UK Health Security Agency

Impact of sex and age on prospective off-site health risk assessments of radiological accidents at nuclear sites

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The UK Health Security Agency (UKHSA) is responsible for protecting every member of every community from the impact of infectious diseases, chemical, biological, radiological and nuclear incidents and other health threats.

Introduction

Background and motivation for the project

Approach adopted

- Modification of PACE to account for age and aging

Example dose results

Example risk results

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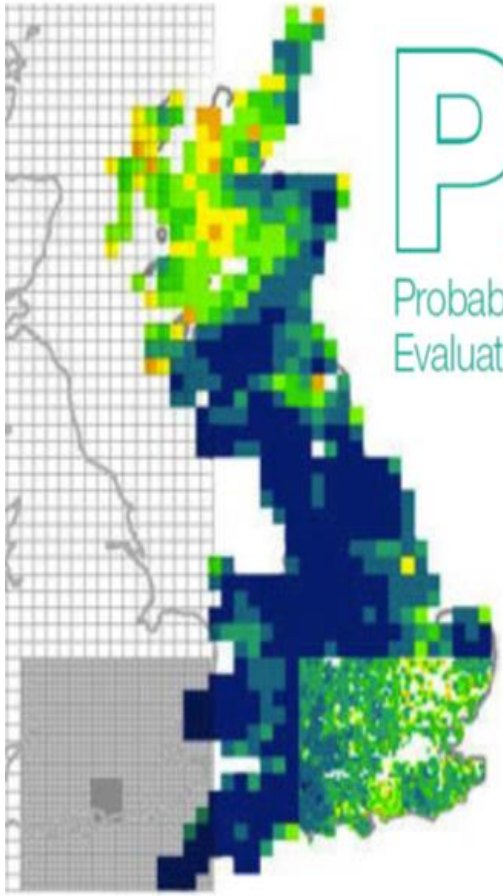
- Implications for operational version of PACE



PACE®
Probabilistic Accident Consequence Evaluation Software

Work sponsored by UK's Office for Nuclear Regulation (ONR)

ONR Office for Nuclear Regulation

Background

- ICRP approach is to use a single age and sex averaged dose to risk conversion factor

- ICRP Publication 147 presents risk of cancer by age – main focus was on medical exposures
  - It states that given the uncertainties with risk projection to low doses, effective dose may be considered as an approximate indicator of possible risk, recognising also that lifetime cancer risk varies with age at exposure, sex and population group

Why do the young and females have a higher lifetime radiation risk?

- Growing tissues more radiosensitive
- Disease has longer to express itself in young
- Some tissues in women more radiosensitive than in men and different organs
- Differences in dietary intake, breathing and smaller body sizes can result in higher tissue doses

Age	**Risk of thyroid cancer in European/Americans (cases per 100 per Gy)**	
	Males	Females
0 to 9 y	0.4	**1.9**
10 to 19 y	0.2	0.8
20 to 29 y	0.06	0.3
From 50 y	0.0	0.01

From ICRP Publication 147 Table 2.4

Motivation

- UK's Office for Nuclear Regulation uses Safety Assessment Principles* to judge nuclear safety cases which includes numerical **risk** targets

- Aim of project was to examine the additional risk for the young and between the sexes to help inform and support regulatory positions taken on new build projects.

- **Assessment of individual risk to people off the site from accidents (Target 7) –** sum of all potential accidents

    - 1×10^{-4} per annum Basic Safety Level (BSL)
    - 1×10^{-6} per annum Basic Safety Objective (BSO)

- **Total risk of 100 or more fatalities (Target 9)** - addressing societal risks from severe accidents

    - 1×10^{-5} per annum BSL
    - 1×10^{-7} per annum BSO

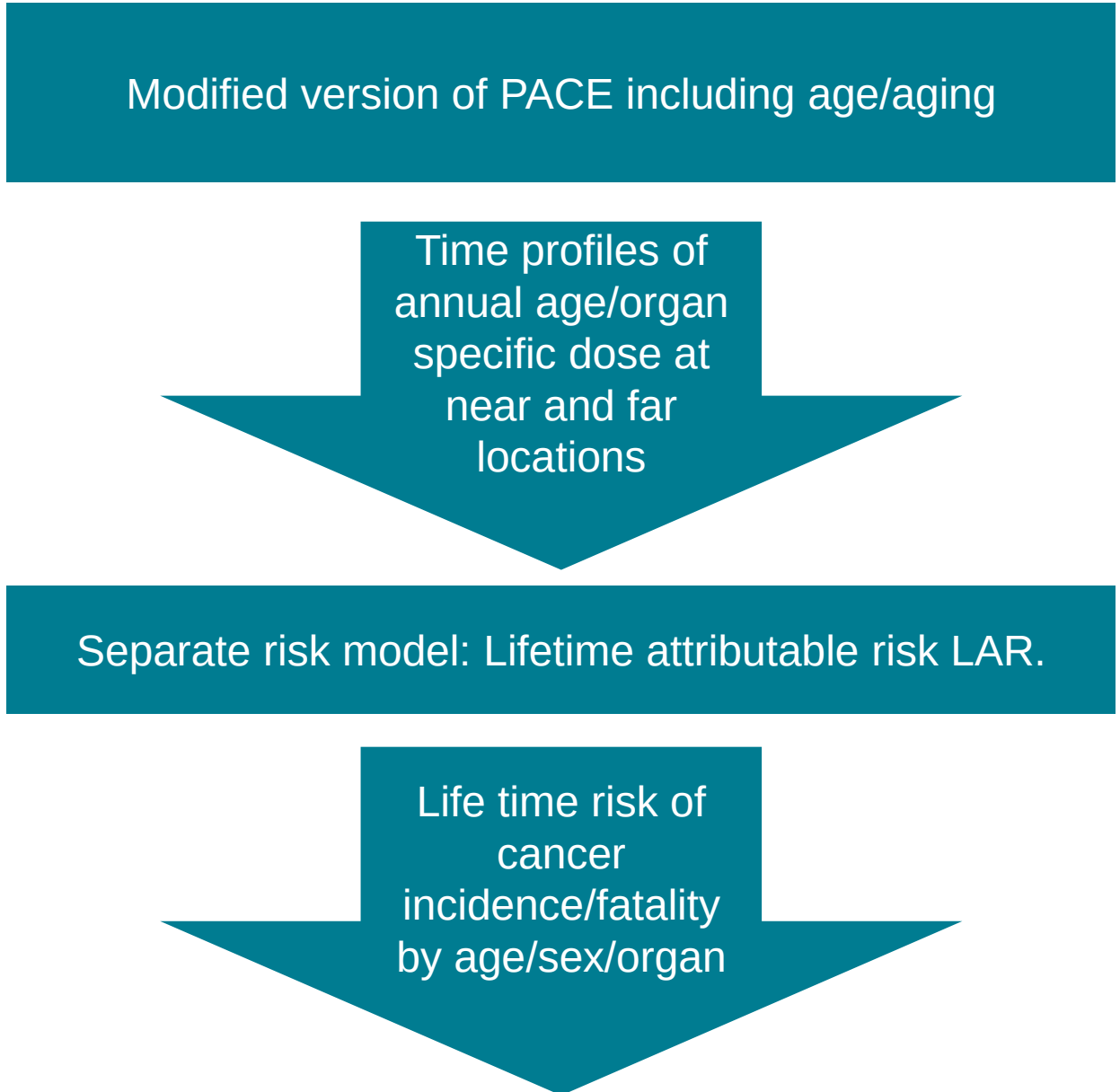
* ONR (rev 1, 2020), Safety Assessment Principles for Nuclear Facilities

Approach – example calculations to explore issues using PACE

- **Four generic theoretical accident source terms** covering range - LWR DB LOCA (ST1), LWR Severe, including ST3, a generic fuel facility based on Mayak, and ST4 based on Chornobyl.
- Deterministic simulations with modified PACE code
- **Two weather conditions (wet/dry), two locations (near/far)**
  - A generic location not intended to represent any specific UK site, facility or process
  - Near, highest risk – target 7
  - Far, societal risk – target 9
- **Dose calculations**
  - Age groups: 1 yr, 10 yr, 35 yr, and 60 yr at time of accident
  - Pathways: inhalation, external from cloud, external from ground and ingestion of contaminated food
  - Range of tissues: thyroid, red bone marrow, colon, breast, oesophagus, lungs, stomach, liver, ovaries, bladder, and remainder tissues
- **Risk calculations** Age and sex dependent risk of death, incidence (ICRP and BEIR VII), ICRP detriment concept
  - Age/sex averaged risk

Modification of PACE

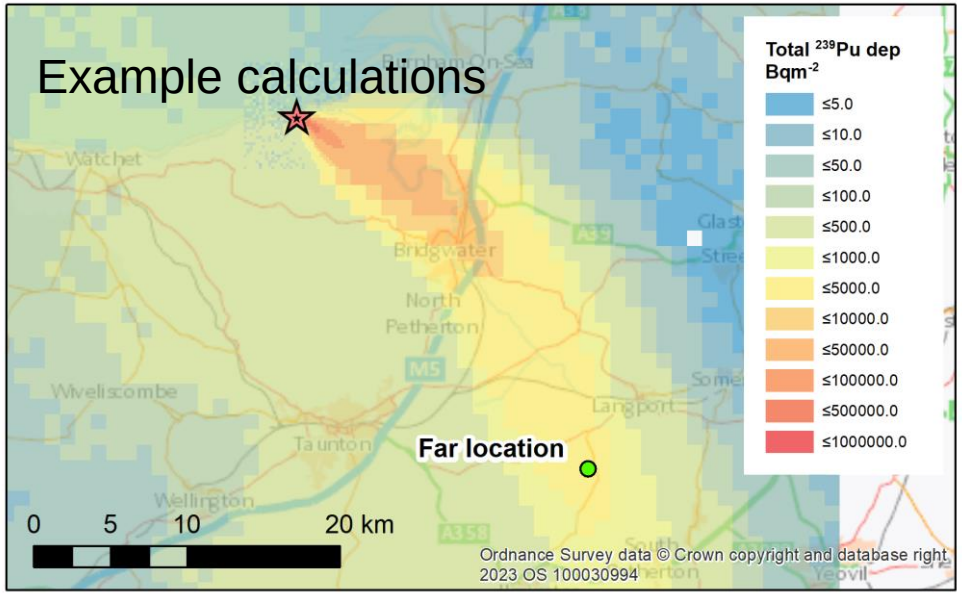
- PACE Probabilistic Accident Consequence Evaluation – Level 3 PSA
- Currently stochastic risk calculation assumes the population is adult, calculates lifetime organ doses, applies risk factors from ICRP 103
- The project required a modified PACE that accounted for age and aging

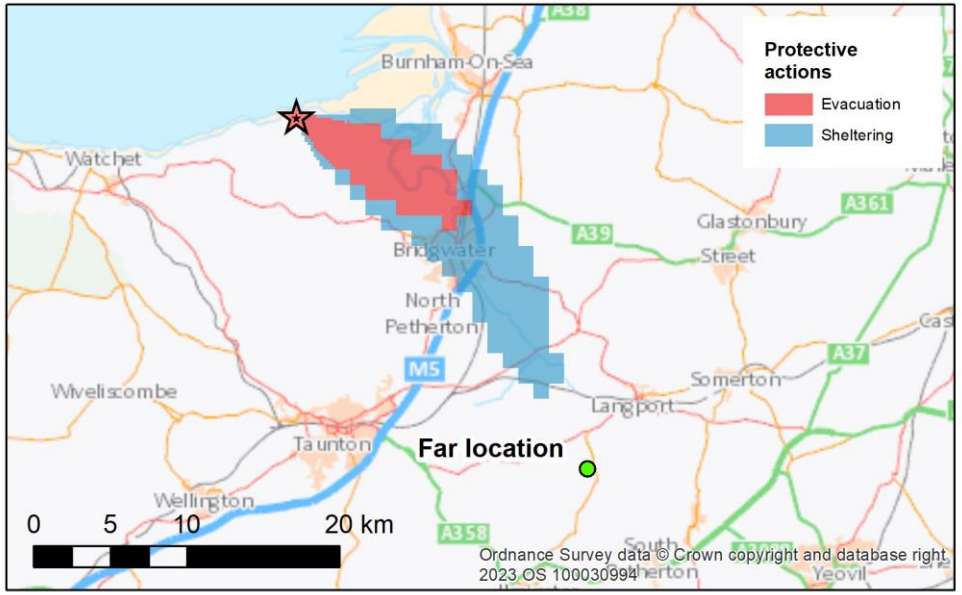


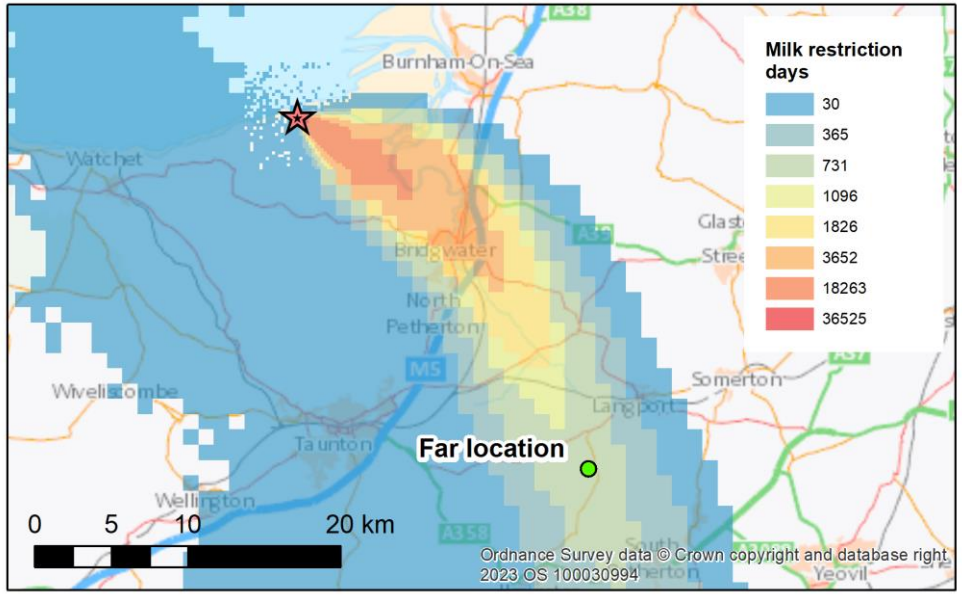
Age and Aging

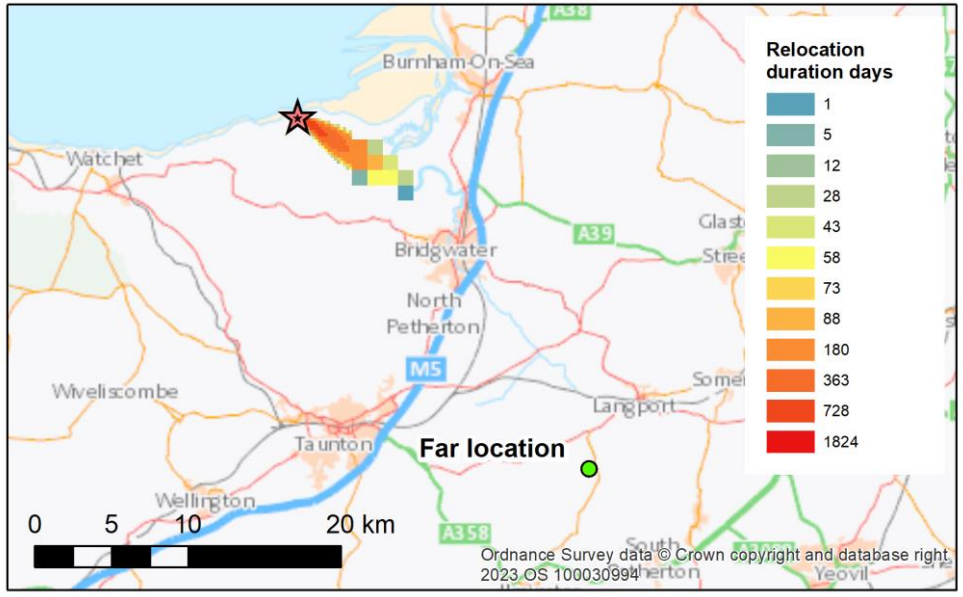
- Exposures in the post-accident situation can be protracted over years, and intakes, habits, and dose coefficients are age dependent
- Exposure is by internal and external pathways
- Risk models require a breakdown of how the dose is delivered over the lifetime of the individual
- Challenge for internal doses:
  - Cancer risk factors are based largely on epidemiological studies of short-term exposures to external sources
  - ICRP 147: it is reasonable to assume that internal doses give an equivalent risk, and summing external dose and lifetime committed dose is acceptable but notes this is conservative for long-lived radionuclides
  - Generally, conservatism is to be avoided in PSA calculations
  - Ingestion - both intake and subsequent exposure are protracted. Food restrictions may mean the highest exposures are not at the time of the accident but occur later.
  - Therefore, delivery of internal doses calculated annually. Then combined with annual external doses and passed to the risk model as a profile of annual total doses over the lifetime of each age group.

Example: severe “fuel cycle” accident based upon the Mayak accident (ST3) – dry conditions









Sheltering and evacuation based on UK’s upper Emergency Reference Levels*

Relocation based on a criteria of 20 mSv y^{-1}

Food restriction based on Maximum Permitted Levels‡

Stable iodine not required for this scenario

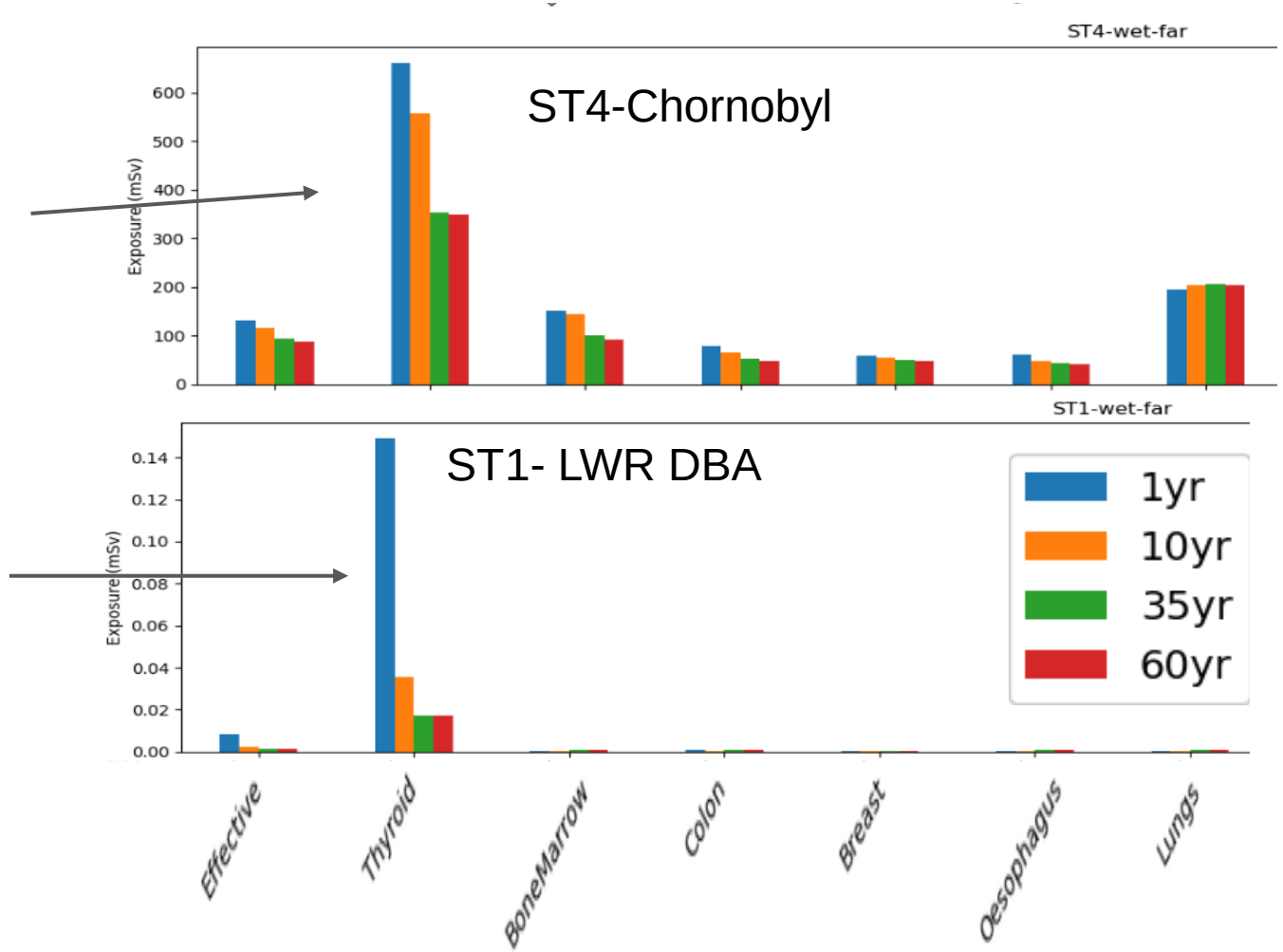
* Public Health Protection in Radiation Emergencies (PHE, 2019)

‡The Food and Feed (Maximum Permitted Levels of Radioactive Contamination) (Amendment) (EU Exit) Regulations 2019

Lifetime organ dose by age, LWR DBA (ST1) compared with Chornobyl (ST4) (far, wet location)

Some dependency seen in lifetime doses. Lower ages almost always have higher doses, but usually less than a factor of 2 higher

Very large difference in LWR DBA due to iodine in ingestion pathway and 1-year-old consumption rates. No food restrictions as very low deposition means not justified and hence doses are low



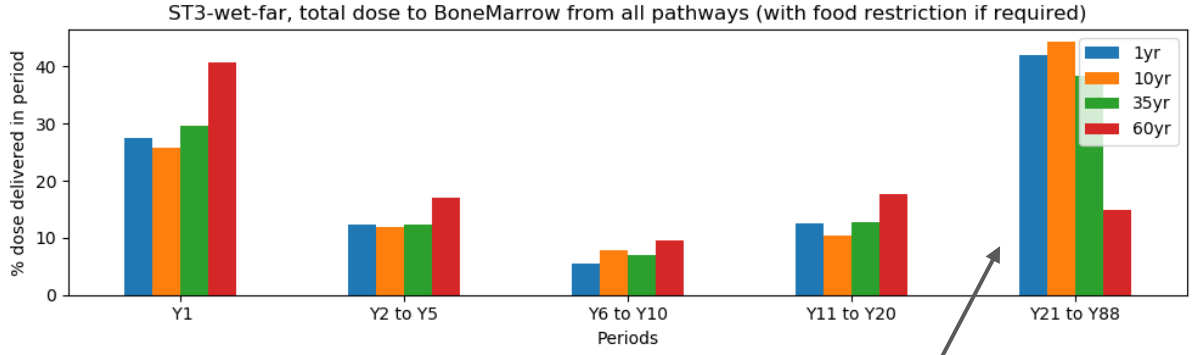
Example dose results severe fuel (ST3) vs Chornobyl (ST4)
% of total dose deliver by period

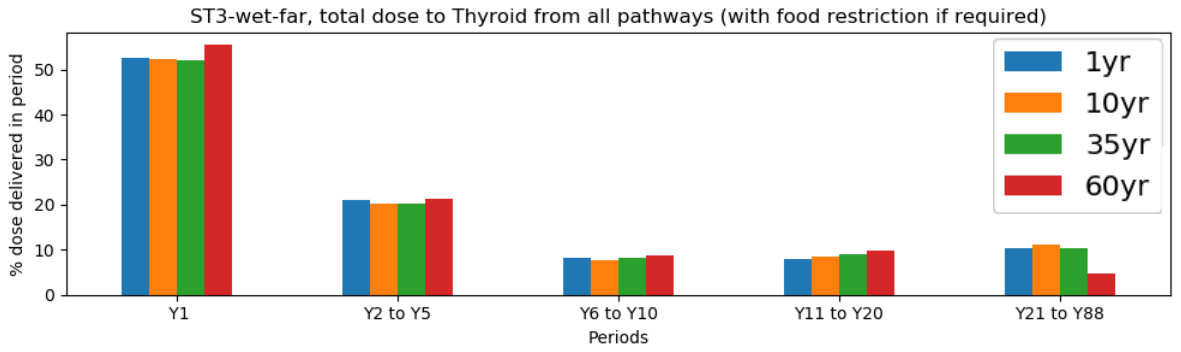
Bone Marrow

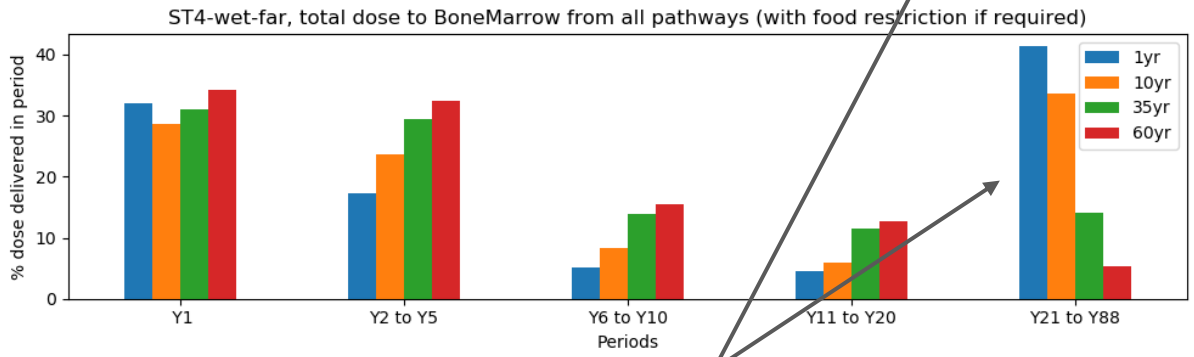
Thyroid

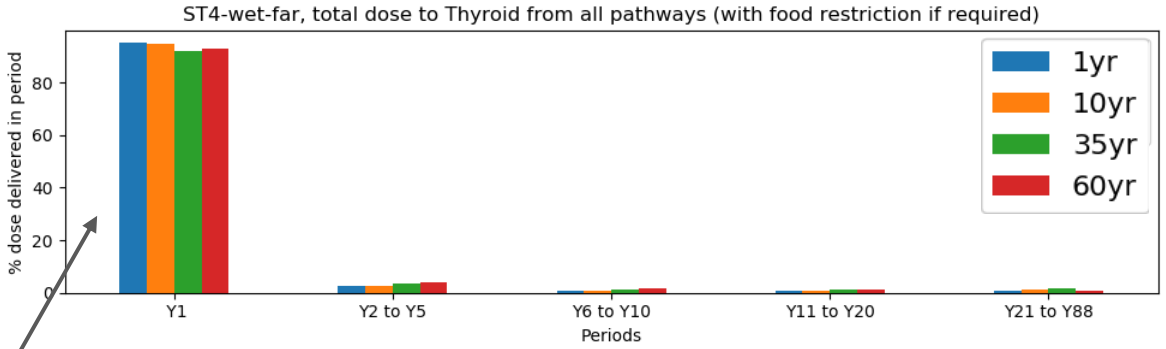
ST3 fuel

ST4 Chornobyl







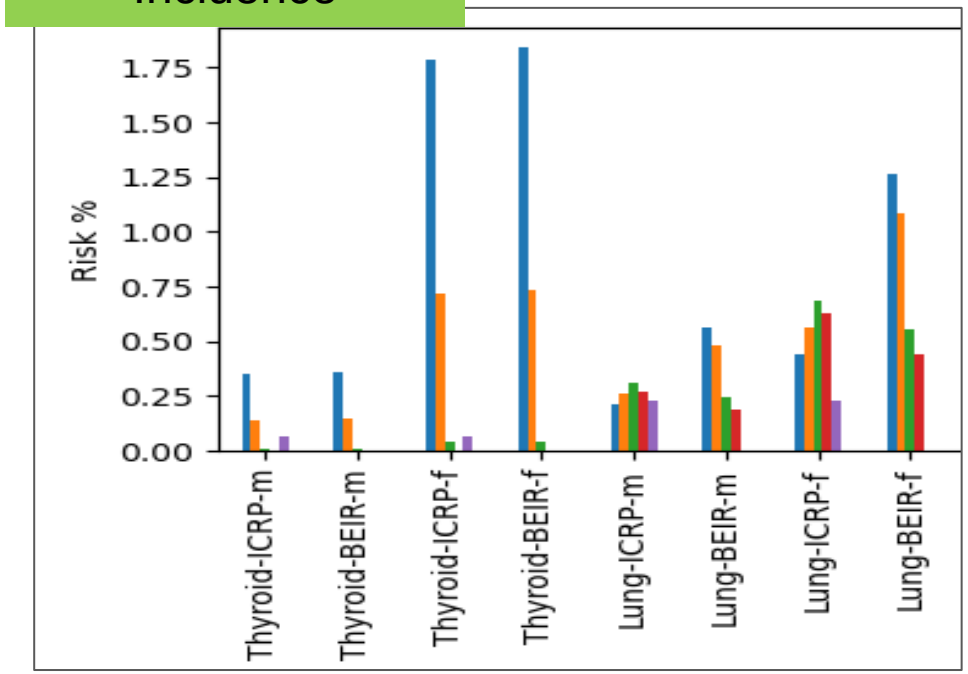


Dose is not necessarily delivered early. For example, about 40% 1-year-old bone marrow dose delivered after 20 years – not appropriate to assume a 1-year-old risk factor?

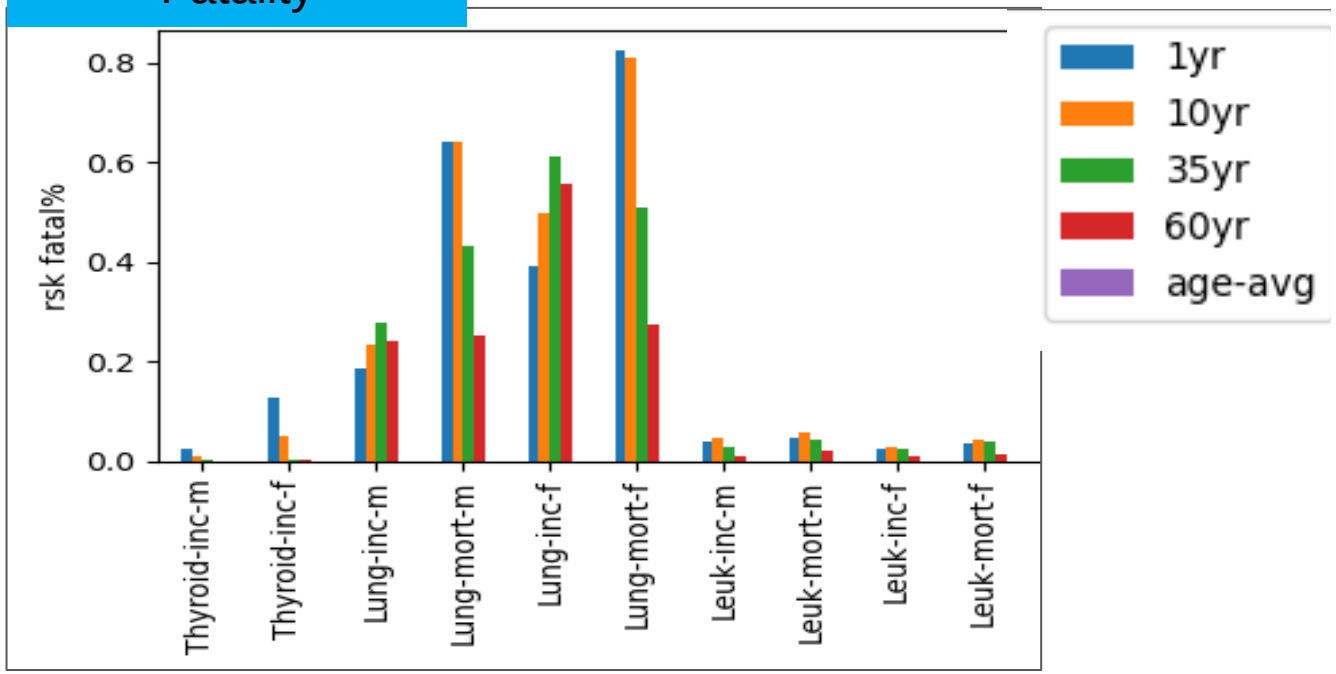
Thyroid dose is delivered early, especially for source terms including iodine.

% organ lifetime attributable risk of incidence and fatality for Chornobyl scenario, far location , dry conditions

Incidence



Fatality



Generally, age-average risk comparable to the 35yr LAR incidence risk
Females generally show higher risk than males of same age (less apparent at older age)
Younger age groups generally show higher risk than older ones of same sex (combined effect of higher doses and higher risk)

"ICRP" – ICRP model
"BEIR" – BEIR model
"m"- male "f" – female
"inc"- a lethality fraction applied to ICRP incidence risk above
"mort" – directly estimated by ICRP LAR model
"m"- male "f" - female

Risks summed across all organs

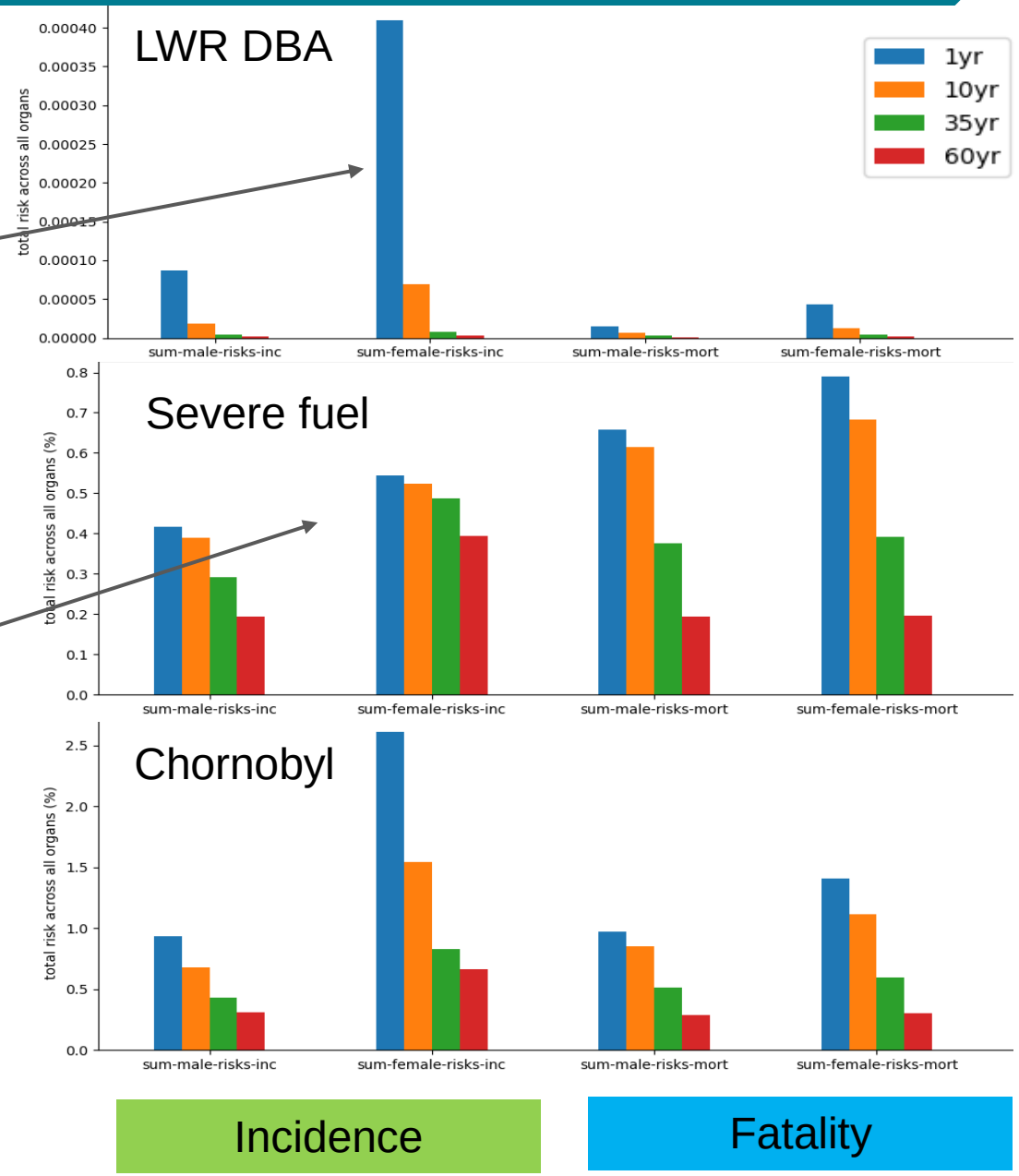
Summed risks show pattern of young females most at risk

However, most of difference driven by thyroid dose/risk differences, esp. Light Water Reactor Design Basis scenario (ST1)

- very low deposition meaning no food restriction justified, very large thyroid dose to infants from ingestion pathway

Uncertainty present in all steps of the calculation

- Risk models involve fitting parameters to observations and are presented without uncertainties. Clearly present e.g. predicted fatality risk > incidence risk!
- Choice of model constraints and parameters e.g. DDREF
- Risk models are largely based on A-bomb survivors, with short acute external exposures. Expected to be more uncertainty in younger ages because of smaller sample sizes - will improve after next analysis



Summary results

1-year old female thyroid cancer incidence risk ranges from up to 100 times the population weighted risk. Large values driven by thyroid dose and ingestion pathway

1-year-old female summed risk of fatality range up to 20 times higher than a population weighted risk

Differences reduce but are still present for 10-yr female (but with arguably less uncertainty)

Table 10 Ratio of effective doses, risk of incidence of cancer for specific organs, cancer fatality and cancer detriment for 1 and 10-year females to corresponding age and sex averaged endpoints for the considered scenarios

		ST1		ST2		ST3		ST4	
		near	far	near[a]	far	near	far	near[a]	far
1-year-old female									
Effective dose		4	5	2	2	1	1	1	1
Incidence[b]	Thyroid	89	106	1	27	13	13	15	27
	Lung	2	2	1	3	2	3	2	2
	Breast[b]	12	12	8	15	13	13	14	13
	Bone marrow (Leukaemia)[c]	1	1	12	1	11	1	3	1
	Remainder	5	5	4	7	6	6	8	8
Fatality		22	22	1	15	3	8	6	7
10-year-old female									
Effective dose		2	2	1	1	1	1	1	1
Incidence	Thyroid	13	14	1	11	6	6	11	11
	Lung	2	2	1	3	2	3	3	3
	Breast[b]	7	7	5	9	8	8	8	8
	Bone marrow (Leukaemia)[c]	1	1	9	1	5	1	3	1
	Remainder	3	3	3	4	4	4	5	5
Fatality		6	6	1	7	3	5	5	5

Implications for PACE

This project used a modified version of PACE and exported dose by year profiles to an external lifetime attributable risk (LAR) model code. Implementation of a full LAR model directly into PACE considered impractical.

Comparison of project results with risks estimated using ICRP147 age/sex specific risk factors and age-specific lifetime organ doses, showed reasonable agreement.

- PACE will be modified to allow multiple age/sex specific cohorts and age/sex specific factors
- Implementation of the aging scheme also considered impractical (especially without a LAR model). Simplified aging model later?

		ST1 near	ST1 far	ST2 near	ST2 far	ST3 near	ST3 far	ST4 near	ST4 far
Incidence	Thyroid	2	2	1	2	2	2	1	2
	Lung	2	2	1	2	2	2	2	2
	Breast	2	2	2	2	2	2	2	2
	Bone marrow (Leukaemia)	1	1	8[b]	1	7[b]	1	3[b]	1
	Remainder	2	2	2	2	2	2	2	2
Fatality[a]		3	3	1	4	2	4	3	4

Table 11 from Project report ONR863.
onr863-onr-rrr-132-impact-of-age-and-sex-on-risk-issue-1_redacted.pdf

Closing remarks

- The full report can be found here

[onr863-onr-rrr-132-impact-of-age-and-sex-on-risk-issue-1_redacted.pdf]

- ONR consider that the current targets in their Safety Assessment Principles still work, but nuclear site licensees and regulators need to understand why and how this is the case, the limitations, and current international developments and improvements in this area
- ICRP are working to update their risk estimates and their system of radiological protection including Task Group on Update of Detriment Calculation for Cancer

- Any questions?