CIRMS 2026 — Need

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Progress in **accurately estimating deterministic RBEs of neutrons in humans** is currently blocked because we lack **adequate radiobiology and exposure data for all factors impacting effects**, which prevents **the accurate estimation of human health risks in a wide range of exposure scenarios**.

Revisiting Deterministic Neutron RBEs:

Insights from Urban Nuclear Detonation Scenario Analyses and their Implications in Other Exposure Settings

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Presented at CIRMS 2026

Disclaimer:

The findings and conclusions in this presentation are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention (NIOSH), the Defense Threat Reduction Agency (DTRA), or any other governmental agency.

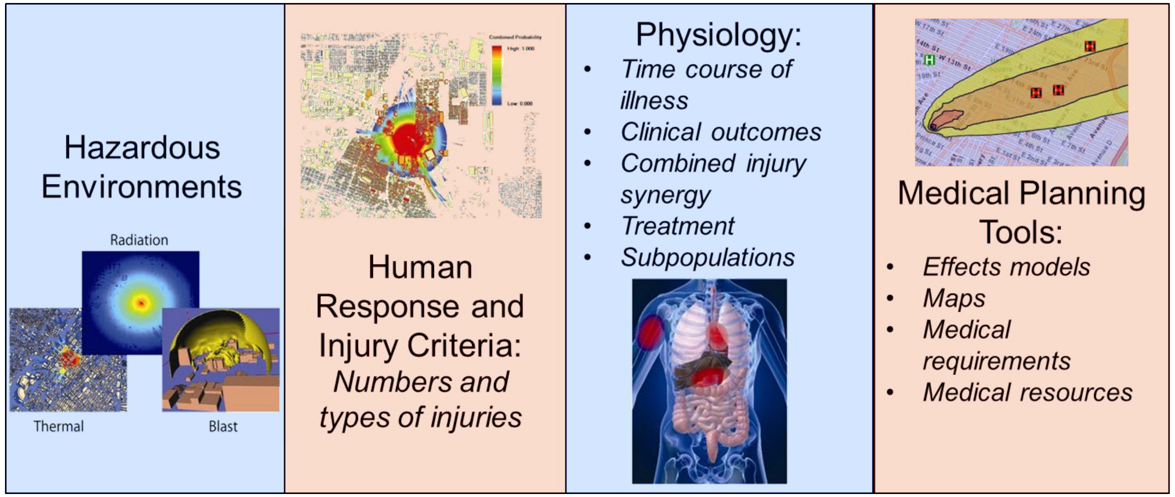
Agenda

- Nuclear detonation (NUDET) scenario analyses
  - Defense Threat Reduction Agency mission
  - Simulations and urban modeling
  - Radiobiology
- Occupational Exposures
  - Criticality accidents
  - Case study
- Gaps and priorities

Background

- Defense Threat Reduction Agency (DTRA)
  - Safeguards USA & allies from WMD by providing capabilities to reduce, eliminate, and counter the threat and mitigate its effects.
  - Maintains DoD's **WMD assessment codes**.

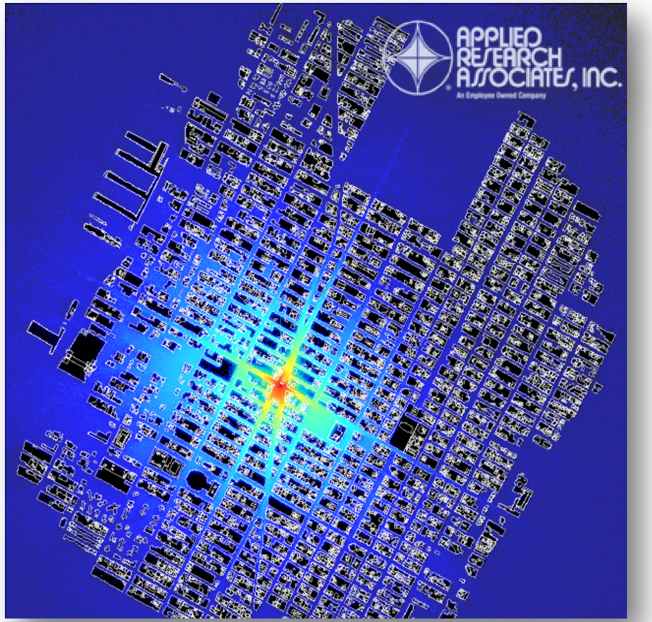
- DTRA Human Survivability R&D (HSRD) from 2014-2019
  - Improve **human injury models** for nuclear weapon environments.
  - Develop **S&T code** and integrate into operational code.



Overview of NUDET Health Effects

- Prompt radiation exposures
  - Gamma and **neutron**
- Protracted radiation exposures
  - Neutron activation products
  - Radioactive fallout
- Blast-related Injuries
  - Flying debris
  - Glass shattering
  - Structural collapse
- Thermal-related Injuries
  - Flash burns
  - Secondary fires
- Inhalation Hazards
  - Smoke and heat from burning materials
  - Dense dust generated from building damage

Urban Radiation Shielding



Many complex injuries with potentially survivable doses of radiation exposure

Do neutrons matter?

- Prompt Exposures
  - **Depends** on device characteristics, height of burst (HOB), and urban environment
  - **Neutron/gamma** $(n{:}\,\gamma)$ ratio varies
- Neutron Relative Biological Effectiveness (RBE)
  - Dictated by both **neutron dose and energy**
  - **RBE** generally increases with decreasing neutron energy (ICRP 1989)
  - Can be different for different organ systems (Alpen 1991)
  - Impact to outcome depends on the precise dose and neutron/gamma ratio
  - ***How might neutron exposures impact deterministic endpoints / acute radiation syndrome?***

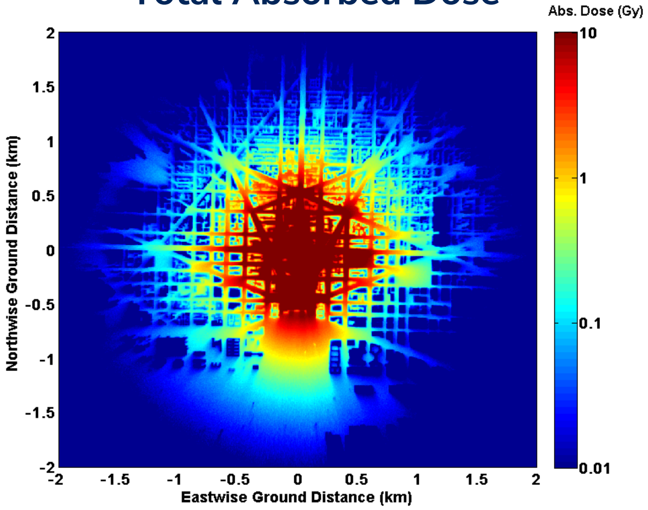
To answer this, we sought to characterize neutron exposures and relevant RBEs

Problem:
Most casualty estimation codes do not account for neutron RBE.

Approach:
- **Environment modeling**:
  - What energies and doses would survivors of a NUDET be exposed to?
- Review of **neutron radiobiology**:
  - What is the appropriate RBE for these neutron exposures?
- **Scenario analyses**:
  - Are the impacts sufficient to require updating codes?

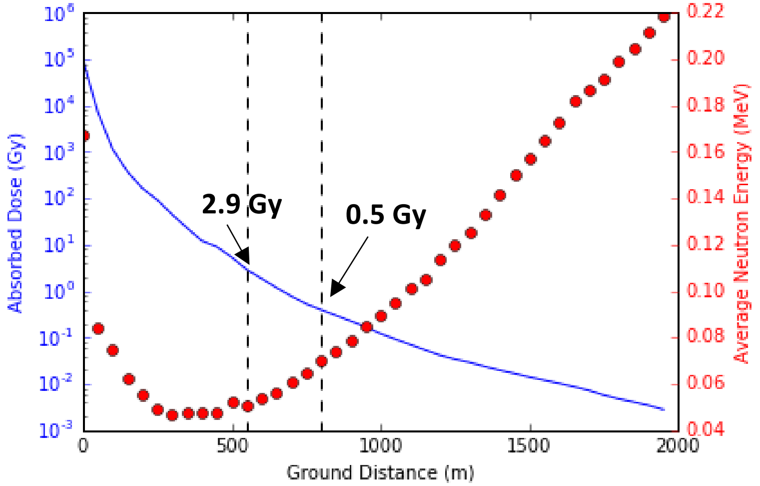
Potential Energy and Doses of Neutrons in NUDET Survivors in Urban Area

Total Absorbed Dose



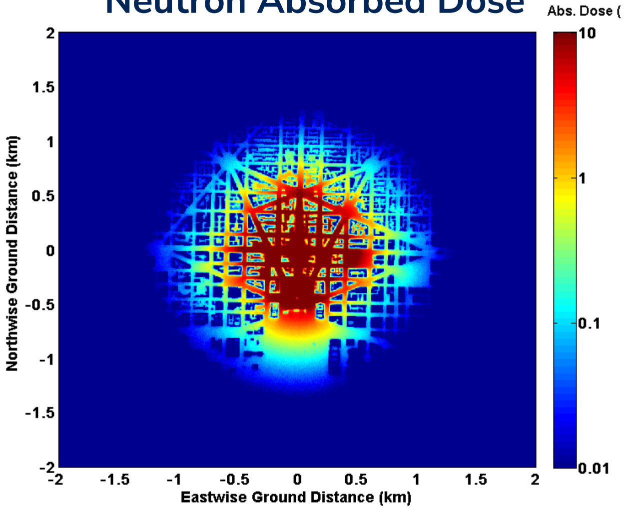
Neutron dose and energy to potential survivors depend on:

- Urban Terrain
- Source
- Location and posture individual
- Other scenario specific details

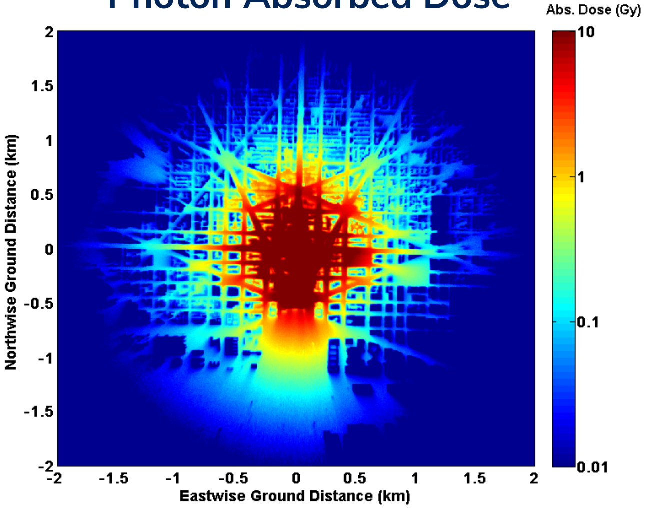


Neutron energies and absorbed doses (RBM, ICRP-116) in a NUDET scenario (Scenario 1)

Neutron Absorbed Dose



Photon Absorbed Dose



	Source Input 1	Source Input 2
Average Distance (km)	0.5 – 1	0.7 – 1
Mean energy (keV)	~40 – 60	~130 – 200
% neutron in total dose	24 – 37	31 – 51

Kramer, et al. DTRA-TR-13-045-R1, 2016.

Stricklin, et al. DTRA-TR-19-001, 2018

Neutron Relative Biological Effectiveness (RBEs)

What would be an appropriate RBE for $LD_{50/60}$ for casualty estimation?

- A dose response curve, **$LD_{50/60}$ and slope**, for estimating fatalities; threshold for deterministic effects

- Reviewed large animal lethality studies
- Observed RBEs range from **2.9 to 0.9**

- **Need consistent parameters for comparison**
  - % neutron, energy, dose rate, comparison radiation, bi- or unilateral exposure

Species	Exposure	Dose Rate (Gy/min)	Endpoint	MLT Dose Gy (bilateral)	RBE	Reference
Beagle	0.85 MeV ave. (n/γ, 5.4/1) ^{60}Co (comparator)	0.4 0.1	$LD_{50/30}$	(1.5) (2.6)	1.7	(MacVittie, et al. 1991)
Mongrel	Mixed field (90% n) Mixed field (50% n) Mixed field (10% n) ^{60}Co	0.01 0.4 0.6 0.3-1.1	$LD_{50/5}$	2.8 5.0 7.0 7.7	2.9 1.6 1.1 -	(Wang, et al. 1991)
Mongrel	Mixed field (90% n) Mixed field (50% n) Mixed field (10% n) ^{60}Co	0.01 0.4 0.6 0.3-1.1	$LD_{50/30}$	1.7 2.3 2.8 3.0	1.7 1.3 1.1 -	(Wang, et al. 1991)
Beagle	1 MeV neutrons (n/γ, 6/1) ^{60}Co 1 MeV neutrons (n/γ, 6/1) 250 kVp x-rays	0.6 0.1 0.6 0.2	$LD_{50/30}$	1.2 2.6 1.2 2.3	2.3 2.0	(MacVittie, et al. 1984)
Beagle	14.6 MeV neutrons 1 MVp x-rays	0.02 0.09	$LD_{50/30}$	2.8 2.9	1.0	(Earle, et al. 1971)
Beagle	Mixed field, 1MeV, n/γ 0.67/1 250 kVp x-rays	0.2 0.2	$LD_{50/60}$	(2.2) 2.1	0.9	(George, et al. 1968)
Beagle	Pulse mixed field (1MeV)	up to 2000	$LD_{50/30}$	(2.1)	1.24[1]	(Pitchford and Thorp 1968)
Mongrel	Fission neutrons (n/γ, 2.3/1) 1 Mvp x-rays	up to 4000 0.1	$LD_{50/30}$	2.0 (2.3) 2.8 (3.4)	1.38 (1.46)	(Ainsworth, et al. 1965)
Mongrel	Fast neutrons (n/γ, 2.2/1) 250 kVp x-rays	Not provided	$LD_{50/30}$	2.4 2.1	0.9	(Alpen, et al. 1960)
Beagle	Fast neutrons	~0.2	$LD_{50/30}$	2.7	1.3	(Bond, et al. 1956)
Sheep	Mixed field neutrons	$0.1\text{-}10^{6}$	$LD_{50/60}$	(1.7)	NR	(Mobley, et al. 1974)
Minipig	Pulsed mixed field	up to 2000	$LD_{50/30}$	2.2		(Wise and Turbyfill 1970)
Minipig	Mixed field (n/γ, 5) Gamma mixed (n/γ, 0.7)	1.3-2.5 1.3-2.5	$LD_{50/7.5}$	4.3 8.7	2	(Jones, et al. 1972)
Macaca mulatta	Mixed field 250 kVp x-rays	0.2 0.2	$LD_{50/60}$	3.8 5.0	1.3	(Stanley, et al. 1966)
Macaca mulatta	Pulse mixed field	up to 2000	$LD_{50/60}$	(3.8)	1.34[2]	(Wise and Turbyfill 1968)

Due to dose dependence of RBE, must also examine LD10 and LD90

RBEs for LD_{10}, LD_{50}, and LD_{90} were examined for select studies having comparable dose rates and data available for reconstructing the full dose response curves.

Study	Animal	Radiation Source	LD_{10}	LD_{50}	LD_{90}	Slope
(Wise and Turbyfill 1968)	NHP	Reactor	2.3 ± 0.9	3.8 ± 0.2	5.2 ± 0.3	0.9 ± 0.3
(MacVittie, et al. 2015)	NHP	^{60}Co	5.3 ± 0.2	6.4 ± 0.15	7.6 ± 0.2	1.2 ± 0.2
	NHP Est. RBE		**2.3 ± 0.8**	**1.7 ± 0.1**	**1.5 ± 0.1**	
(Ainsworth, et al. 1965)	Dog	Reactor	1.2 ± 0.3	2.0 ± 0.1	2.9 ± 0.2	1.5 ± 0.4
(Shively, et al. 1958)	Dog	^{60}Co	2.8 ± 0.2	3.3 ± 0.1	3.9 ± 0.1	2.4 ± 0.7
	Dog Est. RBE		**2.3 ± 0.5**	**1.6 ± 0.1**	**1.3 ± 0.1**	
(Wise and Turbyfill 1970)	Minipig	Reactor	1.5 ± 0.4	2.2 ± 0.1	2.8 ± 0.1	2.0 ± 0.6
(Moroni 2018)	Minipig	^{60}Co	2.6 ± 0.1	2.9 ± 0.1	3.2 ± 0.2	3.9 ± 1.8
	Minipig Est. RBE		**1.7 ± 0.4**	**1.3 ± 0.1**	**1.1 ± 0.1**	
(George, et al. 1968)	Beagle	Reactor	2.0 ± 0.0	2.2 ± 0.0	2.4 ± 0.0	6.7 ± 1.5
(Norris, et al. 1968)	Beagle	^{60}Co	2.9 ± 0.1	3.2 ± 0.0	3.6 ± 0.1	4.0 ± 0.9
	Beagle Est. RBE		**1.5 ± 0.0**	**1.5 ± 0.0**	**1.5 ± 0.0**	

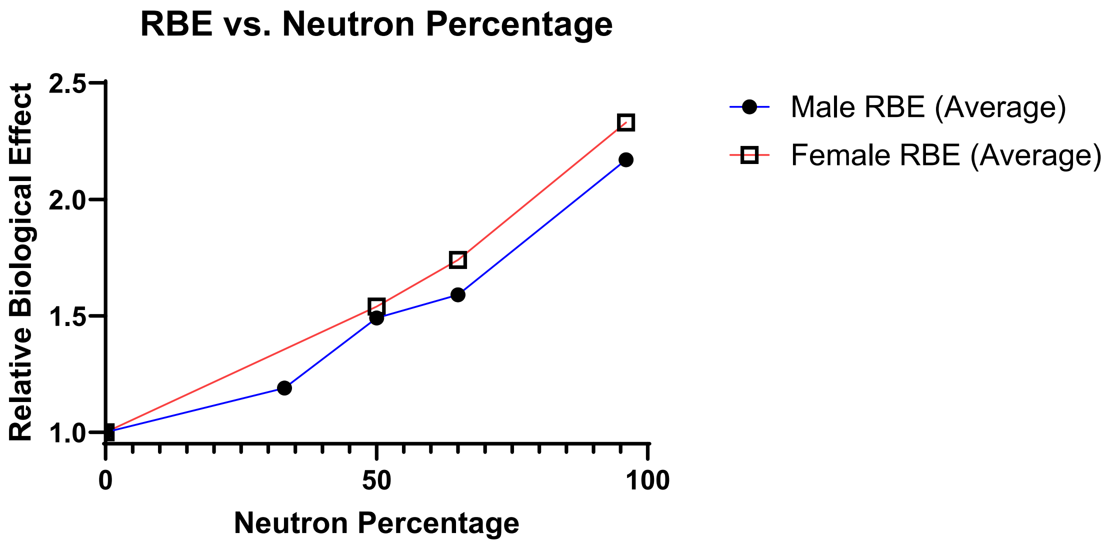
Stricklin, et al. DTRA-TR-19-001, 2018

Impact of Neutron Ratio on RBEs

- Recent AFRRI/DTRA collaboration
  - Comparing Co-60 and TRIGA Reactor Irradiation:
    - 96, 65, 50, 30% neutron contribution
    - Male and female C57BL/6 mice
- Objective:
  - Identify a continuum of lethality doses ($LD_{1/30}$→$LD_{99/30}$) for various $n:\gamma$ ratios and utilizing references biological outcomes determine variation to RBE.
- Additional analyses at ~15% and 4% neutrons planned
  - Female shifts from more radiosensitive at **high neutron ratio** to more radioresistant at **low neutron ratios**.

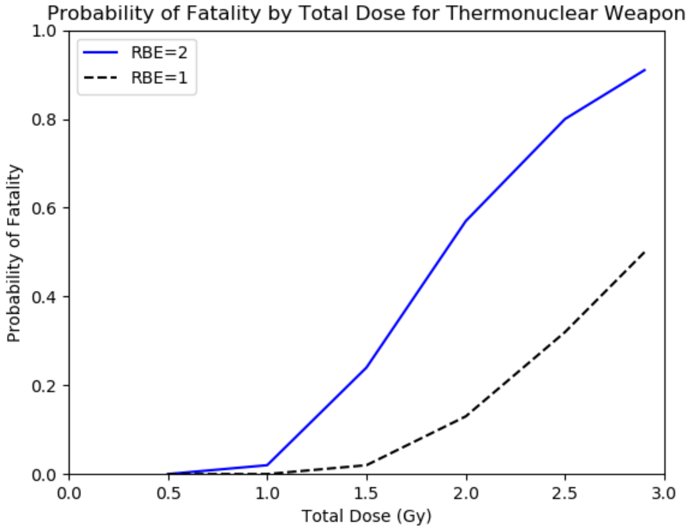
$$\frac{LDx/30_{Cobalt}}{LDx/30_{TRIGA}} = RBE$$

Neutron %	Male $LD_{50/30}$ (Gy)	Female $LD_{50/30}$ (Gy)
96%	3.63	3.48
65%	4.96	4.65
50%	5.26	5.24
33%	6.60	6.54
0% (Co-60)	**7.86**	**8.10**

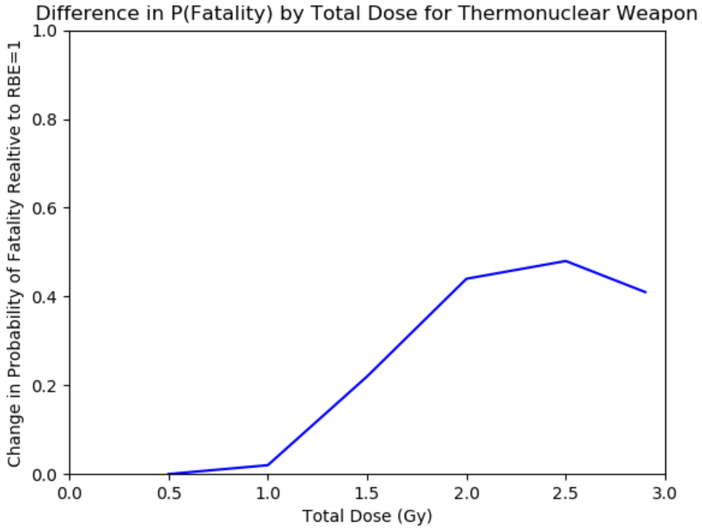


SCENARIO ANALYSES

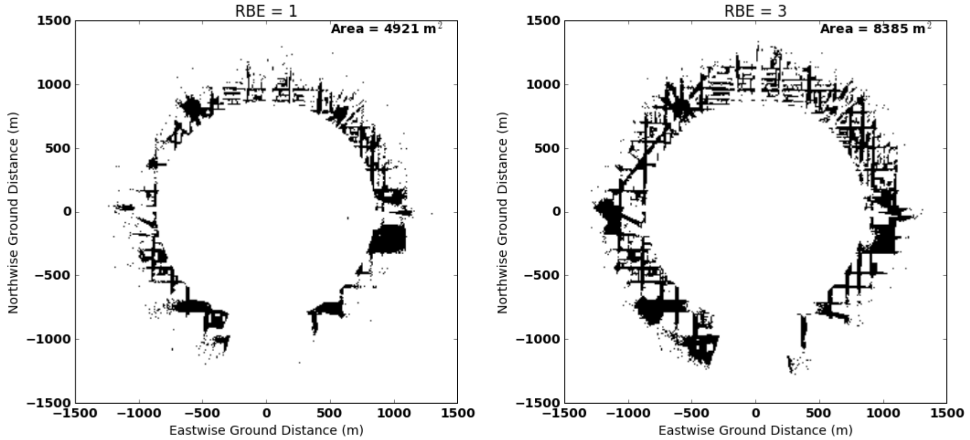
Are the impacts sufficient to require updating codes?



Greater than 40% change in probability in the surviving population with *potentially survivable* doses



“Moderate Radiation Injury” Zone (0.5 to 2.9 Gy) with RBE = 1 and 3



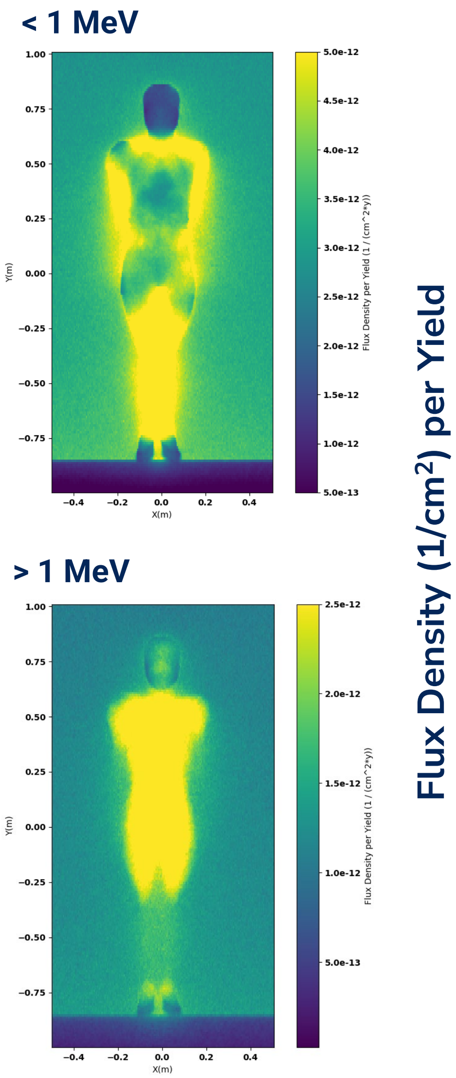
In the DC scenario analysis, approximately **69% of surviving population has some neutron dose**.

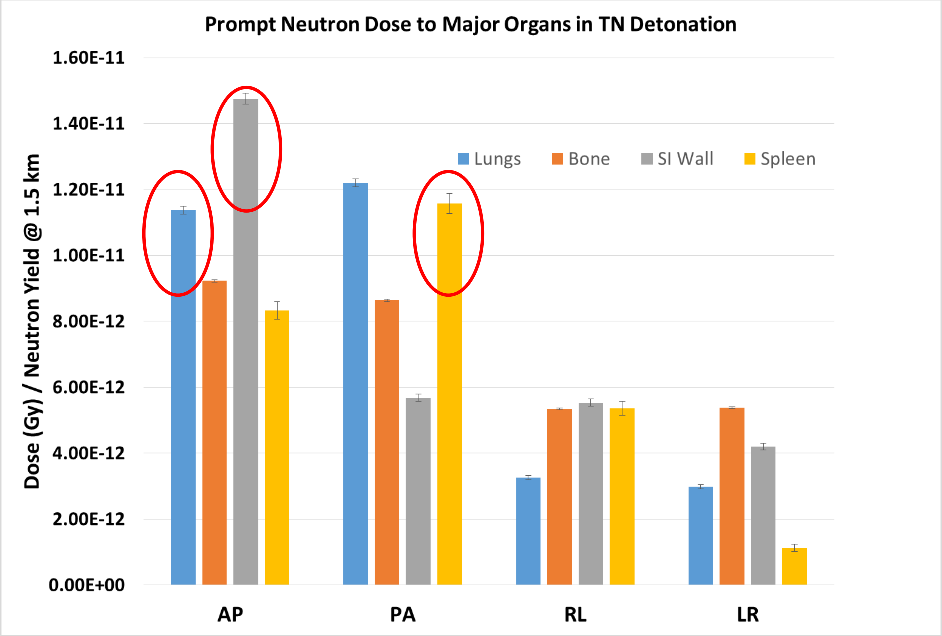
Kramer, et al. ARA-HS-TN-18-006

Dant, et al. ARA-HS-TN-18-005
Dant, et al. HPS Presentation 2018
Kramer, et al. DTRA-TR-17-026-R1, 2017

Example Computational Studies

- Objective:
  - To provide insight on potential **organ doses** using a computational phantom and a neutron spectrum at a survivable distance from ground zero.
- Computational Modeling
  - MCNP6.2
  - All neutron reactions accounted for given in a particular cross-section.
  - KT-Man 2 computational phantom from RSICC
  - Cell fluence and energy deposition
- Evaluations included:
  - Tissue activation (<0.3%)
  - Directional dependency and ground scatter
  - Specific organ doses





Prins, et al. DTRA-TR-19-008, 2019

Will neutron exposure alter classical ARS manifestation?

DOD Plans and Updates

- Determine the best neutron RBE integration strategy for the near-term
    - What do current environment codes provide – neutron dose and energy or just dose?
        - Ensure codes provide neutron and gamma dose separately (not just total absorbed dose)
    - Consider revising DoD policy (JP 3-11) to address biological impact of neutron dose (e.g. Gy-Eq)
    - Consider revising DoD effects models (single RBE or function)

- Continue to examine the radiobiology:
    - Coordinated Interagency Workshop in 2019 to better understand existing knowledge and gaps
    - Collaborative neutron ratio study provided valuable estimates for integration into HENRE
    - Investigate impact of specific organ dose and resulting performance decrement

Occupational Sources of Neutron Exposures

- Nuclear Power and Research Reactors
  - Workers in reprocessing and fuel fabrication facilities
  - Nuclear Navy
- High Energy Particle Accelerators
  - Therapists/Medical staff from LINACs
- Industrial Neutron Sources
  - Industrial radiography/non-destructive testing
- Aerospace and Aviation
  - Airline crew members
- Nuclear Weapons Production / Handling
  - Workers involved in design, assembly, maintenance

Americium-241 is the most frequently used alpha emitter in Alpha neutron sources. Alpha emitters are typically mixed with Beryllium (Be)-9, a low atomic number (Z) material with a relatively high neutron yield. [Be-9 + $\alpha \rightarrow$ Carbon (C)-12 + neutron + 4.44 MeV γ]. Other low Z materials including fluorine, lithium, and boron can but are not frequently used to liberate neutrons.

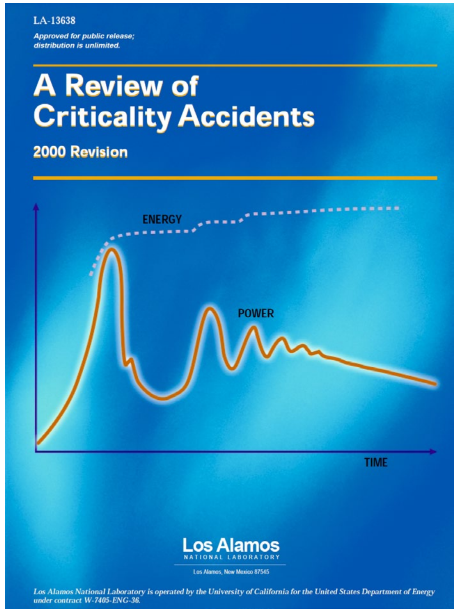
The majority of occupational exposures are lower-level exposures and health effects of concern are generally stochastic long-term in nature.

However, **accidents** in the occupational setting do occur and **solar events** can trigger high dose and dose rate exposures.

Criticality Accidents

- At least 60 criticality accidents since 1945
- Resulting in 21 deaths world-wide
- Criticality accidents result from an uncontrolled nuclear reaction.

- Persons in the immediate area can be exposed to potentially lethal doses of radiation
  - Persons closest in receive high dose, heterogeneous exposure
  - Persons further away more uniform, lower dose exposures
  - Both gamma and neutron exposures
  - Physical dose reconstruction very difficult: large variability in dose reconstructions



McLaughlin, Thomas P. et al (2000). *A Review of Criticality Accidents*. LANL. LA-13638.

Uncertainty in Physical Dosimetry and Health Impacts of Neutrons

- Vinca Criticality accident, Yugoslavia, 1958
  - Patient data were used to develop hematopoietic cell kinetic models
- Doses were reconstructed based on shielding, Na neutron activation, etc.
  - Jammet et al. 1959, Hurst et al. 1961. Pendic 1961, Auxier 1961, Mole 1984, Pesic 2012

Patient	Jammet 1959	Hurst 1959	Auxier 1961	Pesic 2012
	rem	rad	rad	rad
V	840	640	436	363
M	856	580	426	352
G	920	600	414	351
D	1024	500	419	**266**
H	694	420	323	312
B	408	350	207	**479**

Case Study: JCO Criticality in Tokai-Mura

- 1999 criticality in Japanese NPP resulted in 3 highly exposed workers.
  - 677 people received neutron and photon doses
  - 62 of 148 workers and residents had detectable ^{24}Na activation

- Exposure was a “***complex combination of neutrons and γ -rays of different energies***.”
  - Presented doses in “GyEq”
    - A.) 16–20 GyEq, B.) 6–10 GyEq, and C.) 1–4.5 GyEq
  - Akashi, et al. *J Radiat Res* 2001

- “The extreme unevenness of the dose distribution and the neutron versus γ -ray component made the clinical manifestation very complicated.”
  - Ishii, et al. *J Radiat Res* 2001

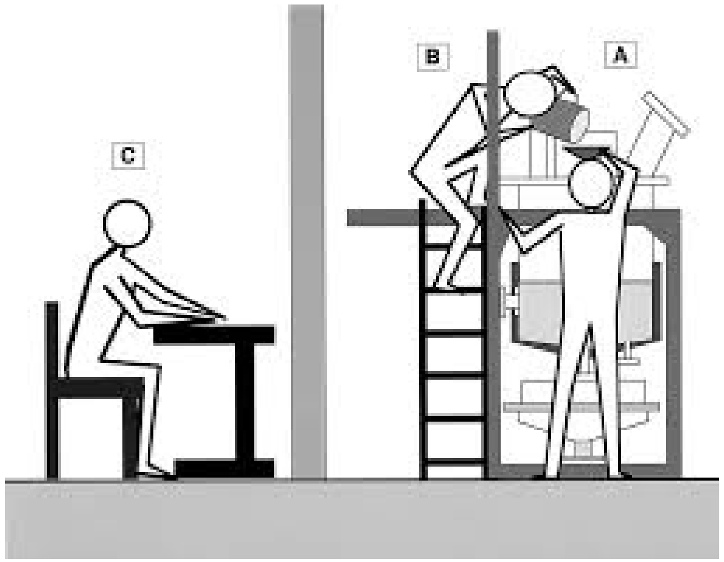
- 2 lethally irradiated patients had severe multi-organ necrosis, survivor had classical H-ARS and gross defects to the oral mucosal

Case Study: JCO Criticality in Tokai-Mura

- Dose Reconstruction
  - Physical dose estimates based on ^{24}Na activation (Ishigure 2001)
  - Biological dosimetry using PCC-rings (Hayata 2001)
  - Computational phantoms
    - Accounting for **posture** (6 and 26 Gy),
    - Estimating organ doses (Vazquez 2014)

- Multi-organ involvement in surviving patient
  - Hirama, et al. BJR 2003, BJR 2005

- 0.81 Gy neutrons and 1.3 Gy photons
  - Severe bone marrow failure
  - Hypoxemia, interstitial pulmonary edema, epilation and gingival lesion
  - Chronic phase, cataract and hypothyroidism

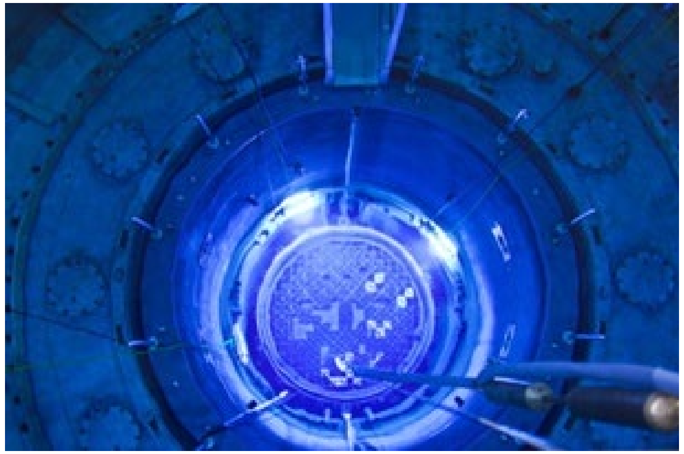


Summary of Gaps for NUDET and NPP Scenarios

- NUDET Scenarios:
  - The degree of neutron exposure is dependent on specific scenario
  - Variable neutron energies, doses, and ratios
  - Neutron energies would likely be sub-MeV

- NPP Scenarios:
  - Uncertainties in historical physical dose reconstructions
  - Acute high dose for immediate workers
  - Low dose exposures to surrounding populations
  - Significant neutron activation

- Needs:
  - Appropriate approach for integrating RBE for deterministic effects
  - Methods for extrapolating animal data to humans – with focus on **variation in organ doses**
  - Better understanding of how neutrons impact ARS:
    - Non-classical manifestation



Mühleberg nuclear power reactor

What are the highest priority gaps?

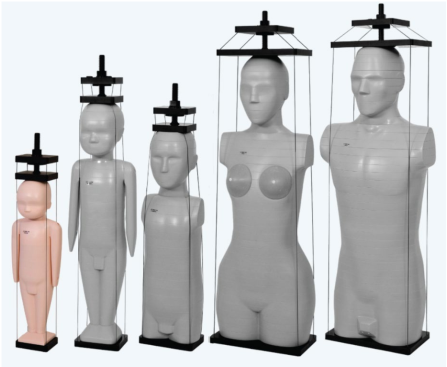
- Neutron interactions are complex, and a significant base of knowledge is needed to adequately assess their health effects.
  - What is a reasonable scheme for estimation?
    - Continuous functions within energy range – or grouped value estimate (single RBE for specific ranges)
    - Community consensus on approach needed
  - Is there a way to characterize existing uncertainty?
    - What are the sources and which can be improved upon

- Comparable doses in humans:
  - Examine **target organ doses** from computational studies and revisit organ specific RBEs
  - **Species translation** (geometry matters) or surrogate endpoints
  - Use knowledge from above to update mechanistic models if appropriate and/or use to better estimate **ARS impacts**

- Reproducible Dosimetry and Dose Reconstruction
  - Method validation
  - Consistent, harmonized methods

Factors Affecting Neutron RBE

Biological	Physical
Endpoint	LET
Tissue Type	Energy
Tissue volume and depth	Dose
Micro-environment	Dose rate
Cell cycle	Material composition



Example of Physical Phantoms

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