Quantification of Errors in Doses,

International Collaborative Study of Cancer Risk among Radiation Workers in the Nuclear Industry

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Studies of radiation workers

Atomic bomb survivors + *People exposed for therapeutic reasons*

Moderate to high doses
High dose rate

↓

Protection standards against ionizing radiation

↓

General population + *Nuclear workers*

International Collaborative Study among Radiation Workers

Low doses
Low dose rate

Estimation of risk due to low doses of radiation

Radiation workers

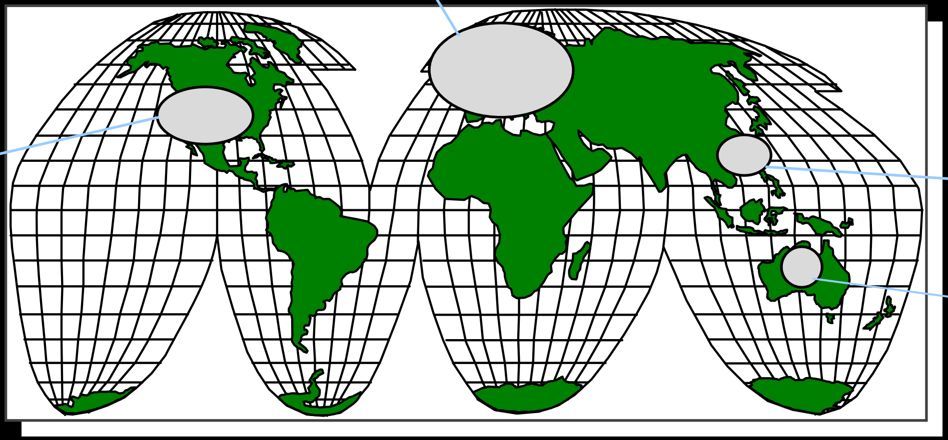
- **Characteristics of the population**
  - ✓ *Very large, stable populations*
  - ✓ *Well characterized external exposures*
    - ➔Generally low doses, protracted
    - ➔Mainly external γ–radiation
  - ✓ *Detailed individual annual dose estimates*
    - ➔measured in real time with personal dosimeters

… Relevant population for radiation protection

International Study

Belgium Finland France Hungary Lithuania Slovakia Spain Sweden Switzerland United-Kingdom

Canada
United-States



Japan
South Korea

Australia

International Agency for Research on Cancer

World Health Organization

Study population

- **All workers** **598,068**
- **Main exclusions**
  - ✓ *Employed less than 1 year:* *113,711*
  - ✓ *Not-monitored for external radiation:* *38,521*
  - ✓ *Potential for substantial doses from radionuclide intake:* *39,730*
  - ✓ *Potential for substantial doses from neutrons:* *19,041*
- **Main study population:** **407,391**

Radiation types

- **Workers exposed to neutrons, intake of radioactivity (other than tritium)**

  … flagged and excluded from main analyses

  - ✓ *Problems of dose estimation*
    - ➔ Inadequate technology, monitoring
    - ➔ Recording of different quantities (%ALI, …)
    - ➔ Lack of information on chemical form, intake route, etc.
  - ✓ *Proportion of such workers generally small (high dose group)*

- **Study of errors in dosimetry restricted to workers exposed predominantly to “higher” energy photon radiation (100 to 3 000 keV)**

Study of Errors in Dosimetry

- **Objectives of the Study**

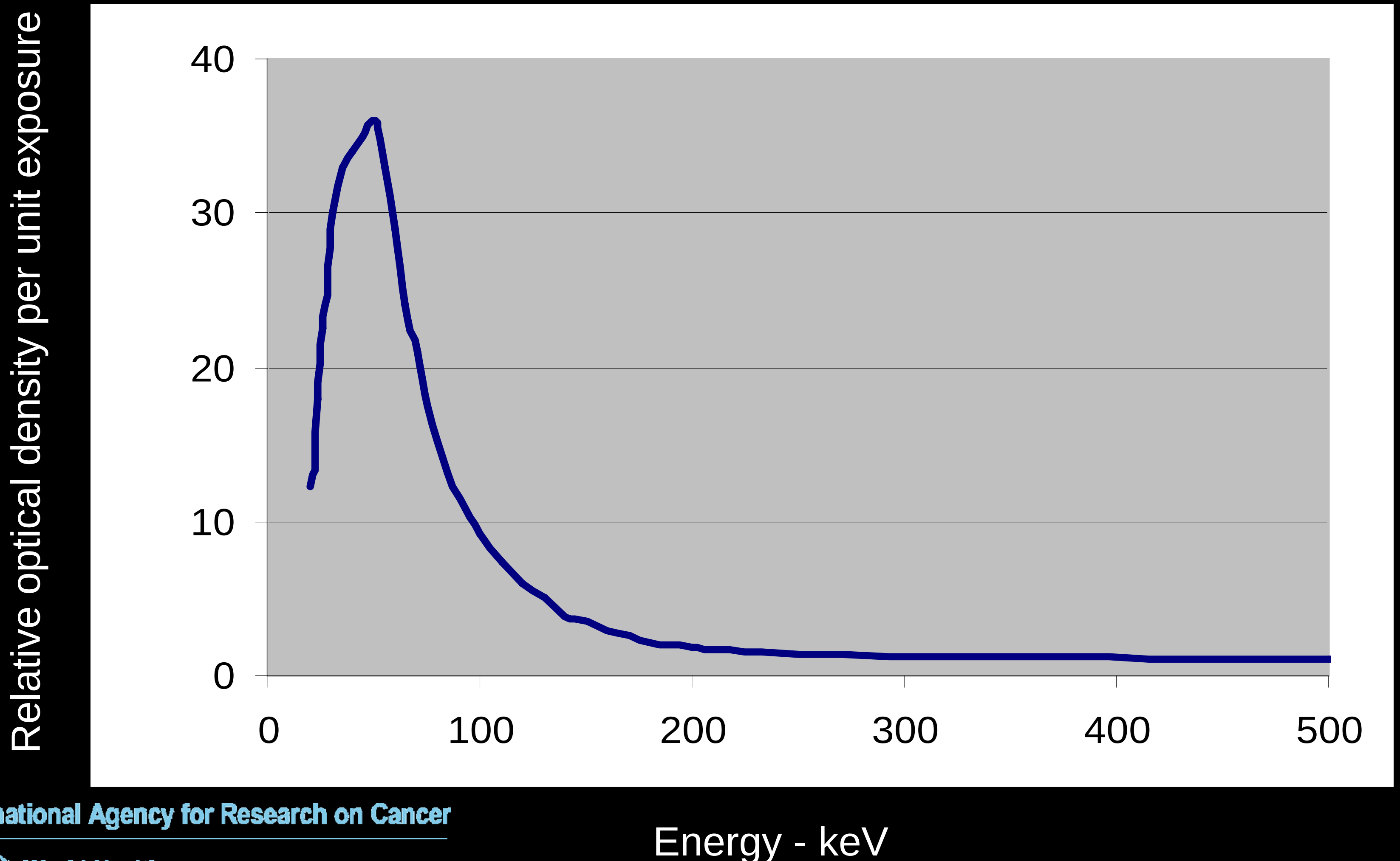
  - ✓ *Comparability of doses recorded in different facilities from the 1940 's up to now*
  - ✓ *Identification of sources of errors*
  - ✓ *Quantification of errors to take them into account in the risk estimate*

Identification of sources of errors

- **Dosimetry technology**
  - ➔ Response to energy & geometry
  - ➔ Laboratory practices (dosimeter processing & reading)
- **Conditions of exposure**
  - ➔ Energy and geometry
  - ➔ Other environmental factors (heat, humidity, light..)
- **Calibration practices**
  - ➔ Dosimetric quantity
  - ➔ Radiation source used for calibration & factors affecting sources
  - ➔ Backscatter factor
- **Administrative practices**
  - ➔ Frequency and criteria of monitoring
  - ➔ Rules for below threshold doses and for missing doses

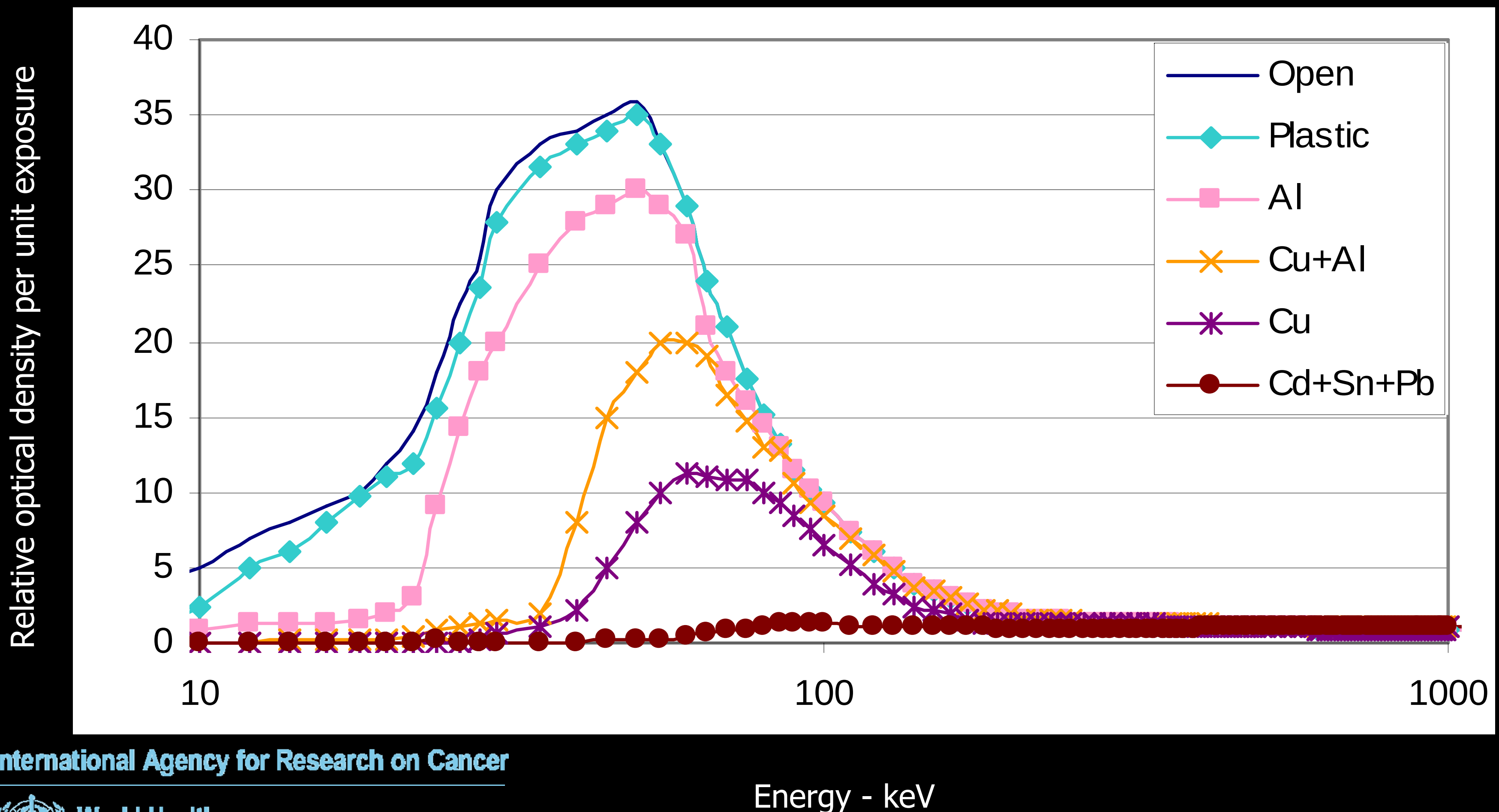
Film dosimetry

- **Energy response of the film (Kodak type 1)**



Film dosimetry

- **Filters (PS-1 Dosimeter)**



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Study of dosimeter response

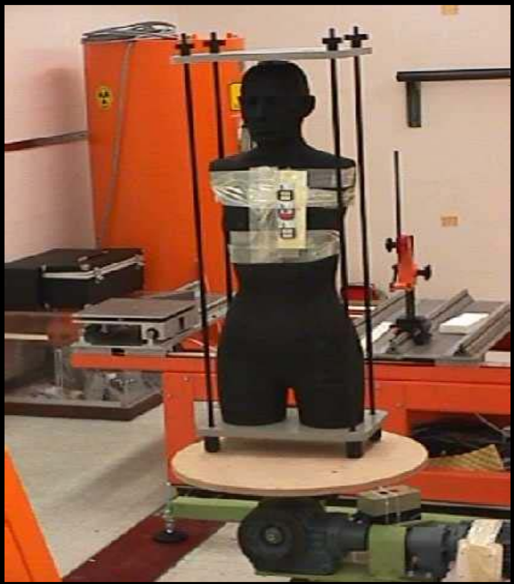
- **Classification by category**
  - ✓ Photographic dosimeters
    - ➔ **bare film**
    - ➔ **one filter**
    - ➔ **multi-element**
  - ✓ TLDs
  - ✓ Uncommon dosimeters

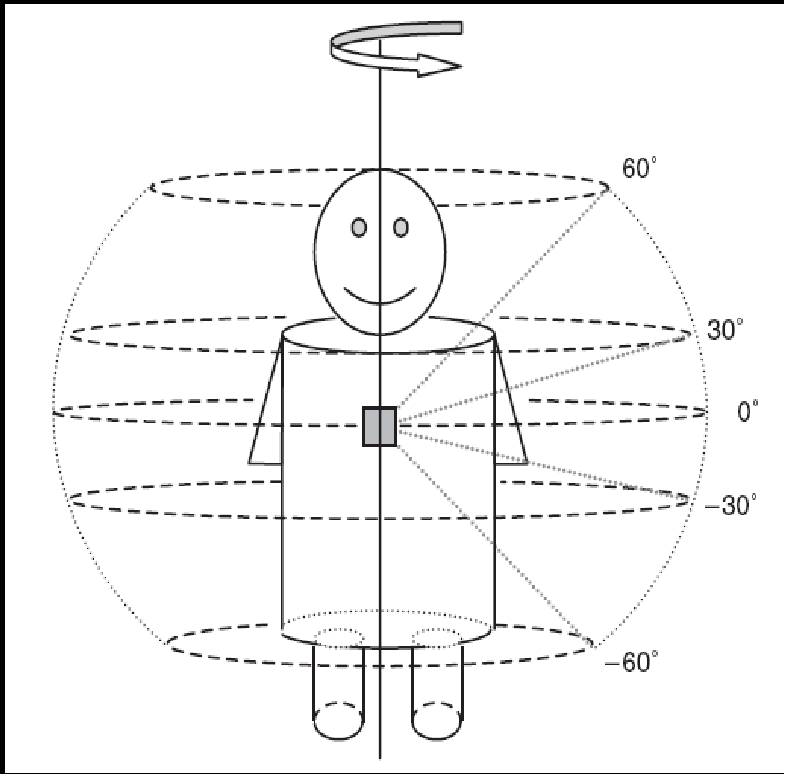
- **Selection for experiments**
  - ✓ 10 types – 5 dosimeters per type
  - ✓ 3 energies (118 – 208 – 662 keV)
  - ✓ 3 geometries (AP – ROT – ISO)

Thierry-Chef I. et al (2002). Radiat. Prot. Dosim. 102(2): 101-113.

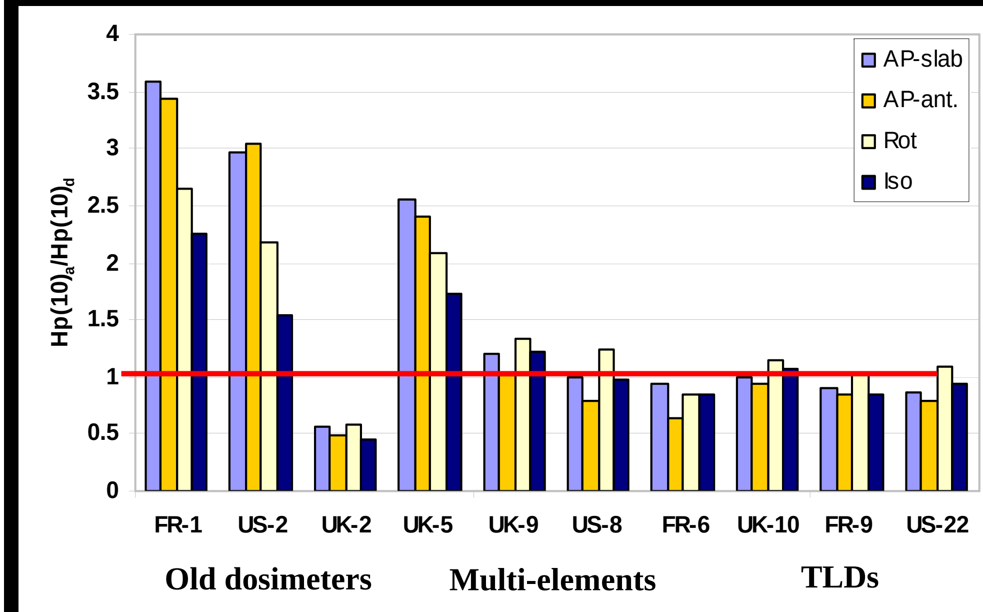
Experiments

- AP
- Rotational
- Isotropic



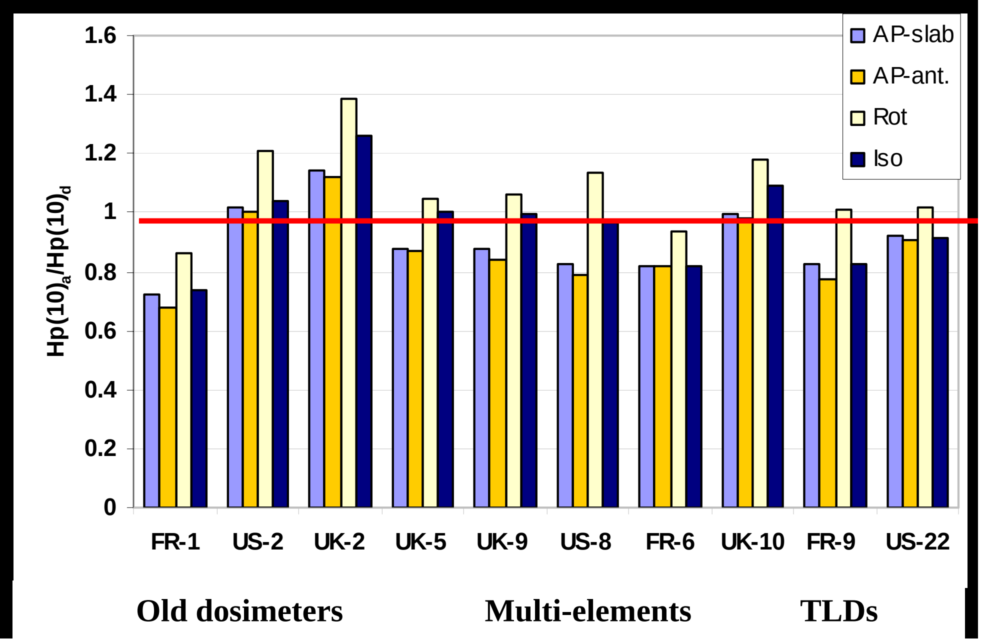


Dosimeter response



662 keV

118 keV



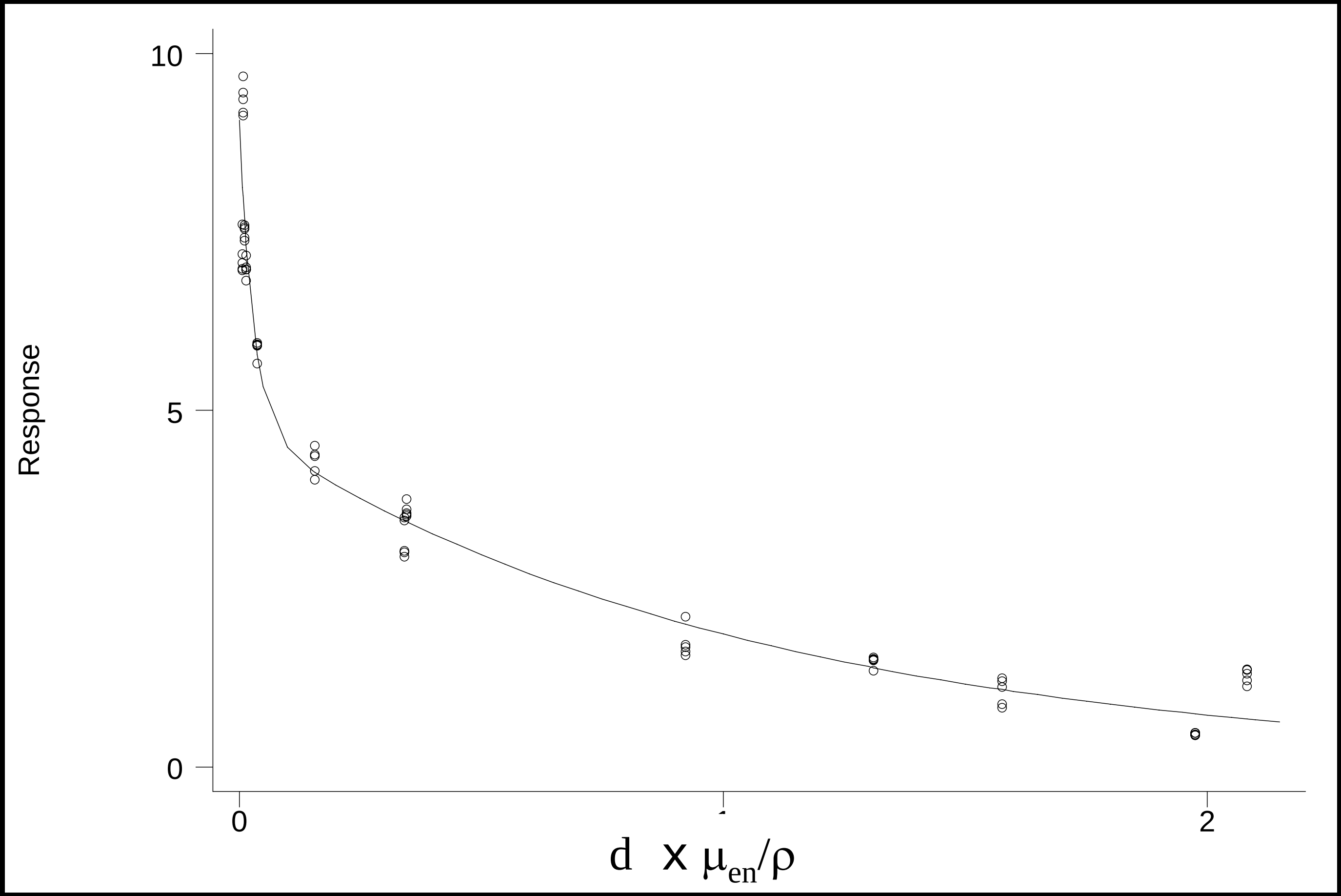
Dosimeter response

- **Bias** - $B_{energy,geometry}$

Code	FILTERS	DENSITY (mg cm^{-2})	RESPONSE $H_p(10)_a/H_p(10)_d$ (Bias factor)								
			118 keV			*208 keV*			*662 keV*		
			A.P.	*ROT*	*ISO*	*A.P.*	*ROT*	*ISO*	*A.P.*	*ROT*	*ISO*
Open											
CA-1	Cd	346									
CA-2	Cd	864									
UK-1	Cd	864									
US-1	Cd	1000									
US-2	Ag	**1000**	***3.04***	***2.17***	***1.55***	***1.18***	***1.38***	***1.11***	***1***	***1.03***	***1.04***
US-3	Pb	580									
UK-2			***0.49***	***0.58***	***0.46***	***0.86***	***0.70***	***0.52***	***1.12***	***1.38***	***1.26***
….	….	….									
UK-4	Fe + Pb +Al	250+635+124									
UK-5	Tinplate		***2.40***	***2.09***	***1.73***	***1.24***	***1.22***	***1.12***	***0.87***	***1.05***	***1***
Multielements			*0.82*	*1.14*	*1.01*	*0.89*	*1.04*	*0.98*	*0.81*	*1.04*	*0.93*
TLDs			*0.86*	*1.09*	*0.95*	*0.92*	*1.09*	*0.98*	*0.89*	*1.07*	*0.94*

Extrapolation of results

- Old dosimeters



Uncertainties on dosimeter response

- **Uncertainty related with the conduct of the experiments including:**
  - ✓ *Reproducibility of position of dosimeters*
  - ✓ *Uncertainty in dose delivered*

  … $K_{experiment} = 1.1$

- **Uncertainty related to dosimeter response**
  - ✓ *Based on the 5 dosimeters per type irradiated at each energy and for each geometry*

  … $K_{response}$

Condition of exposure

- **Nuclear power plants - Swiss power plants**
- **Mixed activity facilities - Saclay – France**

- **Expertise**
  - ✓ *<u>Predominant energies</u> :*
    - ➔ **%** of average dose due to photons in 3 energy ranges: 0-100, 100-300, 300-3000 keV
  - ✓ *<u>Predominant geometries</u>:*
    - ➔ **%** of average dose due to 3 geometries of exposure : A.P., rotational or isotropic

Expert evaluation in Saclay

Waste sector	INB-1							INB-2						
		Energy (keV)			Geometry				Energy (keV)			Geometry		
Activity	Number	0-100	100-300	300-3000	A/P	Iso	Rot	Number	0-100	100-300	300-3000	A/P	Iso	Rot
Health physics	3	-	20	80	-	100	-	3	-	-	100	-	100	-
cleaners	2	-	20	80	-	100	-	1	-	-	100	-	100	-
Maintenance	2	-	20	80	-	100	-	2	-	30	70	50	50	-
Decontamination	15	-	20	80	20	80	-							
Waste treatment								3	-	-	100	80	20	-
Waste reception treatment								3	33	33	33	-	100	-
Conditining of combustible waste								4	-	-	100	100	-	-

Thierry-Chef, I. et al. (2001) Radiat. Prot. Dosim. 94(3):215-225

Conditions of exposure – Summary

- *f(energy) & f(geometry)*

Coefficients	ENERGY -keV-			GEOMETRY		
	0-100	*100-300*	*300-3000*	*A.P.*	*ISO*	*ROT*
NPP	***0***	***0.1***	***0.9***	***0.5***	***0.5***	***0***
Variations between workers	0-0.01	0.05-0.2	0.8-1	0.1-0.8	0.2-0.9	0
Mixed activities	***0***	***0.2***	***0.8***	***0.5***	***0.5***	***0***
Variations between workers	0	0.15-0.25	0.75-0.85	0-0.6	0.4-1	0
Variations between installat.	0	0.15-0.25	0.75-0.85	0.4-0.55	0.45-0.6	0

Dosimetric bias

$$B_d = \mathbf{Exp}\Big[\, f(100\text{-}300) * f(AP) * Ln(B_{100\text{-}300,AP}) +$$

$$f(100\text{-}300) * f(iso) * Ln(B_{100\text{-}300,iso}) +$$

$$f(300\text{-}3000) * f(AP) * Ln(B_{300\text{-}3000,AP}) +$$

$$f(300\text{-}3000) * f(iso) * Ln(B_{300\text{-}3000,iso}) \Big]$$

Related uncertainties

- K_d

$$ln K = 1.96 \sqrt{(\sum_i S_i^2)}]$$

  - ✓ $K_{experiment}$
  - ✓ $K_{response}$
  - ✓ $K_{exposure}$
    - ➔Uncertainty related to conditions of exposure, takes into account the response of dosimeter in "extreme" conditions
    - ➔the upper and lower bounds provided by the experts

Dosimetric factors – Hp(10)

Facility type					Calendar	Dosimeter		*100-300*		*300-3000*		B_d	K_d
	$f_{100\text{-}300}$	$f_{300\text{-}3000}$	f_{AP}	f_{ISO}	Period			AP	ISO	AP	ISO	$H_p(10)$	$H_p(10)$
1-Mixed Activities	0.2	0.8	0.5	0.5	1950-56	Bare	Film	3.27	4.82	0.9	0.99	**1.26**	*1.40*
					1957-66	E-1	Film	1.17	1.17	0.68	0.73	**0.78**	*1.12*
					1967-95	E-6	Multi.	0.63	0.62	0.81	0.81	**0.77**	*1.11*
					1985-95	E-9	TLD	0.86	0.83	0.78	0.82	**0.81**	*1.15*
2-NPP	0.1	0.9	0.5	0.5	1968-82	E-3	Film	1.80	1.61	0.90	0.99	**1.00**	*1.12*
					1982-97	E-4	Film	0.73	0.56	0.90	0.99	**0.91**	*1.12*

Conversion to organ dose

Conversion	100-300 keV		300-3000 keV	
Organ dose	AP	ISO	AP	ISO
RBM	0.52	0.77	0.63	0.79
Colon	0.79	0.69	0.85	0.73
Lung	0.74	0.86	0.82	0.85

Uncertainty factor K_{organ}=1.103

Dosimetric factors – organ dose

Facility	Period		Dosimeter		B_d $H_p(10)$	K_d $H_p(10)$	B_d lung	K_d lung	B_d RBM	K_d RBM	B_d colon	K_d colon
1	50	56	Bare	Film	**1.26**	*1.40*	**1.53**	*1.43*	**1.83**	*1.22*	**1.62**	*1.85*
	57	66	E-1	Film	**0.78**	*1.12*	**0.95**	*1.16*	**1.14**	*1.19*	**1.01**	*1.27*
	67	95	E-6	Multi.	**0.77**	*1.11*	**0.94**	*1.16*	**1.12**	*1.29*	**1.00**	*1.18*
	85	95	E-9	TLD	**0.81**	*1.15*	**0.98**	*1.18*	**1.18**	*1.27*	**1.04**	*1.25*
2	68	82	E-3	Film	**1.00**	*1.12*	**1.21**	*1.19*	**1.44**	*1.37*	**1.28**	*1.15*
	82	97	E-4	Film	**0.91**	*1.12*	**1.09**	*1.16*	**1.31**	*1.17*	**1.16**	*1.26*

Calibration factors

- ✓ *Backscatter*
- ✓ *Calibration source*
- ✓ *Factors affecting sources*

Facility	Period		Backscatter		Calibration source		Other factors		Final cal. factors	
	Start	End	B_{back}	K_{back}	B_{source}	$K_{soucrce}$	B_{fact}	K_{fact}	B_c	K_c
1	67	97	1.06	1.05	1	1	1	1.05	**1.06**	**1.07**
2	45	58	1.06	1.05	1	1.2	1	1.05	**1.06**	**1.22**
	59	97	0.96	1.04	1	1	1	1.05	**0.96**	**1.07**

Overall bias and uncertainty

- **Response of dosimeters to conditions of exposure**
  - ✓ $B_d\,(B_{d,\ Hp(10)}\ \text{-}\ B_{d,\ lung}\ \text{-}\ B_{d,\ RBM}\ \text{-}\ B_{d,\ colon})$
  - ✓ $K_d\,(K_{d,\ Hp(10)}\ \text{-}\ K_{d,\ lung}\ \text{-}\ K_{d,\ RBM}\ \text{-}\ K_{d,\ colon})$
- **Calibration practices**
  - ✓ B_c
  - ✓ K_c
- **Overall bias**
  - ✓ $B=B_d*B_c$
- **Overall uncertainty**
  - ✓ $\ln K= 1.96\ \sqrt{(\sum_i S_i^2)]}$

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Overall bias and uncertainty

Facility	Period		Dosimeter		*B* $H_p(10)$	*K* $H_p(10)$	*B* lung	*K* lung	*B* RBM	*K* RBM	*B* colon	*K* colon
1	50	56	Bare	Film	**1.33**	*1.48*	**1.62**	*1.51*	**1.94**	*1.33*	**1.72**	*1.69*
	57	66	E-1	Film	**0.83**	*1.26*	**1.01**	*1.28*	**1.21**	*1.31*	**1.07**	*1.22*
	67	95	E-6	Multi.	**0.82**	*1.13*	**1.00**	*1.17*	**1.19**	*1.30*	**1.06**	*1.07*
	85	95	E-9	TLD	**0.86**	*1.17*	**1.04**	*1.20*	**1.25**	*1.28*	**1.10**	*1.08*
2	68	82	E-3	Film	**0.96**	*1.14*	**1.16**	*1.21*	**1.38**	*1.38*	**1.23**	*1.29*
	82	97	E-4	Film	**0.87**	*1.14*	**1.05**	*1.17*	**1.26**	*1.19*	**1.11**	*1.18*

$$CF = B/(\exp[S^2/2])$$

Dose distribution

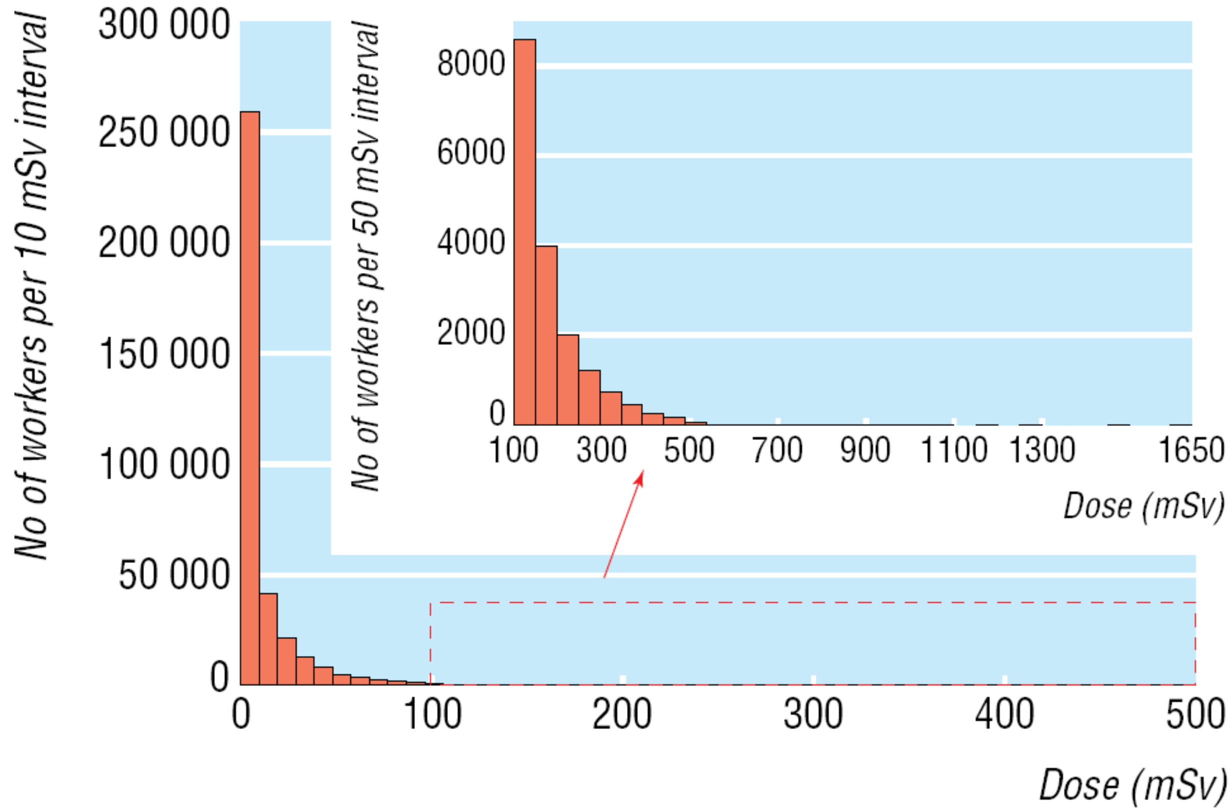

Fig 1 Distribution of cumulative radiation doses among workers included in the analyses

Average cumulative dose = 19.4 mSv

Characteristics of the cohort

Average age at end of follow-up	46.2
Average age at first exposure	30.7
Average length of follow-up	12.7
% of deaths	5.9
Number of deaths	24,158
Number of cancer deaths	6,794

Some important results

- **All cancers excluding leukemia**
  - ✓ *Based on adjusted dose estimates – colon doses*

Inclusion/exclusion	ERR/Sv	90% confidence interval
All countries included	0.97	0.27 – 1.80
Canada excluded	0.58	0.1 – 1.39
UK excluded	1.25	0.26 – 2.43

- **Leukemia excluding CLL**
  - ✓ *Based on adjusted dose estimates – RBM doses*
  - ✓ *ERR= 1.93 per Sv (90% CI < 0 to 7.14)*

Main publications on the 15 country study

- **Methods papers**
  - ✓ *Study of Errors in Dosimetry*
    - ➔ Thierry-Chef et al. (2007) Radiat. Res. 167: 380-395
  - ✓ *Methods and descriptive results*
    - ➔ Vrijheid et al. (2007) Radiat. Res. 167: 361-379
  - ✓ *Method for estimating uncertainties from shared errors*
    - ➔ Stayner et al. (2008) Radiat. Res. 168: 757-763
- **Results papers**
  - ✓ *Short paper : First results*
    - ➔ Cardis et al. (2005) Br. Med. J. 331:77
  - ✓ *Estimates of radiation-related cancer risks*
    - ➔ Cardis et al. (2007) Radiat. Res. 167: 361-379
  - ✓ *Mortality from diseases other than cancer*
    - ➔ Vrijheid et al. (2007) Int. J. of Epi
  - ✓ *Risk of chronic lymphocytic leukemia*
    - ➔ Vrijheid et al. (2008) Radiat. Res. 170:661-665

Conclusions

- **Study of errors in dosimetry focused on photon radiation**
- **Areas of interest for future work**
  - ✓ *Neutron*
  - ✓ *Internal contamination*
  - ✓ *Administrative practices*
    - ➔Need to explore the impact on doses
- **Need for follow-up studies**
  - ✓ *Age of the population (still young)*

Acknowledgement

- Dr Elisabeth Cardis

- The Radiation Group at IARC
  - ✓ Richardson DB, Pearce MS, Vrijheid M, Tardy H, Combalot E

- The Dosimetry Subcommittee members
  - ✓ Marshall M, Fix JJ, Bermann F, Gilbert ES, Hacker C, Heinmiller B, Utterback D, Cowper G

- The Dosimetry and Medical Radiation Physics Section of the IAEA
  - ✓ Andreo P, Pernicka F

- The collaborators from the participating facilities
  - ✓ Murray W, Bernar J, Deboodt P, Eklof M, Griciene B, Holan K, Hyvonen H, Kerekes A, Lee M-C, Moser M, Delacroix D