INTRODUCTION OF PLUTONIUM SYSTEMS TO
THE NUCLEAR CRITICALITY SLIDE RULE

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Nuclear Criticality Accident

- The release of energy as the result of inadvertently producing a self-sustaining or divergent fission chain reaction
  - Intense production of neutrons and gamma radiations

- 60 reported criticality accidents in the world

- 21 deaths
April 1997, An Updated Nuclear Criticality Slide Rule
  - ORNL/TM-13322/V1 & V2: Technical Basis / Functional Slide Rule

This document gives order of magnitude estimates of key parameters, useful for emergency response teams and public authorities:

- The magnitude of the **number of fissions** based on personnel or field radiation measurements or various critical system parameter inputs,
- Neutron- and gamma-**dose** at variable unshielded distances from the accident,
- The **skyshine** component of the dose,
- Time-integrated radiation **dose** estimates,
- One-minute **decay-gamma** radiation dose,
- **Dose-reduction factors** for variable thicknesses of steel, concrete and water.
US Slide Rule

IRSN « Slide Rule »
Long term DOE/NNSA NCSP - IRSN collaboration

NCSP wants to develop and maintain modern Slide Rule

IRSN wants to review and improve its “Slide Rule”

Proposal of a complete work, divided into several steps:

- **Step 1**: Redo with modern radiation transport tools, for the same configurations and assumptions, the calculations performed initially for the 1997 estimation of the doses

- **Step 2**: Perform additional configurations/calculations
  - New configurations (new geometry of the source, new fissile media including plutonium systems, etc.)
  - New flux-to-dose conversion factors
Step 1: Slide Rule « Initial » Configuration

**Geometry:** One Air (sky) layer above a ~30 cm concrete layer (ground)

**Source:** Unreflected spherical uranium critical system – 1 meter over the ground
- U(4.95)O₂F₂ – (H/²³⁵U = 410)
- U(5)O₂ – (H/²³⁵U = 200)
- U(93.2)O₂(NO₃)₂ – (H/²³⁵U = 500)
- U(93.2) metal
- U(93.2)_3O₈ – (H/²³⁵U = 10)

**Dose Detection:** 0.3 to 1200 meters between source and dose detection.

Originally, Slide Rule results from DORT (2-D deterministic code) with the Henderson flux-to-dose conversion factor
Step 1: Slide Rule « Initial » Configuration

Codes used:
- MCNP 6.1
- SCALE 6.2
- COG 11.1

Various methods used:
- 1 step / 2 steps methods
- Size and shape of the detector
- Variance Reduction technics (WWG, CADIS, etc.)

But one:
- Cross-section library data: ENDF/B-VII.1 (CE)
- Flux-to-dose conversion factor: Henderson (1959)

Results presented at the ICRS13-RPSD2016 conference (2016)
“Update of the Nuclear Criticality Slide Rule for the Emergency Response to a Nuclear Criticality Accident”
Step 2: “Introduction Of Plutonium Systems”

**Geometry**: One Air (sky) layer above a 50 cm concrete layer (ground)

**Source**: Plutonium critical system – 1 meter over the ground

**Composition**: $^{239}\text{Pu}$ metal homogeneously mixed with water

- 5 moderation ratios ($H/^{239}\text{Pu}$): 0 (=metal), 10, 100, 900 and 2000

**Geometry**: bare sphere, bare cylinder, steel reflected sphere

**Dose Detection**: 0.3 to 1200 meters between source and dose detection.

**Flux-to-dose conversion factors**: ANSI/HPS N13.3 standard
Step 2: “Introduction Of Plutonium Systems”

- **Codes used:**
  - MCNP 6.1
  - SCALE 6.2.1
  - COG 11.2

- **Various methods used:**
  - 1 step / 2 steps methods
  - Variance Reduction technics (ADVANTG, CADIS, etc.)

- **But one:**
  - Cross-section library data: ENDF/B-VII.1 (CE)
  - Kind of detector: a cylindrical shell with a square cross-section of 5 cm x 5 cm

Examples of prompt dose results shown for accidents that generate $10^{17}$ fissions
Bare sphere (prompt dose results)
Bare sphere (comparison between codes)
Bare sphere (comparison between conversion factors)
Bare cylinder (prompt dose results for Pu metal (H/Pu=0))
Sphere surrounded by a steel reflector (prompt dose results for Pu metal (H/Pu=0))

Reflector/bare sphere ratio for neutron doses calculations (COG results)

Reflector/bare sphere ratio for gamma doses calculations (COG results)

R steel = 0.1 cm

R steel = 20 cm
Conclusions and perspectives

Conclusions:

- **Introduction of plutonium systems and new flux to dose conversion factors** (more penalizing than the previous one)

- **Prompt doses**: consistency between modern codes with small discrepancies on prompt gamma due to the different codes gamma transport treatment of bremsstrahlung

- **Bare cylinders**: up to 30% compared to the bare sphere but approach, more or less quickly, to the sphere dose for long distances

- **Steel reflector**: deeply modifies doses and the effect depends on several parameters (distance, moderation ratio, type of radiation)
  - difficulties to attribute one reduction factor value to a given thickness of steel
Conclusions and perspectives

 Perspectives:

- Finalization of Step 2 for prompt doses
- Calculation of delayed gamma doses for the Step 2
- Calculation of additional configurations (impact of multiple layers of shielding, of the thickness and the composition of the surrounding environment (ground, humidity of the air, etc.))

- Opportunity to create “computer benchmarks”:
  - test and validate the various variance reduction methods
  - establish best practices for this kind of problems (e.g. fission source calculation)
- Opportunity to suggest new experiments for the validation of the tool (benchmarking effort)

- Then... beginning of the next Steps:
  - Step 3: review of the section regarding the estimation of the number of fissions
  - Step 4: addition of others sections (like actions to stop an on-going criticality accident)
  - Step 5: development of a Slide Rule "application" for a handheld device
Thank you for your attention