

The Linear Non-Threshold Model and Its Implications for Radiological Security

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Radiological source security is tied to action thresholds.

- The threat of malicious use of a radiological source is tied to the goals of an adversary.
- It is difficult to cause radiological harm through dispersal of radioactive material due to dilution of the material. An individual with basic health physics capability will know this.
- Therefore, a goal might be to cause havoc by exceeding a threshold and causing fear through sheltering in place or fear plus associated harm through evacuation and relocation.
- Evacuation and relocation thresholds are generally dose-based and below doses that could cause harm or a meaningful increase in cancer risk.

This presentation discusses the importance of weighting the risks between terrorist objectives, radiological harm, and harm from recovery actions in a radiological dispersal event.

Stress and accidents from evacuations have been shown to result in casualties.

- 107 deaths attributed to Hurricane Rita in southwest United States
- “Stress and other illnesses” killed 1656 people in the Fukushima Prefecture
- “There were no predetermined criteria (i.e. generic, in terms of dose, or operational, in terms of measurable quantities) for relocation.”



Thresholds are tied to type of effect of concern.

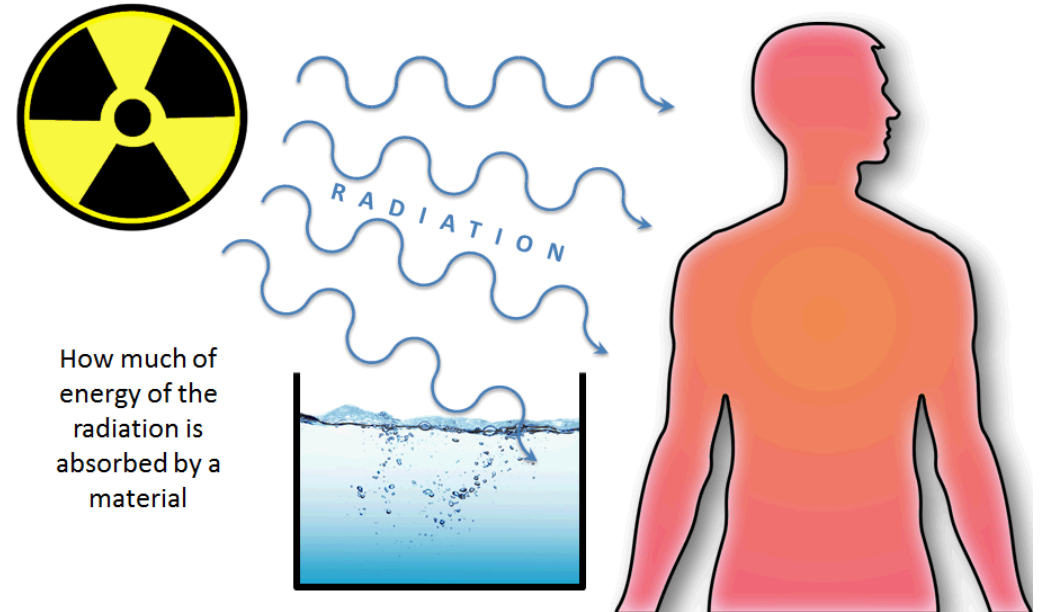
Deterministic Effect

- Effect that can be seen as specifically caused by radiation.
- Effect does not occur until threshold dose is reached.
 - Greater than 0.1 Gy
- Severity of effect is proportional to radiation dose received.
- Units of Gy.

Unit of radiation dose Gy

Gy gray

Amount of energy of the radiation is absorbed by a material



Thresholds are tied to type of effect of concern.

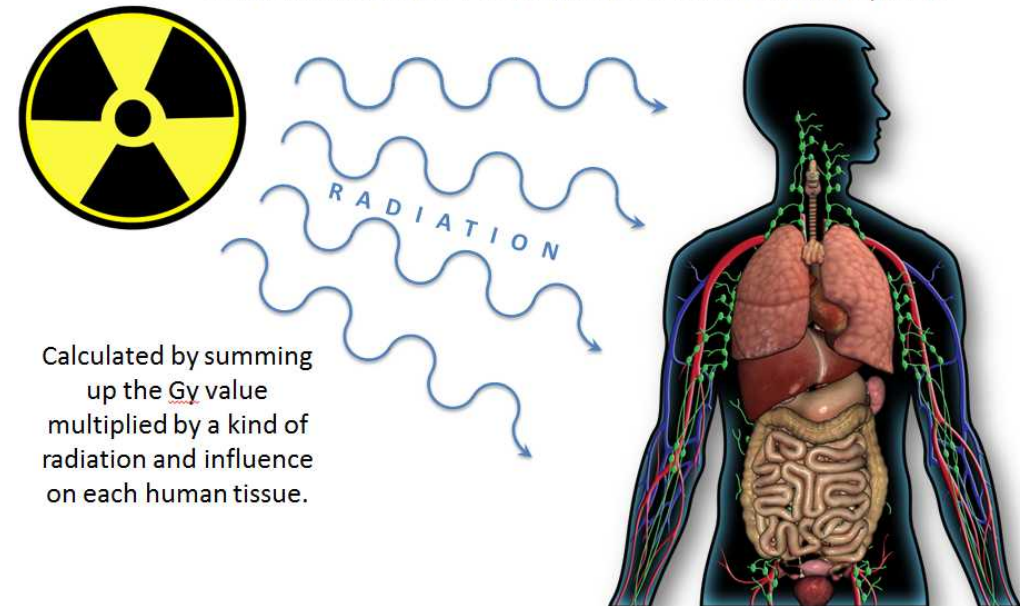
Stochastic effect

- Increase in risk of cancer or other probabilistic malady.
- Risk is an increase in effect over exposed population.
 - ICRP uses 4% per Sv.
- Number of effected individuals in population is proportional to radiation dose received.
- Units of Sv.

Unit of radiation dose Sv

Sv sievert

Amount of radiation in consideration of the influence on person



There are thresholds for either effect.

IAEA Code of Conduct

- Category 3 based on “dangerous quantities.”
- Categories 1 & 2 are multiplicatives of category 3.
- “Fatal effects that ... lead to death”
- “Non-fatal effects that ... reduce the quality of life”

ICRP Recommendations

- Relocation: 1000 or 100 mSv in the first year.
- Temporary evacuation: 50 mSv in 1 week.
- Sheltering: 10 mSv in 2 days.

The IAEA sets security requirements by radioactivity (A) amounts.

TABLE 5. RECOMMENDED DEFAULT SECURITY LEVELS FOR COMMON PRACTICES

Category	A/D	Practice	Security level
1	$A/D \geq 1000$	RTGs Irradiators Teletherapy Fixed multibeam teletherapy (gamma knife)	A
2	$1000 > A/D \geq 10$	Industrial gamma radiography High/medium dose rate brachytherapy	B
3	$10 > A/D \geq 1$	Fixed industrial gauges that incorporate high activity sources Well logging gauges	C
4	$1 > A/D \geq 0.01$	Low dose rate brachytherapy (except eye plaques and permanent implants) Industrial gauges that do not incorporate high activity sources Bone densitometers Static eliminators	Apply measures as described in GSR Part 3 [5]
5	$0.01 > A/D$ and $A > \text{exempt}$	Low dose rate brachytherapy eye plaques and permanent implant sources XRF devices which contain radioactive material Electron capture devices Mossbauer spectrometry Positron emission tomography (PET)	

Where do you want to go now?

Protection thresholds and their development



Case studies of radiological events



Discussion of what should be considered in
the development of security thresholds



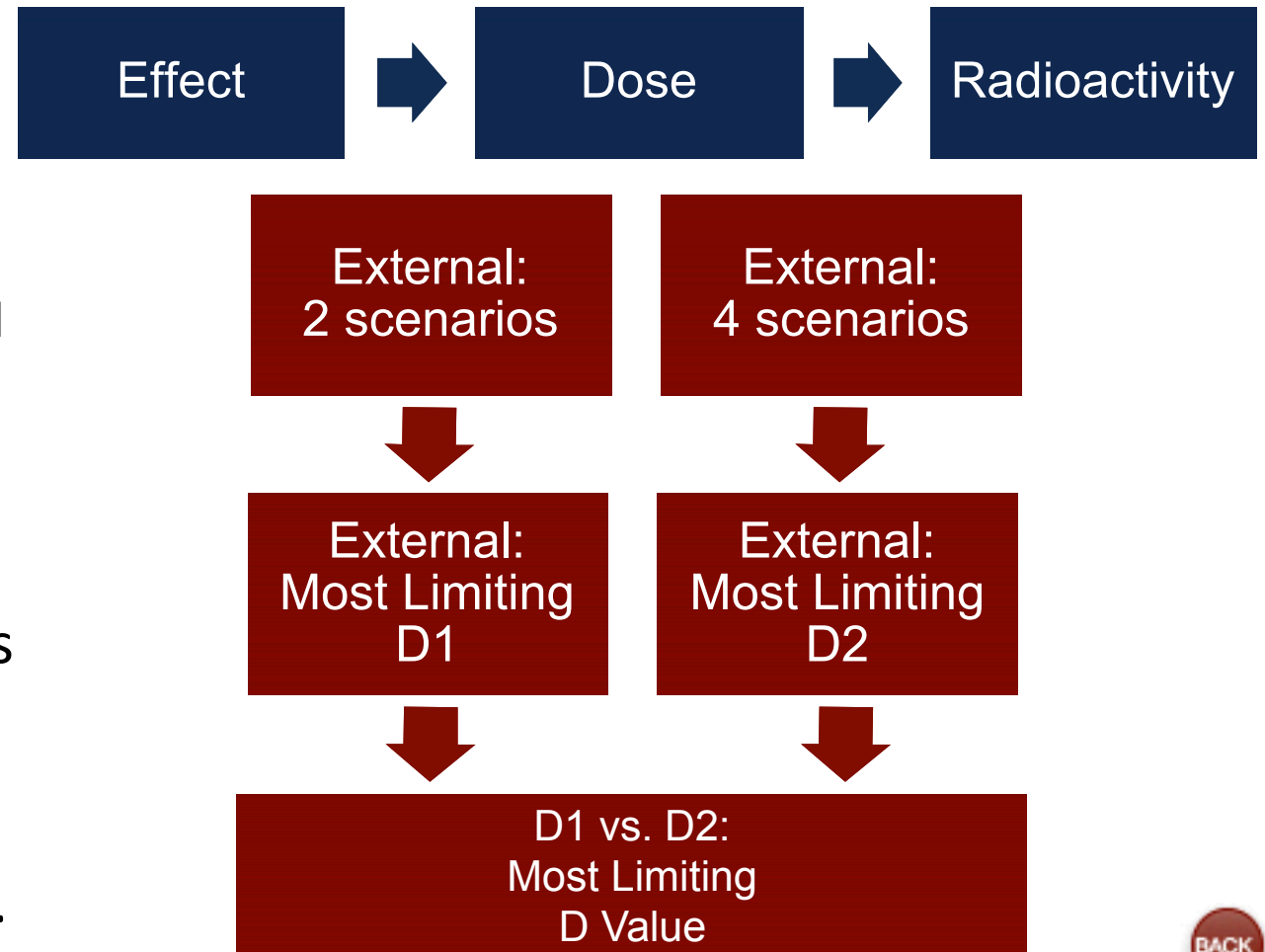
Framework for Safety and Security Thresholds



PROTECTION THRESHOLDS

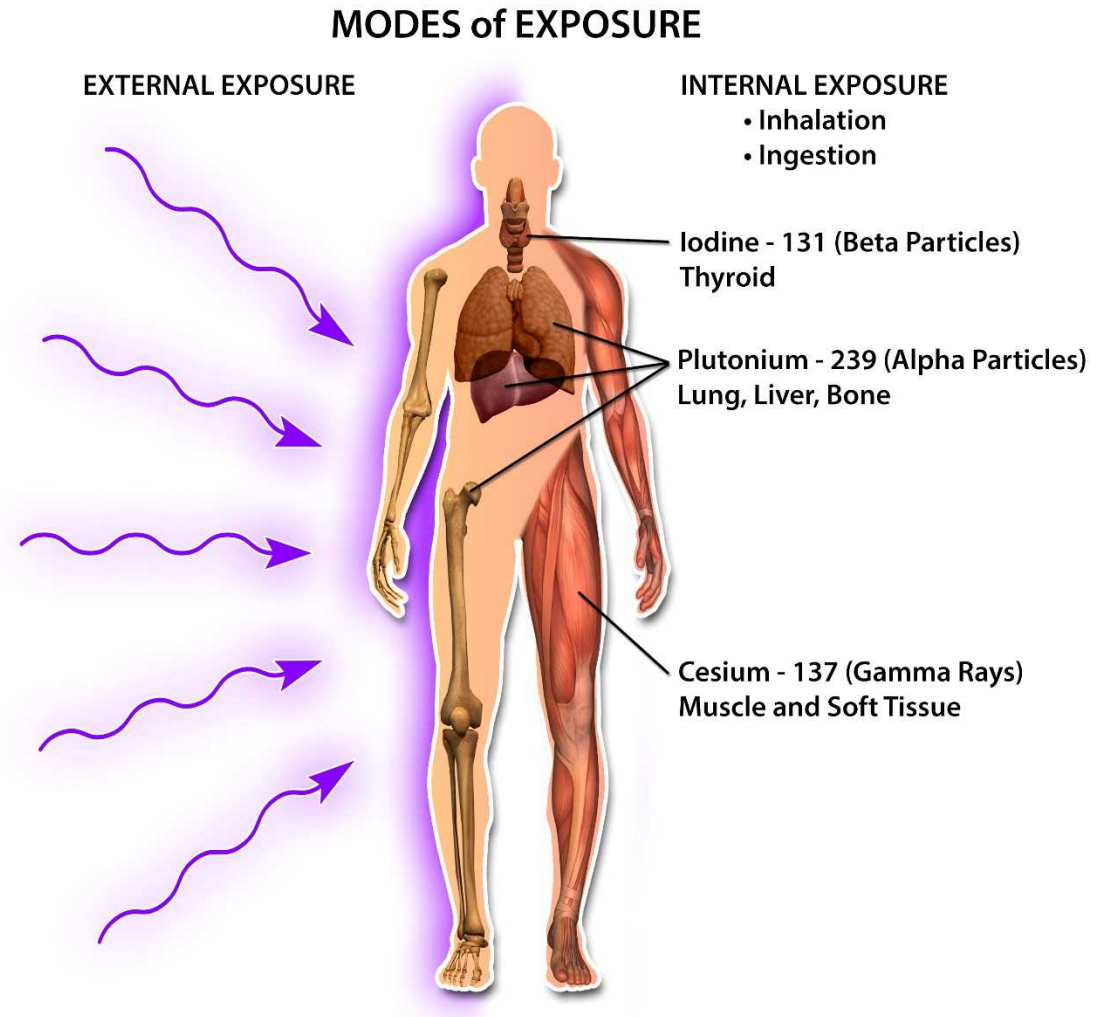
The IAEA published “D-values” for source protection in 2006.

- D-value stands for “dangerous quantity”
- Evaluations were made to deterministic effects:
 - “Fatal effects are those that, if developed, lead to death”
 - “Non-fatal effects are those that reduce the quality of life and are organ or tissue specific”
- Stochastic effects not a part of the analysis (except for thoracic lung)
- D-values are used in the assignment of security categories and associated actions.



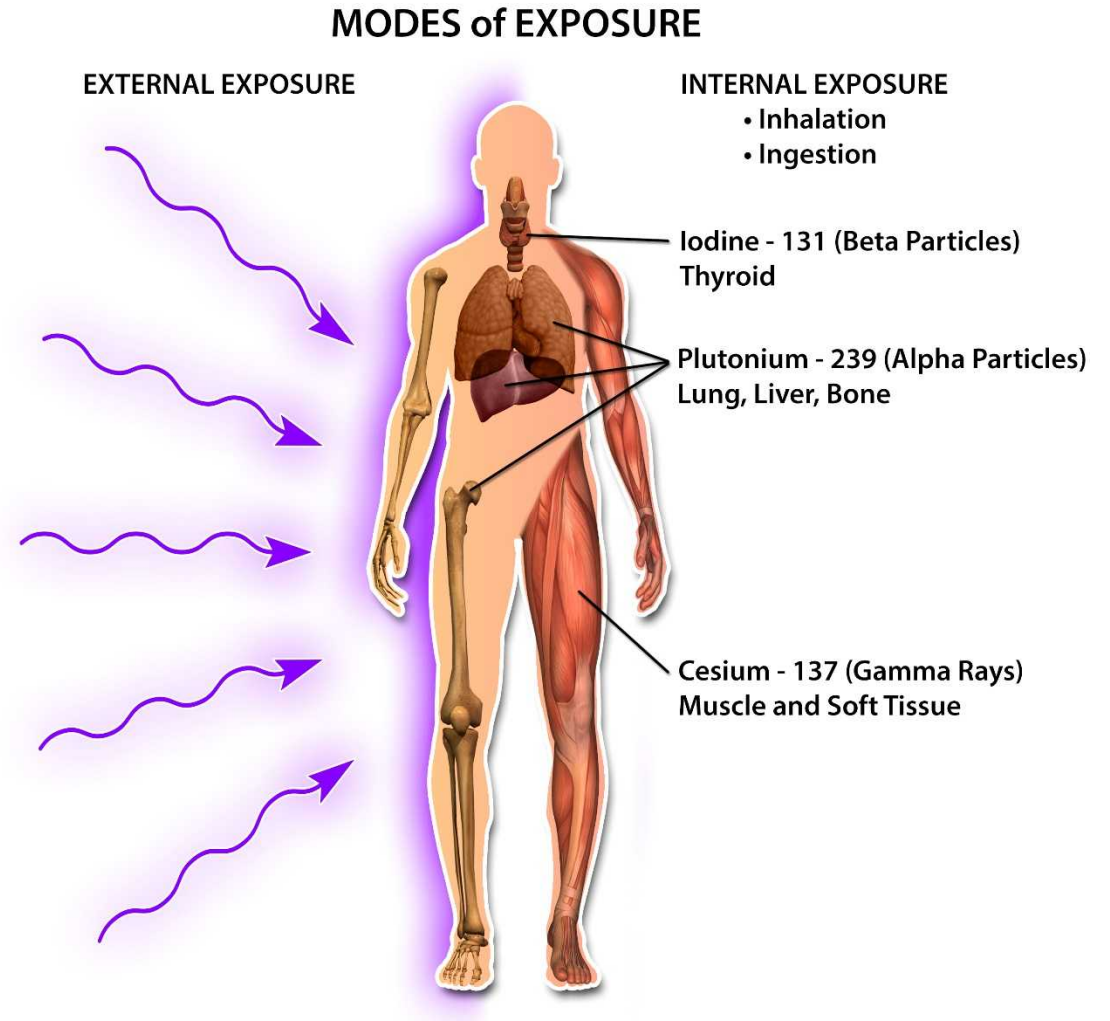
D-value scenarios represent the onset of an effect.

- Pocket: person carrying an unshielded source resulting in localized damage to soft tissue
- Room: person in the vicinity of an unshielded source for days to weeks resulting in exposure to the total body by external penetrating radiation
- Inhalation: fire or explosion exposing individual to airborne radioactive material



D-value scenarios represent the onset of an effect.

- Ingestion: more limiting of leaking and handled source resulting in inadvertent ingestion or source placed in public water supply with drinking of contaminated water
- Contamination: skin contaminated from leaking source
- Immersion: activity of noble gas released into room exposing occupants and causing external exposure of red marrow.



IAEA categories add period of exposure.

Category 1: $1000 \times D$

“Likely to cause permanent injury to a person who handled them ... for more than a few minutes. It would probably be fatal to be close to this amount of unshielded material for a period of a few minutes to an hour.”

Category 2: $10 \times D$

Could cause permanent injury to a person who handled them ... for a short time (minutes to hours). It could possibly be fatal to be close to this amount of unshielded radioactive material for a period of hours to days.

Category 3: D

if not safely managed or securely protected, could cause permanent injury to a person who handled them ... for some hours. It could possibly ... be fatal to be close to this amount of unshielded radioactive material for a period of days to weeks.

Evacuation and relocation are initiated by prospective guidance.

US: recommendations from the Environmental Protection Agency – protective action guides

- Early: shelter-in-place at 10 – 50 mSv over four days
- Intermediate: relocation of the public at 20 mSv over the first year

ICRP: generic optimized protection levels

- Relocation: 1000 or 100 mSv in the first year.
- Temporary evacuation: 50 mSv in 1 week.
- Sheltering: 10 mSv in 2 days.

IAEA: generic criteria for protective actions

- Sheltering: 100 mSv in first 7 days.
- Temporary relocation: 100 mSv in first year.

Evacuation and relocation may not be justified at 10 mSv.

- Health Physics Society in its position paper, Radiation Risk in Perspective states, below levels of about 100 mSv above background from all sources combined, the observed radiation effects in people are not statistically different from zero.
- This means that protective action criteria corresponding to doses below 100 mSv put people at risk by encouraging adversaries to consider the use of radiological weapons with the knowledge that dispersal does not have to be efficient, nor concentrated in radioactivity to result in significant protective actions.

CASE STUDIES

Goiana accident resulted in social and psychological effects.

- 52 TBq $^{137}\text{CsCl}$ in radiotherapy head
- Spread throughout area by contact
- 36 tonnes of waste generated from cleanup
- 112,000 individuals tested for contamination.

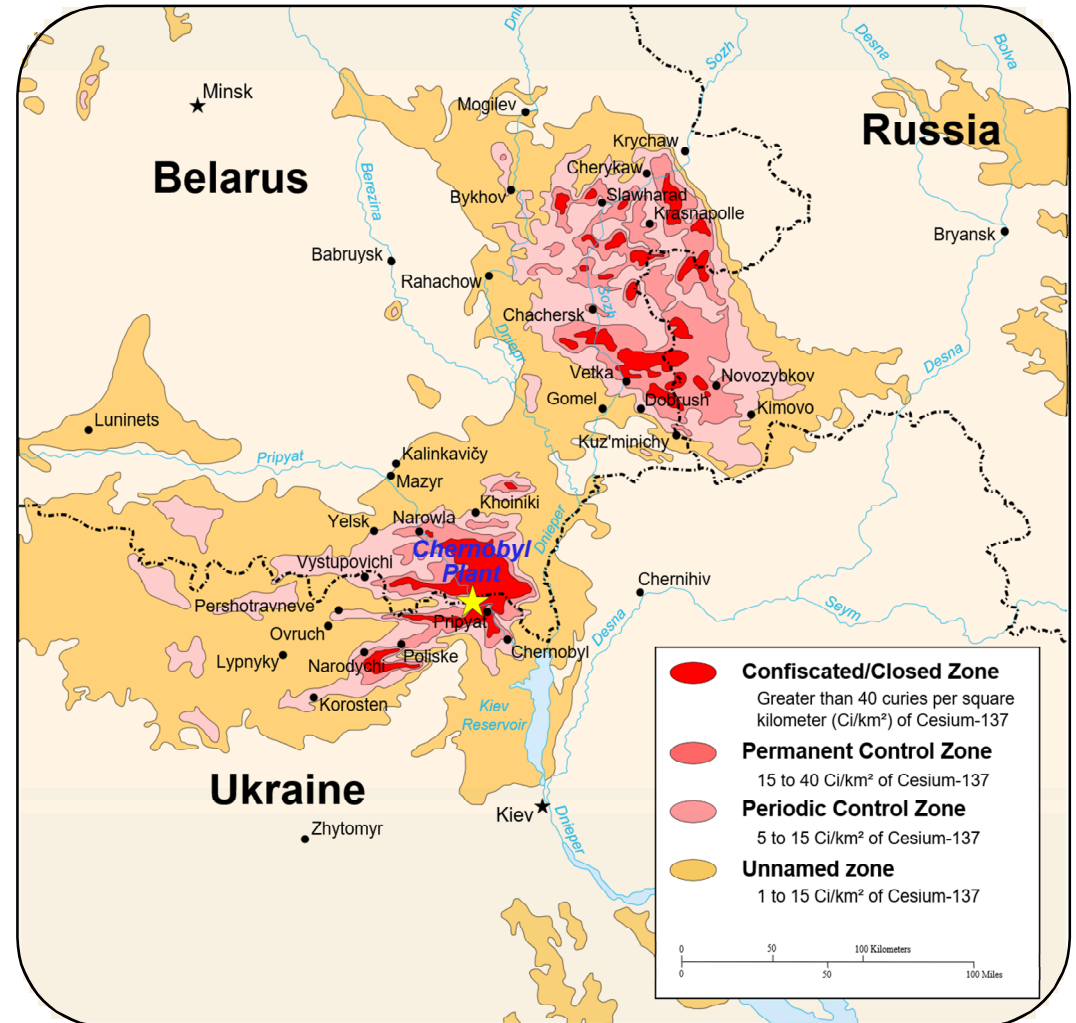


Cs-137 teletherapy machine



The Chernobyl disaster shows long-term exclusion limits.

- The closed zone activity concentration is greater than 1.5 TBq/km²
- Chernobyl exclusion zone corresponds to 20 mSv/year.
- This is the same as the US EPA protective action guide for relocation.
- This corresponds to an increased cancer incidence of 588 per 100,000.
 - Base risk is 40,000 per 100,000 (BEIR 7)

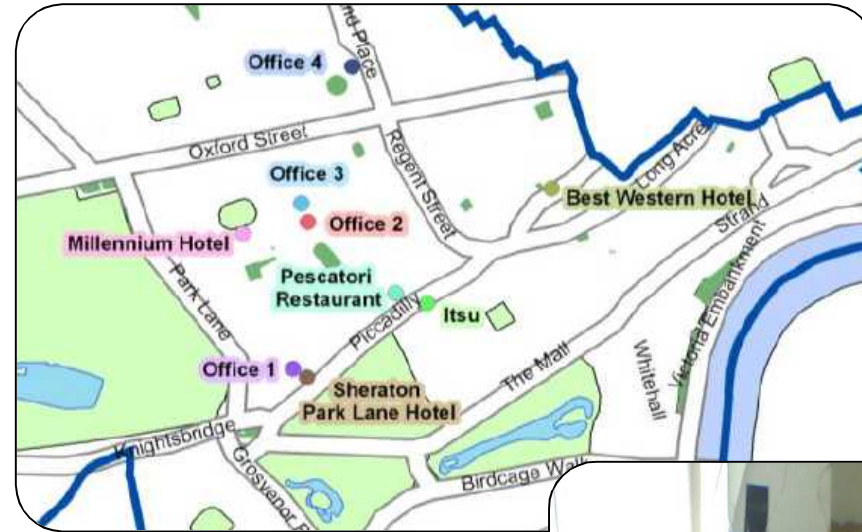


Wikipedia, attrib. to The World Factbook



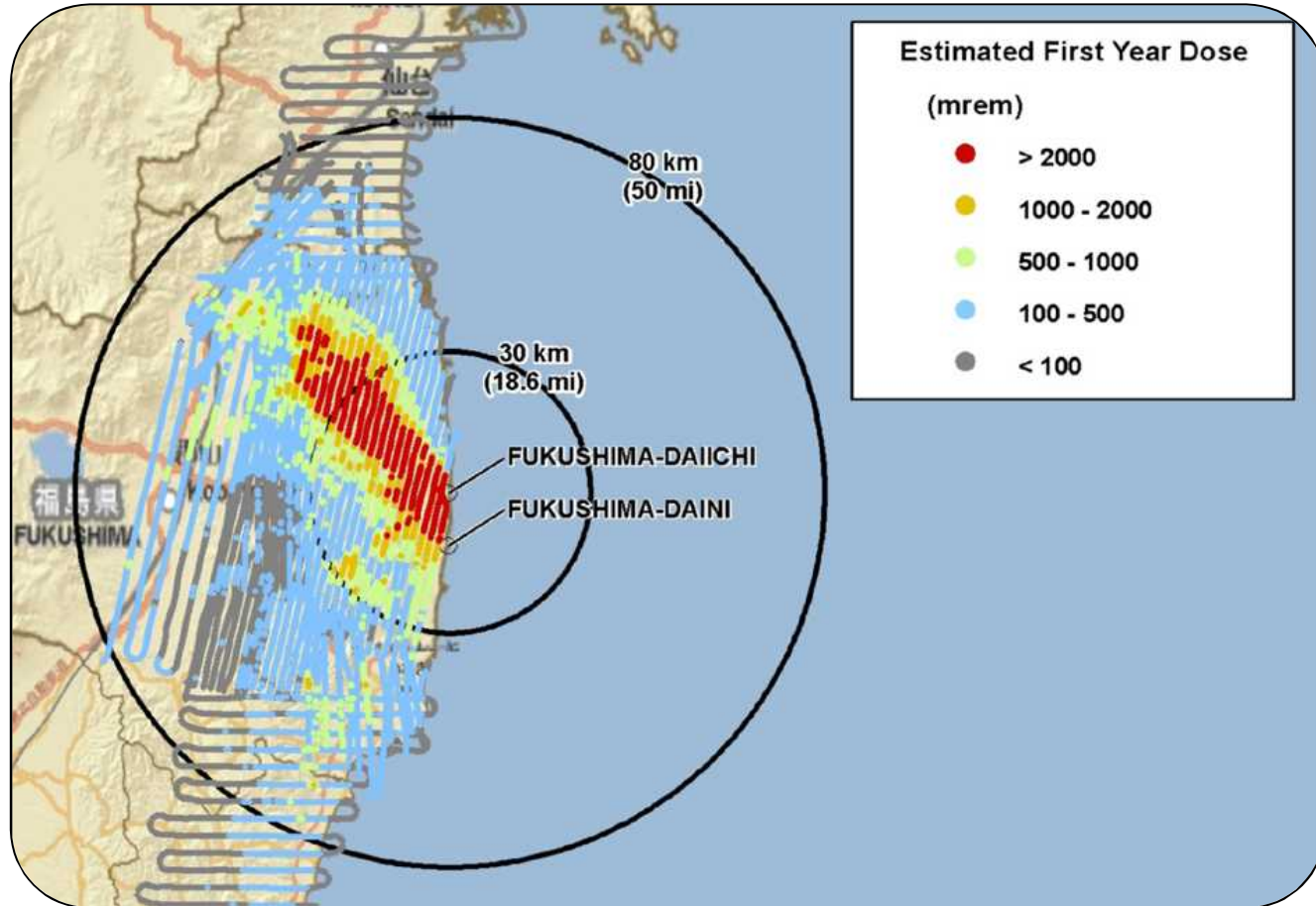
The poisoning of Alexander Litvinenko led to a significant clean-up effort.

- Clean-up standard was 10 Bq/cm².
- This corresponds to:
 - 0.07 μ Sv/hr
 - 1.7 mSv over 7 half-lives of ²¹⁰Po



Westminster City Council, Govt. Decontamination Service

The Fukushima disaster was exacerbated by lack of data and proper guidance.



US Department of Energy

- “There were no predetermined criteria (i.e. generic, in terms of dose, or operational, in terms of measurable quantities) for relocation.”
- 20 mSv used as exclusion zone criteria.
- Approximately 100,000 relocated.

Low response and cleanup standards do not address actual risk.

- The Goiania accident resulted in 36 tonnes of radiological waste and 112,000 individuals with unfounded health concerns.
- The Chernobyl accident follow-up included the use of a 20 mSv/y criterion for permanent exclusion.
- A malicious dispersion could result in panic and chaos followed by health concerns and considerable cleanup, even if the actual health risks were insignificant.
- The Litvinenko poisoning decontamination was to a zero-risk level.
- Fukushima response 20 mSv for exclusion and had little or no means for evaluating that criterion.

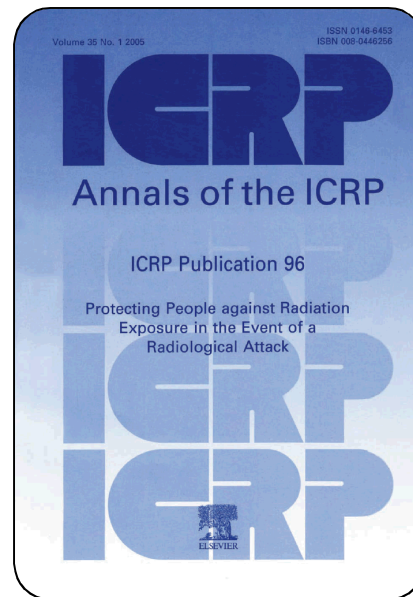
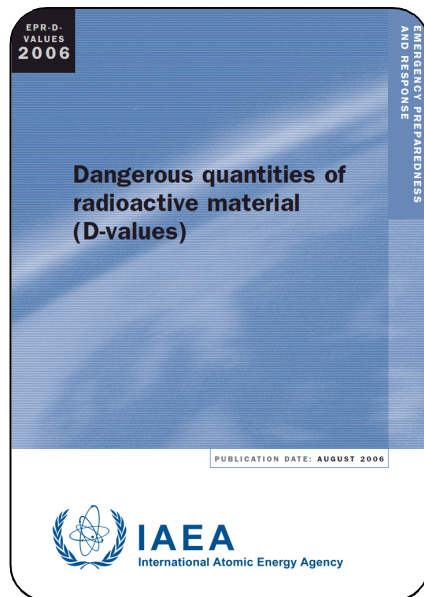
SECURITY THRESHOLDS

Low response levels make it easier for the adversary to cause panic, chaos, injury, and economic effects.

- An adversary's goal is to provoke a significant response.
- International guidance and national requirements result in relocation for areas where there is little risk.
- International guidance and national requirements result in decontamination to levels well below those where risk exists.
- An adversary need not contaminate an area to a significant level to achieve their goals.

Deterministic and stochastic risk should be discussed when determining thresholds.

- The IAEA D-values adequately address deterministic scenarios and associated exposure.
- The ICRP-96 relocation recommendations consider stochastic risk to the thoracic lung.
- Thresholds should not overemphasize either risk such that an adversary is encouraged to use radioactive material as a weapon.



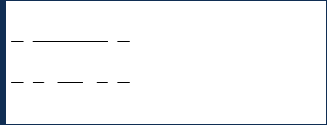
The linear non-threshold model of stochastic risk is part of the problem.

- LNT is responsible for exceedingly low relocation thresholds in the US corresponding to 0.02 Sv in the first year. There is likely no risk at this dose.
- Even with the LNT, the ICRP cancer risk coefficient is 0.04/Sv. This is in comparison to a base cancer incidence 40%.
- Assuming the base cancer incidence is normally distributed, this corresponds to a 2σ range of 27 – 53 cancers in a population of 100.
- Using the cancer risk coefficient of 0.04/Sv, the 13th cancer in a population of 100 would require a dose of 3.25 Sv. This dose is above that at which deterministic effects would be expected in the population.



Decontamination standards result in “area of denial” and associated costs.

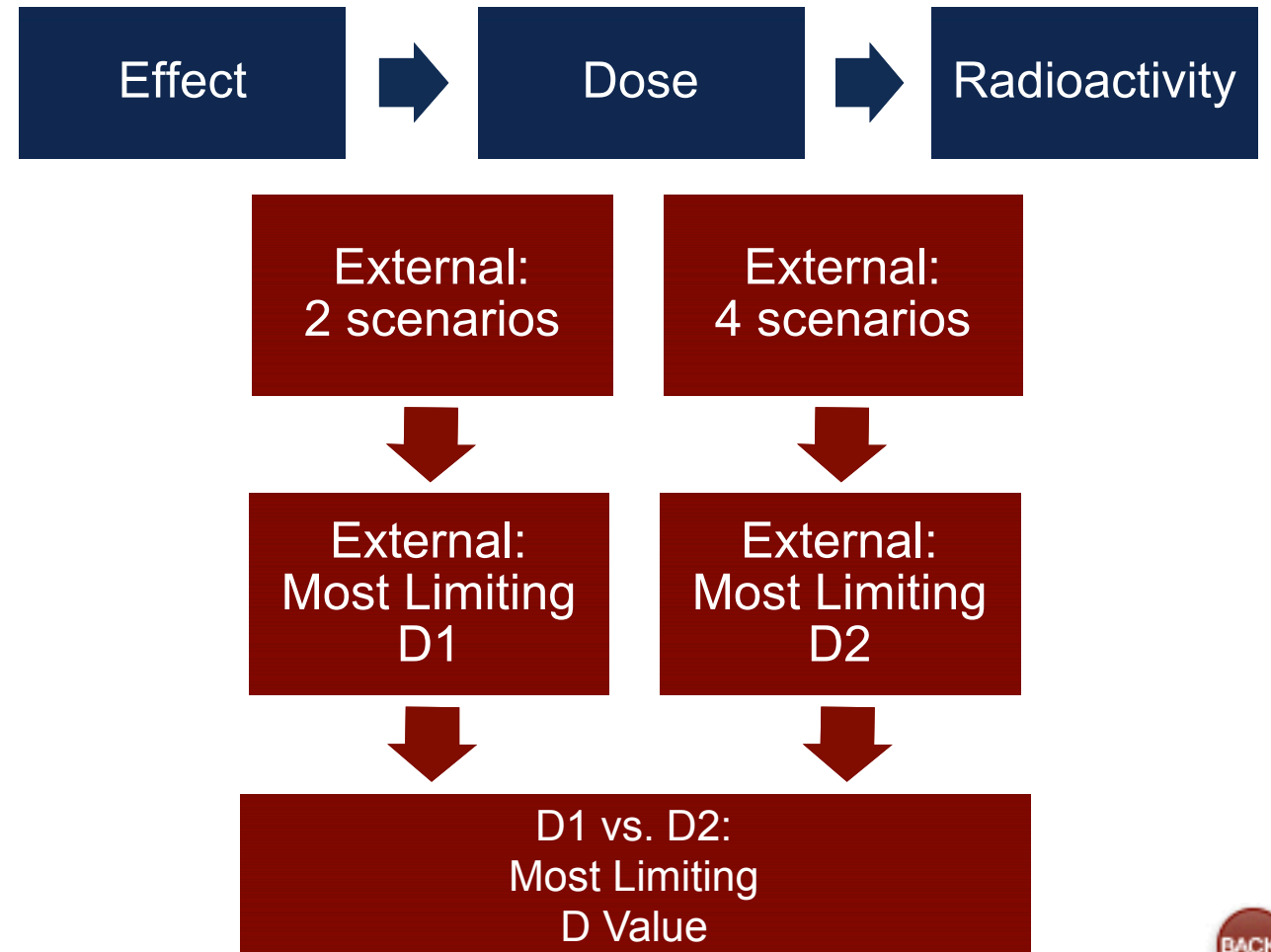
- An area contaminated to an evacuation or relocation guide will be unusable for some period of time.
- A high-value economic target such as a stock exchange or a government building that cannot be inhabited will result in significant cost just by not being useable.
- Decontamination costs are significant and the cost raises geometrically as contamination limits are pushed to zero.



FRAMEWORK FOR SAFETY AND SECURITY THRESHOLDS

D-values are a good starting place for security thresholds.

- The D-values effectively define quantities of concern from a safety standpoint.
- This encompasses both external (D1) and internal (D2) exposure considerations from each radionuclide considered.
- However, they represent amounts of radioactivity that could cause particular effects, rather than result in specific doses.



Stochastic risk must be weighted appropriately.

- The linear non-threshold model is being challenged and stochastic risk may currently be over-compensated.
- Even with consideration of currently accepted risk coefficients, it is difficult to determine when excess cancers are from stochastic radiation risk rather than random fluctuation.
- A desire to reduce stochastic risk to zero has a corresponding effect of making it easier for an adversary to cause widespread disruption (Litveninko response).

Evacuation and relocation thresholds should consider all detriment.

- Stochastic risk – the weight of increased cancer risk has to be appropriate when compared to other hazards.
- Deterministic risk – it is difficult to cause deterministic effects from radionuclide dispersal due to the corresponding dilution of material.
- Safety hazards – an explosive dispersal of material could cause injury or death from the explosion itself or from hazards created from the event (broken glass, shrapnel, etc).
- Evacuation risk – analysis of mass evacuation has shown that there is increased risk of injury or death from the act of evacuation.

Balance threat and risk in development of security thresholds.

- Sacrifice stochastic risk as part of a threat deterrent.
 - If the adversary cannot get the response they are looking for, they may not commit the act.
- Minimize evacuation thresholds for radiological security events.
 - Evacuation is a risky activity that likely will result in injury or death.
- Set decontamination standards that are reasonable for both additional risk and cost.
 - Adversaries are familiar with “area of denial” and associated economic impacts.