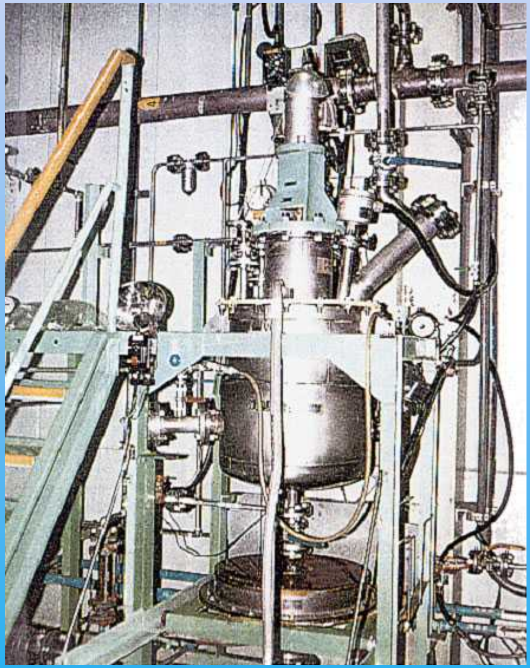
Tokai-Mura

- System
  - Purpose – UO_2 scrap recovery and recycle
  - Process
    - Dissolution in nitric acid
      – "Campaign" mode
      – ~100 kgU batches
    - Homogenize batches & precipitate to yellowcake

Approved Procedure



Limited Volume



50-cm (20-in.)

Tokai-Mura

Mass Limits	
< 5 wt%	16 Kg U
16-20 wt %	2.4 Kg U
Volume Limit	
< 20% wt%	9.5 L

- System
  - Operations Manual
    - Approved by regulator
    - Material weighed & added to dissolver tank
    - Batch size limited based on enrichment
  - Operational limits based on enrichment

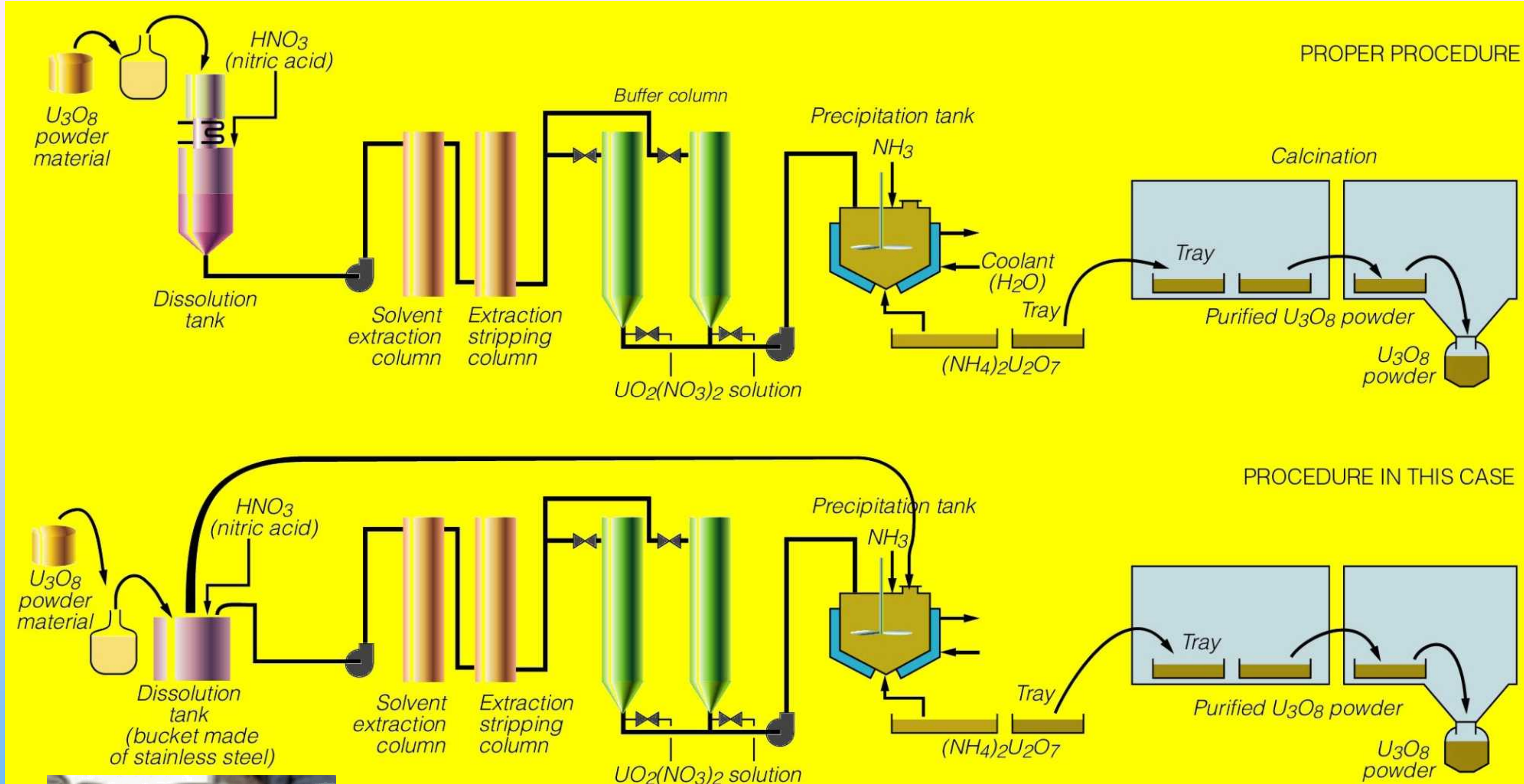
Less than 5% enrichment	Mass limit ≤ 16 kgU
16-20% enrichment	Mass limit ≤ 2.4 kgU
Enrichment less than 20%	Volume limit ≤ 9.5 L

Tokai-Mura

- Scenario
  - Operating manual changed 1985-87
    - Not approved by regulator
    - Speed-up process (to cut costs)
      – Bypass dissolver tank
      – Use 5-L steel bucket & funnel
      – Heat on stove
    - No change in operational limits

Mass Limits	
< 5 wt%	16 Kg U
16-20 wt %	2.4 Kg U
Volume Limit	
< 20% wt%	9.5 L

Comparison: Approved-to-Changed Procedure



Tokai-Mura

- Scenario
  - Change feed material
    - 5 wt%^{235}U for LWR for past three years
    - Now 18.8 wt% ^{235}U for Joyo Fast Reactor prototype
  - Campaign began in late September 1999
    - Three inexperienced operators
    - None had dealt with 18.8 wt%^{235}U
    - One had been on the job for only a few months

Tokai-Mura

- Scenario

. . . . . *Wednesday, Sept. 29, 1999* . . . . .

  - Work delayed ~5 hours
  - Operators sought to "catch up"
    - Mixed 4 batches (one at a time)
    - Poured each batch into tank
    - Days end
      - ~9.2 kgU
      - **18.8 wt%^{235}U**
      - **20 L volume**

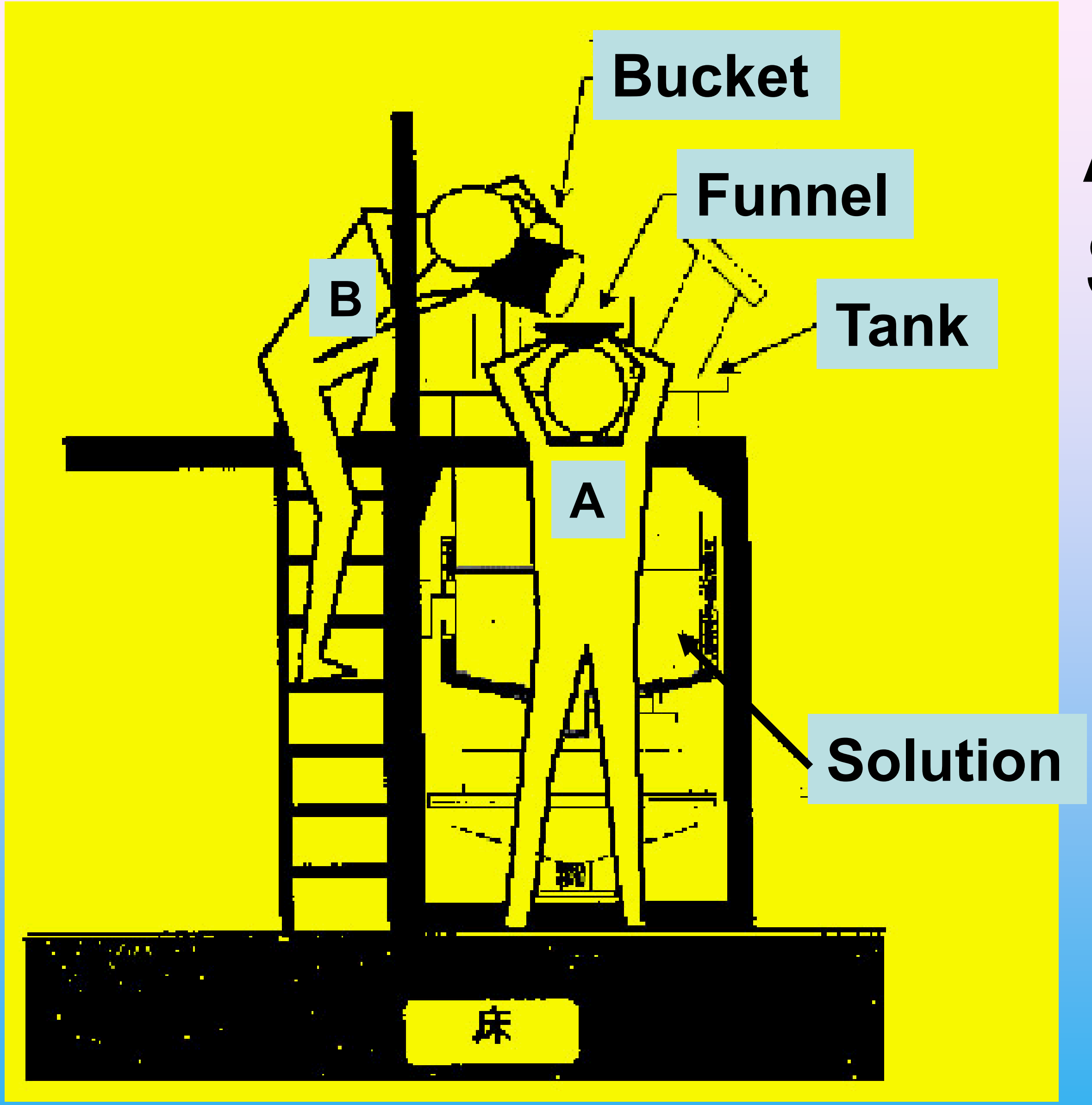
Mass Limits

< 5 wt%	16 Kg U
16-20 wt %	2.4 Kg U

Volume Limit

< 20% wt%	9.5 L

Accident Scene



Tokai-Mura

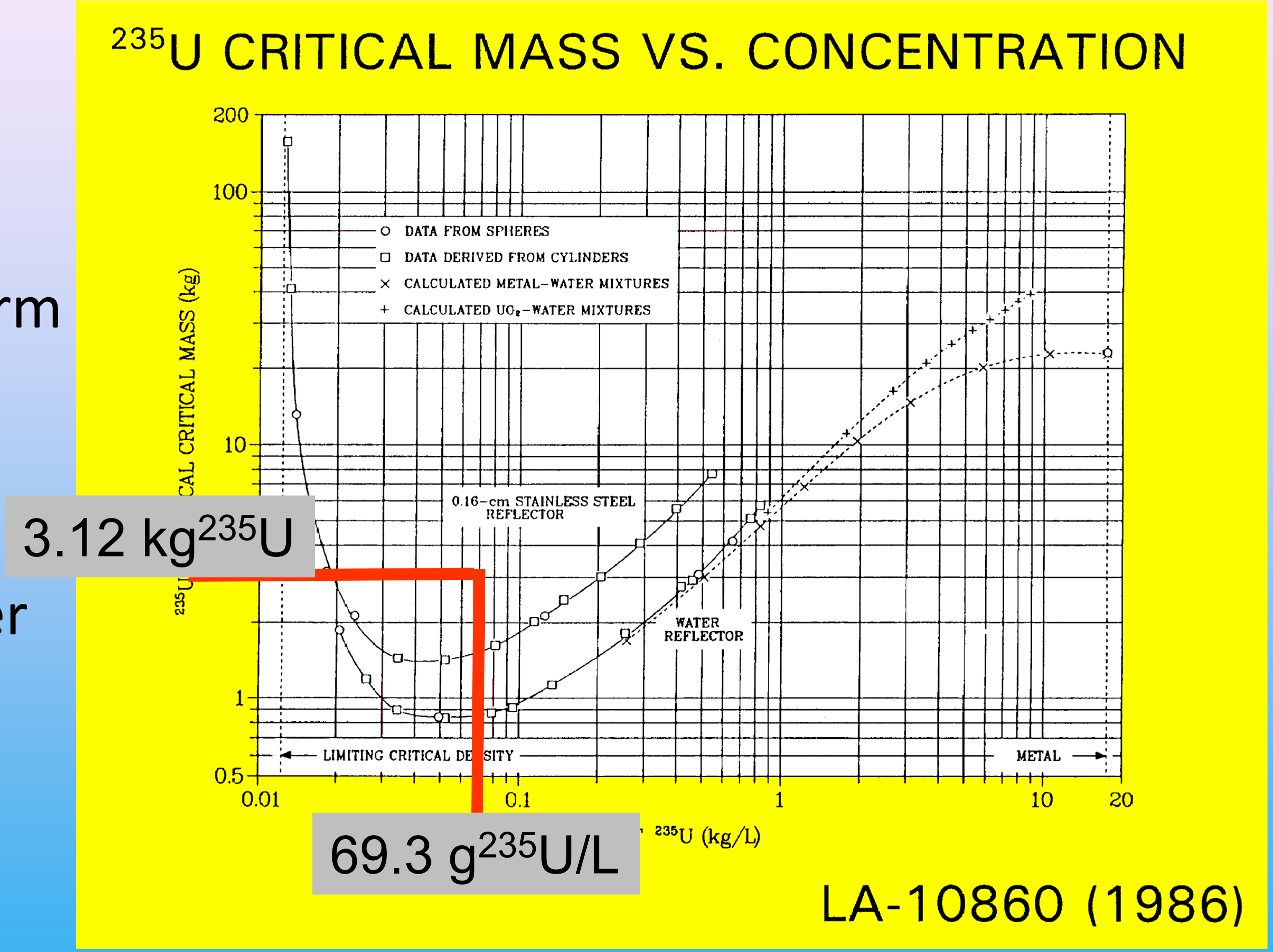
- Scenario

. . . . . Thursday, Sept. 30, 1999 . . . . .

  - Three “operators”
    - Supervisor and operators
    - Still trying to catch up
  - Mixed 3 more buckets
  - Added each to tank

Tokai-Mura

- Scenario
  - ~16 kgU / 45 L
  - Critical @ 10:35 a.m.
    - High-rad alarm
    - Operators evacuated
    - Others mustered per site emergency plan



Tokai-mura

- Scenario – Recovery
  - Operators
    - Saw “blue flash,” reported feeling ill
    - Hospitalized (11:15 a.m.)
  - High dose rates indicated ongoing reaction
  - Local-population evacuated per <u>power-reactor</u> emergency plan
    - Residents within 350-m – evacuate
    - Residents in 10-km radius – “shelter in place”

Tokai-mura

- Scenario – Recovery

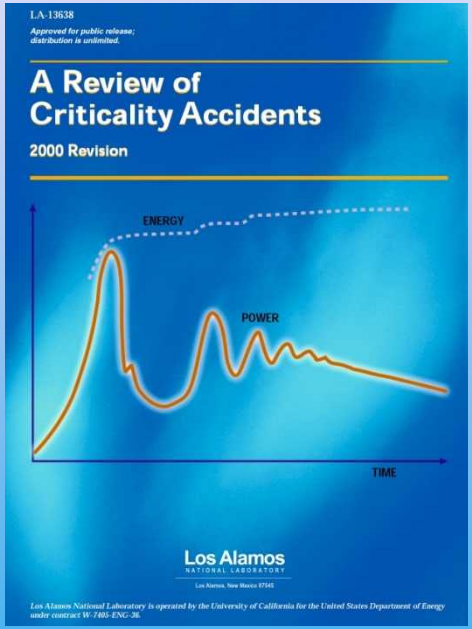
. . . . . *Friday, October 1, 1999* . . . . .

  - Fission chain reaction continued
  - Shutdown targeted tank cooling jacket
    - Neutron poison couldn't be used safely
    - Cooling water drained
    - Chain-reaction subsided
  - Dose rates outside tank area ultimately fell to background levels

Sandia National Laboratories

Tokai-mura

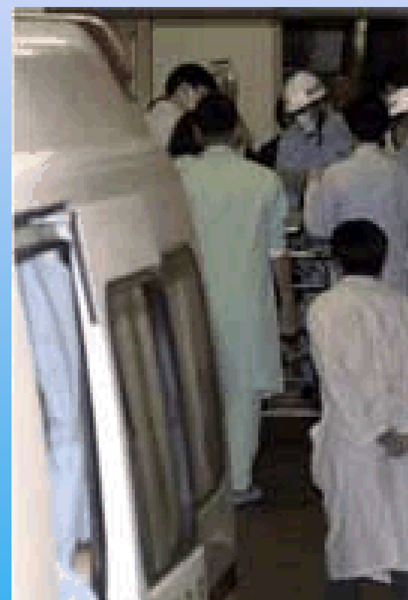
- Excursion
  - First pulse – 4-81x10^{16} fissions
  - Multiple pulses
  - Quasi-steady-state w/ gradual decrease in power
  - Total duration of event ~ 20 hours
  - Total yield – 2.5 x 10^{18} fissions



Tokai-Mura

- Consequences
  - Personnel doses
    - Operator "A" (held funnel)
      - – 16-20 Gy[eq]   1600-2000 rad
      - – Died 12/21/99
    - Operator "B" (poured liquid)
      - – 6 -10 Gy[eq]   600-1000 rad
      - – Died 4/27/00
    - Operator "C" (team leader/supervisor)
      - – 1.2-5.5 Gy[eq]   120-550 rad
      - – Released from hospital

Operator “A”



Operator “B”

Tokai-mura

- Consequences
  - Personnel doses
    - 37-56 response & cleanup workers
      - <0.1 Gy[eq] <10 rad
    - Residents
      - <0.1 Gy[eq] <10 rad

Note:

Onset of illness	0.25 Gy	25 rad
Fatality likely	7 Gy	700 rad

Tokai-Mura

- Other Consequences
  - Unprecedented for a criticality accident!!!
    - Evacuation and sheltering
    - Regulatory and criminal investigations & evaluations
    - Fines & law suits
    - Public confidence/relations (anti-nuclear “boost” affecting entire nuclear industry)

Apologies to the Community and Nation

Loss of Operating License

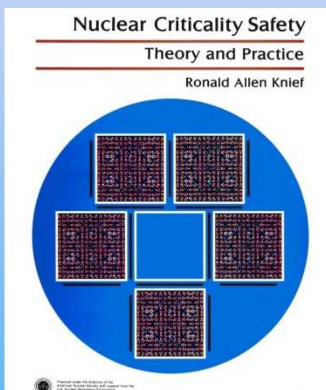
End of a Company and the Employment It Provided

And the story continued . . .

- General Manager of JCO and five other employees pleaded guilty to charges of negligence.
- Ruling – acted illegally
  - "not ensuring . . . proper safety training"
  - "sloppy operating procedures"
- General Manager – 3-yr sentence, suspended for 5 yr; fined 500,000 yen [$4,100]
- Other employees - Lesser sentences
- JCO – 1 million yen [$8,300] fine

Sandia National Laboratories

Questions?



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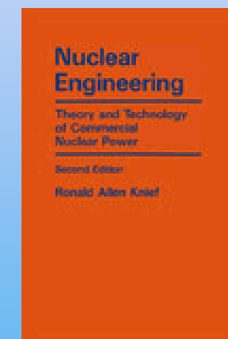

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