Norwegian University of Life Sciences

Norwegian Institute of Public Health

Norwegian Institute for Water Research

CERAD

CENTRE FOR ENVIRONMENTAL RADIOACTIVITY

Norwegian Meteorological Institute

Statens strålevern
Norwegian Radiation Protection Authority

Environmental impact and risk assessments - overall uncertainties

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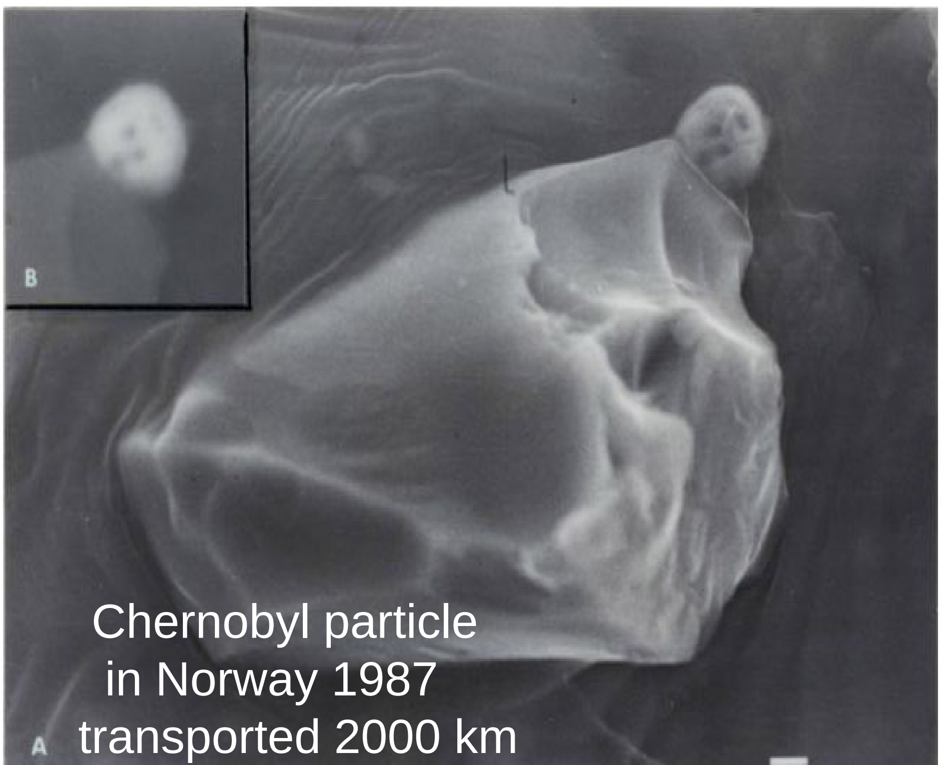
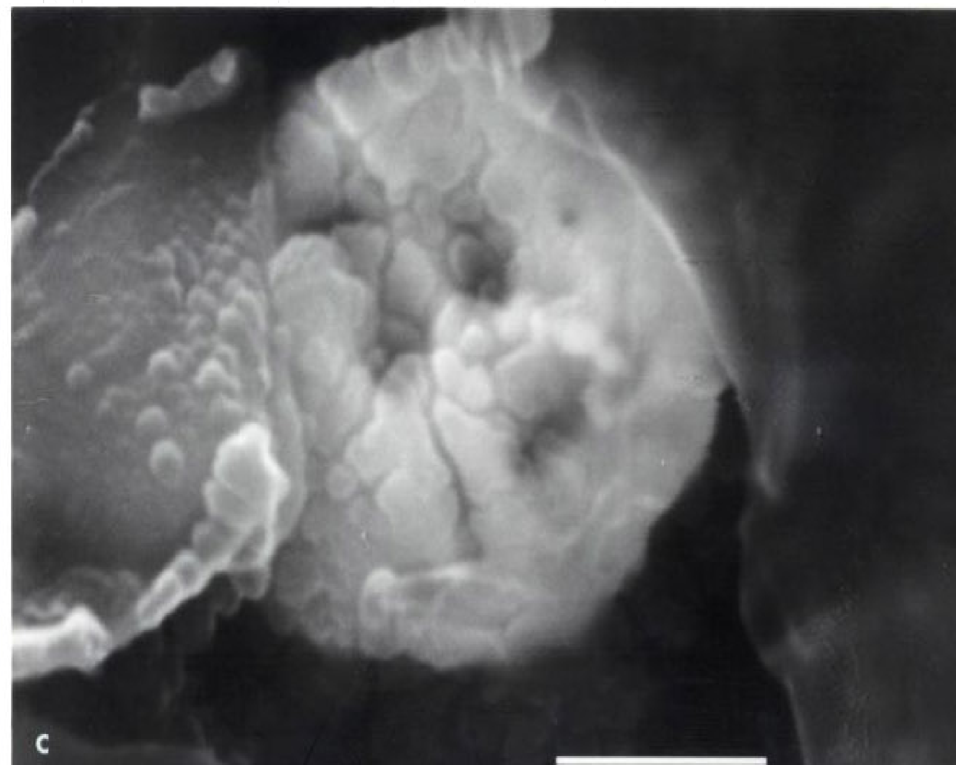




Take home messages

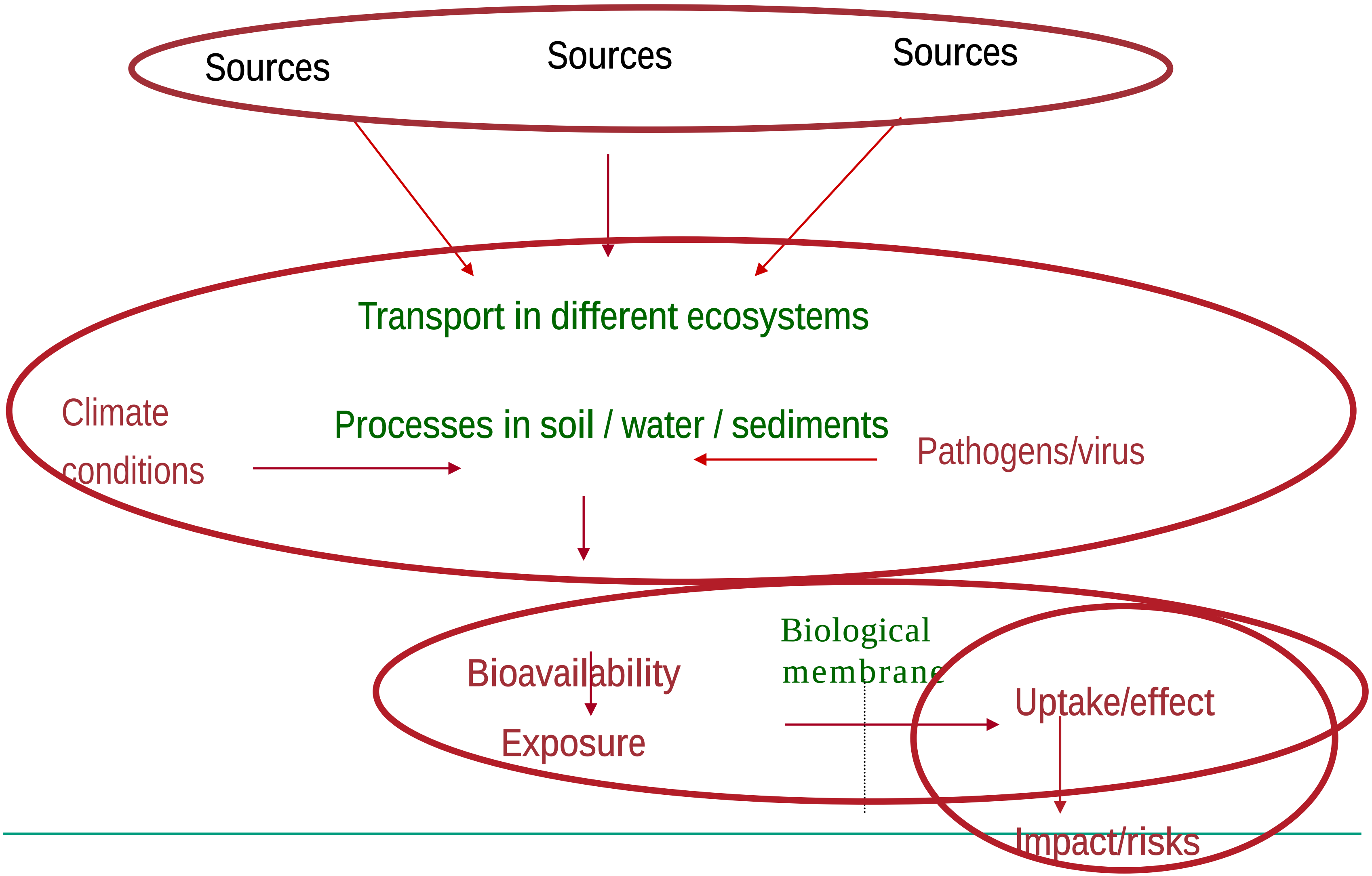
- Many sources can affect the same territory, a series of processes will influence the ecosystem transfer, a multitude of stressors may influence biological responses in exposed organisms at different sensitive history life stages.

- Adding problems with variability, questionable assumptions, gaps in knowledge, conceptual model structure etc: a series of factors are contributing to uncertainties in impact and risk assessment.
- Research effort priorities should be put on variables, parameters, processes and model structures contributing most to the overall uncertainties

- Sensitivity analysis is a useful tool to identify key factors contributing to the overall uncertainties, and to prioritize the research effort.

- Validation of predicting models are crucial.

Radioecology: to link releases of radionuclide species from different sources via ecosystem transfer to dose, effects, impact and risk assessment under various climate conditions



Complex system – many stressors/variable antioxidant status

Source term - ecosystem transport – uptake - effects form the basis for impact and risk assessments

Source term → **Transport** → **Biol. uptake** → **Biol. effects**

Bq | **Kd** | **BCF, TF, TC** | **mSv/y, mGy/y**

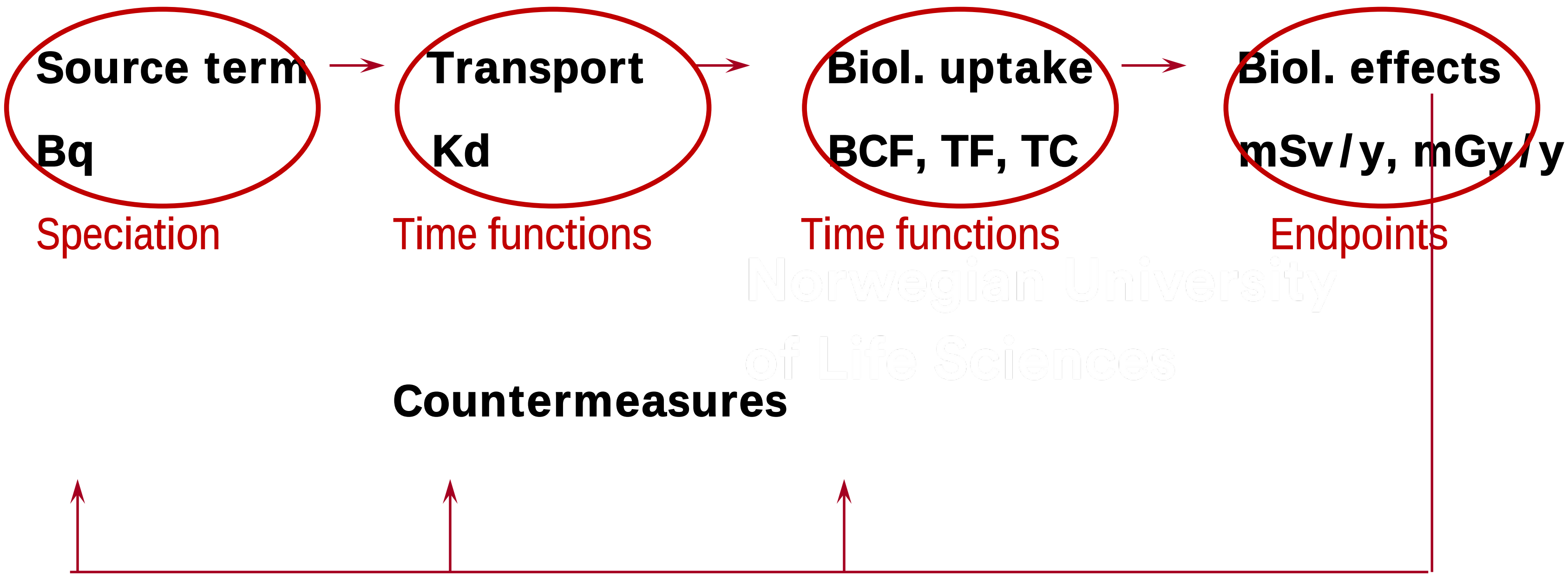
Countermeasures

Short and long term dose, impact and risk assessments

If the predicted biological effects is acceptable (below screening value) – no countermeasures

If predicted biological effects is acceptable (below screening value) – alternative countermeasures can be applied (dose saved/cost)

Predicting power of the model depends on the uncertainties: Source term - ecosystem transport – uptake - effects



Short and long term dose, impact and risk assessments

Focus: Factors contributing to uncertainties in the:
Source term/deposition, ecosystem transfer, and effect estimates

Sources of uncertainty

Sources of uncertainty can be categorized as

- ***Experimental u*** f measurement data),
- ***Inte*** f available d
-
- ***P*** cannot be ex
- ***Algorithmic un*** or approximations),
- ***Structural uncertainty*** (model bias or discrepancy due to lack of knowledge of the underlying mechanisms or processes).

Alternatively, uncertainties can be classified as

- ***Epistemic uncertainty*** (systematic uncertainty due to missing data on phenomena that could be investigated),
- ***Aleatoric uncertainty*** which includes unknowns that may affect all experiments

Some key factors that contributes to large uncertainties

- Source term, transport, dispersion and deposition estimates, ignoring radionuclide speciation and particle size distribution.
- Ecosystem transfer parameters, ignoring the system dynamics and kinetics.
- Biological responses in exposed organisms that are based on extrapolations from high to low doses and dose rates, from one species to others, from individual effects to population level impacts, from lab experiments to complex ecosystems), ignoring sensitive history life stages, transgenerational effects etc.
- Overly simplistic treatment, or total disregard, of multiple stressor effects.

These aspects can be improved!

Input - mathematical models

- Mathematical models are built on
  - a set of equations,
  - default parameters, and
  - Input: experimentally measured input variables relevant to specific processes.
- Sources of uncertainty in Model input: Representative sampling, relevant variables, systematic and random errors (procedures, measurements, independent data, data gaps or missing variables?

Uncertainties associated with Representative sampling may well exceed those of the measurements.

To account for knowledge gaps, extrapolations or Bayesian statistics can be applied to reduce parametric uncertainties – which also may be problematic

People not performing measurements, believe in numbers
Especially if numbers are given with 3 decimals

Other sources of uncertainties

More difficult to account for

- Questionable default parameters - relevant for the purpose?
- Questionable assumptions – equilibrium?
- Extrapolation issues - to cover knowledge gaps
- Model uncertainties that arise from simplified mathematical representation, numerical solutions or structural errors in describing the processes of interests

Model and Conceptual Uncertainty

(Day, 2004; CERRIE, 2004, van der Sjuis et al, 2006)

Model

– Models are by definition a simplification of reality

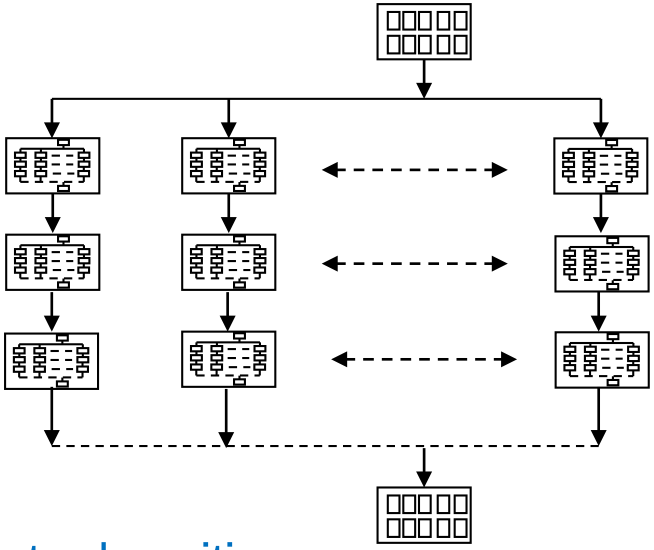
– Model structure may be inadequate - mismatch between model and reality

– Model may be over-complex in relation to knowledge (system over-parameterised - parameters uncertain)

Concept

– Overall model structure may be wrong

– Concepts may be inappropriate



Interfacing different models linking the source term – transport – deposition – ecosystem transfer – uptake – dose/effect – consequences – risk must often be based on compromises!

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How to deal with the overall uncertainty problem?

- The overall uncertainty represents a limit in our confidence in the output of models.
- Good modelling practice:
  - Quantification of the uncertainty (uncertainty analysis) and/or
  - Evaluation of how much each input variable contributes to the output uncertainty (sensitivity analysis).

Sensitivity analysis can also provide information on

- the robustness of experimental or modelling results, and
- a better understanding of the relationships between input and output variables.

Sensitivity analysis can also be used to prioritize science- to focus on factors reducing the overall uncertainties.

Despite all mathematics, statistics, assumptions and extrapolations, model output should be compared and, where possible, evaluated by field investigations using representative field sites

Source term – transport - deposition

Source terms usually estimated from the inventory, the amount of radionuclides released (Bq) as liquids, gas or aerosols, time development of the release, plume height and energy content of the release, ignoring radionuclide speciation and particle size distribution.

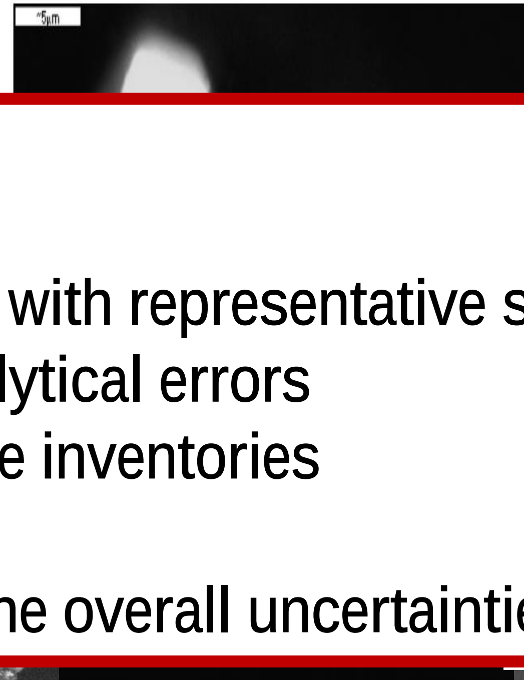
1990: The hot particle phenomenon was considered to be a "peculiarity of the Chernobyl accident"

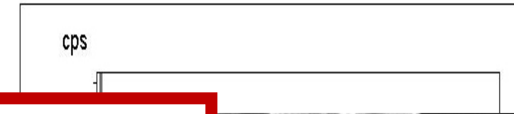
No, radioactive particles/colloids/nanoparticles are released during "all" types of severe nuclear events:

- The source dictates the refractory radionuclide composition and atom/isotopic ratios in particles (e.g., burn-up),
- The release scenarios (e.g., temperature, pressures, redox conditions) influence particle characteristics (size, structure, oxidation states) relevant for particle weathering and ecosystem transfer (IAEA, 2011)

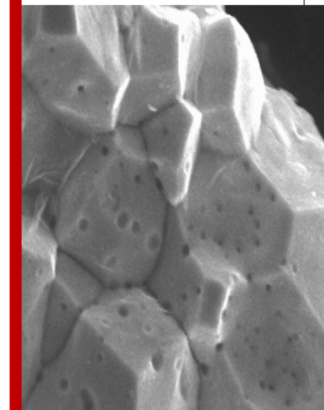
Modelling a hypothetic accident at the Kola reactor and shortest travel to Norway:
Aerosol transport (SNAP model): contamination to be handled
Implementing particle code in SNAP: Evacuation level!
Particle codes implemented in emergency preparedness models (EC PREPARE)

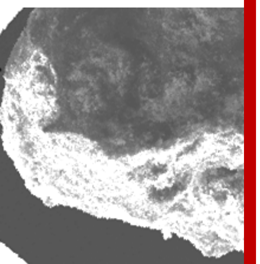
Radioactive particles released during ”all” types of severe nuclear events. Essential to implement particle codes in source term and transport models





Nuclear te
Semipalat



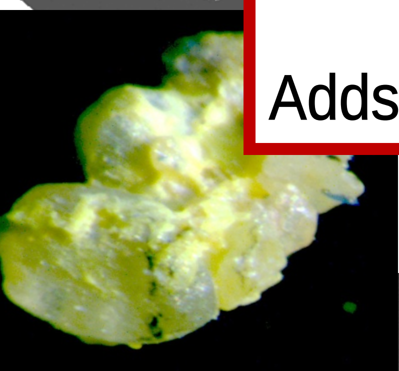


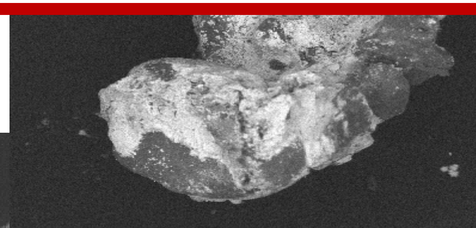
Particle deposition

- Hot spots – problems with representative sampling
- Partial leaching – analytical errors
- May underestimate the inventories

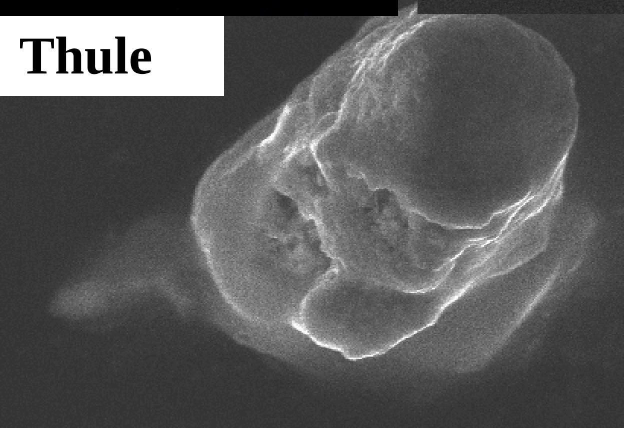
Adds significantly to the overall uncertainties

from the
explosion





Thule



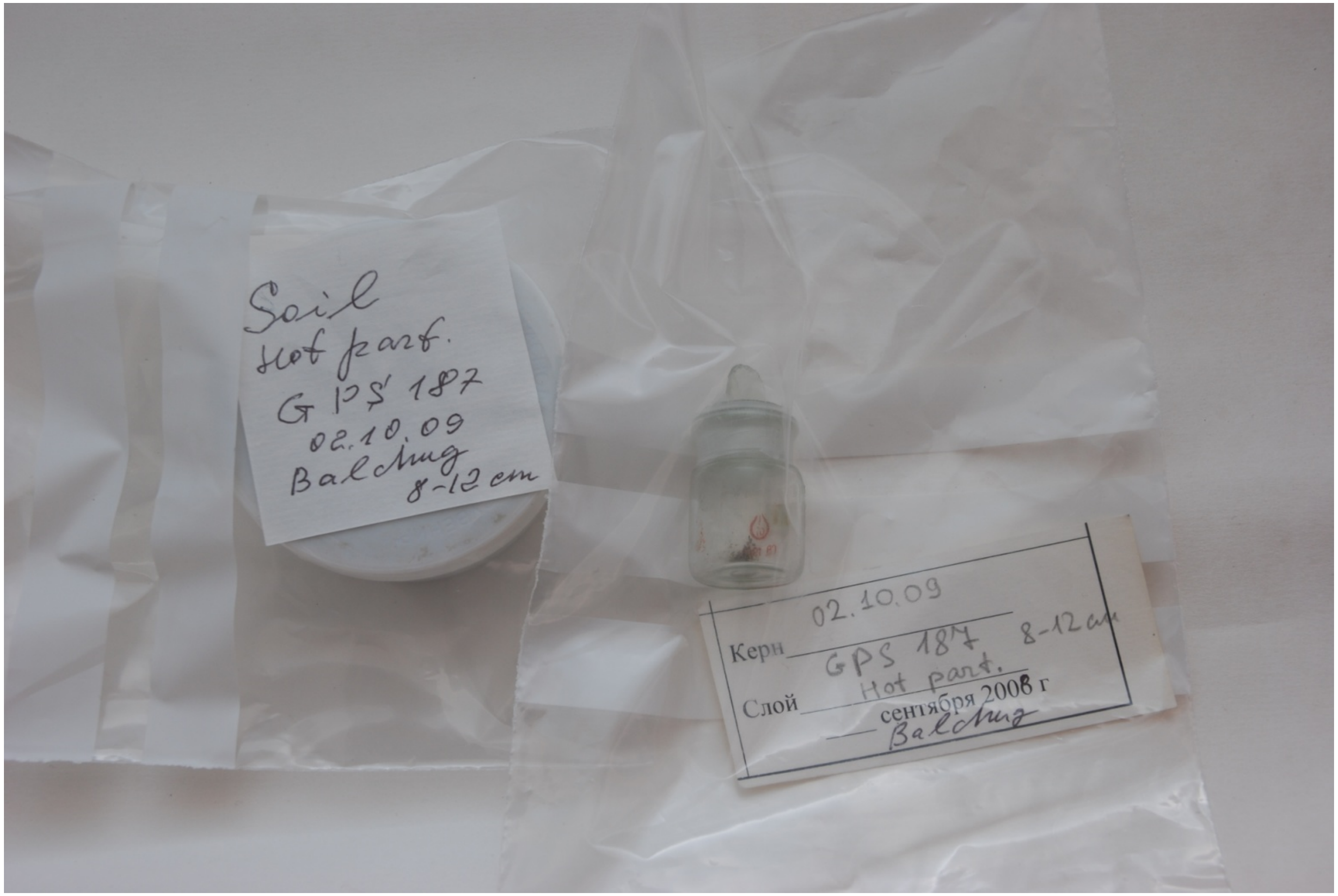
Corrosion product
Waste in Kara Sea

Th in Norm, Norway

Senter for fremragende forskning

Case: ^{137}Cs i bulk soils samples – Bq /kg
ONE radioactive particles present in soils

NMBU



Bulk (minus particle): ~100 g
~40 counts per second
(NaI detector)

→ **Sample splitting**

Isolated grains of soil incl. particle: mg
~60 000 cps - 99,95 %
436 000 Bq ^{137}Cs

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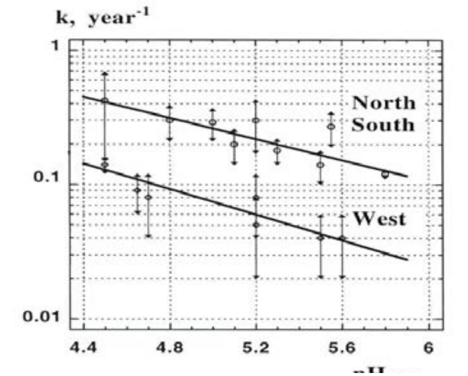
Ecosystem transfer variables/parameters

Ecosystem transfer data: distribution coefficients (Kd), transfer coefficients (TC) and concentration factors (BCF) are usually based on total Bq of radionuclides in bulk samples, assuming equilibrium conditions are valid, ignoring system dynamics and kinetics.

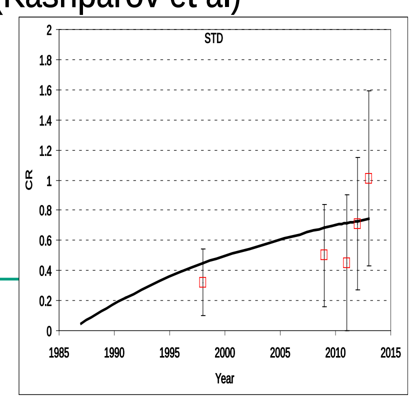
- Mobile low molecular mass species (LMM) can be reduced f(t) due to interactions with clays or humic substances,
- Mobile LMM species can be produced f(t) due to weathering of particles.

Changes in climate, precipitation (acid rain, flodding) and temperature conditions can influence the Kds, TCs and BCFs over time. Data from temperate zones hardly valid in the Arctic



Weathering rates of Chernobyl particles (Kashparov et al 1999)

Uptake Sr-90 in grain (Kashparov et al)



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Uncertainties in ecosystem transfer: Soil – water – vegetation – animal – man

Speciation: ions – complexes - colloids - particles

- Kd: soil – water distribution at equilibrium?
- Kd: sediment - water distribution: at equilibrium?
- CR - TC - TF - Tagg: uptake in plant – soil distribution at equilibrium?

Reindeer (NRPA):

Effective ecological half-times of ^{137}Cs has changed following the Chernobyl deposition in Norway.

- Initially: Effective ecological half-times of about 4 years.
- Mid 1990s: Slow decline, diminishing seasonal differences in concentrations.
- 2005-2010: About 27 years

Similar trends in concentrations in sheep, goats and cattle (NRPA).

Dynamic system - Kd and BCT/TC should rather be expressed as time functions f(t)

Uncertainties: Biological uptake and effects

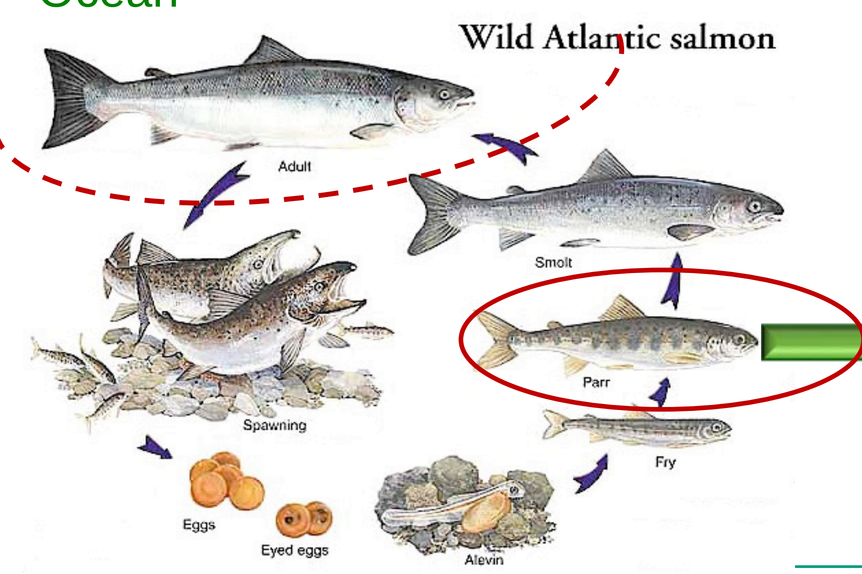
Extrapolation issues: Acute - chronic, High - low doses and dose rates, From one species - others, From individual effects to population level impacts, From lab experiments to complex filed ecosystems → **"Safety Factors" poorly defined**

Sensitivity history life stages - sensitive endpoints

Most tox data – adult fish

Transgenerational effects?

Ocean



Juvenile
Freshwater stage

Uneven dose distribution 30 mGy/hr

Particle exposure of blue mussel

High to low LET?

Effect units for non-human

Organisms –endpoints – advanced methods - to be agreed

Impact of radionuclide speciation (mobile species and inert particles) on ecosystem transfer

Source term →		Transport processes →	Biological uptake →	Dose-assessment
Impact of	Speciation	K_d	CF	mSV
Mobile species	High load of mobile species	Low Increase *f(t)* when transformed into reactive species	High in fish Low in benthic Decrease *f(t)* in fish, Increase in benthic for reactive species	Underestimated short-term dose-assessment Overestimated long-term dose-assessment for reactive species
Hot particles	High load of inert species	Very high Decrease *f(t)* due to weathering	Low in fish High in benthic Increase *f(t)* in fish Decrease *f(t)* in benthic	Overestimated short-term I dose-assessment Underestimated long-term dose-assessment for mobile species

A series of nuclear sources in Europe can potentially release radioactive particles in the future

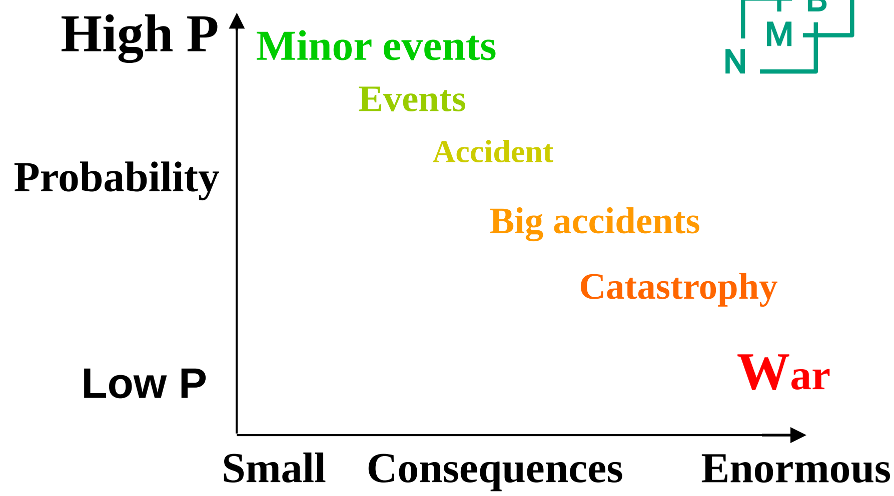
Challenges: Modelling nuclear or radiological events

Paradigm shifts in risk evaluation:

- Three Mile Island, USA, 1979, low probability severe accidents can occur
- Chernobyl,USSR, 1986, consequences can be far more severe than expected, far outside the 30 km zone
- 2011 Fukushima - geohazards are underestimated.
- World Trade Center and Pentagon, USA, 2001, group are capable to induce harm – new ”worst case scenario” estimates

Unforseen acts
- Attack at installations
- Dirty bombs
- Silent killers
- Contamination of food/water supplies

Risk=probability of an event x consequences



Per def.:

- Risk R= P x C

  The risk of a high P and low C events is the same risk as an event with low P and high C

  P and C can be weighted, depending of risk evaluations.

- Absolute risk is based on statistics – events/ reactor year – used for site-specific well known objects with historic records
- Relative risk – comparing the risk for one event with the risks of other events. Used as rough estimates for unforeseen events, categorised as low – middle - high risks.

Probability of unforeseen events

- **The probability of an unforeseen, intended event:**

$R = P \times C$

will depend on: Who will do the harm?

Replaced:

$R = P_A \times P_S \times C$

- **P_A = the probability of occurrence of a terrorist attempt,**
  - the intention
- **P_S = the probability of success of the attempt,**
  - the capacity/capability
- **C = ($0 \leq C \leq 1$) the consequences of a successful attack.**

Intended actions – orphan sources

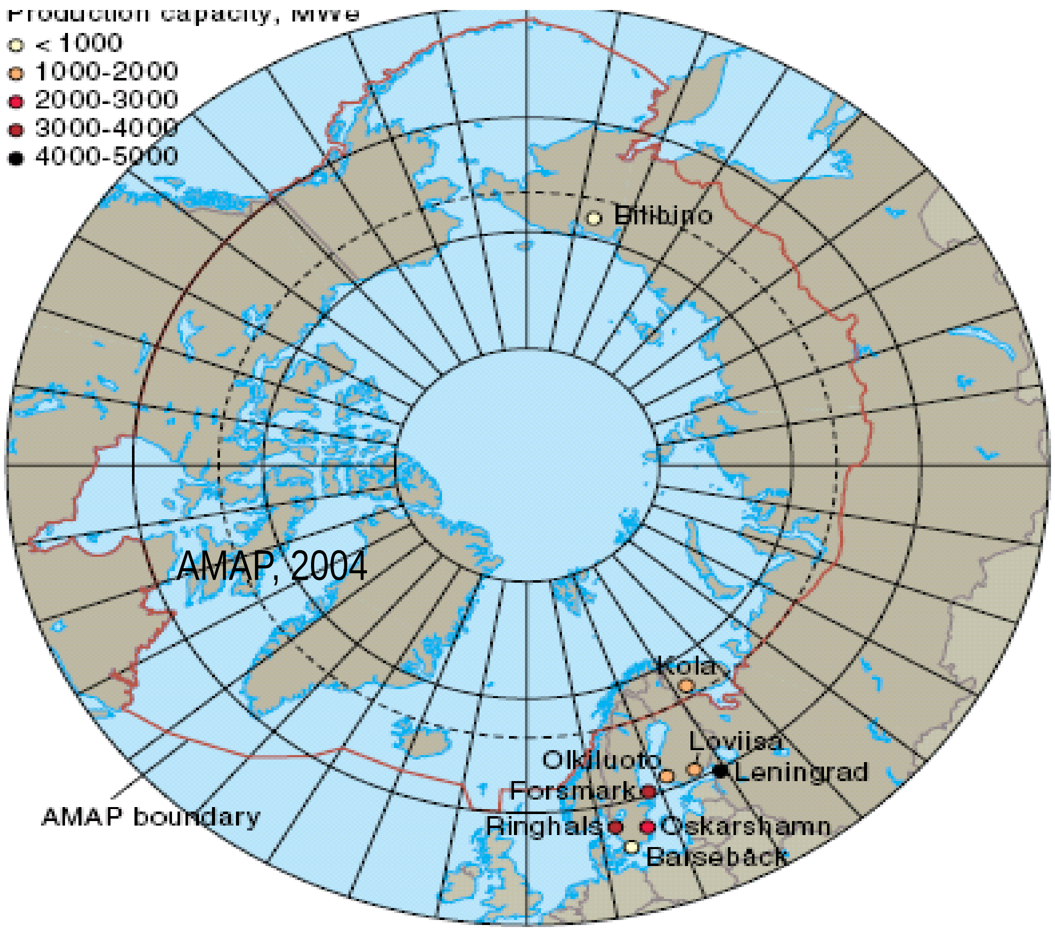
- Dirty Bombs: conventional detonations (TNT) of radioactive material
- Detonation can kill, the radioactivity will hardly kill – panic can kill. Radioactivity must be announced
- Silent killers - target persons/group of person - no announcement
- Contamination of food, drinking water, buildings, streets etc- announcement is essential

Or just the threat of the action!!

Alexander Litvinenko, November 24, 2008 – 15 GBq Po-210

Potential Sources: Nuclear power reactors

- **Reactors without containment** e.g. Kola reactors, Ingalina, Sozno Bor, Bilibino
- **Chernobyl type** reactors (positive void coefficient)
- **Breeder reactors** with liquid Na
- Maintenance, stability of power supplies, safety/ security culture, vulnerable for sabotage/attack?



Photos: http://insp.pnl.gov/-library.htm

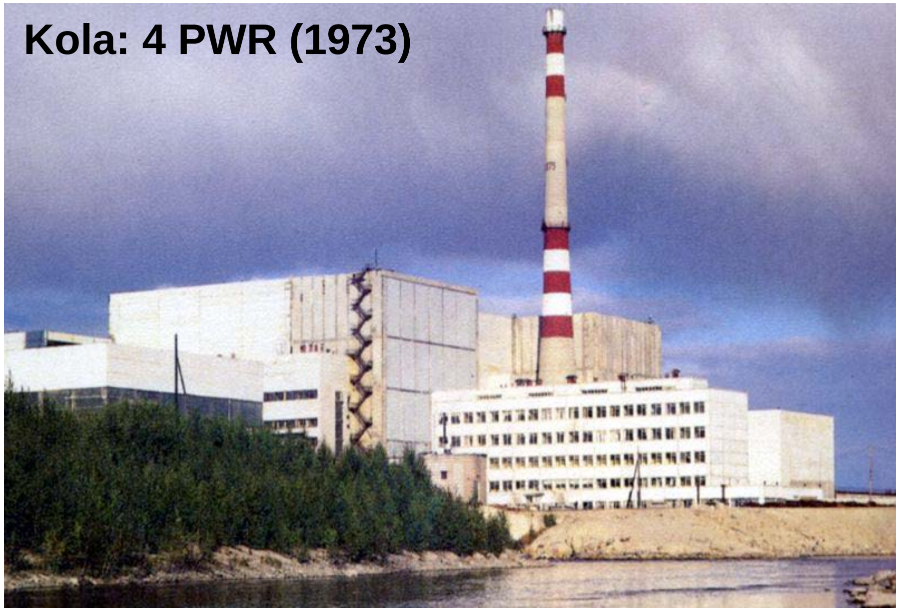
Case: explosion in the Kola reactors - modelling

About 200 km from Norway:

- 4 old reactors
- Poor maintenance
- Poor safety culture

Accidental scenario:

- 1 % of reactor inventory plume.
- Real time weather Norway
- Modelling using SNAP (Severe Nuclear Accident Program)
- Conclusion: Evacuation in Northern Norway should be expected
- Severe impact close to the source, nuclear refugees



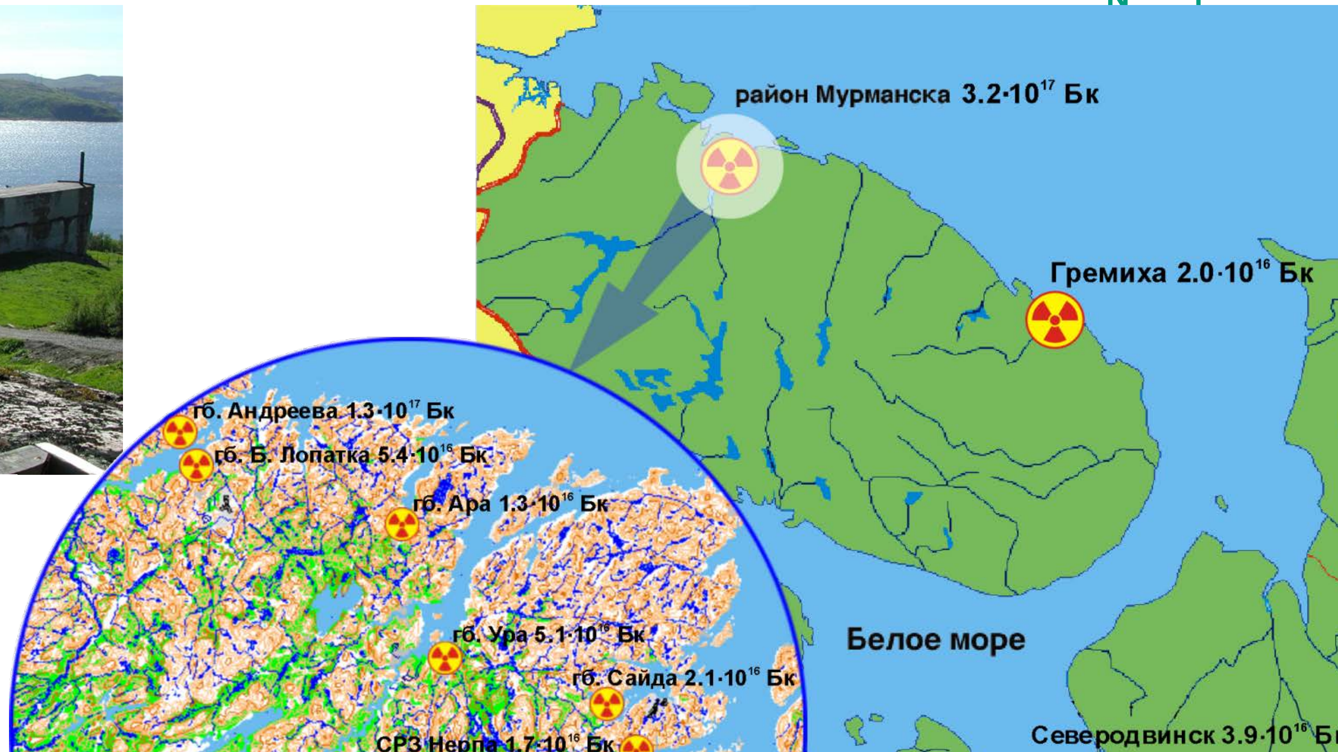
NW Russia: Reactor driven submarines (Ølgaard, 2001)

- Nuclear submarines
  - About 33 operative nuclear Russian submarines
  - North Fleet.
- Nuclear driven ice-breakers
  - Murmansk Shipping Company:
  - six operational icebreakers
  - icebreaking freighter/container ship.
- A floating nuclear power reactor at Kola is under planning.

- Until 2000: 4 submarines are sunken, 36 accidents have occurred, 378 associated fatalities.
- A reactor driven submarine was hijacked at the harbour of Severomorsk, Russia-September 1998. Nine killed.
- Worst case scenario in Norwegian fiords: severe accidents, acute health effects and severe environmental effects are expected

Spent nuclear fuel, solid and liquid radwaste at Andrejeva and Gremikha (FMBA) – relatively easy access

Temporary storage of spent nuclear fuel at the Andreev bay, 50 km from Norway



Facility	SNF		SRW		LRW	
	Number of cores	Bq	tons	Bq	tons	Bq
Andreeva Bay	80	1.3×10^{17}	16824	2.6×10^{14}	3042	8.1×10^{11}
Gremikha	8	2.0×10^{16}	734	1.2×10^{13}	-	-

Norwegian –Russian expert Group: a series of projects carried out to reduce risk of releases

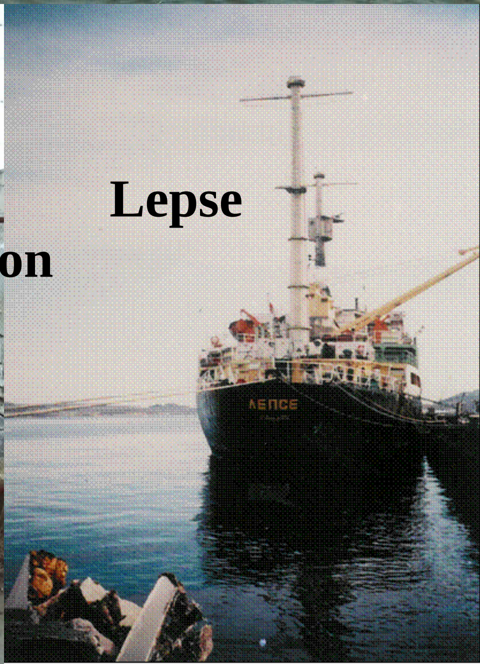
Sources to be removed

- Decommissioning of nuclear powered submarines (4-5)
- Lepse project: decommissioning
- RITEG: 126 Sr-90 batteries in lighthouses replaced by solar cells by 2007

Many sources left

RiTEG

Radon



Lepse

Case: Attack on installations/waste storages - rough estimates of releases from inventories

Crash with air craft and subsequent explosion/fire in

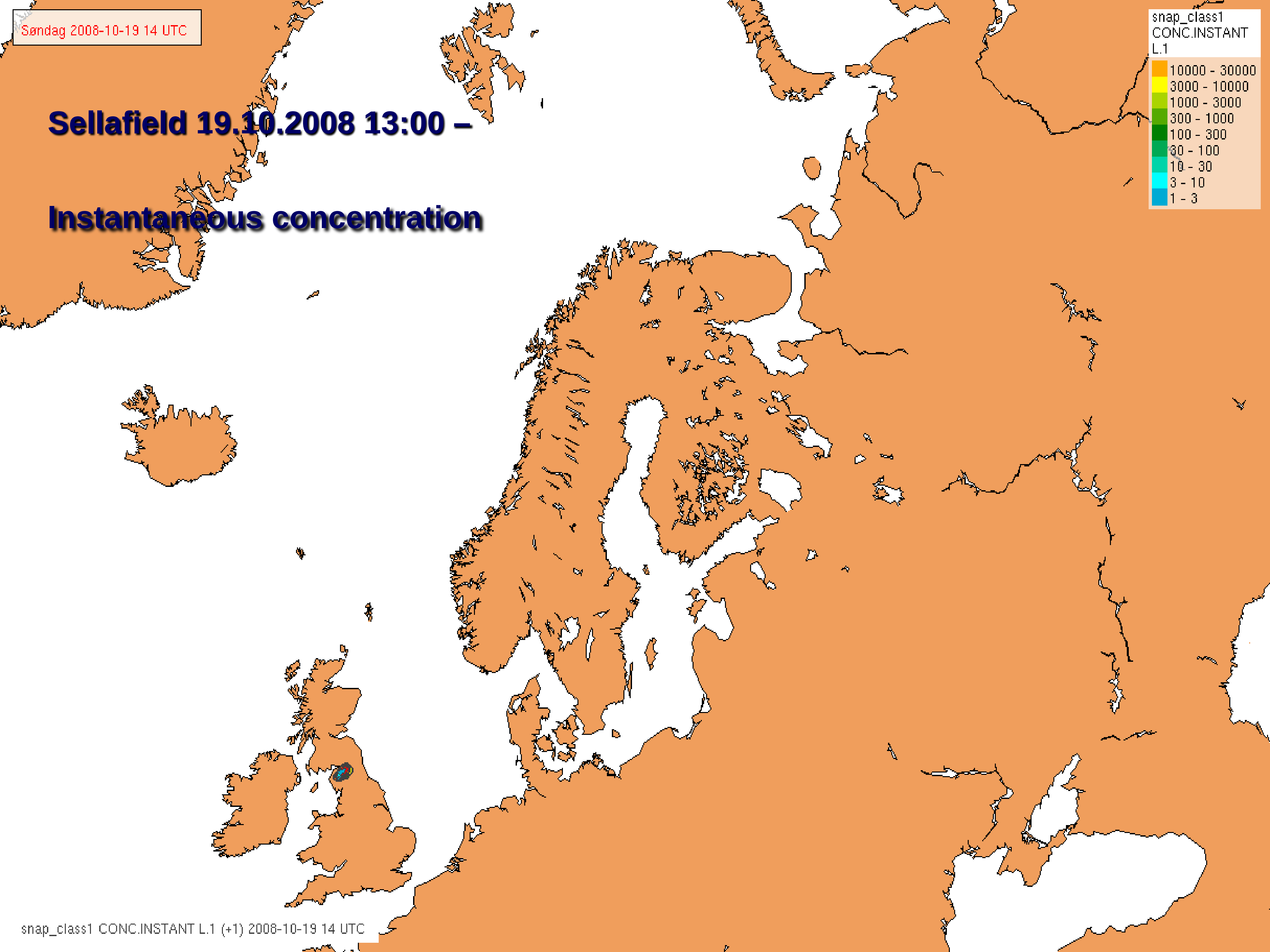
- Case La Hague, France, waste reservoir (reservoir D) – release of Cs-137 to air corresponding to about 70 x that released from the Chernobyl reactor.
- Case Sellafield, UK in waste reservoir (building B215) release of 50 % of Cs-137 to air, corresponding to about 50 x that released from the Chernobyl reactor.

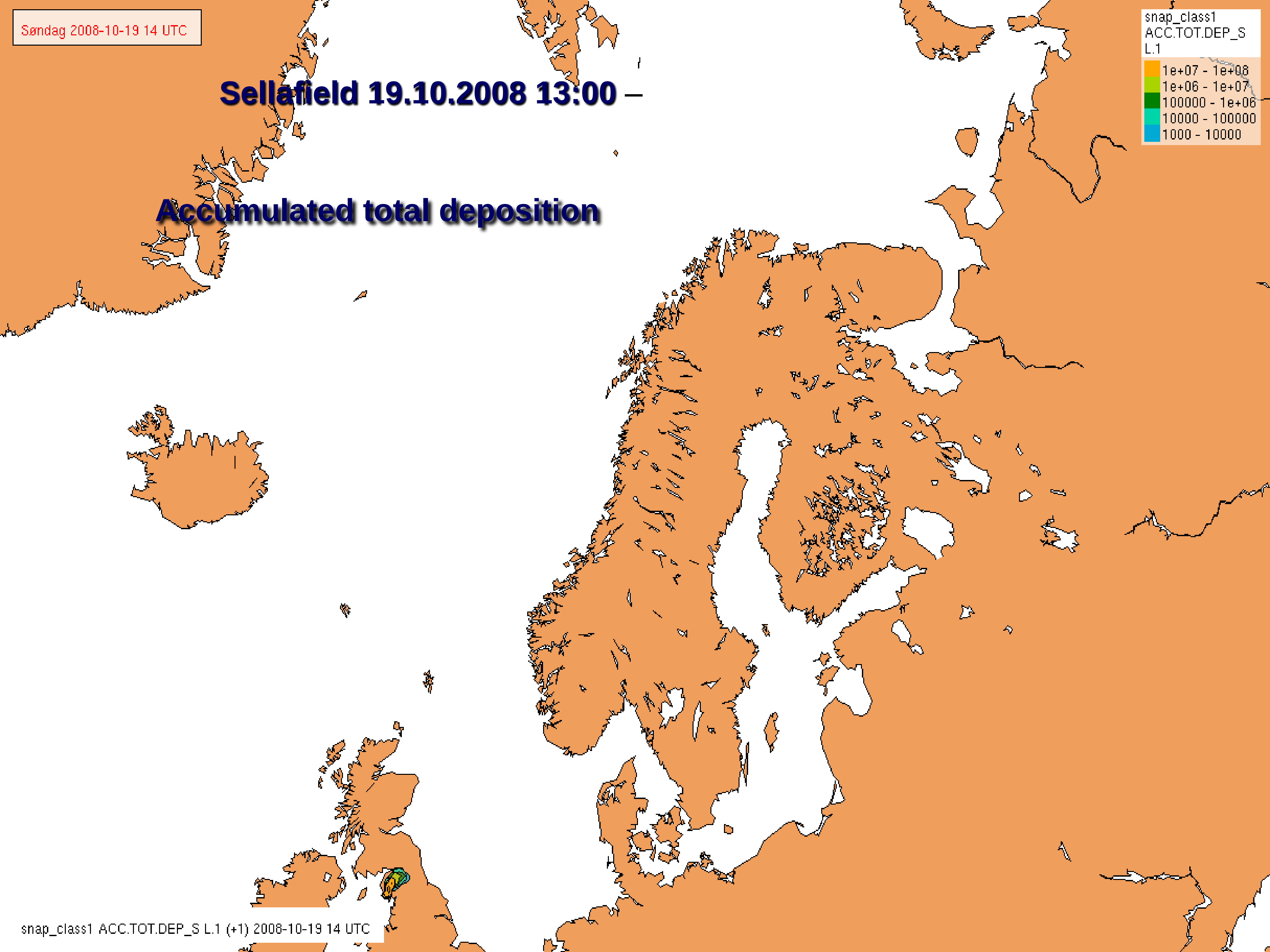
Attack on installations/waste storage - modelling

- Case II Sellafield high activity liquid waste (HAL) from B215 (spent Magnox fuel, Thorp) ca 1000 m^3 waste in 21 containers. Need cooling.
- Accidental scenario: explosion or fire, release of ca 0.1 til 10 % of the Cs-137 in the waste in the form of aerosols and particles varying in size and density.
- Modelling using SNAP and real time meteorological data from October 2008 (prevailing weather conditions).
- Conclusions: 9 hrs after release – deposition over Norway. Deposition at the Western Norway – 10 times higher than the Chernobyl accident (still needed).

Sellafield 19.10.2008 13:00 –

Instantaneous concentration





Søndag 2008-10-19 14 UTC
Sellafield 19.10.2008 13:00 –
Accumulated total deposition
snap_class1
ACC.TOT.DEP_S
L.1
1e+07 - 1e+08
1e+06 - 1e+07
100000 - 1e+06
10000 - 100000
1000 - 10000
snap_class1 ACC.TOT.DEP_S L.1 (+1) 2008-10-19 14 UTC

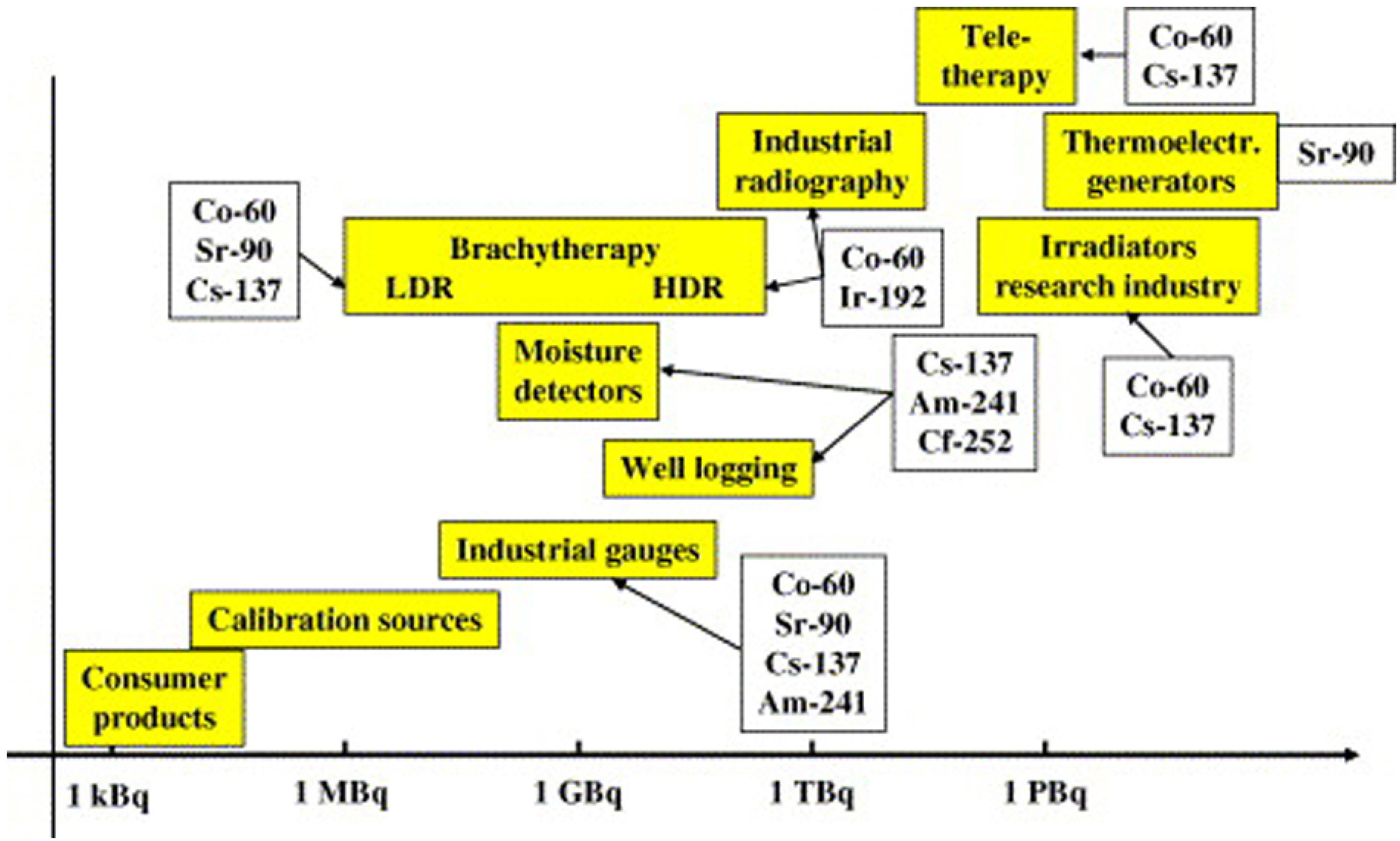
Orphan sources

- High activity radioactive sources are in widespread use around the world – due to civil (medical, industrial and academic) and military purposes (Sr-90 batteries).
- IAEA (2009): No reliable information about number of sources.
- Abundance: US Nuclear Regulatory Commission (2007): about 53 700 Category 1 and 2 sources are in use in USA.
- Central Asia during the last 50 years: estimated more than 100 000 sources - poor regulatory control – 30 % lost?

- Data base on Nuclear Smuggling, Theft and Orphan Radiation Sources (DSTO) records: 33 malevolent radiological acts, of which only 3 are related to terrorism (Steinhausler and Zeitseva, 2007)

- Terror or just incompetence or no knowledge

Orphan sources: harm depends on radionuclide and inventory
Easy access – a series of civil sources (hospitals etc)
The IAEA Safeguard on U and Pu is essential



(IAEA 2003)

Case: dirty bombs – modelling (Smith and Carrigan, 2003)

- Case 1: Cs-137 source (74 TBq) exploded (TNT) at Trafalgar Sq in the middle of the day
- 50 % released as breathable particles - areosols dispersed by the wind
- 50 % large particles that were deposited locally
- Effects from external gamma radiation (for 1 hr) + that inhaled

Conclusion:

- Mortality: due to TNT explosion/blast
- Short term dose to people close to source: about 20 mSv = 10 x average background dose due to natural radioactivity in UK – rise in fatal cancer of about 1 in 1000.
- Mortality: Panic

Securing orphan sources

Essential to secure that orphan sources are kept under regulatory control to reduce the risk of accidental exposure and to avoid any intentional misuse, by supporting the countries with respect to:

1. Regulation: regulating authority in place
2. Registration: national registry of radioactive sources,
3. Identification of lost sources
4. Search and contain strategies
5. Physical security and safety

IAEA Revised: Threat categories

Threat category	Accidental releases from different sources	Consequences
O	Nuclear weapons	Enormous
I	Reactors without containment: old reactors, Chernobyl type reactors	Deterministic effects far outside the site
II	Reactor driven ships, spent fuel storage (criticality accidents)	Deterministic effects locally, serious health and environmental effects regionally
III	Satellite accidents, Waste disposal sites, RTGs (15 PBq Sr-90). Radiation facilities at hospitals	Deterministic effects locally, serious to moderate health and environmental effects regionally
IV	Dirty bombs, lost sources Transport of radioactive materials	Serious to moderate health and environmental effects locally
V	European power reactors with containments	Moderate to insignificant

Sources – transport – consequences: Speciation - mobility - uptake

Source term → Transport → Biol. uptake → Biol. effects

physico-chemical forms

mobility

transformation f(t)

bioavailability

Countermeasures

Short and long term assessment of consequences

Conclusions – unforeseen events

- There are sufficient installations and objects at risk, and thousands of sources are out there
- The risk of unforeseen events – mobile sources - depends on access, intention and capacity/capability:
  - WHO WILL DO THE HARM
- Physical security is more important than ever
- Safeguards and national regulatory system/ control/search procedures are essential. Missing in several countries
- Large sources - best control - major consequences
- Sources under poor control - local consequences, but could be serious for those few affected
- Poor knowledge and panic will kill
- Knowledge is essential to mitigate radiophobia and to properly handle a future nuclear event

Conclusions – uncertainties in impact and rik assessments

Simple models are most useful
if the uncertainties are acceptable.
Model improvement – reduce the overall
uncertainties

- Ma… ses will influ… y influence biolog… at different sensitive history life stages.
- Adding problems with variability, questionable assumptions, and gaps in knowledge; a series of factors are contributing to uncertainties in i…
- P… p… e c…
- S… e t… crucial

The predictions are only valid within the boundaries of the overall uncertainties
The predictions are only useful when uncertainties are estimated, communicated and understood

Foto: UMBs fotoarkiv