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On the Kinetics of Critical Excursions Pertinent to the ANS-8.3 Minimum Accident of Concern

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Acknowledgements Upfront

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Brief Talk

- Motivation & Aims
- NCSD 2009 Paper Highlights
- Minimum Accident – Definition, Specification, Interpretation, Example
- Investigation and Methodology
- Application Cases – Excursion parameters
- Results Discussion - Implications
- Conclusions

Motivation and Aims

- Tie excursion, dose, dose rate and ANS-8.3 specification
- Link static (criticality) to dynamic
- Explore differences
  - accident scenarios
  - reactivity insertion modalities
  - detection thresholds
  - dose in “free air” versus “dose to human tissue”
  - Identify strengths and weaknesses
- Affirm historical context

NCSD 2009 Paper Highlights

Realism in Minimum Accidents

Process analysis justifies excursion formats

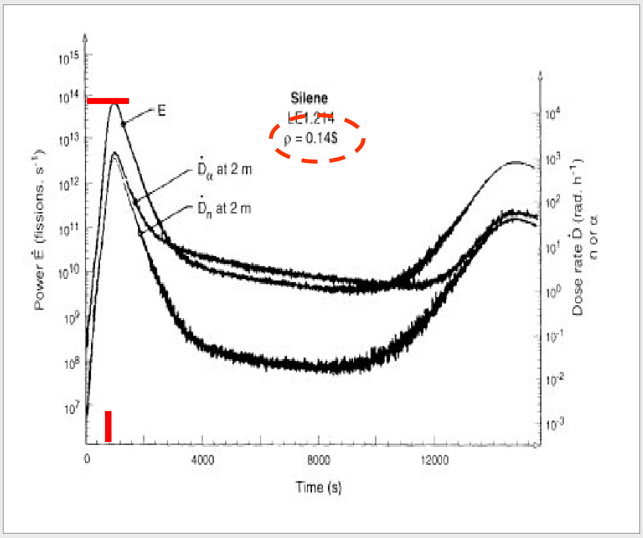
Dose (rate) in air to instrument; Dose (rate) tissue to person

Time to detect @ 0.2 Gy/min air and receive 0.2 Gy (tissue)

Kinetics (inverse period ω) and *Sustained Reaction*

How much dose is received in a very short time after alarm actuation? (initial human response)

Low Power Excursions (< 10 kW)



From Barbry-Malenfant NCSD 1993 Nashville TN

Experiments with SILENE and SHEBA showed that there were excursions that

1) "Spoofed" CAAS detectors – power less than 0.2 Gy/min in AIR

2) Doses greater than 0.2 Gy in less than 1 min

Minimum Accident- Definition, Specification, Interpretation

minimum accident of concern. The smallest accident, in terms of fission yield and dose rate, that a criticality alarm system is required to detect.

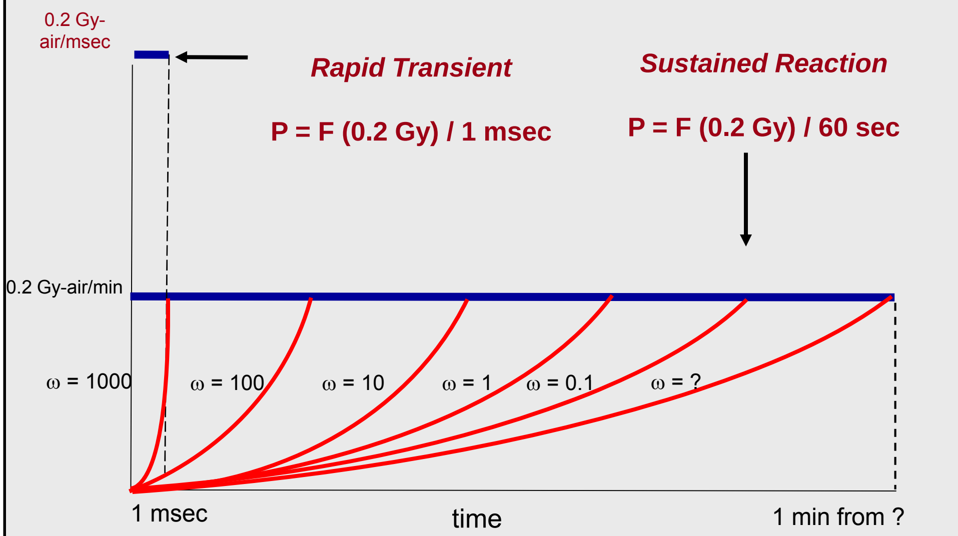
5.6 Detection Criterion. Criticality alarm systems shall be designed to respond immediately to the minimum accident of concern. For this purpose, in areas where material is handled or processed with only nominal shielding, the minimum accident[4] may be assumed to deliver the equivalent of an absorbed dose rate in free air of 0.2 Gy/min (20 rad/min) at 2 meters from the reacting material. The basis for a different minimum accident of concern shall be documented.

INTERPRETATION OF ANSI/ANS-8.3-1979 PARAGRAPH 5.2
(ANSI/ANS-8.3-1986 PARAGRAPH 5.6)

Beginning on page 96 of the January, 1981, issue of 'Nuclear News' (Vol. 24, No. 1), an interpretation of ANSI/ANS-8.3-1979, Paragraph 5.2 is reported. The cited paragraph is identical to Paragraph 5.6 in ANSI/ANS-8.3-1986.

If a delay of one minute is accepted in initiating an alarm for the minimum accident of concern, an operator two meters from the accident can expect an exposure slightly in excess of 20 rads; whereas if the accident is signaled promptly, the operator's exposure would be on the order of one rad.

ANS 8.3 Appendix B Rate Meter "Examples"



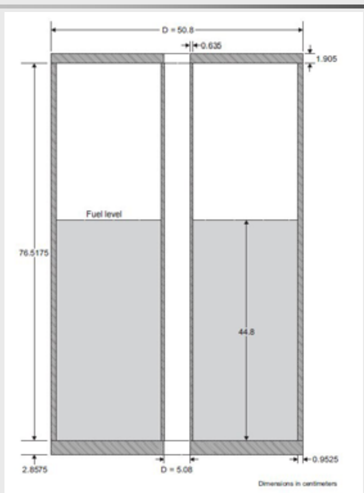
Investigation

- **Determine**
  - Power (kW) → fission rate →dose rate vs. time (air and tissue)
  - Energy (kJ) → fissions → total dose vs. time (air and tissue)
  - Reactivity, inverse period vs. time
  - Total dose and dose rate for minimum excursion
- **Examine**
  - Low-power excursion for two disparate application models
  - Range of reactivity insertion values and modalities (step and ramp)
  - Total Doses at times after detection - assume up to 1 min after trip
  - Three detection criteria
- 0.2 Gy/min-air, 0.2 Gy/min-tissue, and 0.2 Gy total dose

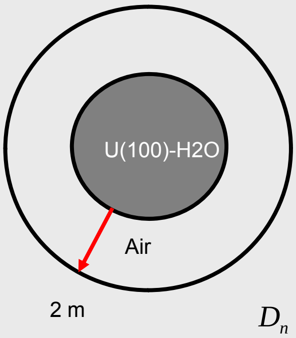
Methodology

- Critical parameters
  - total fissions to 0.2 Gy (air and tissue)
  - fission rate for 0.2 Gy/min air and tissue
- Transient parameters - MCNP5-1.60, published data
- Six-group point kinetics and feedback equations
  - power, energy, reactivity, inverse period vs. time
- "Level 1" PKE simulation at Low Power
- Complete time dependent excursion power history
- Times 0.5, 2.0, 5.0, 10.0, 20.0, 60 sec after detection

Two Application Models



LEU-SOL-THERM-001
(SHEBA-II)



$$D_n = L_n * \nu * \Phi_n * dcf_n$$

$$D_\gamma = L_\gamma * \nu * \Phi_\gamma * dcf_\gamma$$

$$F = 0.2/[D_n + D_\gamma]$$

HEU MOD-METAL
H/X ~ 10, 2500 gU/L

Critical Parameters - Total Fissions, Power, Energy

Dose response	Total Fissions 0.2 Gy	Total Energy (kJ)	Fission Rate (fissions/sec)	Power (kW)
LEU Solution				
Air	1.36E+16	4.35E+02	2.26E+14	**7.25E+00***
Tissue	6.15E+15	**1.97E+02**	1.03E+14	3.28E+00
HEU Moderated Metal				
Air	8.90E+15	2.85E+02	1.48E+14	**4.75E+00**
Tissue	3.90E+15	**1.25E+02**	6.50E+13	2.08E+00

***7.24 kW using SCALE**

Simple Kinetics and Power/Energy Equations

$$\frac{dP(t)}{dt} = \frac{[\beta - \rho(t)]}{\Lambda} \cdot P(t) - \sum_i \lambda_i \cdot C_i(t) + S(t)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} \cdot P(t) - \lambda_i \cdot C_i(t)$$

$$\frac{dT(t,z)}{dt} = f(K_C, P(t), T(t,z))$$

$$\frac{dV(t,z)}{dt} = f(G, P(t), V(t,z))$$

$$\rho(t) = \rho_{ext}(t) + \rho_T(t) + \rho_V(t)$$

$$P(t) = P(0)e^{\omega \cdot t}$$

$$E(t) = \int P(t)dt = \frac{P(t)}{\omega}$$

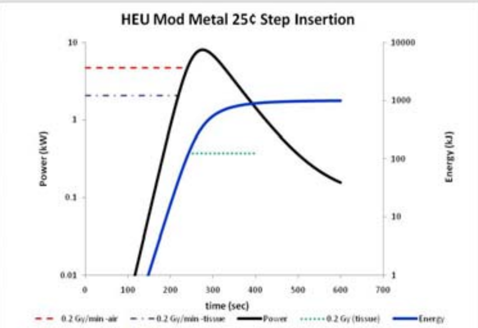
$$\omega(t) = \frac{P(t)}{E(t)} = \frac{1}{\tau}$$

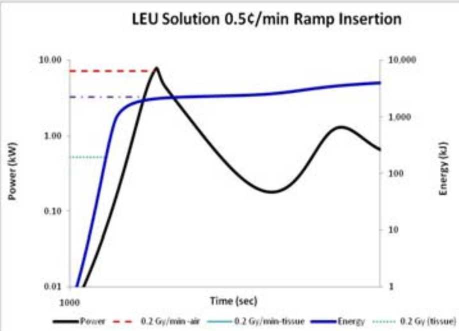
$$\tau \approx \frac{(\beta - \rho)}{\lambda \cdot \rho}$$

Kinetics and Feedback Parameters

Parameter	Name	LEU Solution	HEU Moderated Metal-Water
β	Delayed neutron fraction	7.11e-3 3.60e-3, 1.30e-3, 1.07e-3,3.17e-3, 9.6e-4, 3.4e-4	8.17e-3 2.40e-4,1.22e 3, 1.28e-3,3.97e-3, 1.04e-3,4.2e-4
λ	Delayed neutron decay constants sec^{-1}	2.03e-2 1.29e-2, 3.18e-2, 1.10e-1, 3.18e-1, 1.35e-0, 8.70e-0	3.23e-2 1.29e-2, 3.18e-2, 1.10e-1, 3.17e-1, 1.35e-0, 8.64e-0
Λ	Neutron generation time (sec)	4.011e-5	7.4e-7
β/Λ	Rossi alpha	-1.77e+2	-1.1e+4
α_T	Temperature feedback ($/deg K)	-3.7e-2	-2.0e-2
α_V	Void feedback $/cc	-9.0e-4	-6.0e-4
K_c	Heat Capacity (J/kg-K)	2.16	1.17
G	Gas generation rate cc/kJ	0.67	------------

Power, Energy, Dose Rate and Total Dose





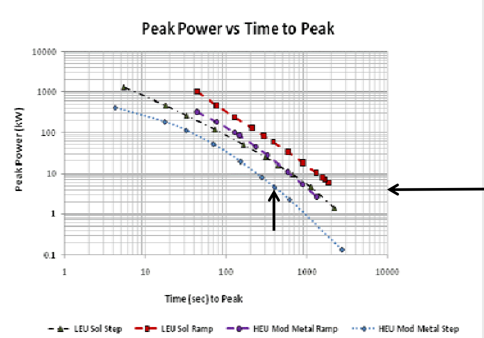
0.2 Gy total dose occurs **AFTER** 0.2 Gy/min Dose Rate

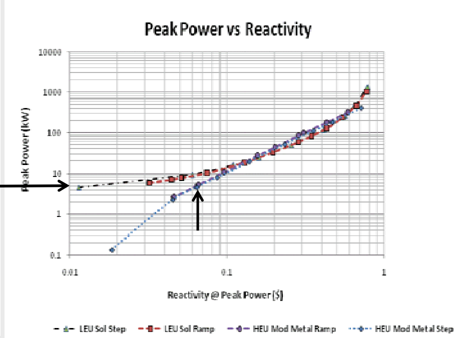
- ΔTime ~ **+ 2 sec (air)**
- ΔTime ~ **+ 24 sec (tissue)**

0.2 Gy total dose occurs **BEFORE** 0.2 Gy/min dose rate

- ΔTime ~ **- 88 sec (air)**
- ΔTime ~ **-9 sec (tissue)**

Peak Power vs Time and Reactivity

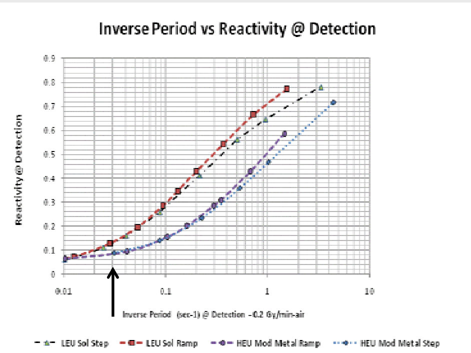


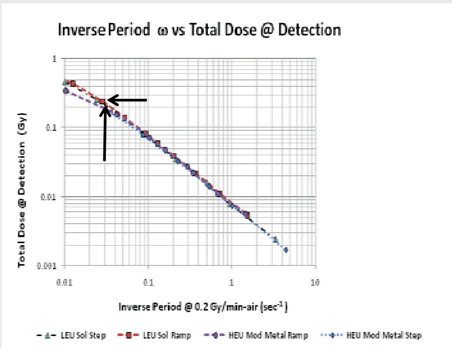


Time to peak power increases for decreasing reactivity

Mod metal step is fastest rise to peak for given reactivity

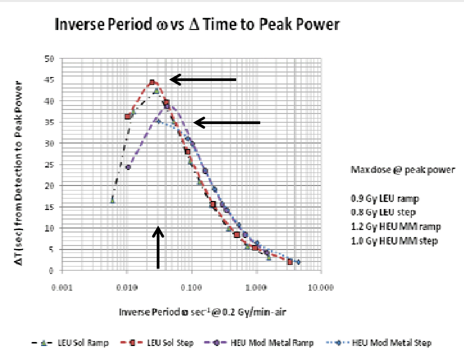
Inverse Period vs Reactivity and Total Dose

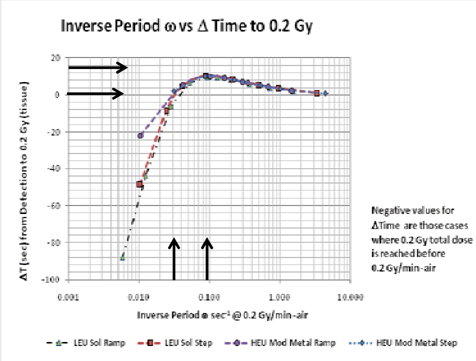




Inverse period at 0.2 Gy/min air for total dose of 0.2 Gy at detection is 30 msec^{-1} corresponds to 10-15 ¢

Inverse Period vs. ΔTime to Peak Power and 0.2 Gy



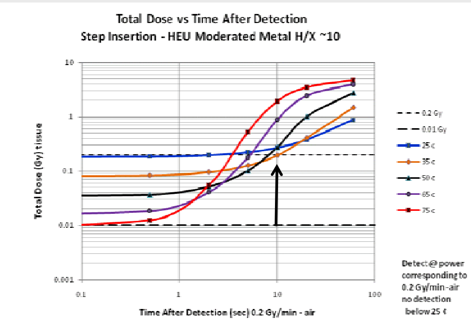


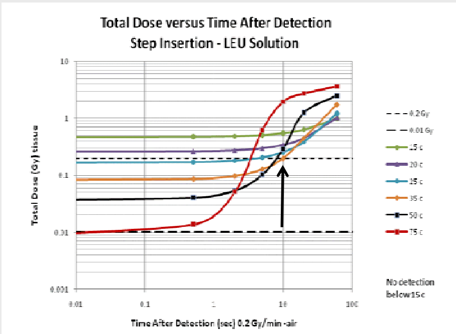
ΔT **35-45 sec** before peak power reached for ω ~ 30 msec^{-1}

Max ΔT is **12-15 sec for ω ~100 msec^{-1}**

For ω < 30 msec^{-1}, 0.2 Gy first

Total Dose vs Time After 0.2 Gy/min air – Step Insertion





0.2 Gy within 10 sec for ~35 ¢

No detection < 25 ¢ step

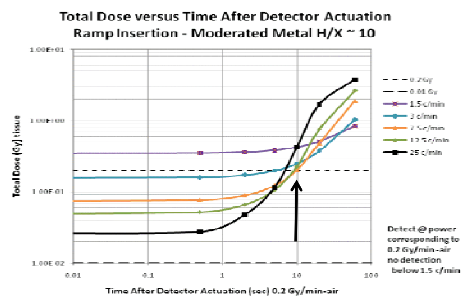
Dose at 1 min ~ 1 Gy

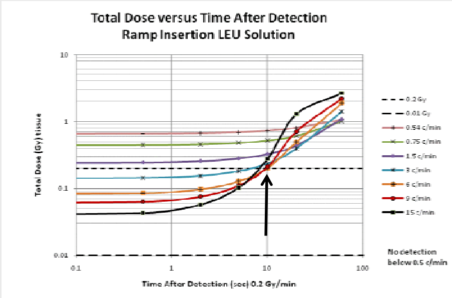
0.2 Gy within 10 sec for ~35 ¢

No detection < **15 ¢ step (B-M '93)**

Dose at 1 min ~ 1 Gy

Total Dose vs Time After 0.2 Gy/min air - Ramp Insertion





0.2 Gy within 10 sec for ~7.5 ¢/min

No detection < 1.5 ¢/min

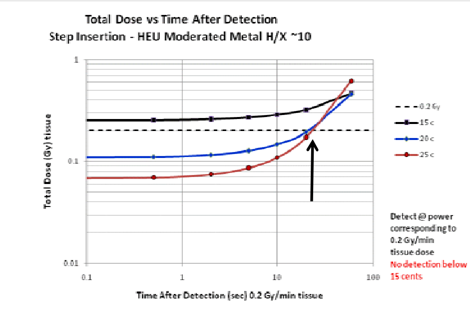
Dose at 1 Min ~ 1 Gy

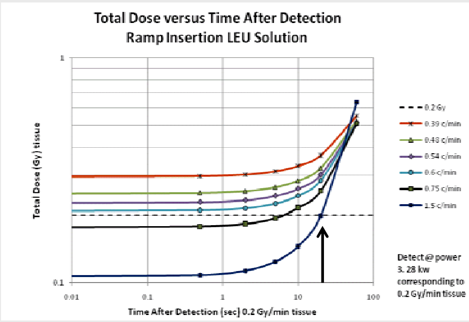
0.2 Gy within 10 sec for ~9 ¢/min

No detection < 0.5 ¢/min

Dose at 1 Min ~ 1 Gy

Total Dose vs time After 0.2 Gy/min in tissue





0.2 Gy within 20 sec for < 25¢

No detection < 15¢ step

(vice 25 for dose rate in air)

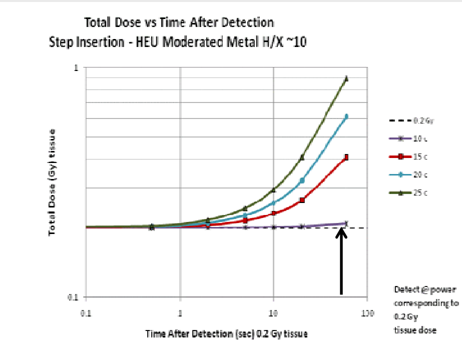
Dose at 1 Min ~ 0.5 Gy

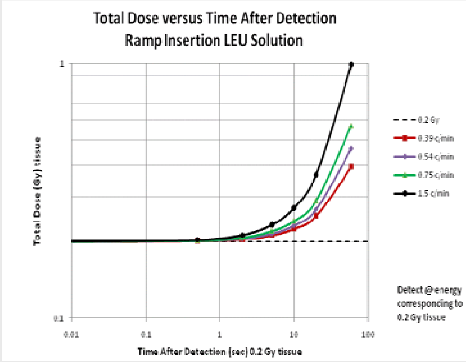
0.2 Gy within 20 sec for < 1.5 ¢/min

No detection < 0.4 ¢/min ramp

(vice 0.5 ¢/min for dose rate in air)

Total Dose vs Time after 0.2 Gy (tissue) detection





0.2 Gy total dose tissue “within 60 sec”

-close to ANS-8.3 Appendix A (step of few cents)

- yet peak power is LOWER than 0.2 Gy/min air

Conclusion

- Critical excursions kinetics and ANS-8.3 detection criteria - problematic
- Delay time assumption results in much larger doses than expected
- Dose rate in air vulnerabilities:

  GREATER than 0.2 Gy tissue at detection for small reactivity insertions
  GREATER than 1 Gy after 1 minute from detection
  LIMITED reactivity insertion (step and ramp) for human reaction and 0.2 Gy
- **Optimal time is ~ 12-15 sec after detection for ω ~ 100 msec^{-1}**
- Excursions with ω < 30 msec^{-1} require detection based on total dose or fissions
- Detection criterion based on minimum excursion kinetics can be justified
- CAAS specification for other than dose or dose rate (trip on minimum period)