Dosimetry aspects and lessons for the ICRP System of radiological protection: from the Chornobyl and Fukushima Daiichi NPP accidents to nuclear terrorism

ICRP online event on lessons from the Chornobyl and Fukushima Daiichi NPP accidents

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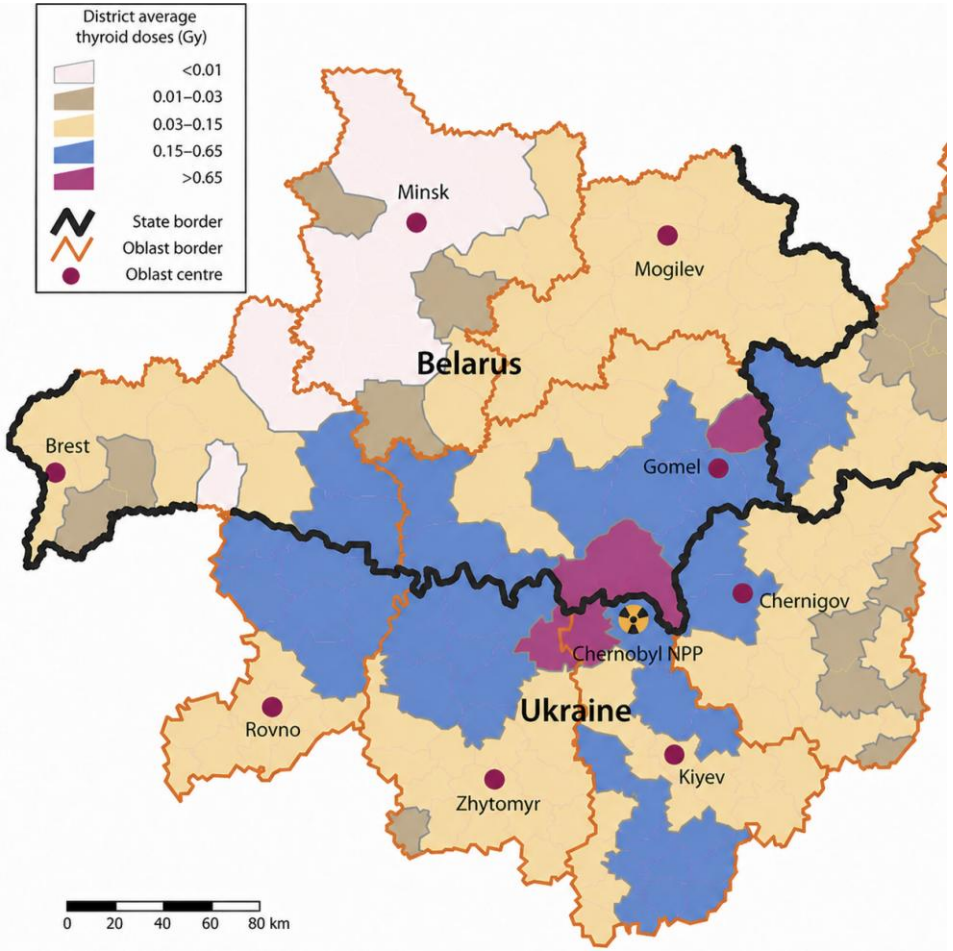
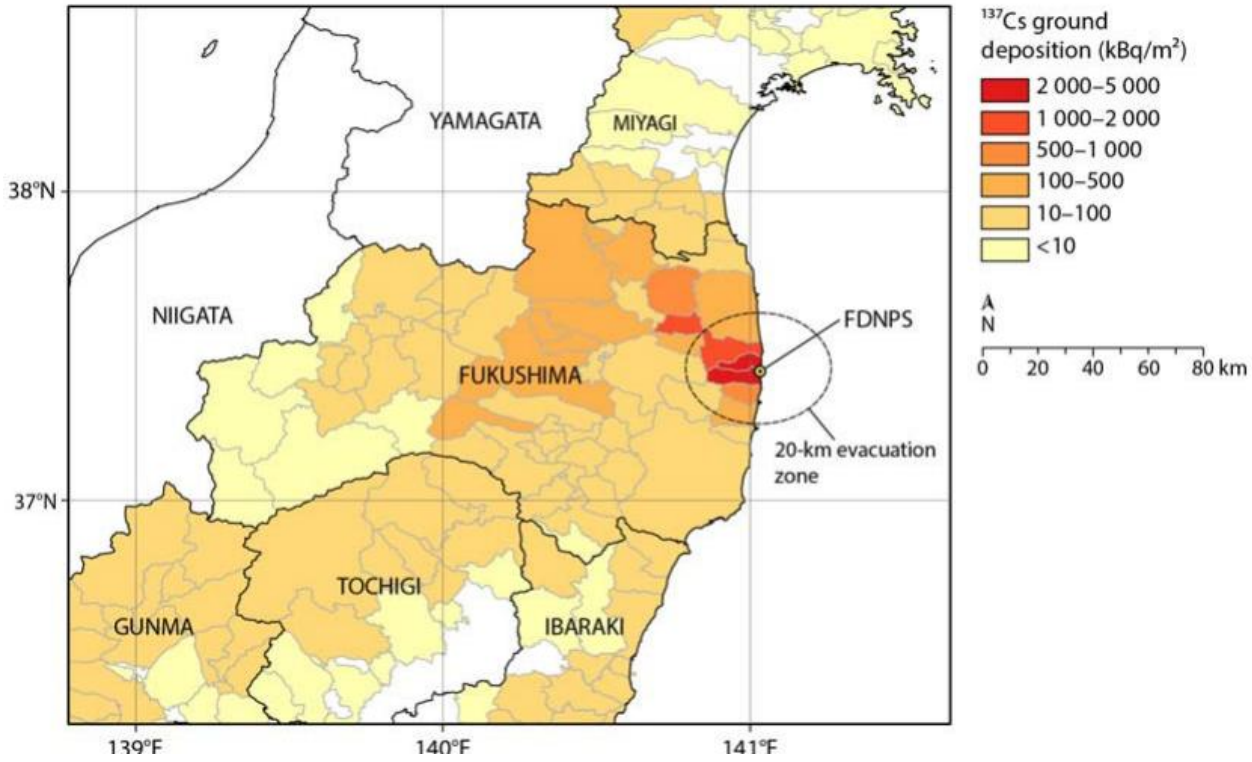
Two accidents, two distinct dosimetric signatures



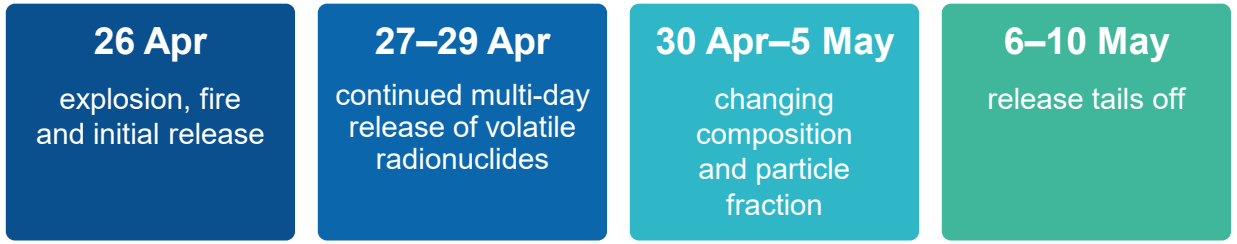
Chornobyl NPP accident: **high thyroid doses** in children and adolescents where **^{131}I entered the diet**, especially through fresh milk. *UNSCEAR 2008 Annex D*



Fukushima-Daiichi NPS accident: lower deposition density than in the Chornobyl NPP accident; in most locations, the dose to members of the public was dominated by **external exposure to deposited radiocaesium**. *UNSCEAR 2013*

Chornobyl NPP accident: source term, release timing and dominant radionuclides

- **The release continued for about ten days after the explosion and the graphite fire.**
- **On the first day, noble gases, particularly Xe-133, accounted for most of the activity. Volatile iodine and tellurium radionuclides were the main contributors to the released activity, apart from noble gases.**
- **The early external gamma dose rate was dominated by short-lived gamma emitters, especially Te-132/I-132, I-131, Ba-140/La-140, and, in the vicinity of the reactor, refractory/fuel-particle radionuclides such as Zr-95/Nb-95, Ru-103/Ru-106, Ce isotopes, and Np-239. Noble gases had little lasting dosimetric significance.**
- **The intake of radioiodines determined the thyroid dose. Human monitoring was therefore essential, with over 350,000 thyroid measurements conducted by June 1986.**
- **The long-term internal dose was dominated by Cs-134 and Cs-137.**



Fukushima-Daiichi NPS accident: source term, release timing and deposition density pattern

- **Multiple releases from 3 units occurred over several days after the tsunami and station blackout.**
- **The public dose-relevant source term was dominated by volatile radionuclides, mainly I-131, Cs-134 and Cs-137.**
- **As at Chornobyl, noble gases dominated the total activity released but had little lasting dosimetric relevance.**
- **Land deposition was lower than after Chornobyl, with much of the release dispersing over the ocean.**
- **Because evacuation and food/water controls limited early intake pathways, doses to members of the public, especially outside the evacuated areas and in the longer term, were dominated by external exposure to deposited Cs-134 and Cs-137.**

12–15 Mar	15–16 Mar	17–22 Mar	afterward
multi-reactor release episode	wet deposition shapes hotspots	continued intermittent release	expanded monitoring

UNSCEAR: doses to emergency/recovery workers
Accidents at Chornobyl and Fukushima Daiichi NPPs

		Chernobyl Nuclear Power Station (Unit 4)	*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*
Number of emergency and recovery workers		Emergency workers: ≈ 600 Recovery workers: ≈530 000	About 21 000 in the first year and varying within a range of ≈14 000 to 21 000 in each subsequent year
Workers with acute radiation syndrome	Number diagnosed	134	None
	Doses	Bone marrow doses ranged from 0.8 to 16 Gy Skin doses 10 to 30 times greater	
Other emergency and recovery workers	Effective dose	Average individual dose: ≈120 mSv	Average annual dose: 13 mSv in first year (declining in subsequent years within a range from ≈6 to ≈2 mSv in the year ending 31 March 2020) Maximum annual dose: 680 mSv in first year (declining in subsequent years within a range from ≈50 to ≈20 mSv in the year ending 31 March 2020) 168 and 6 workers, respectively with doses >100 mSv and 250 mSv in first year
	Thyroid dose		Maximum absorbed dose in first year ~ 32 Gy About 180 workers with thyroid equivalent dose >100 mSv
	Collective effective dose	61 000 man Sv[j]	≈860 man Sv[k] up to March 2020

[j] For the period 1986 to 2005.

[k] On-site workers at FDNPS;

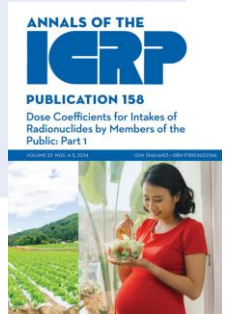
UNSCEAR: public exposure
Accidents at Chornobyl and Fukushima Daiichi NPPs

	Chernobyl Nuclear Power Station (Unit 4)					*Fukushima Daiichi Nuclear Power Station (Units 1, 2 and 3)*				
Measurements of radioiodine in thyroid	400 000[l]					1 200				
Average individual doses to residents in different regions, municipalities or prefectures	*Group*	*Time period*	*Number (thousands)*	*Thyroid dose[m] (mGy)*	*Effective dose[m,n] (mSv)*	*Group (adults)*	*Time period*	*Number (thousands)*	*Thyroid dose[m] (mGy)*	*Effective dose[m] (mSv)*
	Evacuees	First year	115	≈500	≈50	Evacuees	First year	118	≈0.8–15	≈0.05–6
	"Contaminated areas"[o] in Belarus, Russian Federation[p] and Ukraine	First year for thyroid dose	6 400	≈100	≈13	Municipalities in Fukushima Prefecture	First year for thyroid dose	1 900	≈0.5–10	≈0.2–10
	Belarus, Russian Federation[p] and Ukraine	1986-2005 for effective dose	98 000	≈20	≈2	Municipalities in neighbouring prefectures	First ten years for effective dose	17 000	≈0.3–3	≈0.3–3
	Rest of Europe		500 000	≈1	≈0.4	Prefectures in rest of Japan		110 000	≈0.03–0.5	≈0.009–1
Ranges of individual doses	Absorbed doses to the thyroids of evacuees ranged from <50 mGy to >5 Gy, with several hundred evacuees receiving doses in excess of 5 Gy Absorbed doses to the rest of the population of Belarus, Russian Federation and Ukraine (98 million) varied over a wide range, with most receiving thyroid doses <50 mGy and about 1% doses >200 mGy					Absorbed doses to the thyroids of evacuees varied over a wide range (5th to 95th percentile) from less than about 1 mGy to about 15 mGy Absorbed doses to the thyroids of non-evacuees range up to about 15 mGy (95th percentile) with about 1% >20 mGy				

ICRP dosimetry system for general public

- **Chornobyl showed that age matters in emergency dosimetry: members of the general public, especially children, can receive organ doses that differ markedly from those of adults.**
- **By 1986, the ICRP had emergency criteria for the protection of the general public, but not dedicated child-specific criteria, nor an age-dependent dosimetry system.**
- **For stable iodine, ICRP Publication 40 (1984) stated that there is "***no need to consider selecting special groups … e.g. pregnant women, the neonate or young infants for treatment different from adults***", while it also asked authorities to give special consideration to *in utero* effects.**
- **In 1986, the ICRP dosimetry system was largely based on adult worker models, which posed a significant issue for dosimetric support of protective actions for the general public.**
- **The experience of the Chornobyl accident stimulates the revision of the protection system and the development of the ICRP age-dependent dosimetry system for the general public.**
- **Dosimetry for children is now based on age-specific anatomy, physiology, and computational phantoms that support both internal and external dose assessments.**

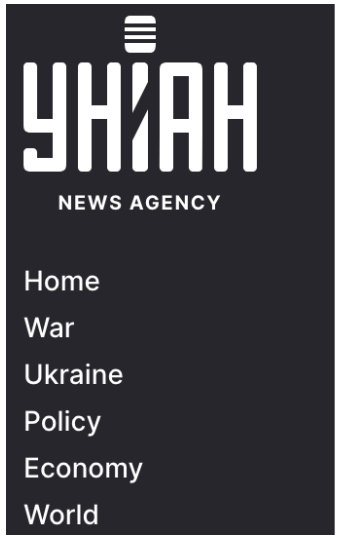
1989–96	56 series (56, 67, 69, 71, 72): first ICRP age-dependent series for intake of radionuclides
2002	89: reference anatomy & physiology
2006–12	100/103/119: revised alimentary tract models, new weighting factors and sex averaging for effective dose, interim compendium in 119
2020	143 + 144: voxel phantoms and first age-dependent external environmental dose coefficients
2024	156: mesh paediatric phantoms for next-generation calculations
2025–27	158: **PIR (Public Intakes of Radionuclides) series** new age-dependent series, Part 1 (2025), replacing the 56 series.



Emergency dosimetry for *in utero* exposure

- **After Chornobyl, evidence suggests a significant fear-driven rise in medically induced abortions.**
- **The lack of reliable dose estimates, clear messages from scientists and misconceptions of physicians led to the mother's unjustified fears and to the termination of pregnancies.**
- **Greece had an estimated abortion of 23% of fetuses in early gestation in May 1986, and Italy had an estimated 28 to 52 unnecessary abortions per day for five months after the accident. Quantitative data for the former USSR are not available.**
- **Tissue absorbed doses to *in utero*-exposed individuals should be explicitly assessed, rather than inferred solely from adult doses.**

Misconceptions still circulate, even among medical professionals and scientists



In Ukraine, radionuclides (atoms with unstable nuclei that spontaneously decay, releasing ionizing radiation) are still being found in the placentas of pregnant women. This negatively affects pregnancy and the health of children.

This was stated by Yuriy Antipkin, General Director of the State Institution "All-Ukrainian Center for Motherhood and Childhood of the National Academy of Medical Sciences of Ukraine", Doctor of Medical Sciences, Professor, Academician of the National Academy of Medical Sciences of Ukraine, during the press conference "40 Years of the Chernobyl Disaster: Consequences, Challenges, Threats".

"We have been monitoring these studies for 40 years. At the beginning of this year, we also noted the accumulation of radionuclides in the placenta. These are primarily strontium and cesium 137. We have proven that if approximately 10 becquerels per kilogram of mass are found in the placenta, then this is a risk of miscarriage and changes in the health of the child who is born. And at the beginning of this year, we noted 19 becquerels per kilogram of mass," said Antipkin.

He also added that children born to liquidators of the Chernobyl disaster have an inherited mutation.

ICRP on *in utero* exposure in emergencies

- Publication 88 provides dosimetric models and dose coefficients for assessing in utero exposure.
- The forthcoming dosimetry-related ICRP publications will update and expand the currently available material.
- Publication 103 establishes the framework and explicitly includes protection for embryos and foetuses.
- Publication 96 provides recommendations for operational protection for potentially pregnant responders.
- Publications 109 and 146 identify pregnant women as a priority subgroup in emergency response, particularly for radioiodine avoidance and early monitoring.
- Publication 111 addresses pregnant women in the recovery/long-term contaminated-area phase through optimisation, surveillance, and food-consumption advice.
- The TG84 Fukushima lessons report explicitly identifies the remaining gap for pregnant women following an emergency.
- For medical exposure, ICRP has dose benchmarks: termination of pregnancy is not justified on radiation-risk grounds below 100 mGy total foetal dose; above 100 mGy, the decision should be individualised, with consideration of the dose threshold for severe mental retardation, which is at least 300 mGy received during the most sensitive period. The most sensitive are 8 to 15 weeks post-conception, and 16–25 weeks are associated with the lower sensitivity of the central nervous system.

- **For emergencies, more direct and specialised ICRP recommendations on protection strategies and dosimetric criteria are highly advisable. ICRP TG120 is working on these issues.**

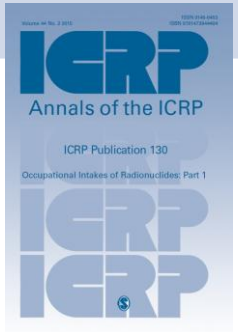
Exposure from breast milk

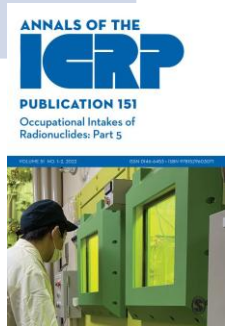
- After the Chornobyl accident, fear and concern about breast milk were evident. Several monitoring programmes were conducted, but due to a lack of reliable dose-estimation models, dose estimates were unavailable, and risks were not properly communicated to mothers, physicians, and decision-makers.
- After the Fukushima Daiichi accident, fear of breast milk contamination led to avoidable breastfeeding interruptions and prompted consultations.
- The ICRP addressed this dosimetric issue in ICRP Publication 95 (2004), which provides transfer models and infant dose coefficients for radionuclides ingested via mothers' milk. The forthcoming dosimetry-related ICRP publications will update and expand the available materials.
- In emergency/recovery publications (96, 109, 111 and 146), ICRP treated women primarily as a group for protective actions and dietary advice, rather than as a distinct population group in emergency management.
- More direct, specialised recommendations and quantitative criteria from the ICRP are highly advisable.
- **ICRP TG120 is working on these issues. Future ICRP updates aim to enhance guidance by recognising breastfeeding women as a group who require tailored protective actions and dietary advice.**

Development of the ICRP dosimetric system for workers

- **ICRP moved from mostly non-recycling biokinetic models, simplified dosimetry, and ALI/DAC to a layered reference-worker system. The modern system includes:**
  - revised protection quantities and dose limits
  - recycling and physiologically realistic biokinetic modes
  - independent biokinetics of progeny radionuclides
  - bioassay-centred monitoring guidance
  - voxel and mesh adult phantoms
  - improved energy transport calculations
- **OIR publications with digital datasets and a data viewer**
- **Emergency dosimetry datasets are under development**

1979–82	30 series: adult worker, ALI / DAC system + radionuclide dosimetric data
1989	54: worker's bioassay monitoring, estimation of intake by interpretation of bioassay monitoring data
1991–97	60 / 68 / 74 / 78: revised dose limits, worker coefficients, external-operational link, updated bioassay guidance
2009–12	110 / 116 / 119: adult voxel phantoms, external coefficients, interim compendium
2015–22	130→151: **Occupational Intakes of Radionuclides** (**OIR) series** replaces 30/54/68/78, introduction of "dose per content" concept (Berkovski et al., 2003) and supporting ICRP electronic datasets





ICRP Dose Assessment Resources

The International Commission on Radiological Protection (ICRP) has developed Dose Viewer applications and released datasets for dose assessments that are free to use.

ICRP Dose Viewer Mobile App

Available for Apple and Android devices

This viewer is a user-friendly, educative, and non-commercial mobile app to enable users to easily access the ICRP dose coefficients for intake of radionuclides for occupationally exposed individuals, members of the public, and for patients in diagnostic nuclear medicine.

Datasets for Assessment of Internal Occupational Exposure

Available for Windows and compatibility layers for MacOS and Linux

These Electronic Annex and Data Viewer accompany the ICRP Occupational Intake of Radionuclides (OIR) publication series. The Electronic Annex can be run directly from the unzipped folder and does not require installation.

Datasets accompany the following publications:
ICRP Publication 130 Occupational Intakes of Radionuclides: Part 1
ICRP Publication 134 Occupational Intakes of Radionuclides: Part 2
ICRP Publication 137 Occupational Intakes of Radionuclides: Part 3
ICRP Publication 141 Occupational Intakes of Radionuclides: Part 4
ICRP Publication 151 Occupational Intakes of Radionuclides: Part 5

Datasets for Assessment of Internal Exposure of Members of the Public

Available for Windows and compatibility layers for MacOS and Linux

These Electronic Annex and Data Viewer accompany the ICRP intake of radionuclides by members of the public (PIR) publication series. The datasets for the forthcoming second part of the series have been released in advance of publication. The Electronic Annex can be run directly from the unzipped folder and does not require installation.

Datasets accompany the following publications:
ICRP Publication 158 Dose Coefficients for Intakes of Radionuclides by Members of the Public: Part 1
ICRP Publication Dose Coefficients for Intakes of Radionuclides by Members of the Public: Part 2 (in press)

Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures

Available for Windows

The viewer is an excel-based window software which allows comfortable access in tabular and graphical form to the reference adult male and female organ absorbed and effective dose coefficients for broad unidirectional external beams, assumed to represent occupational exposures.

Datasets accompany the following publication:
ICRP Publication 116 Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures

EDC Viewer

Dose Coefficients for External Environmental Sources

Desktop App

Available for Windows

This viewer includes data for age-dependent reference dose-rate coefficients of effective dose and organ equivalent doses for the three environmental exposures simulated: soil contamination, submersion in contaminated air, and immersion in contaminated water. Download includes a Windows installable.

Datasets accompany the following publication:
ICRP Publication 144 Dose Coefficients for External Exposures to Environmental Sources

ICRP

Recommended improvement to the ICRP system: Shift focus from the effective dose to organ/tissue absorbed doses as the key quantity in emergencies

- Protective actions are organ- and radionuclide-specific. Preventing tissue reactions and loss of life is an absolute priority. Management of stochastic effects in emergencies is also organ- and radionuclide-specific.
- Decisions on most protective actions, such as thyroid blockade, protection of in utero-exposed individuals, and initial triage and medical management of radiation casualties, require estimates of tissue absorbed doses during both the preparedness and response phases.
- Effective dose can seriously mask non-uniform exposure. An adult woman who inhaled ^{131}I and received an effective dose of 100 mSv will have an absorbed dose of about 2.8 Gy in the thyroid.
- Harmful tissue reactions cannot be adequately quantified using an effective dose designed for stochastic effects.
- **ICRP TG112 is developing datasets and tools for emergency dosimetry, including the coefficients "tissue absorbed doses per measured bioassay quantity" for children.**

Committed effective dose in emergency management

- **The committed effective dose is particularly misleading in assessments of acute clinical effects following intakes of long-lived radionuclides with substantial biological half-lives, as it is integrated over 50 years for adults and to age 70 for children.**

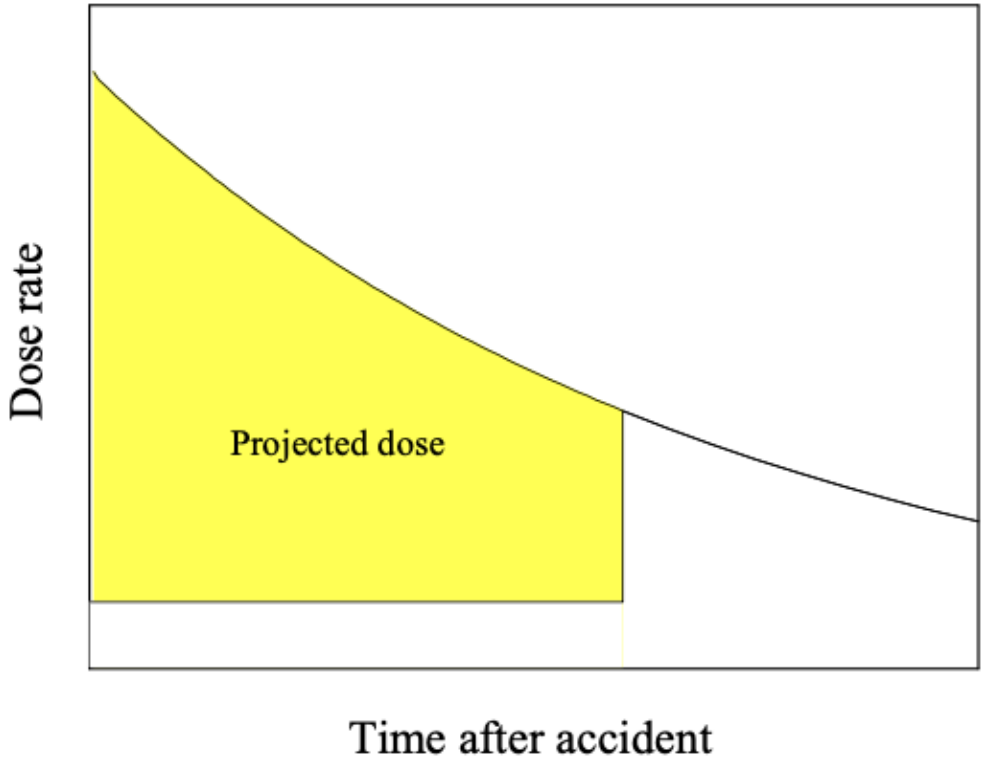
- **For ^{239}Pu, less than 1% of the tissue doses is delivered within the first 30 days.**

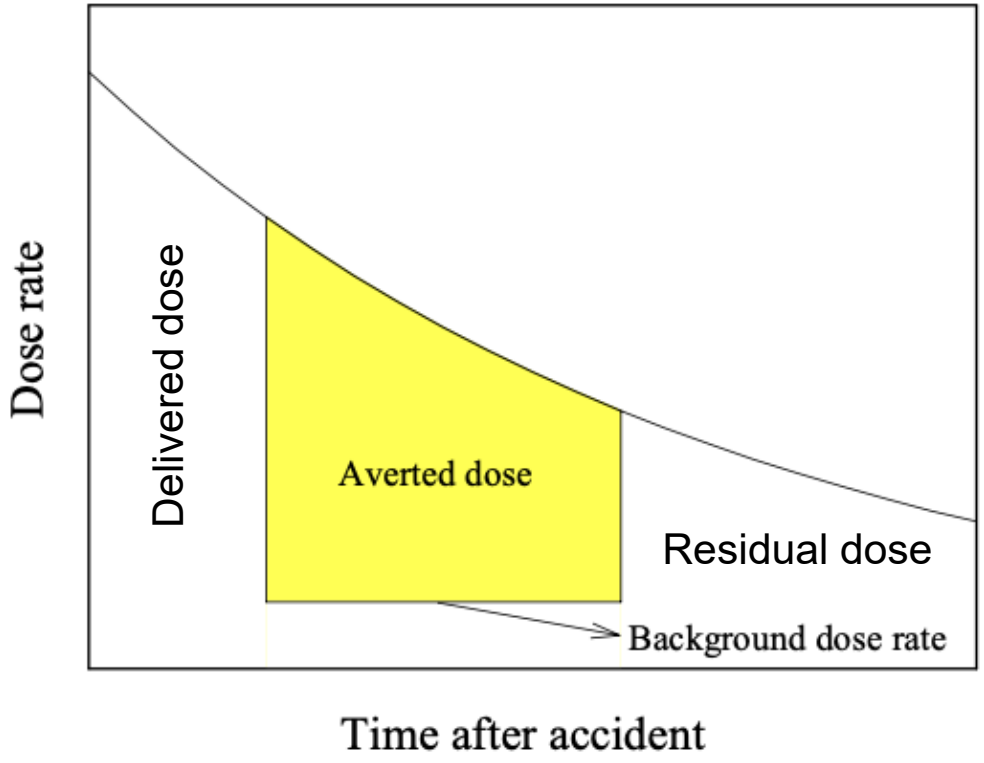
- **Distinctive dosimetric signatures of the Chornobyl and Fukushima Daiichi accidents are clearly visible when considered in terms of tissue absorbed doses.**
- **Hiding them behind a single effective-dose quantity severely weakens decision-making.**

Recommended clarification in the ICRP system: focus on the most exposed individuals and dose distribution, rather than on a representative person

- The ICRP 101 “representative person” construct is a prospective assessment and compliance tool, not an emergency triage/protection quantity. In prospective probabilistic assessments, it is defined so that the probability is less than about 5% that a person drawn at random from the population will receive a greater dose.
- In assessments and in establishing decision-making criteria for emergency management, this is a serious weakness: a number of vulnerable individuals, such as children and those exposed in utero, may be “outliers”. Moreover, their exposure can exceed not only reference levels but also the thresholds for tissue reactions.
- The Chornobyl accident resulted in thyroid absorbed doses among evacuees spanning two orders of magnitude, with several hundred children receiving thyroid doses exceeding 5 Gy.
- A single dose to a representative person could have masked the scale of thyroid exposure in a large cohort of the most affected individuals.
- ICRP 111, therefore, states that protection should prioritise those with the highest exposures and that the dose distribution should be assessed.
- **The new ICRP recommendations should reinforce and highlight this approach to dosimetric criteria and dose assessments for emergency management.**

Projected, averted, delivered and residual doses





- ***Projected dose.*** A prospective estimate of the dose expected to be received by individuals over the specified period in the absence of protective actions (such as evacuation, sheltering, thyroid blocking, decontamination, medical interventions, and decorporation of radionuclides from the body).
- ***Delivered dose.*** The dose received by the time protective actions are initiated.
- ***Averted dose.*** The dose that can be avoided or has been avoided due to protective actions.
- **Residual dose.** The “tail” dose after protective measures have been implemented, or after a decision not to implement them.

Dose quantities and datasets for emergency management

- The projected dose is the primary prospective quantity for preparedness and response.
- The averted dose informs the justification and optimisation process. It quantifies the effectiveness of protective actions or decisions in the medical management of casualties with internal contamination.
- The delivered (received) dose supports adjustments to protective actions, triage, medical management, and counselling of casualties.
- The Residual dose is the dose expected after protective measures have been implemented, or after deciding not to implement them.
- **To improve the ICRP system, each ICRP emergency management dosimetric criterion and its associated dose estimates should be clearly specified in terms of one of the quantities listed above.**
- **TG112 will provide data and tools for estimating projected, delivered, averted, and residual tissue absorbed doses integrated over a user-specified period.**

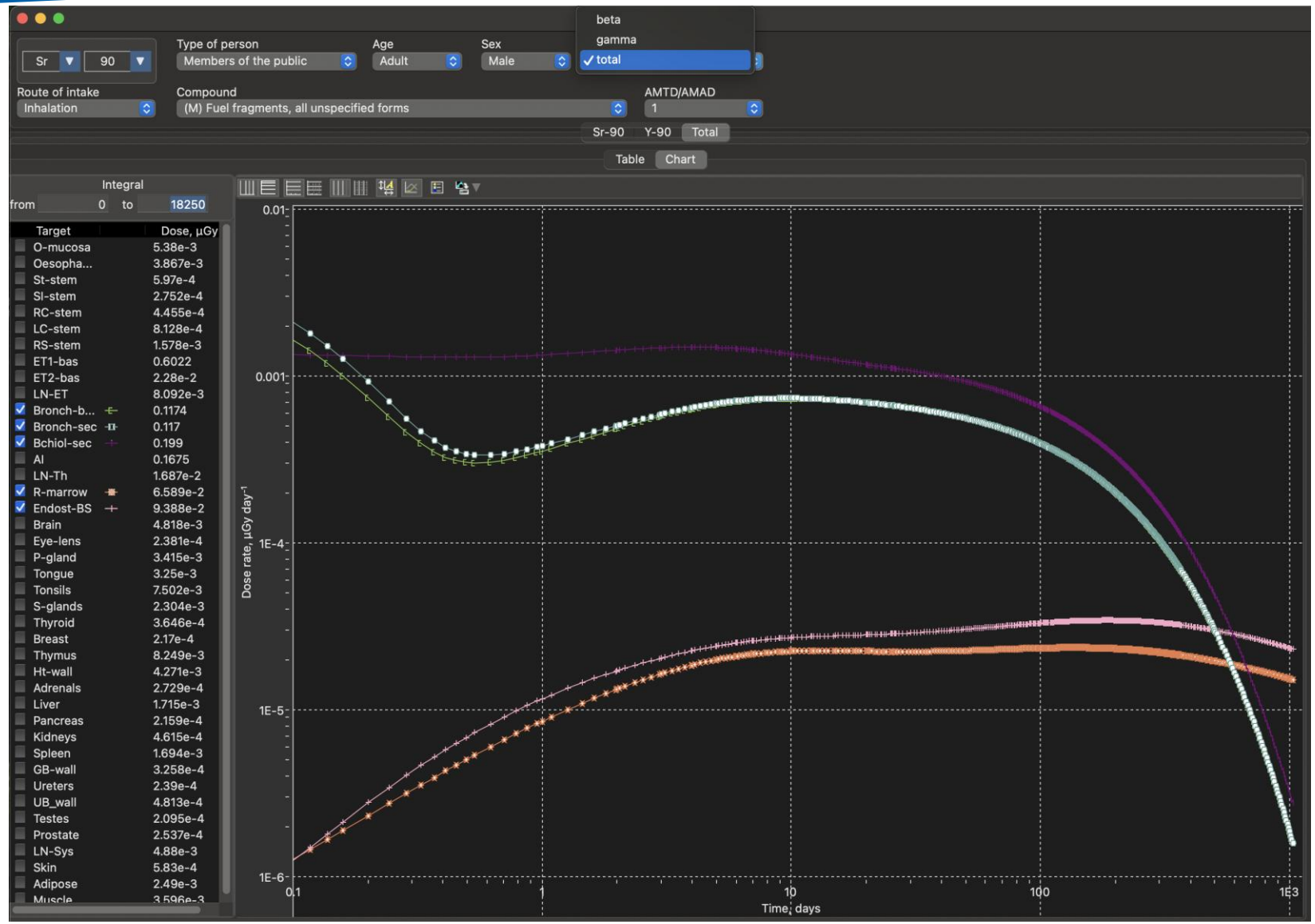
ICRP TG112 mandate, datasets and tools

- The goal of the TG112 is to **develop dosimetric datasets and tools** for radiological assessments in emergencies
- New datasets **consider harmful tissue reactions, stochastic effects,** and situation-specific conditions. They complement and expand the current ICRP reference datasets
- **New datasets and tools consider members of the public, first responders, and workers, and include:**
  - Radionuclide-specific tissue absorbed dose and dose rate coefficients for both internal and external exposures
  - Tissue absorbed doses per inhalation exposure and per measured bioassay quantity (“doses per content”)
  - Software that facilitates the use of extensive datasets and enables situation-specific assessments.

Datasets and tools for internal exposure

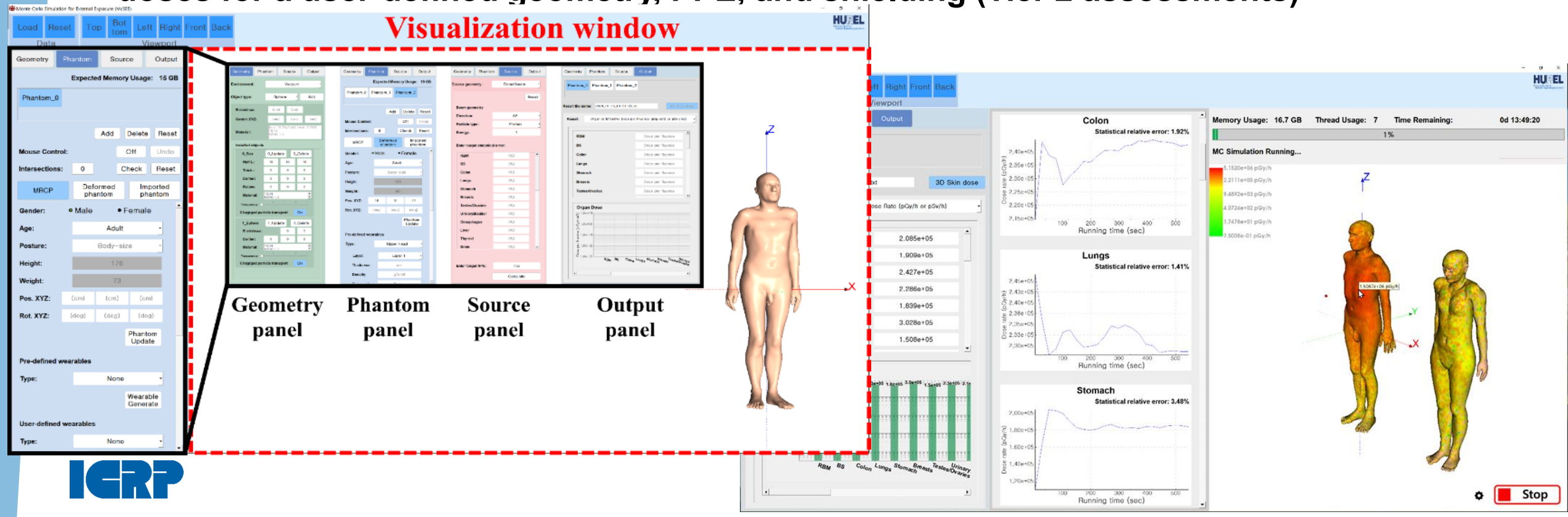
TG112 Dosimetric Datasets and Software for assessment of tissue absorbed dose and dose rates

- **Supports the development of radiological criteria for protective actions, assists in decision-making on protective actions and medical treatment**
- **Provides tissue absorbed doses and dose rates with:**
  - Integration over an arbitrary period (incl. projected and delivered doses)
  - Breakdown by members of the decay chain
  - Breakdown by types of radiation



Datasets and tools for external exposure

- **Pre-calculated tables for simple geometries and various radionuclides (Tier 0 and 1 assessments)**
- **ICRP free software McSEE (by Hanyang University) for assessing tissue absorbed doses for a user-defined geometry, PPE, and shielding (Tier 2 assessments)**



Nuclear terrorism and hostile states pose new challenges for the ICRP dosimetry system

- Threat and source-term ranges are very broad: nuclear detonations, military attacks on and sabotage of civilian nuclear installations, and medical, research and industrial facilities with large inventories of radionuclides.
- Dose assessments must support life-saving decisions and medical management of mass casualties with combined conventional trauma, body surface contamination, internal intake, contaminated wounds, burns, blast injuries and psychological effects.
- Responders, security and defence forces, and large population groups involved in national defence may operate under operational necessity amid dominant non-radiological risks for health and life.

- The updated ICRP recommendations should propose protection logic and appropriate dosimetric criteria for civil defence, security, and military forces: dose-status categories, action levels for medical assessment and bioassay, and triage/decontamination/decorporation thresholds.

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