CRITICALITY ACCIDENTS
HISTORY AND RELEVANCE TO WIPP

- When, Where, How?
- Vignettes from Russia and Lessons Learned for Everyone
- Waste Transportation and Storage Considerations
  - Is a Criticality Accident at WIPP Credible?
  - What Conditions Would be Necessary?

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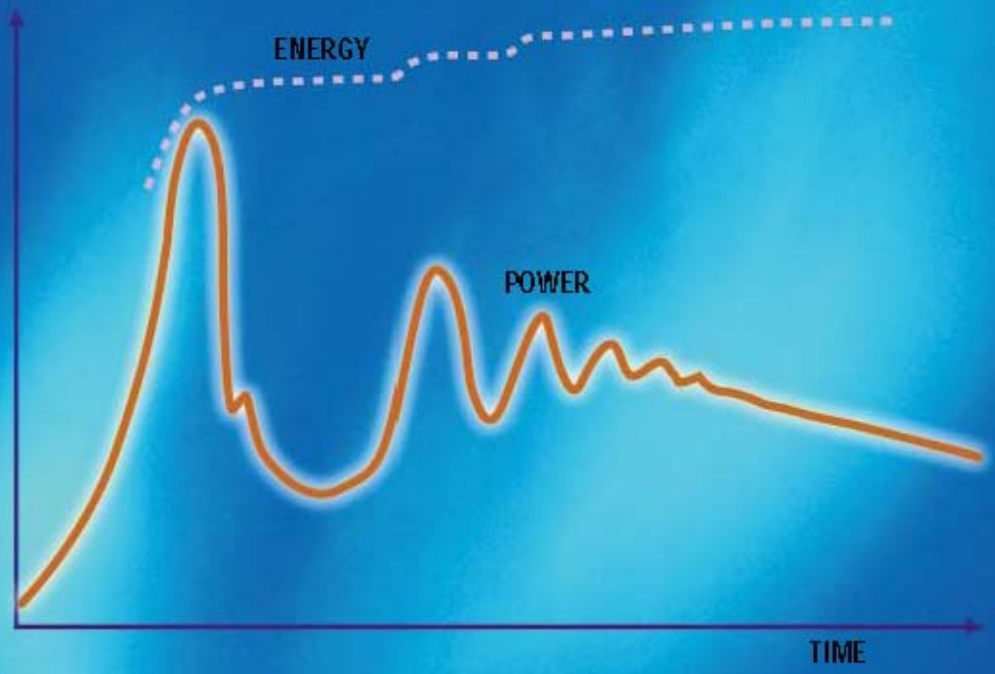
ANS Local Section Meeting, March 2018

Carlsbad, New Mexico

LA-13638

A Review of Criticality Accidents

2000 Revision



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LA-13638 - CONTENTS

- Process Accidents
  - Accident Descriptions
  - Physical and Neutronic Characteristics
  - Observations and Lessons Learned
- Reactor and Critical Experiment Accidents
  - Fissile Solution Systems
  - Bare and Reflected Metal Assemblies
  - Moderated Metal or Oxide Systems
  - Miscellaneous Systems
- Power Excursions and Quenching Mechanisms

CATEGORIES OF CRITICALITY ACCIDENTS

Critical Assemblies/ Reactor Experiments	Process Operations
~ 50,000 Experiments	22 Accidents
38 Accidents	21 Solution; 1Metal
12 Fatalities	9 Fatalities

Process Criticality Accidents

Total Reported = 22	21 Solutions; 1 Metal
Worker Fatalities = 9	
Public Exposures:	Not health threatening; Measured levels in only One accident
Environmental Contamination:	Negligible
Equipment Damage:	Negligible

CHRONOLOGY OF PROCESS ACCIDENTS

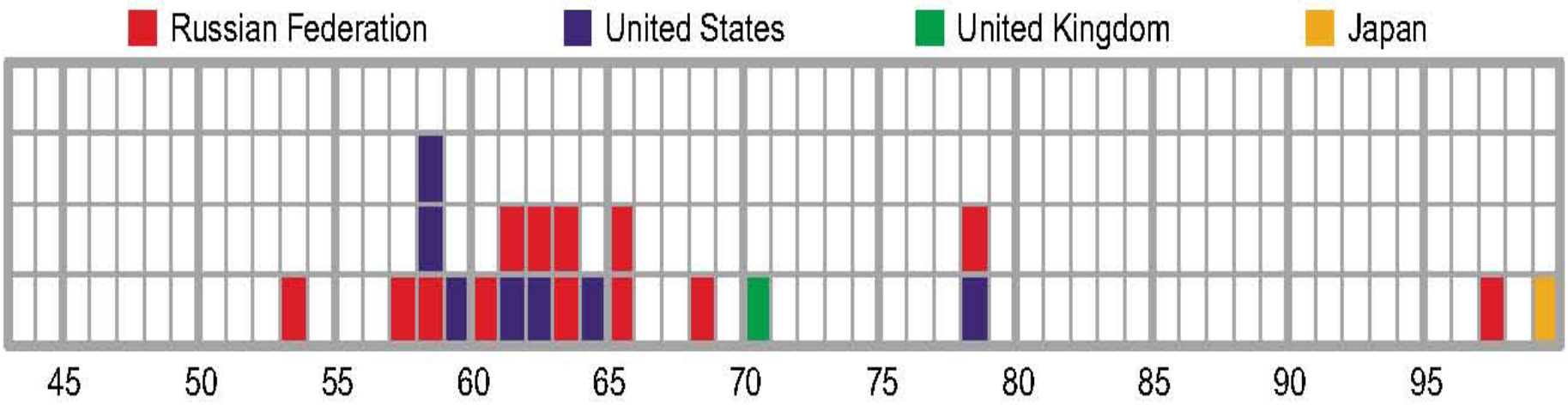


Figure 1. Chronology of process criticality accidents.

RUSSIAN FEDERATION ACCIDENTS

Figure 2. Map of the Russian Federation showing the sites of the process criticality accidents, the capital, Moscow, and Obinisk, the location of the regulating authority, IPPE.

UNITED STATES ACCIDENTS

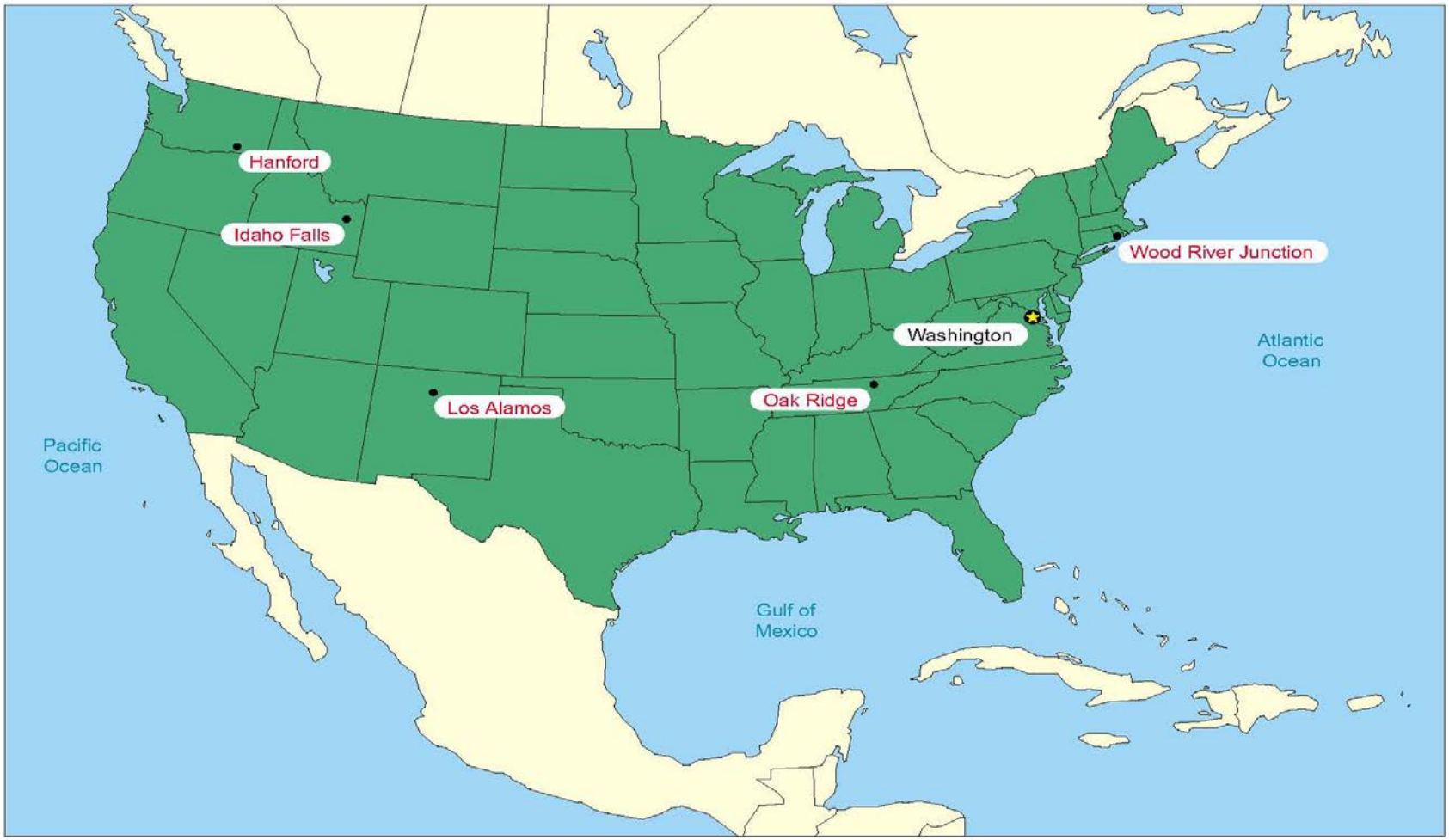


Figure 3. Map of the United States showing the sites of the process criticality accidents, and the capital, Washington.

BRITISH ACCIDENT

Figure 4. Map of the United Kingdom showing the site of the process criticality accident and the capital, London.

JAPANESE ACCIDENT

Figure 5. Map of Japan showing the site of the process criticality accident and the capital, Tokyo.

OBSERVATIONS

- Accident Frequency: zero; 1/yr; 1/10 yrs; ???
- Storage Operations: none
- Transportation Operations: none
- Significant Exposures: Only Immediate Vicinity
- Shielded Operations: Negligible Exposures
- None Attributed Solely to Equipment Failure

OBSERVATIONS

- None Attributed to Faulty Calculations
- Many Occurred During Non-Routine Operations
- Administrative Considerations Determined Facility Down-time
- No New Physical Phenomena

LESSONS LEARNED - OPERATIONAL

- **Avoid unfavorable geometry vessels in areas with high-concentration solutions**.
- Put important instructions, information, and procedural changes in writing.
- Understand processes thoroughly so that credible abnormal conditions are recognized and analyzed.

LESSONS LEARNED - OPERATIONAL

- Fissile material accountability (MC&A) is integral to a good NCS program.
- Operator understanding of NCS implications of proper response to process upsets is important.
- Operations involving both organic and aqueous solutions require extra diligence.

LESSONS LEARNED - OPERATIONAL

- Remote readouts of radiation levels where accidents may occur should be considered.
- Operations personnel should be made aware of criticality hazards and stop work policies.
- Operations personnel should be trained to understand the basis for why they must always follow procedures.

LESSONS LEARNED - OPERATIONAL

- Hardware that is important to criticality control and whose failure or malfunction would not necessarily be apparent to operators should be used with caution.

- Criticality alarms and adherence to emergency procedures have saved lives and reduced exposures.

LESSONS LEARNED – SUPERVISORY, MANAGERIAL AND REGULATORY

- Process supervisors should ensure that operators are knowledgeable and capable.
- Equipment should be designed with ease of operation as a key goal.
- Policies and procedures should encourage self-reporting of upsets and err on the side of learning more, not punishing more.

LESSONS LEARNED – SUPERVISORY, MANAGERIAL AND REGULATORY

- Senior management should be aware of the hazard of accidental criticality and its consequences.
- Senior management and regulators should be aware of operations with criticality hazards.
- Regulators should ensure that those they regulate are knowledgeable and capable.
- Regulations should promote safe and efficient operations

CONCLUSIONS

- Likelihoods of criticality accidents are extremely low, but will never be zero.
  - Elimination of unfavorable geometry process vessels has been a key factor
- Diligence is required to maintain a proper, acceptably low, accident risk **while balancing the need for process ease and efficiency.**

CRITICALITY SAFETY AT WIPP

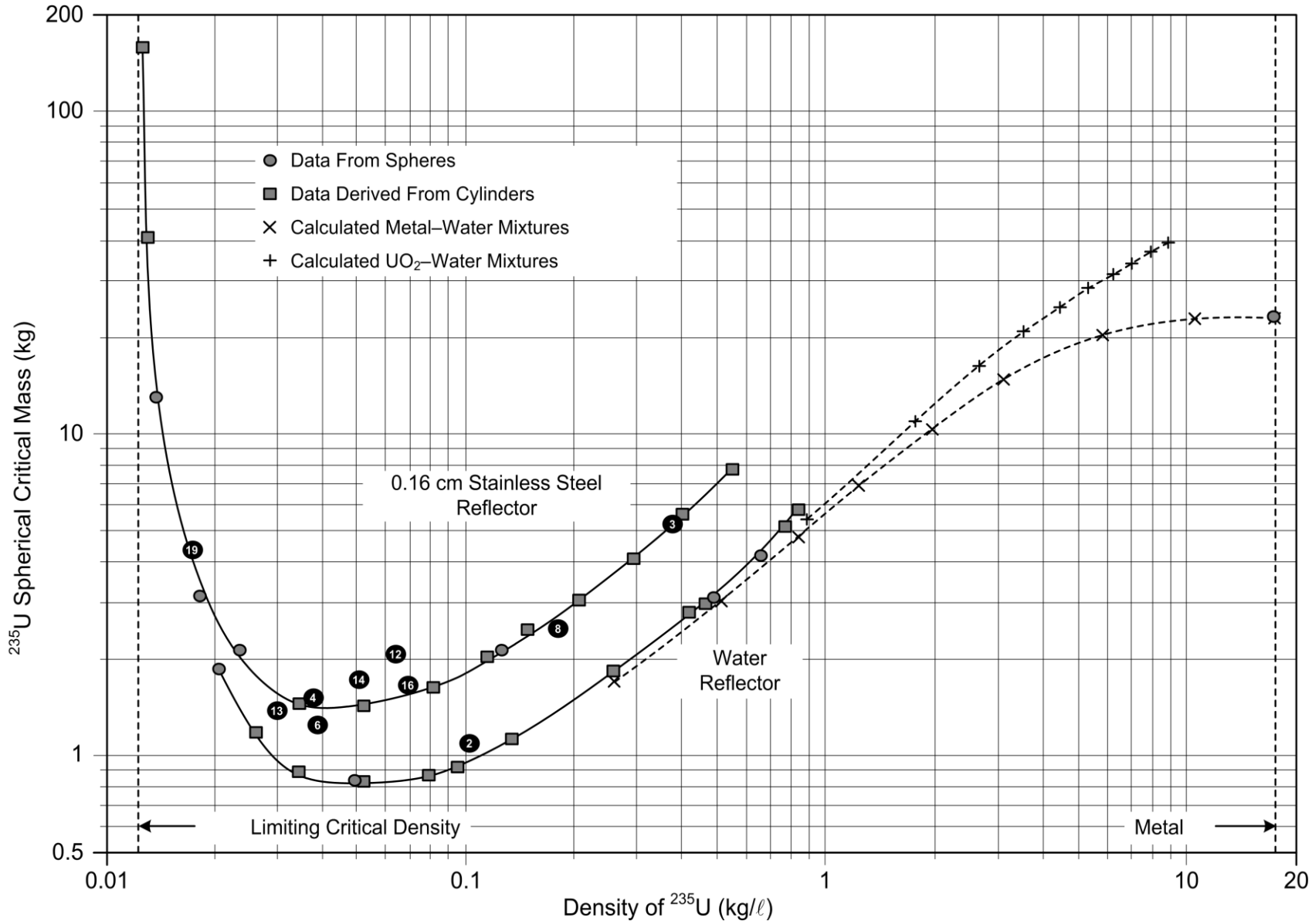
- Why a Criticality Accident is Incredible
  - Regulatory limits on fissile mass and the (unstated) assumptions behind them
  - Minimum Conditions to attain the critical state
  - Actual fissile and non-fissile mass per drum

FISSILE MASS LIMITS

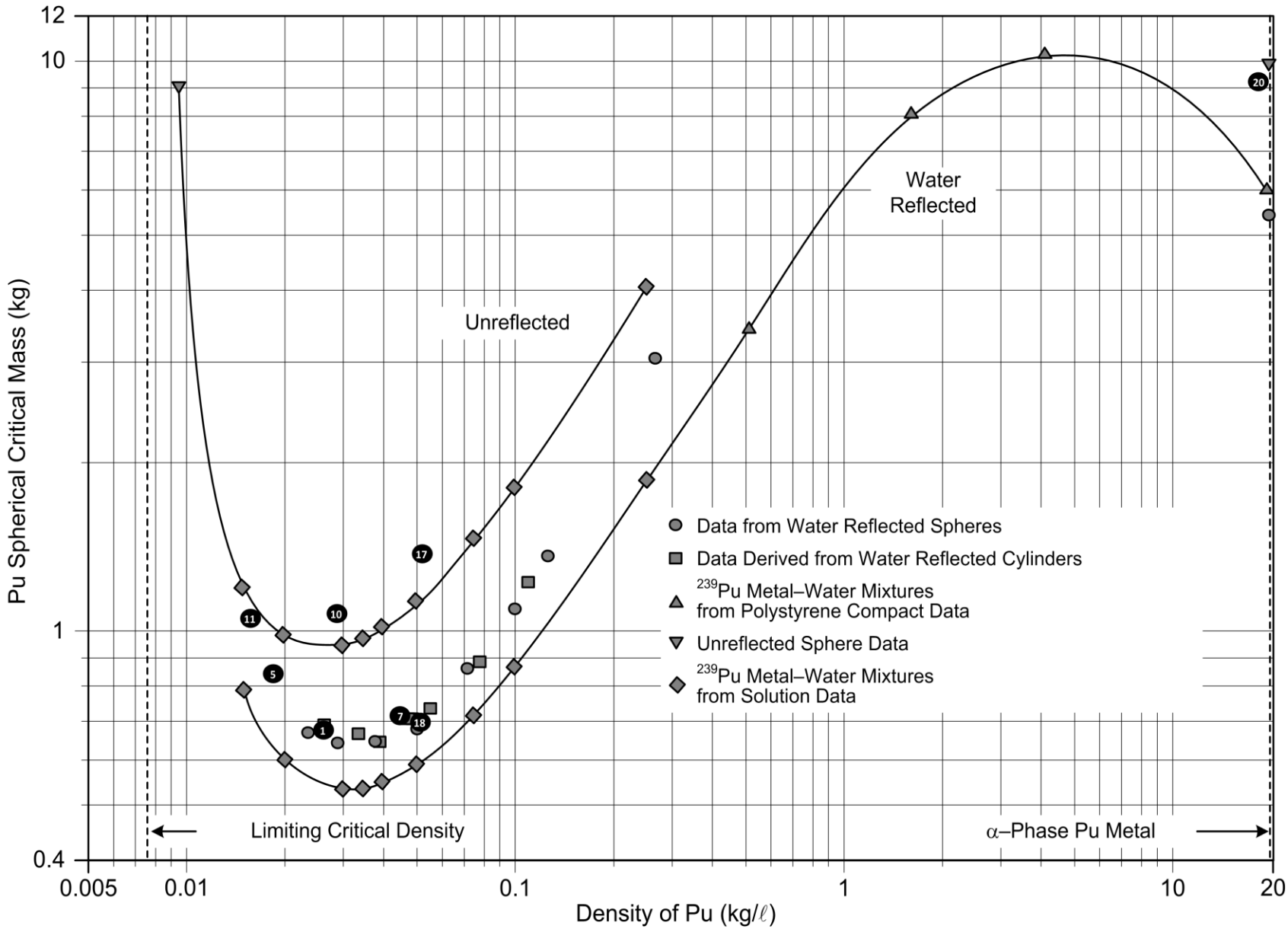
- 200 grams per 55-gallon (~200 liter) drum
  - ~1 gram fissile per liter of volume

- 325 grams per SWB – much lower average fissile density

^{235}U Metal-Water Critical Mass



^{239}Pu Metal-Water Critical Mass Curves



ACTUAL FISSILE AND NON-FISSILE MASSES

- Few grams per 55-gallon (~200 liter) drum
  - ~0.01 gram fissile per liter of volume
- ~20 kilograms iron in the drum itself
- >1000 grams iron/gram fissile – assures subcriticality in an infinite array of drums

REGULATORY REQUIREMENTS
vs
REALITY

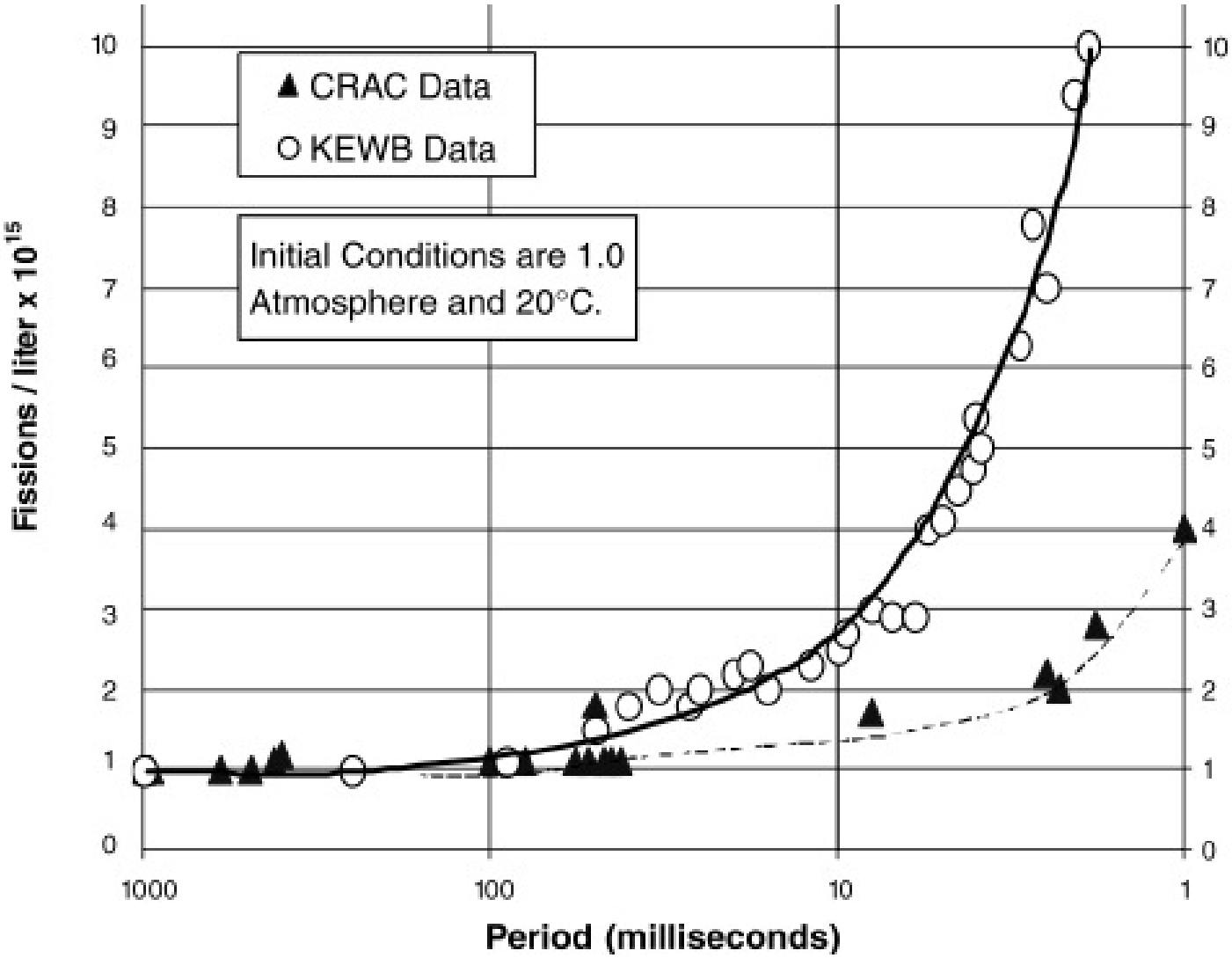
- Criticality Accidents “Regulated” to
  - Incredible if personnel at Risk
  - Unlikely if Personnel not at Risk

- Criticality Accidents Driven to Zero Likelihood

NEW(?) INSIGHTS

- Accident frequency down dramatically since mid-60's
- ANS-8 Standards and Federal Regulations essentially unchanged
- We are remiss to not be reaping benefits from lower accident likelihoods/risks

MAXIMUM SPECIFIC FIRST SPIKE YIELD VS PERIOD



MAXIMUM SPECIFIC FISSION YIELD - FIRST 10 MINUTES

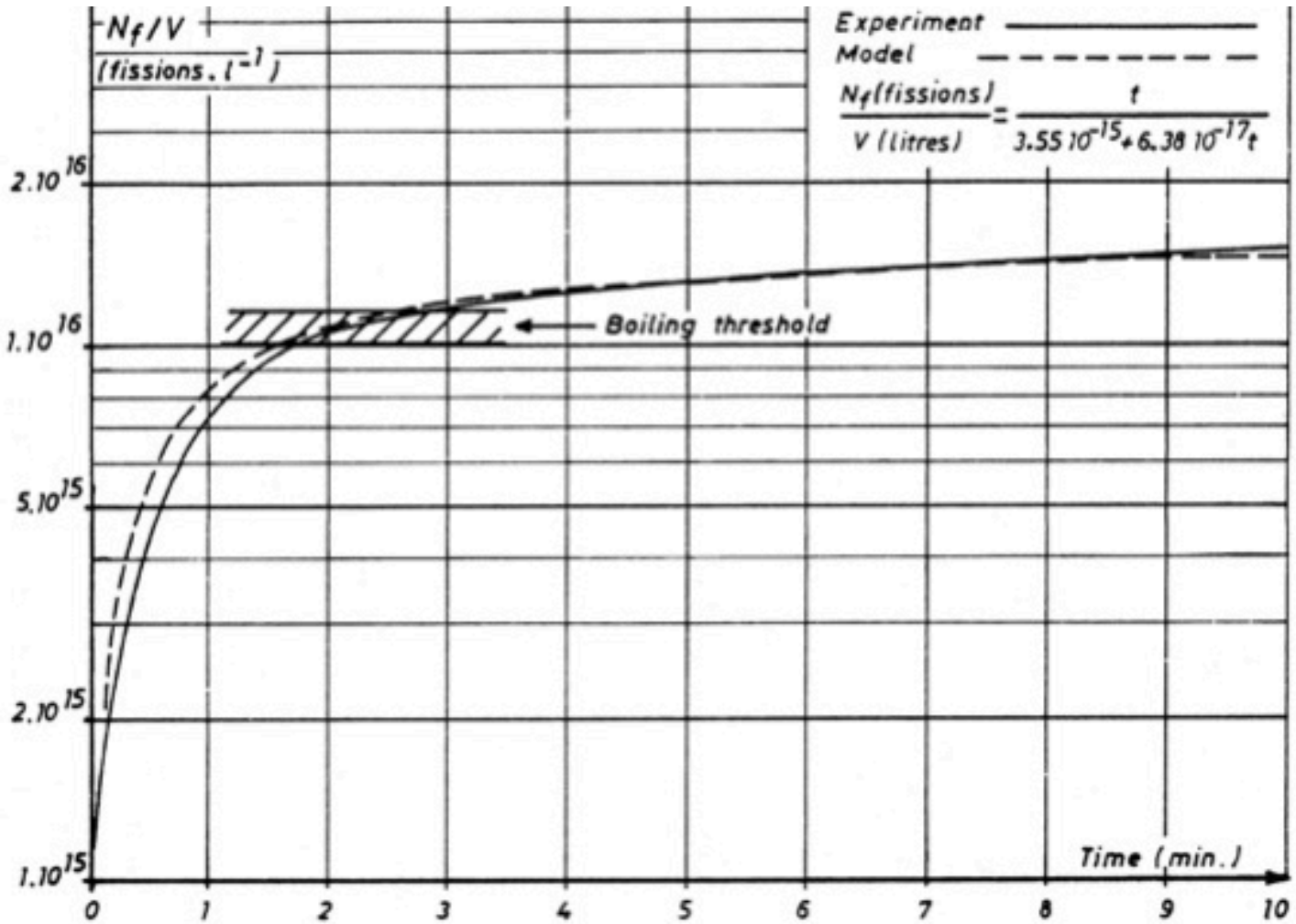


Figure C.2 – Maximum specific fission yield resulting from criticality solution excur-

CRITICAL VOLUMES AND CONCENTRATIONS

- 20 Liters - ONE
- **30-80 Liters - SIXTEEN**
- > 100 Liters - FOUR

- < 100 g/l - NINETEEN
- > 100 g/l - TWO

DELAYED CRITICAL VS PROMPT CRITICAL ACCIDENTS

- **No First Spike = 7 = “Slow Cooker”??**
- Yes - First Spike (~1.0+15 fissions/l) = 9
- Unknown (no data) = 5

OBSERVATIONS

- Criticality Accidents Do NOT Occur in Favorable Geometry Vessels
- **Unfavorable Geometry Vessels ~100% Removed from Rich Solution Process Operations During 60's in Both US & USSR**
- NO Hands-On Accidents in US since 1964
- TWO Hands-On Accidents in USSR since 1965
  - 1968 (deliberate); 1997 (slab tanks)

CHRONOLOGY OF PROCESS ACCIDENTS

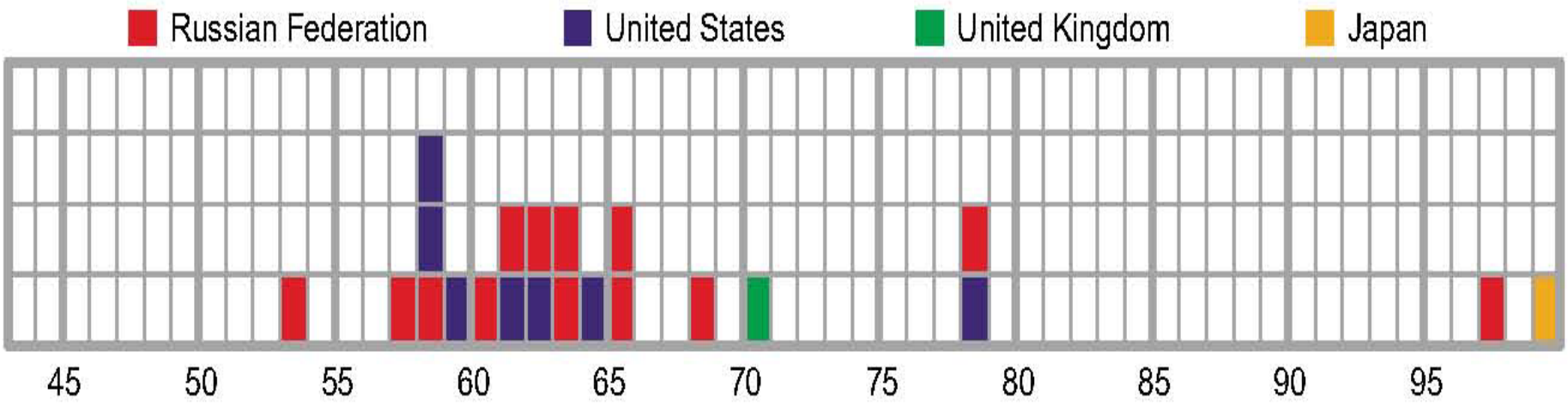


Figure 1. Chronology of process criticality accidents.

CONCLUSIONS

- Accidents in Routine, Rich Solution, Process Vessels “Essentially” Eliminated
  - Thus, Slightly-Above-Delayed-Critical Accidents with Personnel Present “Essentially” Eliminated
  - **That is, Slow Cooker with Personnel Present “Essentially” Eliminated**

WHAT'S LEFT?

- Upset Conditions – Seismic, Fires, ?? - Solutions Flow; Dry Powders Become Moderated …..
- Waste Tank Operations – Unfavorable Geometry
- These situations are **unlikely** to expose personnel

ANS-8 AND REGULATORY IMPLICATIONS ??

- ANS-8.3 “Minimum Accident of Concern”
- ANS-8.1 “Process Analysis” Subsection 4.1.2
- ANS-8.10 General Intent
  - Only “Shielding and confinement” …..or
  - Broadly “When Personnel are not present”??
- ANS-8.23 Applies to all Re-entry operations
  - Including First Responders, Firefighters, etc.

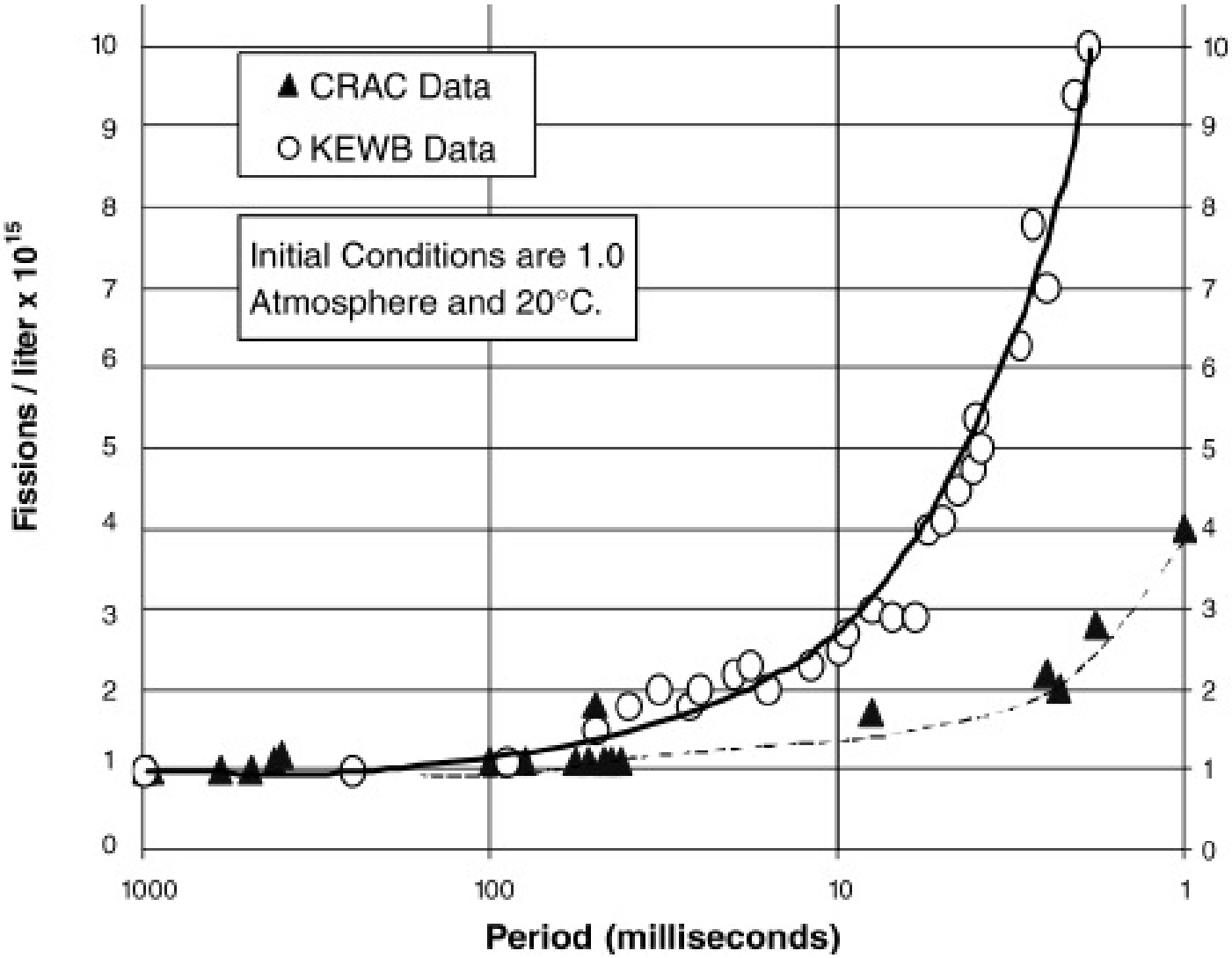
ANS-8.3 - MAC

- Historically/Currently: 20 rad in one minute at 2 meters
- Developed to detect Slow Cooker, down to few cents above delayed critical excursion
- Recent concern that “few cents” not accurate; and thus that 20 rad not accurate

ANS-8.3 - MAC

- If "**Slow Cooker with Personnel Present 'Essentially' Eliminated**"
- What is a realistic, practical MAC?
- ANS-8.3 WG considering/proposing:
  - (Near) Prompt critical first spike (conservatively) consistent with Figure C.1 of ANS-8.23
  - 1.0 E+15 fissions/liter in **10-second** spike
  - I.e., 1.0E+14 fissions/s per liter

MAXIMUM SPECIFIC FIRST SPIKE YIELD VS PERIOD



ANS-8.1 – PROCESS ANALYSIS

- **Historically/Currently, 4.1.2**:

"Before a new operation with fissionable material is begun or before an existing operation is changed, it **SHALL** be determined that the entire process will be subcritical for **all** normal and credible abnormal conditions."

ANS-8.1 – PROCESS ANALYSIS

- DOE/CSSG considering adopting and proposing to ANS Standards:
  - "… **all** normal conditions and, *when personnel are present*, under credible abnormal conditions. When personnel are not at significant risk from the radiation consequences of a criticality accident then the word 'credible' should be replaced by 'unlikely,' consistent with ANS-8.10 guidance. This requirement is not applicable to response and recovery operations for which guidance is provided in ANS-8.23"

ANS-8.10 – SHIELDING AND CONFINEMENT

- DOE/CSSG considering proposing to ANS Standards:
  - Revise Title, Scope and Contents to make it unambiguous that the standard covers all situations (such as evacuation) when personnel are not at risk of significant radiation exposure from a criticality accident.
- DOE/CSSG considering adopting this (always intended) philosophy

ANS-8.23 – EMERGENCY PLANS AND PROCEDURES

- DOE/CSSG considering proposing to ANS Standards:
  - Make it clear in appropriate locations in ANS-8.1 and 8.23 that 8.23 guidance applies to all re-entry situations, including firefighters and other emergency response personnel
- DOE/CSSG considering adopting this (always intended) philosophy