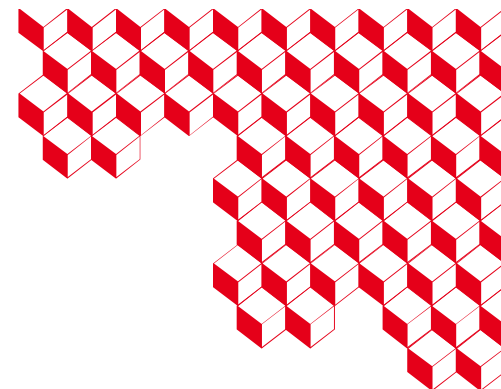




Radiation Dose Assessment in Retrospective Dosimetry Using TRIPOLI-4[®] and ICRP Computational Phantoms

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L.A.R.D. 2025

CEA Paris-Saclay - DOSEO

01-07-2025



Outline

- **Introduction**
- **TRIPOLI-4 Code, Calculation modes, & Applications**
- **2019-2020 EURADOS-RENEB field test of Retrospective Dosimetry**
- **1999 Tokai-Mura Criticality Accident & Workers organ doses**
- **TRIPOLI-4 calculation results**
- **Conclusions**



Introduction

/. This study demonstrates the application of TRIPOLI-4 Monte Carlo radiation transport code for retrospective dosimetry in two critical scenarios:

- (1) the 2019-2020 EURADOS-RENEB field test simulating a small-scale radiological accident and**
- (2) the 1999 Tokai-Mura criticality accident.**

/. The research leverages computational phantoms of ICRP 110 voxel models to assess organ-specific radiation doses, validating TRIPOLI-4 calculations against experimental measurements and alternative codes (e. g., MCNP6).

/. Building on prior publications, this review discusses also current research developments in the field.



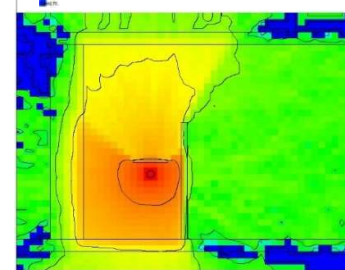
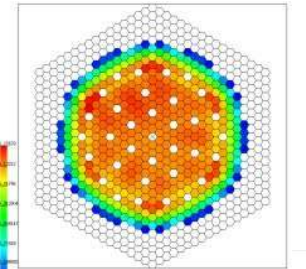
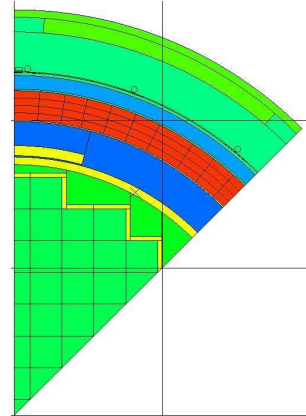
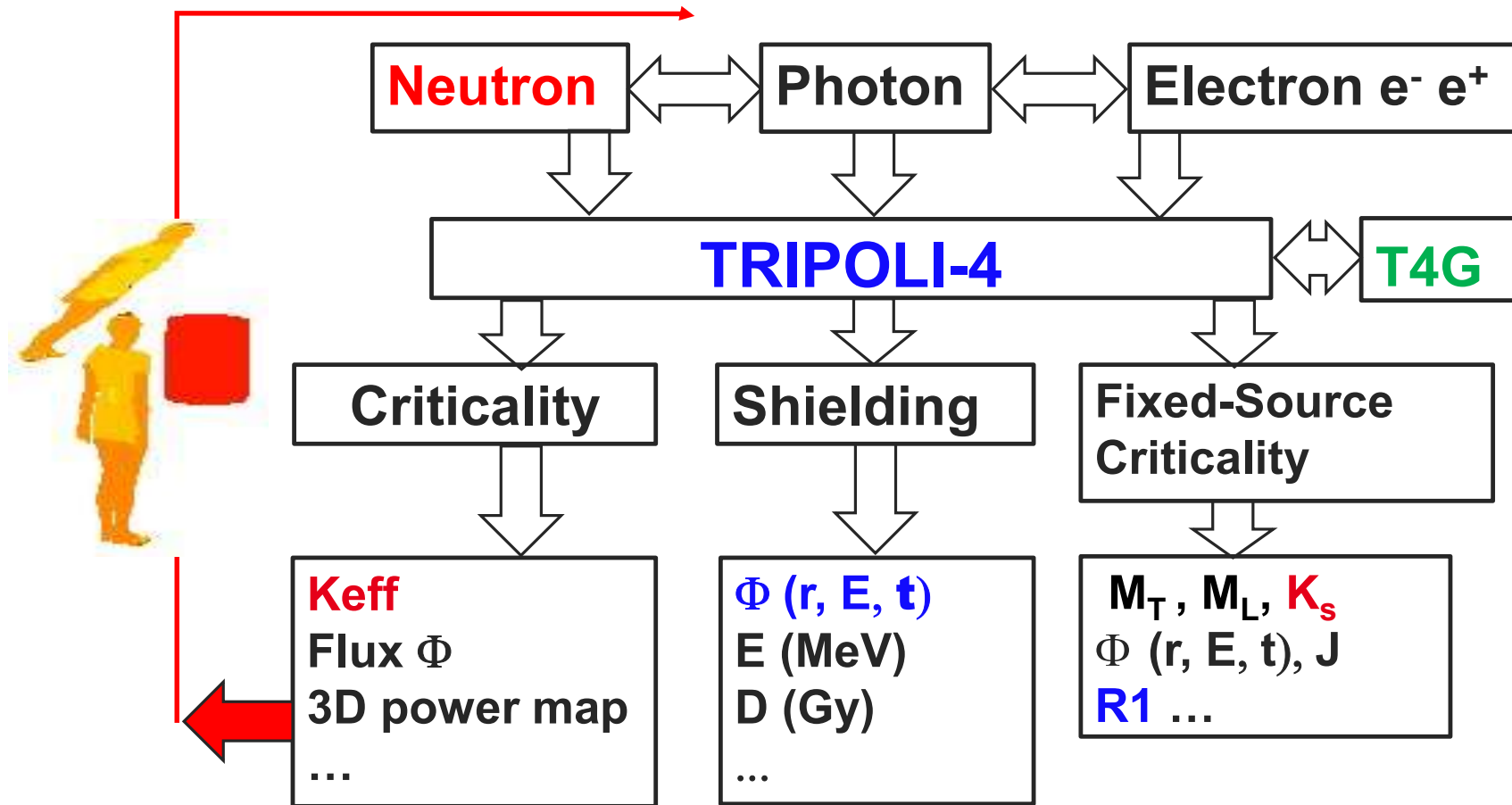
Introduction - 2

Retrospective dosimetry refers to the estimation of radiation exposure from past events. It is particularly relevant in cases of historical **high dose exposures** or exposures over extended periods.

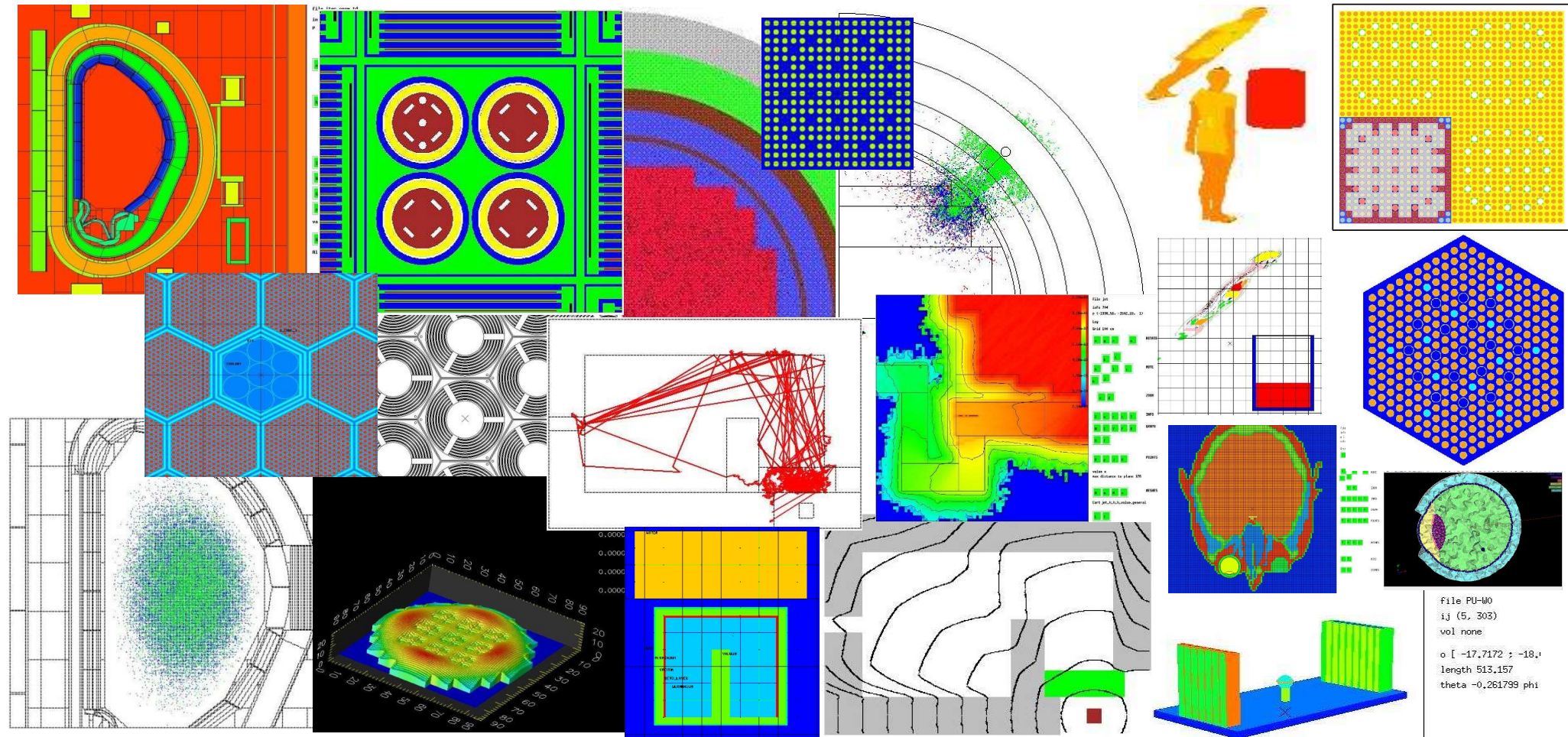
- / In most scenarios, external exposures contribute significantly to the received dose. **Accidental gamma and neutron dose** estimates could be obtained from **bioassay samples** and recently from personal electronic device components of **smartphone**.
- / TRIPOLI-4 is a general-purpose Monte Carlo radiation transport code. Computational **dosimetry in organs using TRIPOLI-4** was developed and applied on external and internal exposure studies for occupational, environmental and medical applications
- / This paper reports on the recent works using TRIPOLI-4 on two retrospective dosimetry applications. The first is the 2019-2020 **EURADOS-RENEB field test**. The second is the organ dose assessment for victims of the 1999 **Tokai-Mura criticality accident**.

TRIPOLI-4 Radiation transport code

T4G – 2D & 3D I/O Viewer



TRIPOLI-4 - Application fields



File PU-W0
ij (5, 303)
vol none
o [-17.7172 ; -18.4
length 513.157
theta -0.261799 phi

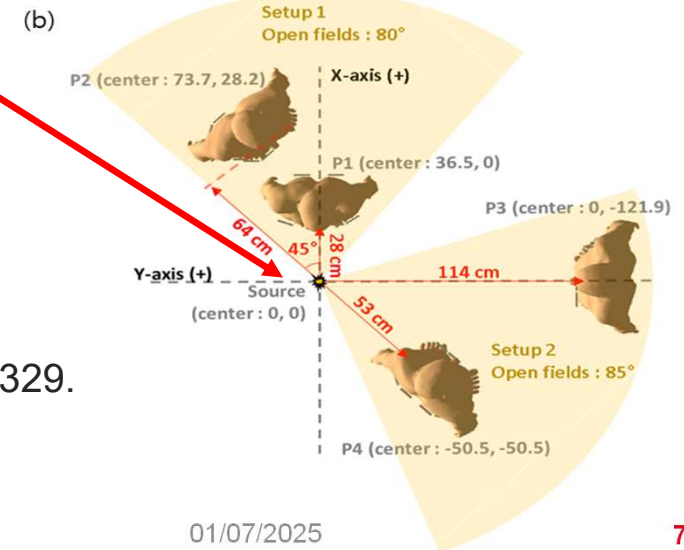
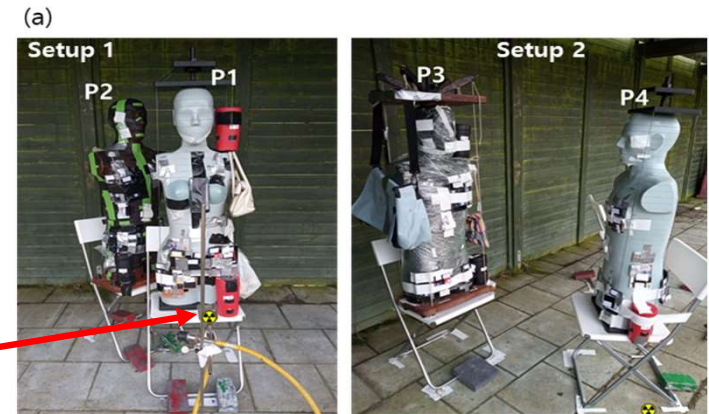
2019-2020 EURADOS-RENEB field test

I. EURADOS-RENEB (European Radiation Dosimetry Group - Running of the European NEtwork of Biological and retrospective physical dosimetry) field test was an exercise of retrospective dosimetry techniques for a small-scale radiological accident.

I. The exposure device was an ^{192}Ir gamma source for industrial radiography. The source was set 59.5 cm above the floor. The irradiation time was 1 hour for setup 1 and 2.5 hours for setup 2.

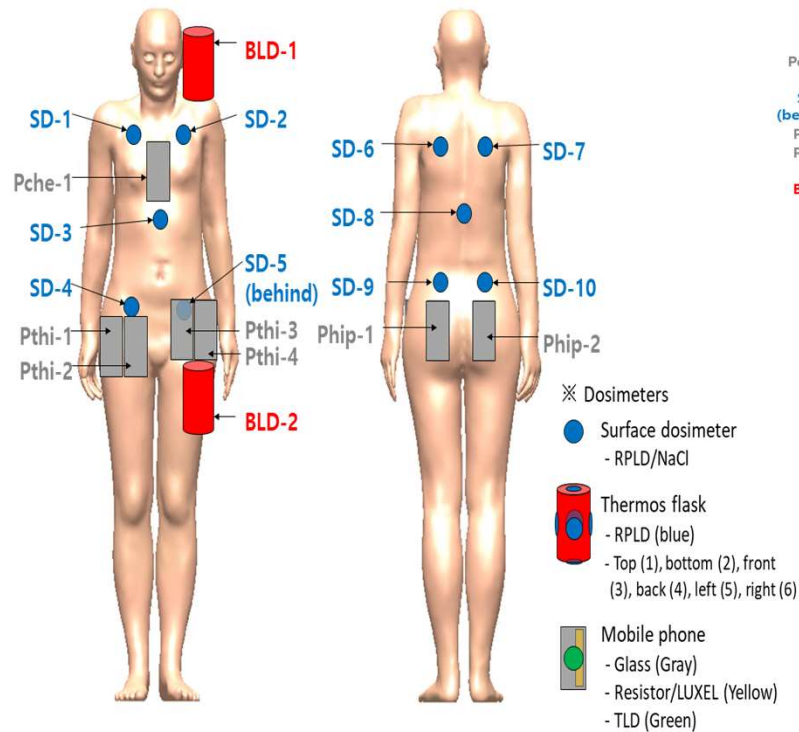
I. RPLD, TLD and OSLD dosimeters were introduced inside the torso phantoms, ATOM[®] models 702 and 701 (P1 and P4) and Alderson RANDO[®] Phantom (P2 and P3), for organ dose measurements.

Ref: L. Waldner et al., *Radiat. Res.*, **195**, 253-264, (2021).
H. Kim et al., *Radiation Measurements*, Vol. **180**, Jan. 2025, 107329.

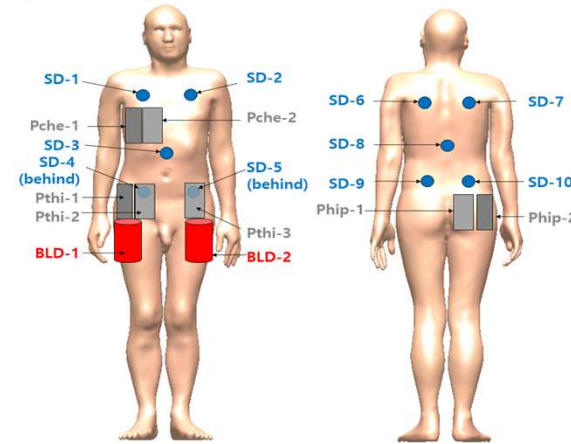


2019-2020 EURADOS RENEb field test

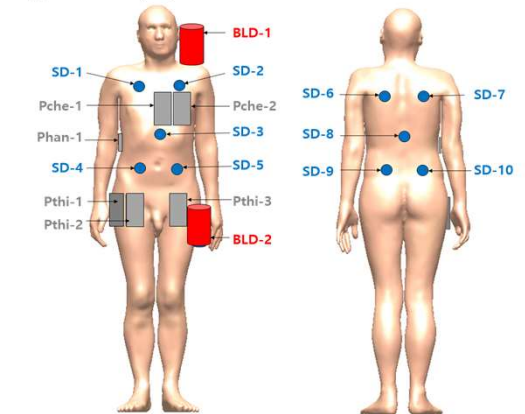
(a) Phantom 1 (P1) and dosimeter structures



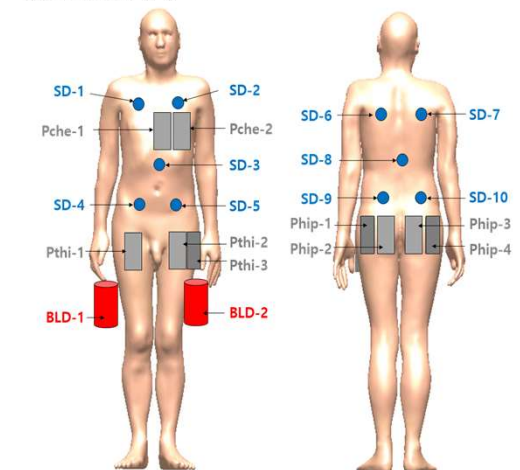
(b) Phantom 2 (P2)



(c) Phantom 3 (P3)



(d) Phantom 4 (P4)

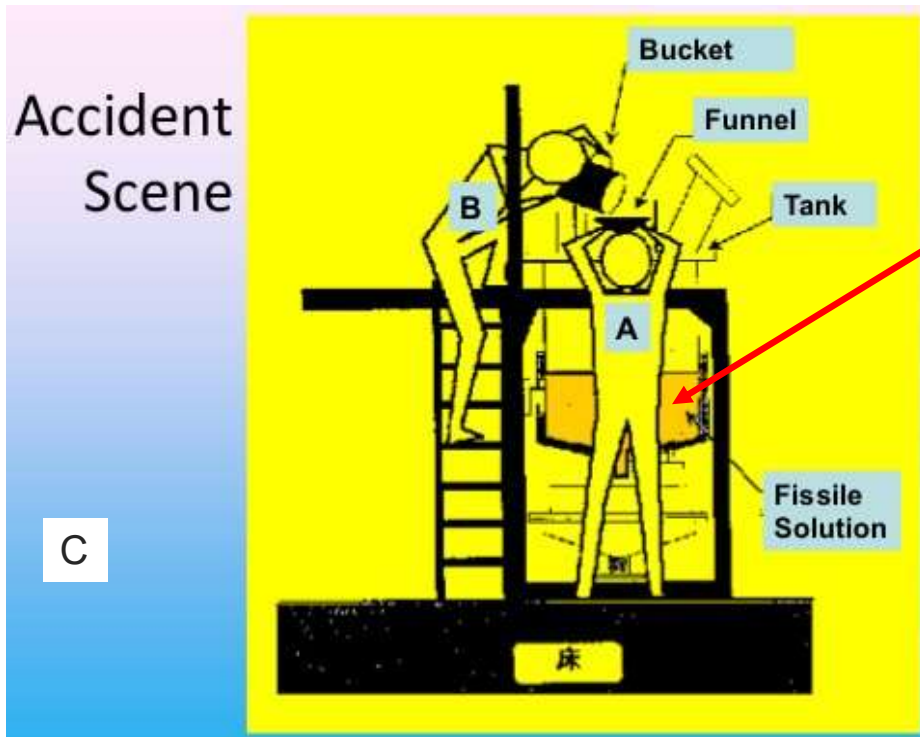


1. **Surface dosimeters (SD-x), smartphones, and blood samples** in Thermos flasks were prepared on the torso phantoms, P1, P2, P3 and P4 for external dose measurements.

Ref: L. Waldner et al., *Radiat. Res.*, **195**, 253-264, (2021).

H. Kim et al., *Radiation Measurements*, Vol. **180**, Jan. 2025, 107329.

Tokai-Mura criticality accident 1999



JCO fuel processing plant

- Uranyl (U-235 18.8%) nitrate in tank → Joyo FBR fuel
- Solution reached criticality → about 16.6 kg U / 45 L
- A: standing beside the tank and holding a funnel → **16-20 Gy+** → 82 days
- B: bending over the tank and pouring the uranyl nitrate solution → **6-10 Gy** → 210 days
- C: team leader 4 m away → **1.2 – 5.5 Gy**

+ High dose estimation: **²⁴Na in blood, Biodosimetry**

Ref: R. A. Knief, SAND2013-6983P
K. Miyamoto et al. Health Physics, 83 (2002) 19

Tokai-Mura criticality accident - Time evolution

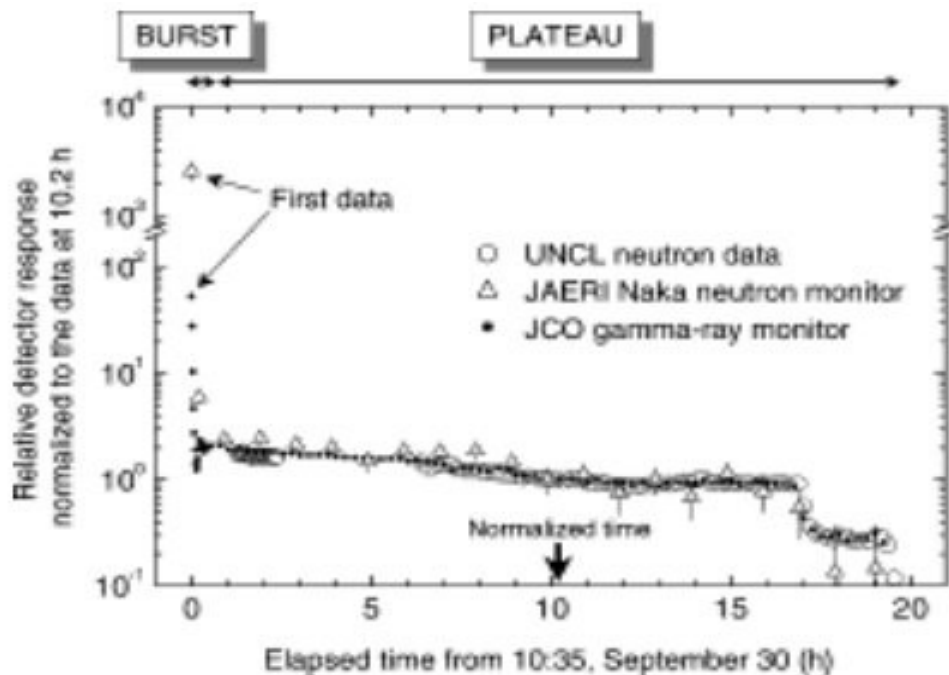


Fig. 3 Comparison of the time evolution of the counting rates measured with UNCL and dose rates measured with the neutron monitor and gamma-ray monitor

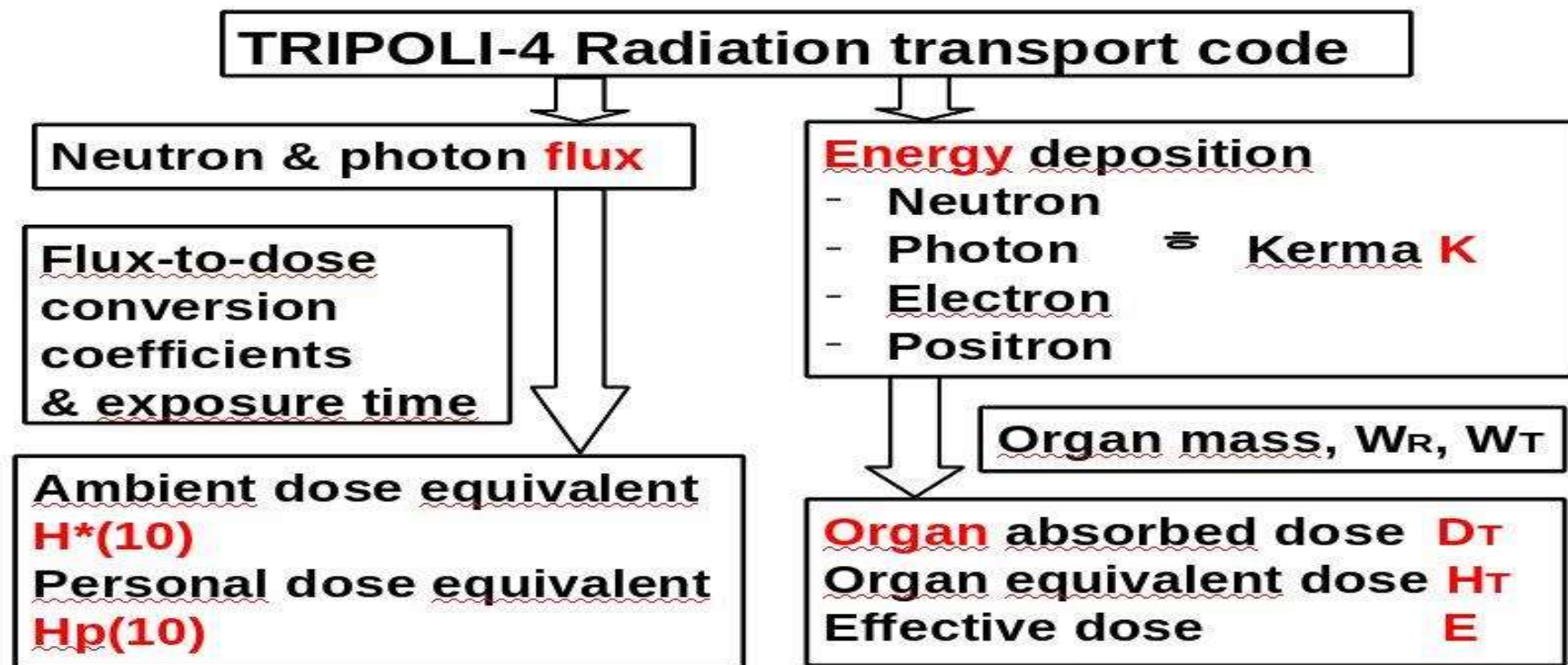
Ref: A. Endo, et al., J. Nucl. Sci. Tech. 40 (2003) 628. A. Endo, Radiat. Measurements **45**, 1484, (2010).
Y.-K. Lee, Talk at SFRP conference 8/3/2023. https://sfrp.asso.fr/wp-content/uploads/2023/03/S9a_LEE_YK_CODES23.pdf

A super-critical and subcritical cycle repeated intermittently over a period of about 20 hours.

- The initial peak of the chain reaction was particularly strong due to the sudden supercritical state and an intense burst of radiation, **neutron** and **gamma**, caused immediate harm to the workers involved.
- Workers A and B received an extremely high dose of radiation within a few seconds. This dose is far beyond the lethal limit for humans.
- The **organs dose** of workers A and B were estimated in this study using the new developed phantom option of TRIPOLI-4 code.



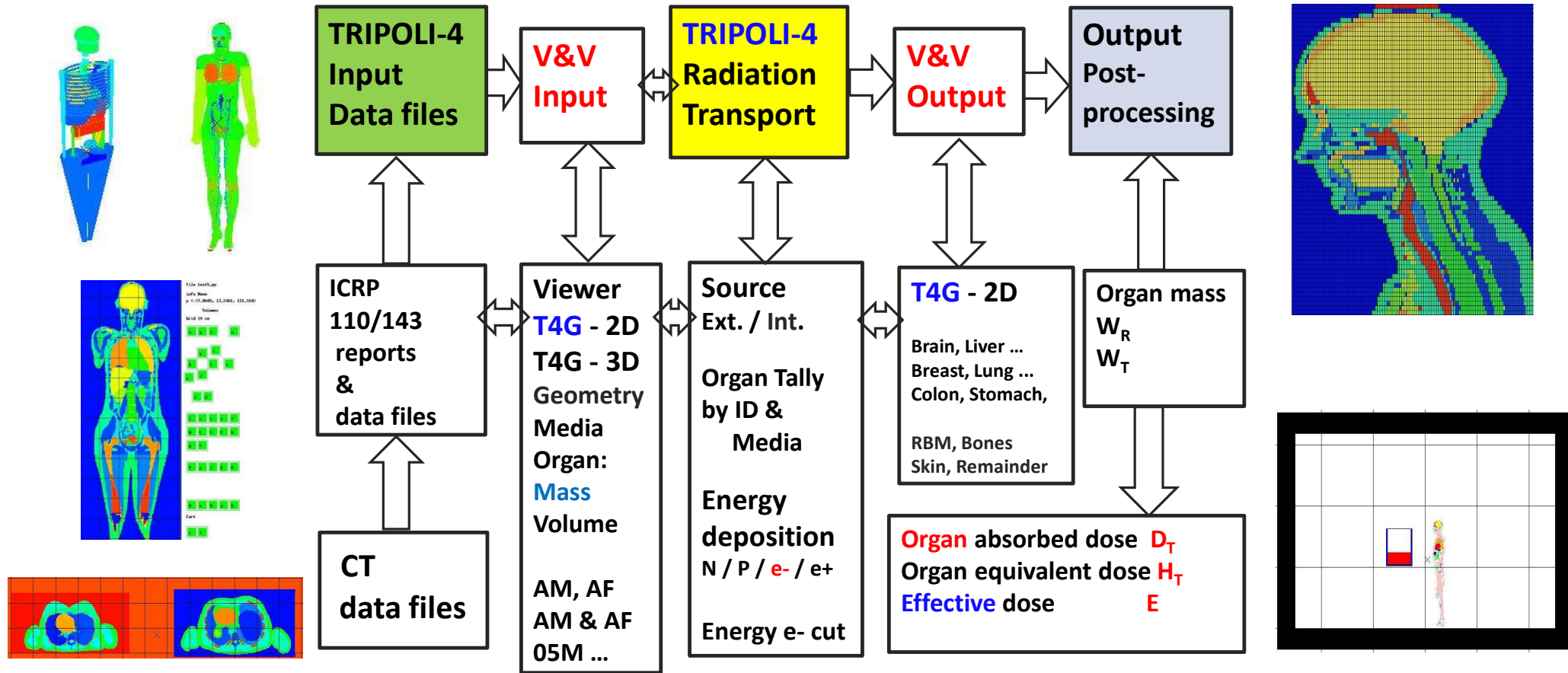
TRIPOLI-4 radiation protection calculations



Ref: Y.-K. Lee and F.-X Hugot, *Nucl. Sci. Eng.*, **198**:2, 274-286, (2024).

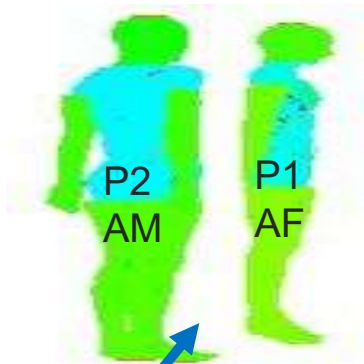
Y.-K. Lee, *ASME J. of Nucl. Eng. and Radiation Science*, **6**(4): 041105, (2020).

TRIPOLI-4 Computational phantoms and organ dose calculations



Ref: Y.-K. Lee et al., Nucl. Sci. Eng. 198(2), 274-286 (2024) & ANS/RPSD 2024

TRIPOLI-4 modeling of EURADOS-RENEB field test

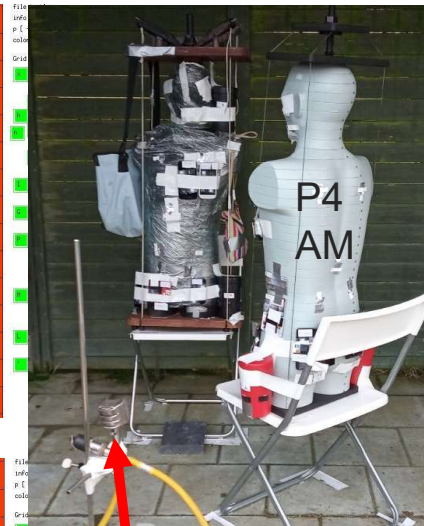
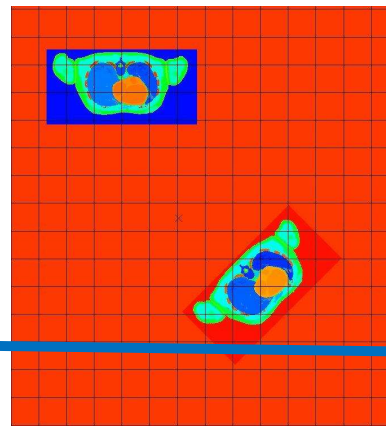
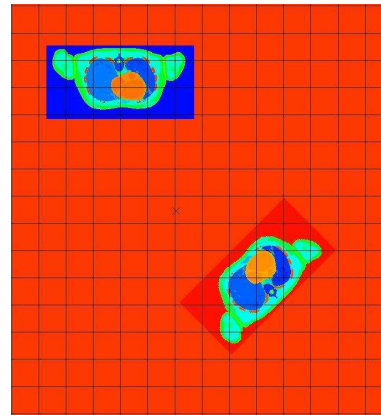


Setup 1 P2 – P1

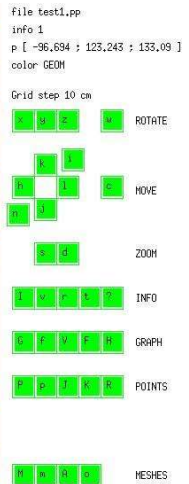
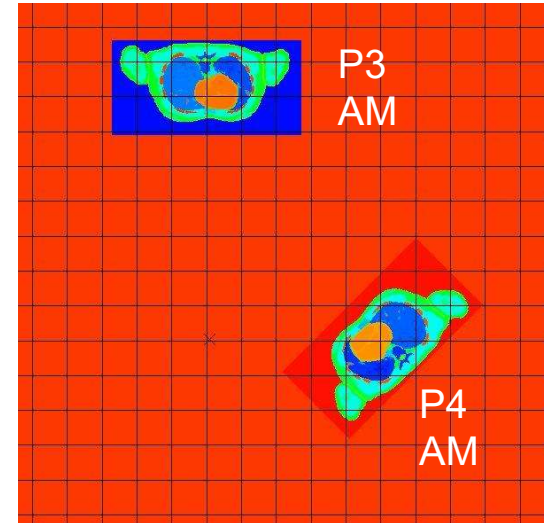
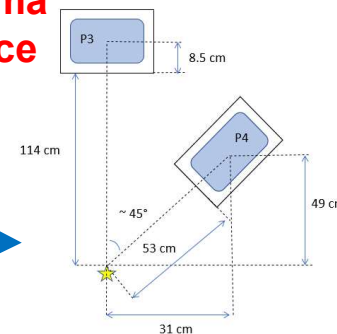
Voxel phantoms
AM-AF

Setup 2 P3 - P4

AM-AM



Gamma
Source



• ICRP 23 & 110 voxel phantoms

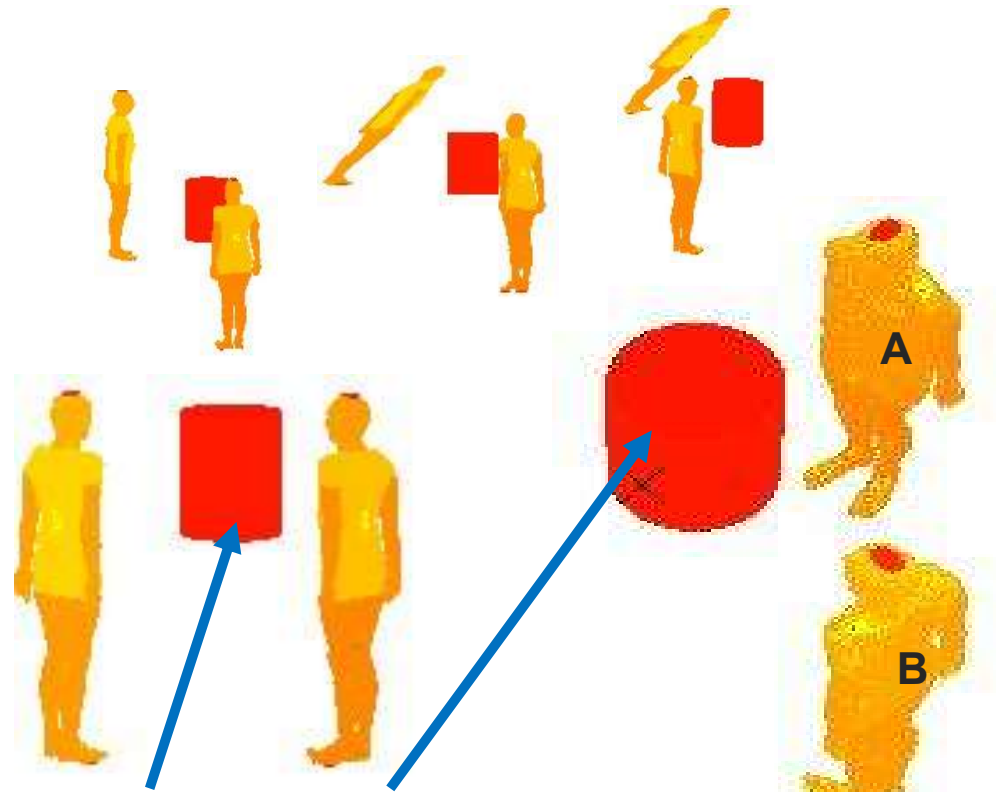
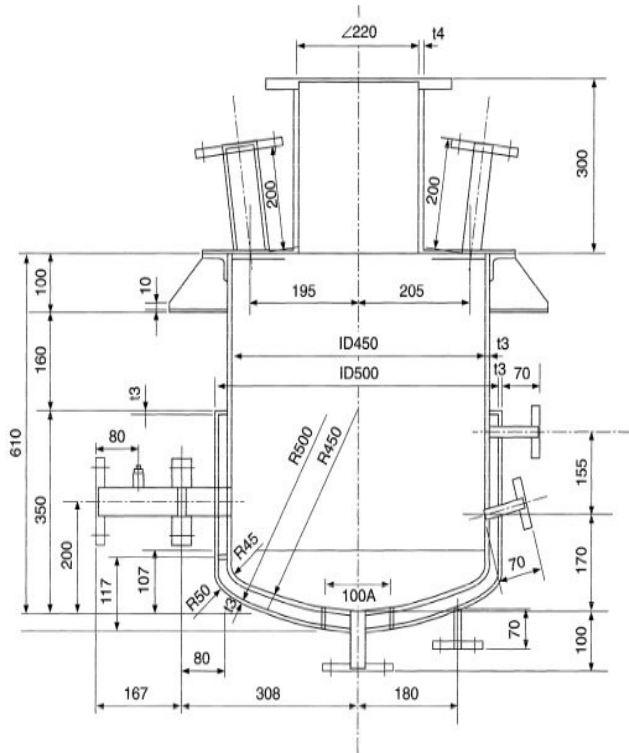
• EURADOS - WG10 field test

AM-AM

• Ref.: L. Waldner, Radiat. Res. 21/12/2020

Ir-192 Retrospective Dosimetry

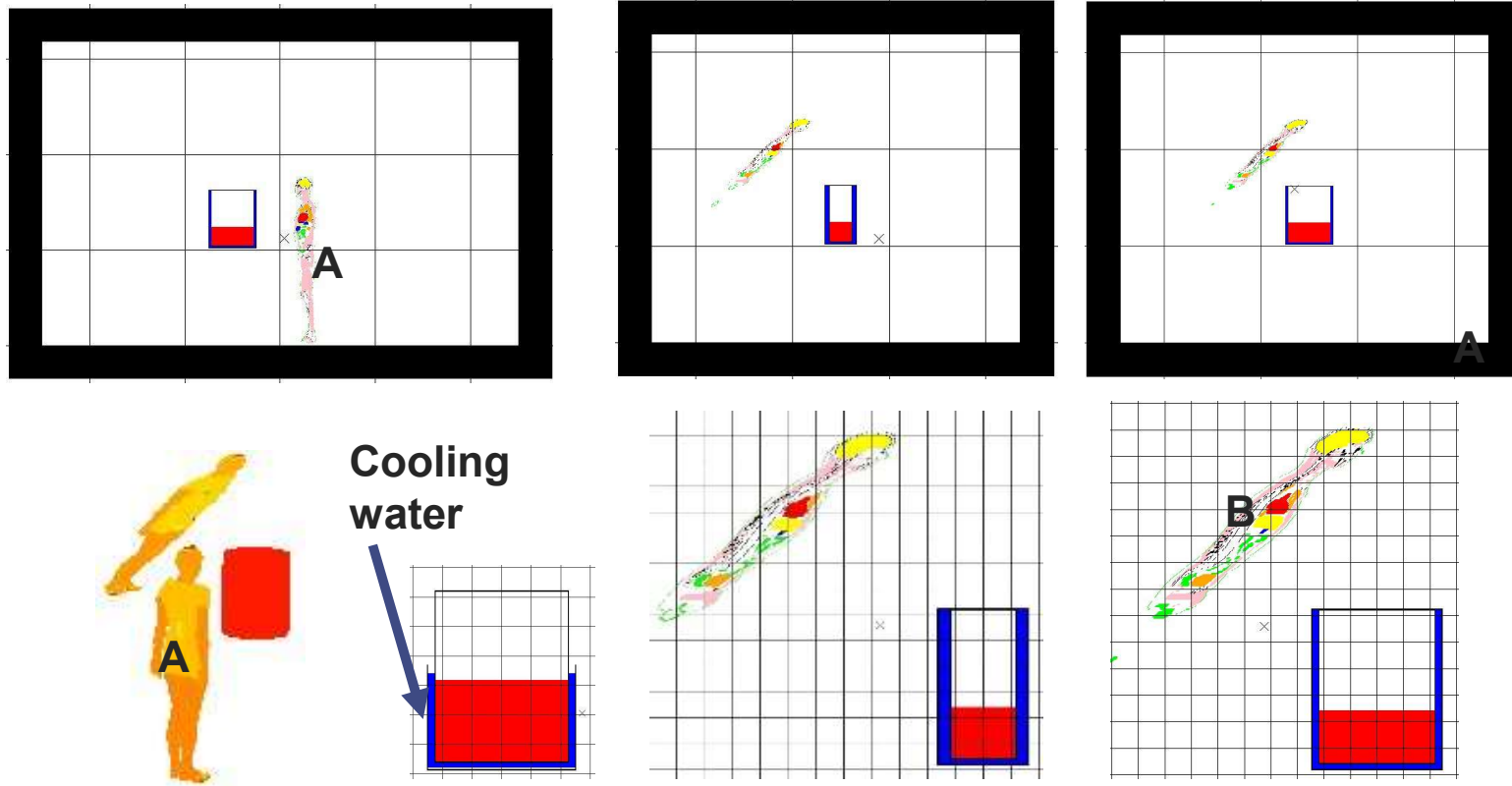
TRIPOLI-4 modeling of Tokai-Mura criticality accident



TRIPOLI-4 modeling of uranyl nitrate in tank + workers A and B

Ref: IAEA mission report, 1999. & LA-13638

TRIPOLI-4 modeling of Tokai-Mura criticality accident



TRIPOLI-4 modeling of fissile solution in tank & workers A and B

Ref: IAEA mission report, 1999. & LA-13638

TRIPOLI-4 modeling of Tokai-Mura criticality accident

Radiation source

■ Initial burst (blue flash reported) →

1.2 E17 fissions
2.- 4.E17 fissions
0.4 - 8.1E17 fissions
2.75 E17 fission ??

(J. A. Vazquez, *Phys. Med. Biol.* 59 (2014) 5277)
(H. Okuno, JAEA-ANSN workshop p.12, Oct. 2013, 10:35-11:00)
(R. A. Knief, Sandia Nat. Lab. 2013)
(A. Endo, JAEA, 2003 & 2010)

TRIPOLI-4 calculations → Criticality mode + Shielding mode

■ $S(r, E, \Omega, t) = C S(r) S(E) S(\Omega) S(t)$

Neutron source → $1.2E17 * 2.43 = 2.92E17 \text{ n}$

Gamma source → $1.2E17 * 8.31 = 9.76E17 \gamma$

$$S(r) = S(R) * S(Z)$$

$S(E)$: U-235 thermal fission for neutron & prompt gamma-rays

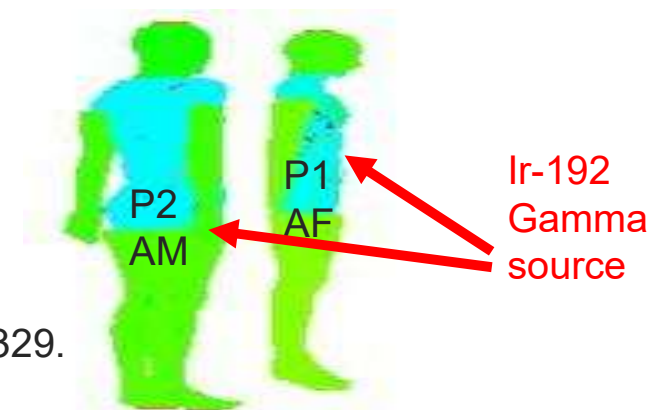
TRIPOLI-4 results of 2020 EURADOS-RENEB field test

Organ dose (mGy)* for Adult female P1				Organ dose Ratio	
Target organ	TRIPOLI-4	MCNP6 [12]	Measurement [11]	T4/M6	T4/M
Thyroid	276	260	242	1.06	1.14
Small intestine wall	1030	990	933	1.04	1.10
Ovaries	938	930	935	1.01	1.00

* One standard deviation: < 2 %

Ref. 11 L. Waldner et al., "Radiat. Res.", **195**, 253-264, (2021).

12 H. Kim et al., Radiation Measurements, Vol. **180**, Jan. 2025, 107329.



TRIPOLI-4 results of 2020 EURADOS RENEb field test



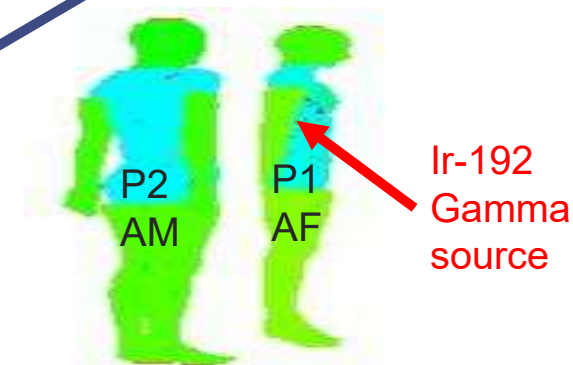
Organ dose (mGy)* for Adult male P2				Organ dose Ratio	
Target organ	TRIPOLI-4	MCNP6 [12]	Measurement [11]	M6/M **	T4/M **
Thyroid	164	114	187	0.61	0.88
Small intestine wall	126	98	187	0.52	0.67
Liver	206	168	282	0.60	0.73
Testes	127	113	153	0.74	0.83

* One standard deviation: < 2 %

** The arms of P1 and P2 voxel phantoms play a shielding role.

Ref. 11 L. Waldner et al., *Radiat. Res.*, **195**, 253-264, (2021).

12 H. Kim et al., *Radiation Measurements*, Vol. **180**, Jan. 2025, 107329.



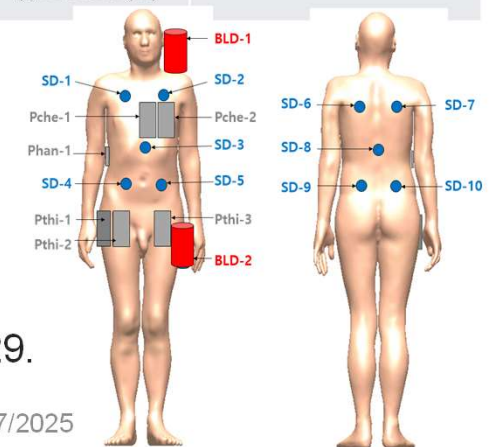
TRIPOLI-4 results of 2020 EURADOS RENEb field test



Screen glass dose (mGy)* for smartphones on P3				Smartphone dose Ratio	
Smartphone Institute name (position)	TRIPOLI-4	MCNP6 [12]	Measurement [12]	T4/M6	T4/M **
IRSN-1 (Bet. Breast)	356	347	340	1.03	1.05
DURHAM-1 (Left waist)	407	387	400	1.05	1.02
OSU-2 (Right waist)	348	348	340	1.00	1.02

(c) Phantom 3 (P3)

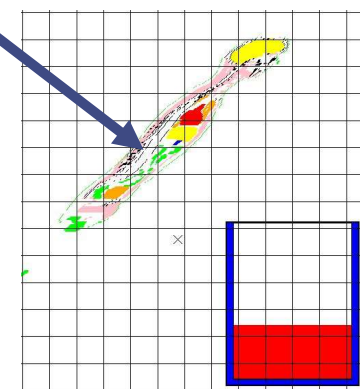
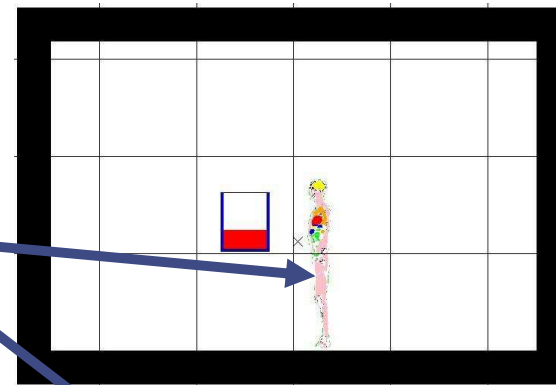
* One standard deviation: < 3 %



Ref. 12 H. Kim et al., Radiation Measurements, Vol. **180**, Jan. 2025, 107329.

TRIPOLI-4 estimated **small intestine wall** dose** for workers A and B of *Tokai-Mura criticality accident*

SI wall - Organ dose (Gy)*		
Radiation source (Initial burst) §	Worker A	Worker B
Neutron	10.9	11.4
Gamma rays (prompt γ)	27.6 (17.3)	18.0
Total	38.5	29.4



* One standard deviation: < 4 %

§ Initial burst (blue flash): $1.2 \text{ E}17$ fissions [17]

** **Gastrointestinal bleeding** was considered to be a major contribution to the death of workers [14].

Ref. J. A. Vazquez et al., Phys. Med. Biol. **59**, 5277 (2014).

https://sfrp.asso.fr/wp-content/uploads/2023/03/S9a_LEE_YK_CODES23.pdf

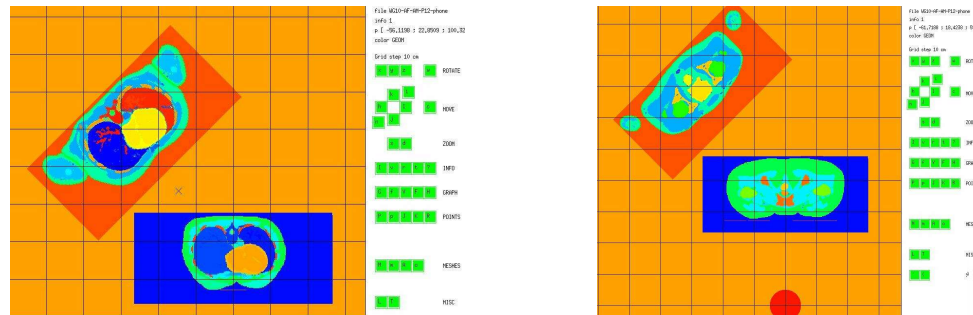


Conclusion

- The **voxel phantom option of TRIPOLI-4® Monte Carlo code for organ dose calculations** was successfully benchmarked against the recent **EURADOS-RENEB** retrospective dosimetry experiments.
- The arms of calculation phantoms play a radiation shielding role for **dosimeters and smartphones responses**. Modeling phantoms without arms will be examined.
- For workers organ doses of Tokai-Mura criticality accident, the radiation dose assessment is still under investigation.
- The **source term of criticality accident initial burst** may be the key factor of calculated dose uncertainty.

Conclusion-2

- The arms of calculation phantoms play a radiation shielding role for dosimeters and smartphones responses. Modeling phantoms without arms will be examined.



- For workers organ doses of Tokai-Mura criticality accident, assessment of bone activation is under investigation.

Ref. K. Miyamoto et al., Health Physics, 83 (2002) 19
T. Rancien., M2 INSTN, Oct. 2024.

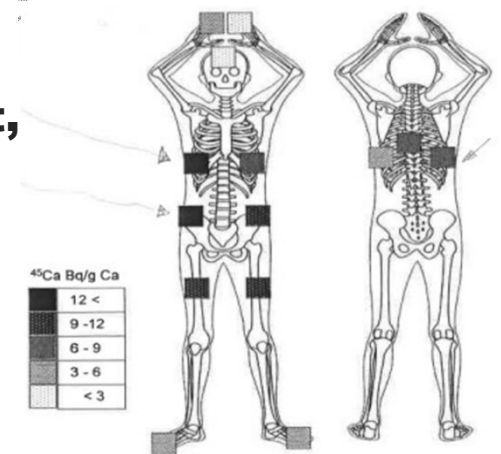
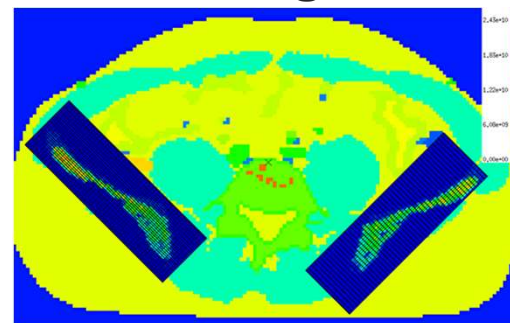
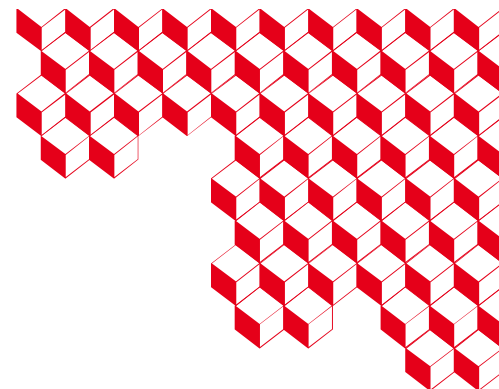


Fig. 4. Illustration of Case 1's orientation assumed at the moment of the burst. Cubes show ^{45}Ca activity level of the spots from which bones were taken.



Thank you for your attention

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