CERN Summer Student Lecture

5 July 2000

AN INTRODUCTION TO RADIATION PROTECTION AT CERN

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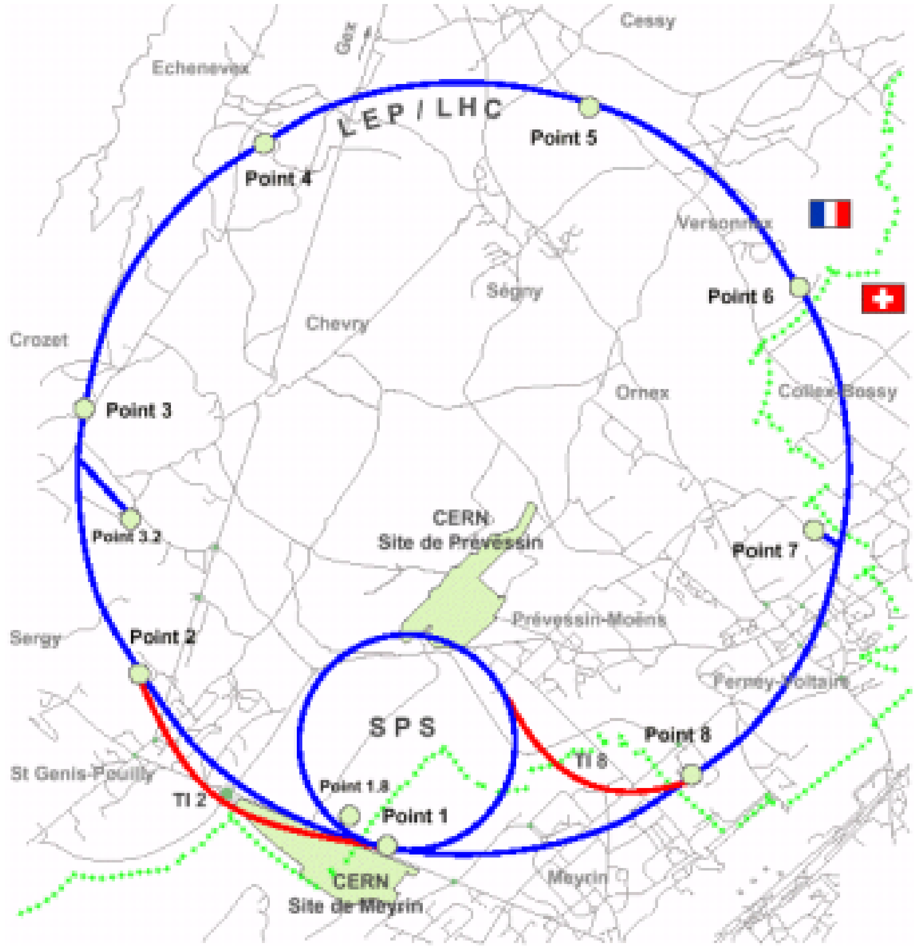
TIS/RP

Objectives of Radiation Protection



- The use of high-energy proton and electron beams for particle physics research automatically brings with it the exposure of persons to prompt radiation escaping from the shielded structures of the accelerators and the production and release of radioactivity into the environment.
- The aim of Radiation Protection is to prevent direct detrimental effects such as death, severe burns *etc.* by shielding and interlocks, and to limit the probability of long-term effects to levels deemed by society to be acceptable.
- All exposures should also be kept as low as reasonable achievable.
- The topics covered in this talk will include:
  1. An Introduction to Radiobiology
  2. Radiation at CERN
  3. Relative Risks

Radiation Units

- The physical quantity used to measure radiation is the:
  ENERGY ABSORBED per UNIT MASS
- This is called DOSE, and the unit used is the GRAY(Gy).
- A dose of 1 Gy is equivalent to 1 J/kg

  - **Temperature rise** $1/(4.2 \times 10^3) = 2.4 \times 10^{-4}$ °C
  - **Kinetic Energy** $\frac{1}{2}mv^2 = mD$
    If $D = 1$ Gy, then $v = 1.4$ m/s
  - **Potential Energy** $\frac{1}{2}mgh = mD$
    If $D = 1$ Gy, then $h = 0.1$ m

Severe Damage Capability

MATERIALS

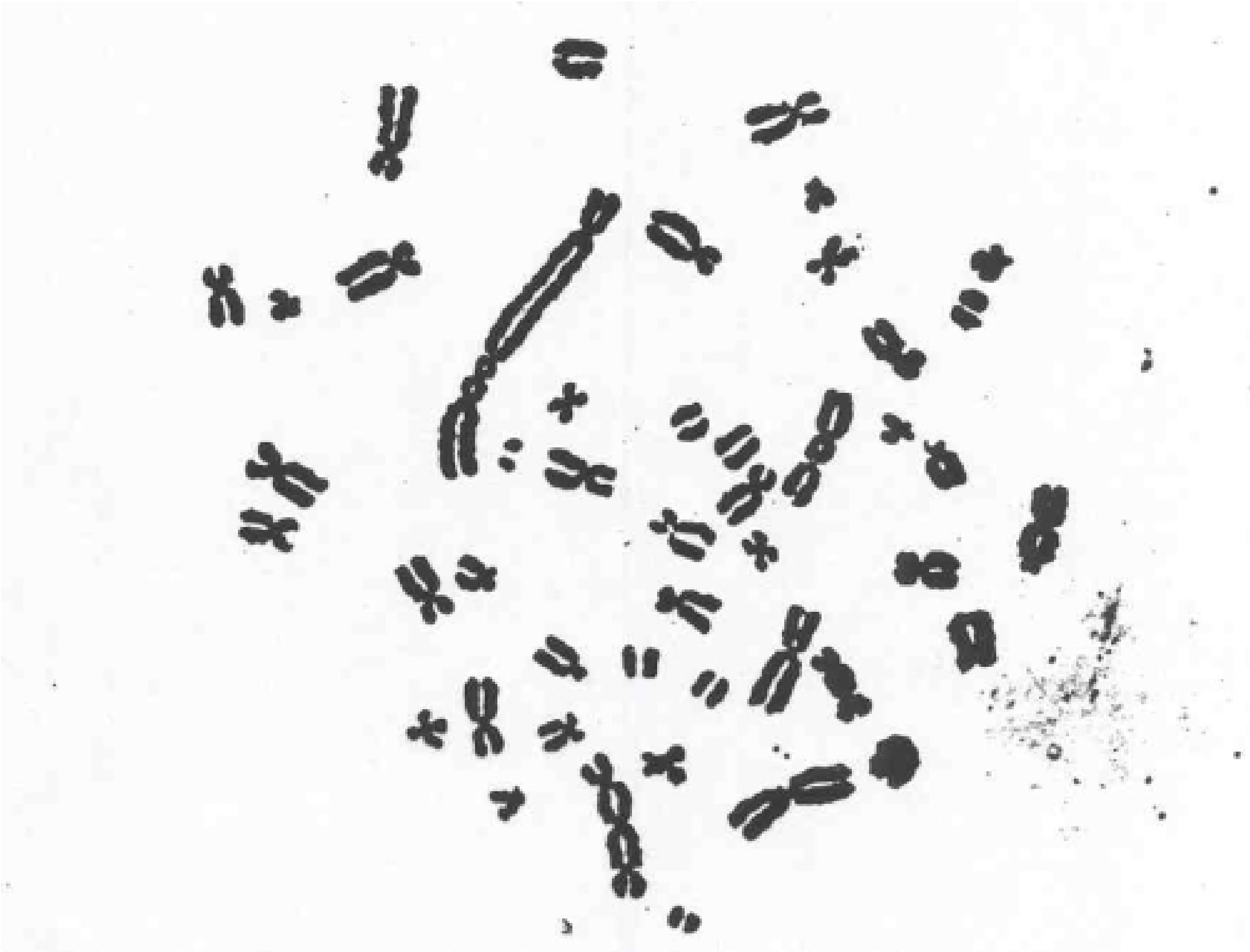
Ceramics	$> 10^{11}$ Gy
Epoxy resins	10^{7}–10^{9} Gy
Perspex (Lucite)	10^{5} Gy
PTFE (Teflon)	10^{3} Gy
Transistors	100–1000 Gy

MAN

Whole Body Dose	Approximate Life Expectancy	Cause of Death
1000 Gy	1 hour	Damage to Central Nervous System
10–100 Gy	3 days	Damage to Gastro-Intestinal Tract
3–10 Gy	30 days	Damage to Blood-forming Tissues (medical treatment successful)
< 1 Gy	> 1–20 years	Normal Life Expectancy (no characteristic effects)

N.B. Damage to white blood cells observed at 0.2 Gy

Chromosome Damage by Radiation



Lethal Doses for Different Species

Animal	$LD_{50/30}$ in Gy
Sheep	1.6
Donkey	1.6
Swine	2.0
Goat	2.3
Dog	2.7
	2.7
Man	2.4
	2.3
Rabbit	8.4
Rat	9.0
Mouse	11–12
Desert Mouse	13–15
Frog	30
Snail	200
Amoeba	3000

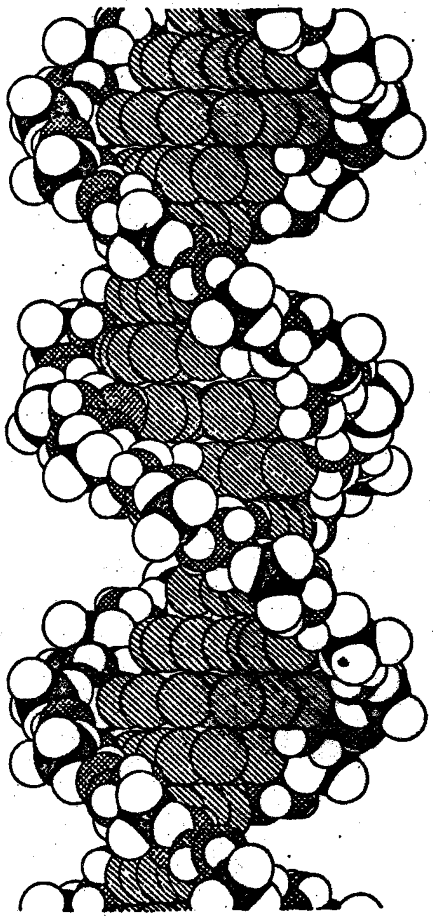
Effects of Whole-Body Irradiation

Dose Range	< 1 Gy	1–2 Gy	2–6 Gy	6–10 Gy	10–15 Gy	> 50 Gy
Vomiting?	No	5–50%	100%	100%	100%	100%
Delay	–	3 h	2 h	1 h	30 min	30 min
Therapy?	Psychotherapy	Psychotherapy, Haematological observation	Blood-transfusion, Antibiotics	Bone Marrow transplant	Electrolyte balance	Symptomatic
Prognosis	Excellent	Excellent	Guarded	Guarded	Poor	Hopeless
Lethality	0	0	0-80%	80-100%	90-100%	100%
Time of death	–	–	2 months	2 months	2 weeks	2 days

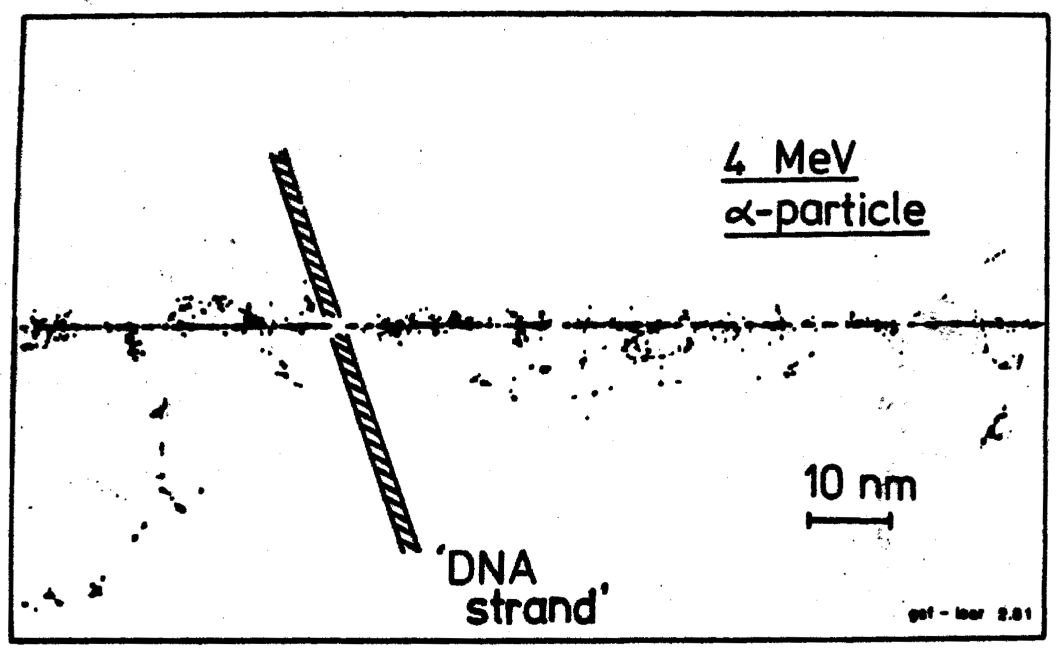
Effects of Partial-Body Irradiation

Tissue and Effect	Threshold (Gy)	Annual Limit (Sv)	
		Alone	Whole-body
Testes			
Temporary sterility	0.15	0.2	0.05
Permanent sterility	3.5	0.2	0.05
Ovaries			
Sterility	2.5–6.0	0.2	0.05
Lens of the eye			
Detectable opacities	0.5–2.0	0.15	0.05
Cataract	5.0	0.15	0.05
Bone Marrow			
Depression of hematopoeises	0.5	0.4	0.05
Fatal aplasia	1.5	0.4	0.05

More on the effect of dE/dx



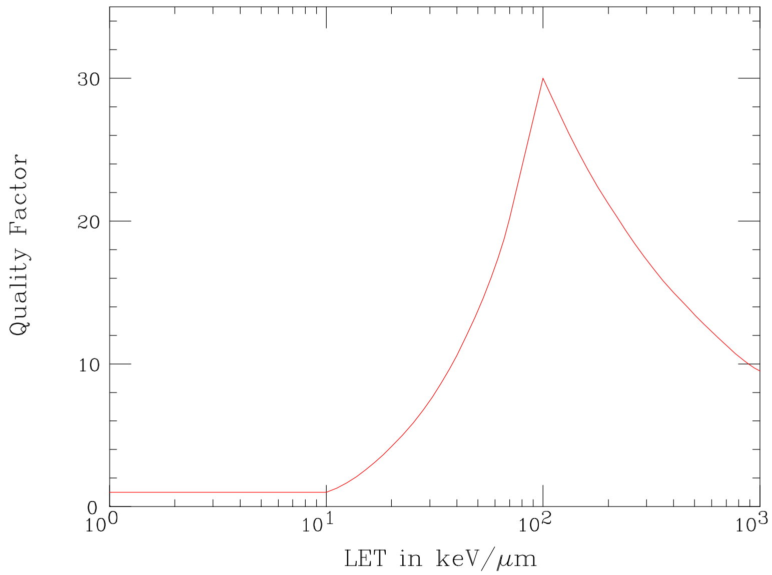
Structure of DNA



Monte-Carlo simulated track segment of a 4 MeV α-particle compared with a cylinder of 2 nm diameter (similar to a DNA molecule)

Quality Factor

- When irradiating a single cell type and looking for a single biological end-point to indicate damage to the cell, we can define a Radiobiological Efficiency – RBE – which is the ratio of the dose of a reference radiation (200keVp x-rays) to the dose of a given test radiation, where both doses produce the same effect.
- When irradiating humans there are a multitude of different cell types and a multitude of possible end-points.
- So we DEFINE a Quality Factor which is a function of dE/dx. (In radiobiology, dE/dx is called Linear Energy Transfer (LET)).



Dose Equivalent

- The Dose Equivalent in an organ of the human body is then defined as

$$H_T = \int D(L)Q(L)\mathrm{d}L,$$

where $D(L)$ is the spectrum of dose in LET and $Q(L)$ is the function of the Quality Factor.

- When D is measured in gray, Gy, H is measured in sievert, Sv.

- The Effective Dose Equivalent is the weighted sum of organ dose equivalents

$$H_E = \sum_T w_T H_T,$$

where the organ weighting factors correspond to the relative risk of a cancer in the particular organ.

Tissue or organ	w_T
Gonads	0.25
Red bone marrow	0.12
Lung	0.12
Breast	0.15
Thyroid	0.03
Bone surfaces	0.03
Remainder	0.30

Effective Dose – 1

- Effective Dose is a recent concept of the International Commission on Radiological Protection which is having difficulty in obtaining acceptance in the Radiation Protection Community because of its completely arbitrary and un-physical nature.
- Quality factor is replaced by a Radiation Weighting Factor which depends on the incident radiation.

Radiation type and energy range	w_R
Photons, all energies	1
Electrons and muons of all energies	1
Neutrons	
$<$ 10 keV	5
10–100 keV	10
100 keV – 2 MeV	20
2 – 20 MeV	10
$>$ 20 MeV	5
Protons, other than recoil protons, with $E > 2$ MeV	5
Alpha particles, fission fragments, heavy nuclei	20

Effective Dose – 2

- The Effective Dose is the weighted sum of organ equivalent doses

$$E = \sum_T w_T H_T,$$

where again the organ weighting factors correspond to the relative risk of a cancer in the particular organ.

Tissue or organ	w_T
Gonads	0.20
Red bone marrow	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surfaces	0.01
Remainder	0.05

Dose Limits at CERN

- **Legal limits**
  - The dose received during any consecutive 12-month period shall not exceed 20 mSv.
  - If it is possible that a dose of more than 1 mSv per month will be exceeded, the group leader or the head of the contracting firm must inform women of child-bearing age to that effect.
    Once pregnancy is diagnosed, the woman shall no longer be authorized to work regularly in a Controlled Area, and shall be subject to a dose limit of 1 mSv during the rest of the pregnancy.
- **Reference Levels**
  - With the aim of keeping exposures at CERN at the ALARA level, a reference dose of 15 mSv has been introduced.

Designated Areas

- Certain parts of the fenced land belonging to CERN are considered to be Designated Areas.
- Outside these areas, the effective dose is kept below the limit of public exposure ($<$ 1 mSv/year).
- Persons who spend their entire working time outside designated areas will not be regarded as being occupationally exposed.
- Designated Areas are either considered as Supervised or Controlled areas.
- Supervised Areas are designated areas in which working conditions are constantly kept under review but no special procedures are required.
- Those employed there are unlikely to receive effective doses above the 1 mSv annual limit in the course of their normal work, taking account of their working hours.

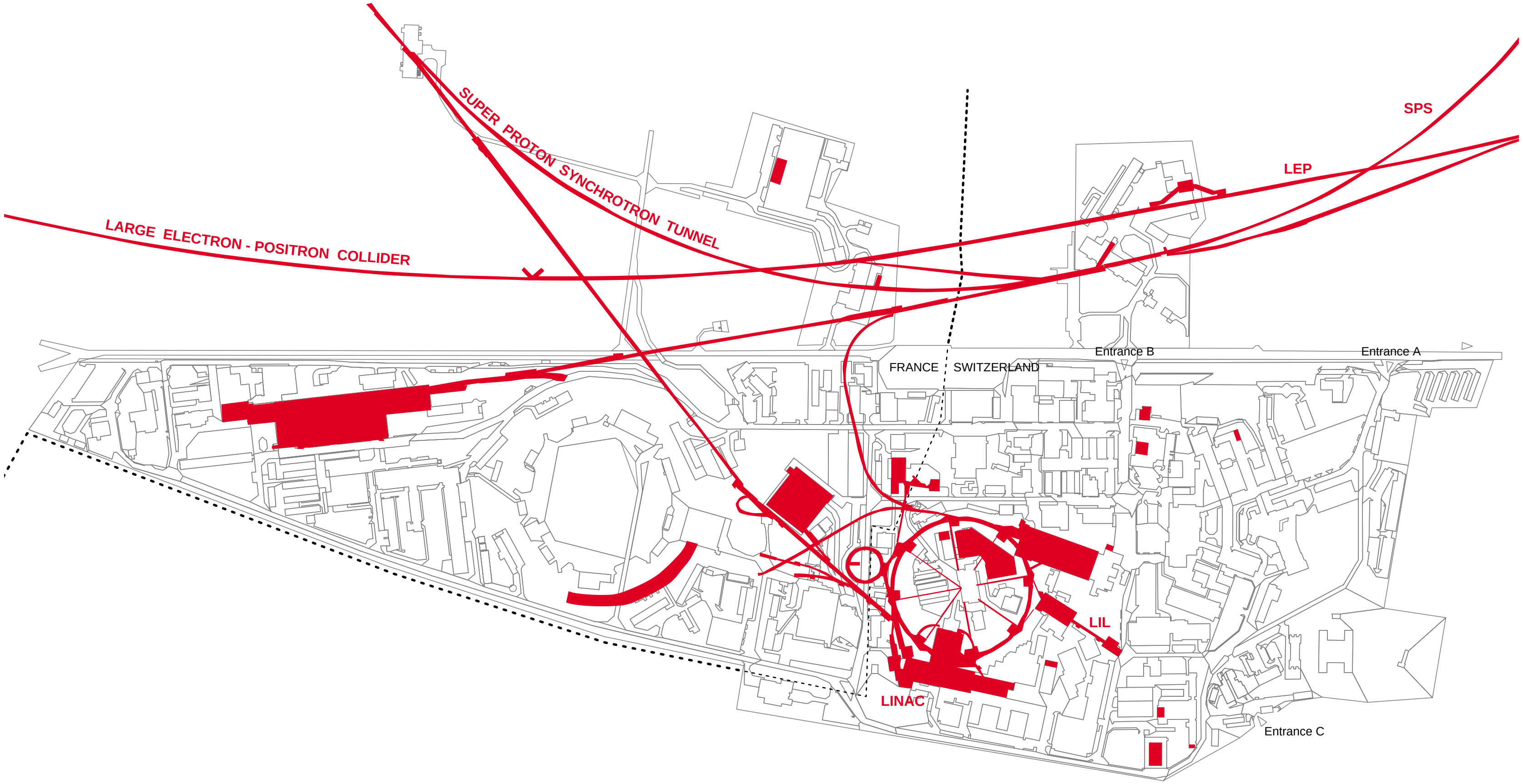
Controlled Areas

- Controlled Areas are designated areas where normal working conditions require persons to follow well-established procedures and to have been given specific information concerning radiation exposures.
- In the normal course of their work, such persons are liable to receive an effective dose of over 1 mSv per year, *i.e.* an effective dose greater than the limit for persons who are not individually monitored.
- Controlled areas are sub-divided as follows:
  - *Simple controlled areas*
  - *Limited-stay areas*
  - *High-radiation areas*
  - *Prohibited areas*

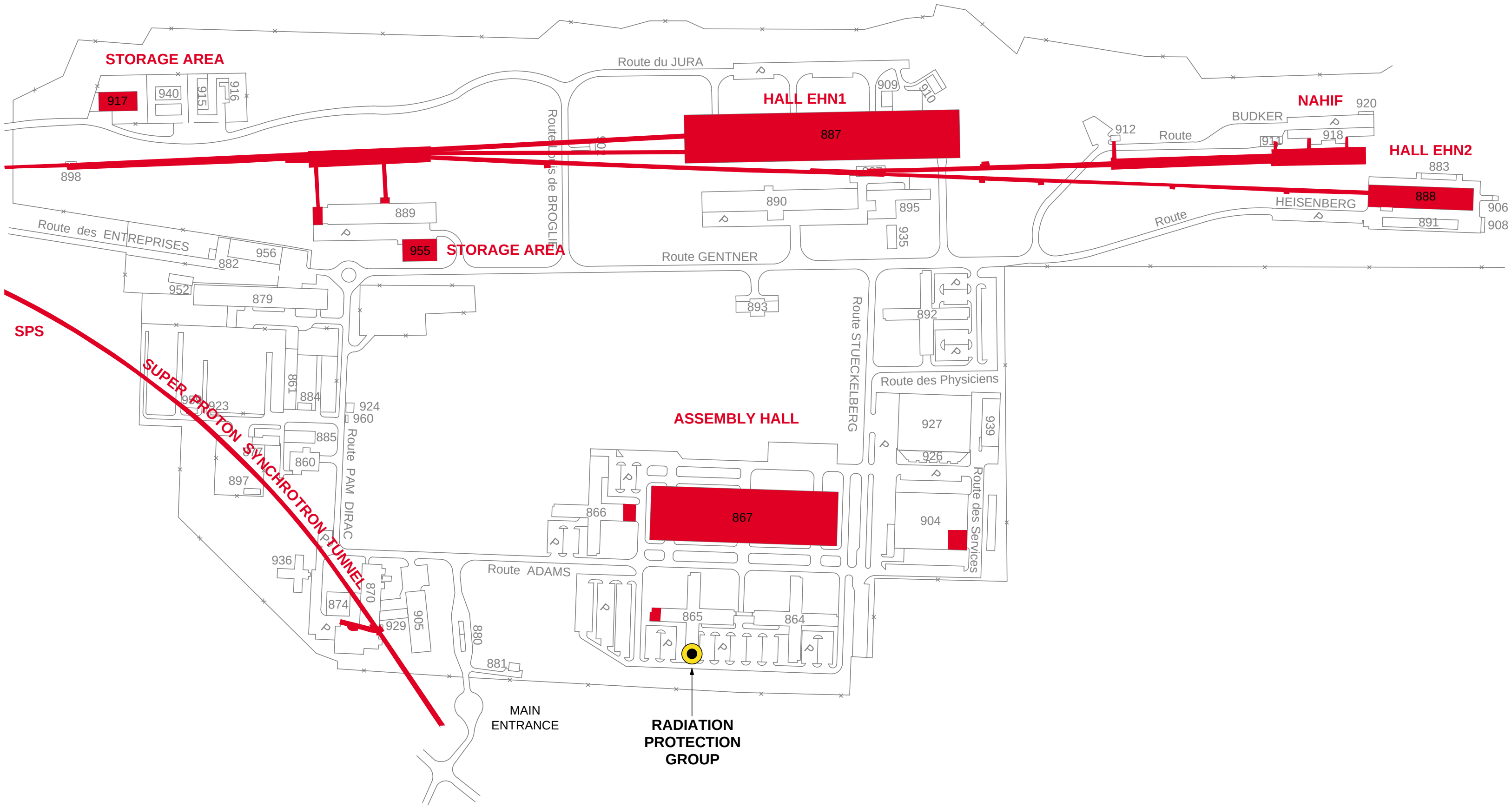
Controlled areas – continued

- In **Simple Controlled Areas**, persons working in the area must carry personal monitors (film-badges), but all precautions are taken (shielding, interlocked areas *etc.*) to ensure that normal work over a year will not give rise to a dose greater than 15 mSv.
- In **Limited-stay Areas**, persons working there must carry personal monitors (film-badges) and it is not possible to authorize any permanent residence in the area. An Operational Dosimetry System (pen dosimeters, electronic dosimeters .....) is necessary to control the rate of accumulation of dose.
- In **High Radiation Areas**, dose rates may reach levels such that the annual dose could be received in less than ten hours work in localized zones inside the area. Thus no visitors can be allowed and strict access control must be maintained.
- In **Forbidden Areas**, dose rates may reach levels such that the annual dose could be received in less than ten minutes work in localized zones inside the area. Access can only be authorized under very special circumstances.

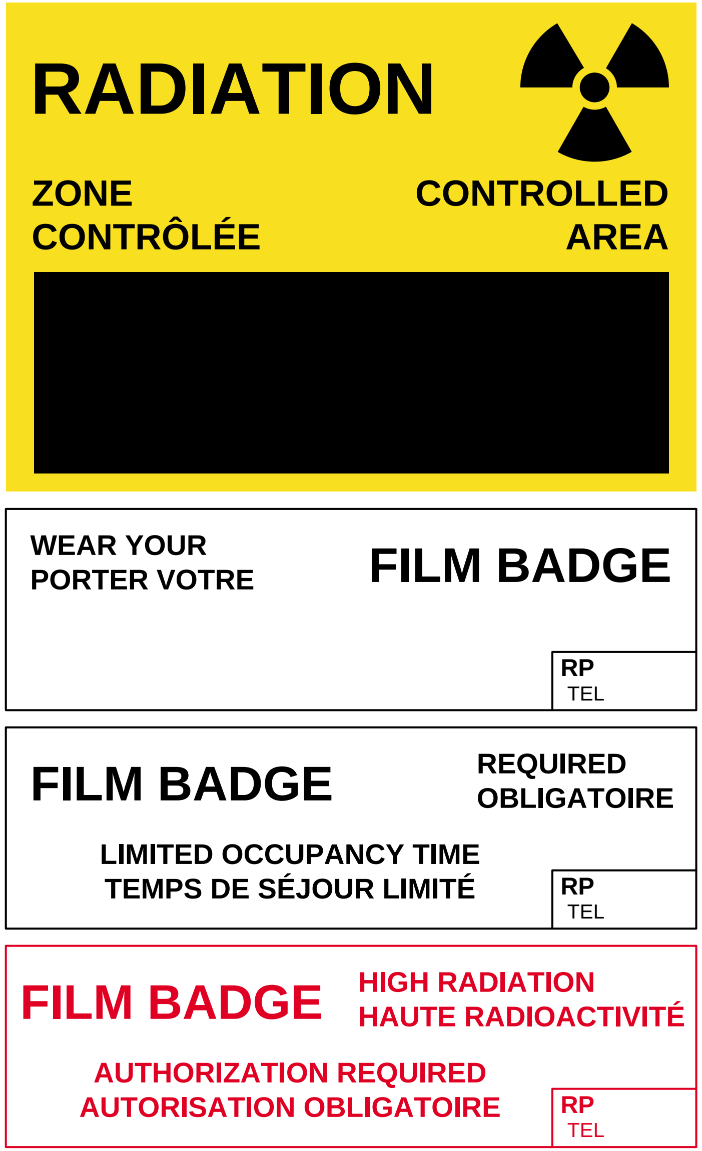
Controlled Areas – Meyrin



Controlled Areas – Prévessin



Controlled Area Warning Signs



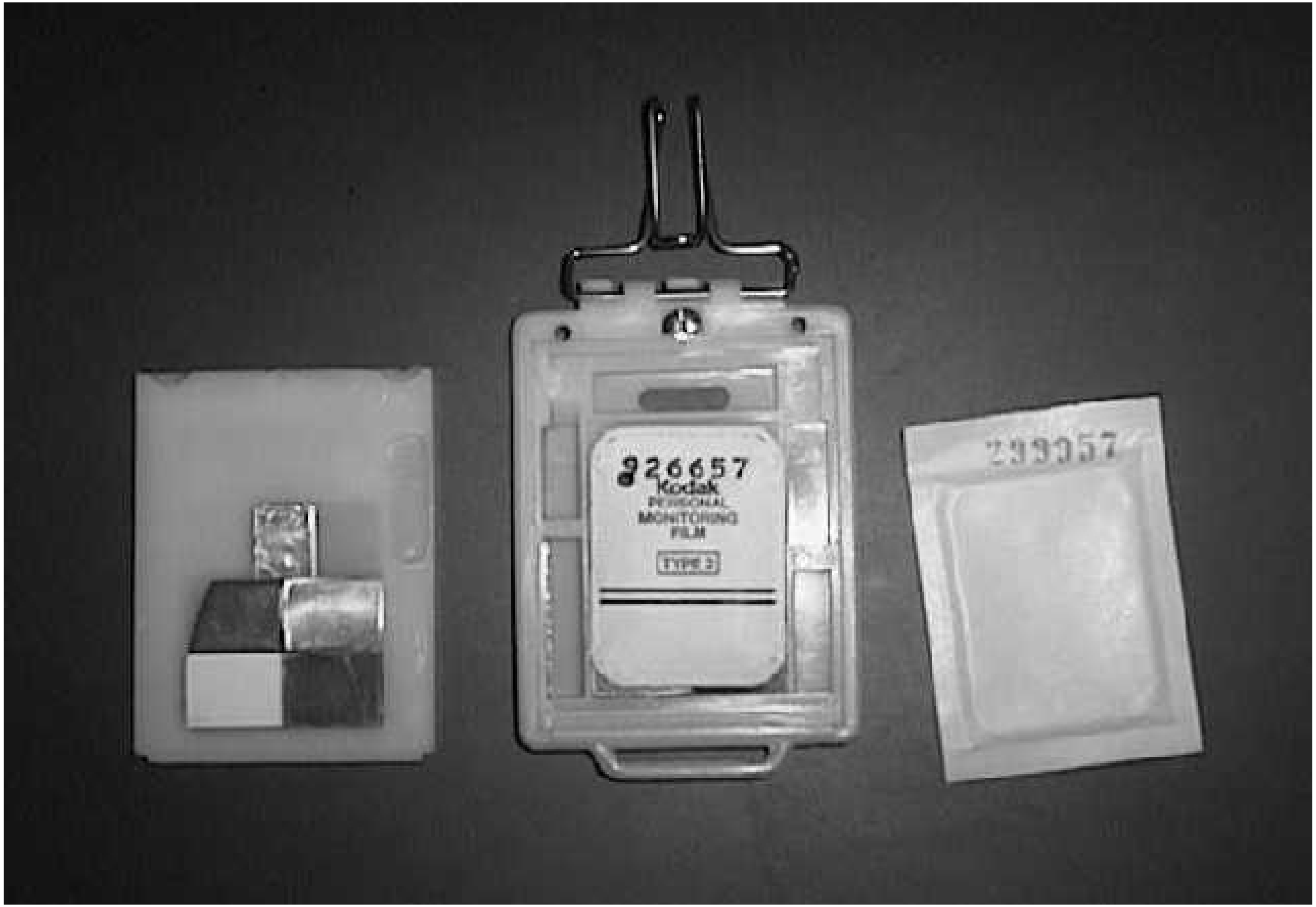
(a) Basic Panel

(b) Simple

(c) Limited Stay

(d) High Radiation

Film Badges



Area Monitors

Alarm Displays

Graham R. Stevenson
Summer Students – July 2000

Area Monitoring

Passive Site Monitors

SPS Machine Access

Radioactivity Monitors

Gate Monitors

Gate Displays

Determining the Risk from Radiation

Uncertainties in the DOSIMETRY for the irradiated populations

- **THERAPY PATIENTS** – the dose to organs in which cancer develops depends on
  - The treatment plan (time and spatial distributions).
  - The apparatus used
  - Collimation
  - Filtration *etc.*
- **MINERS** – the dose has to be determined from individual exposure histories to different concentrations of isotopes in air.
  In addition there are synergistic effects from dust *etc.*
- **A-BOMB SURVIVORS** – "Best" studied group
  - Dose in air as a function of distance is known
  - Individual building shielding factors known
  - Individual body shielding factors known
  - Contribution from fall-out estimated

BUT there are still uncertainties due to the neutron contribution, blast trauma (synergism) and the "Healthy Survivor" effect.

Determining the Risk from Radiation

Uncertainties due to STATISTICS

Cancer Type	Cause	Observed Cases	Expected Cases	Net Cases	Total
Leukaemia	A-bombs	81	20	60	
	Spondylitis	52	6	46	
	Menorrhagia	6	1	5	111
Bone	^{226}Ra (watches)	48	0.4	48	
	^{226}Ra (watches)	45	0.1	45	
	Spondylitis	4	0.6	3	96
Breast	A-bombs	26	13	13	
	Fluoroscopy	22	4	8	
	Mastitis	11	71	7	38
Lung	Uranium mines	135	16	119	
	Fluorspar mines	51	3	48	
	Metal mines	45	16	29	
	Spondylitis	96	54	42	
	A-bombs	71	57	24	262
Gastro-intestinal	A-bombs	378	363	15	
	Spondylitis	53	34	19	34

Total net cases as of 1980 – 541

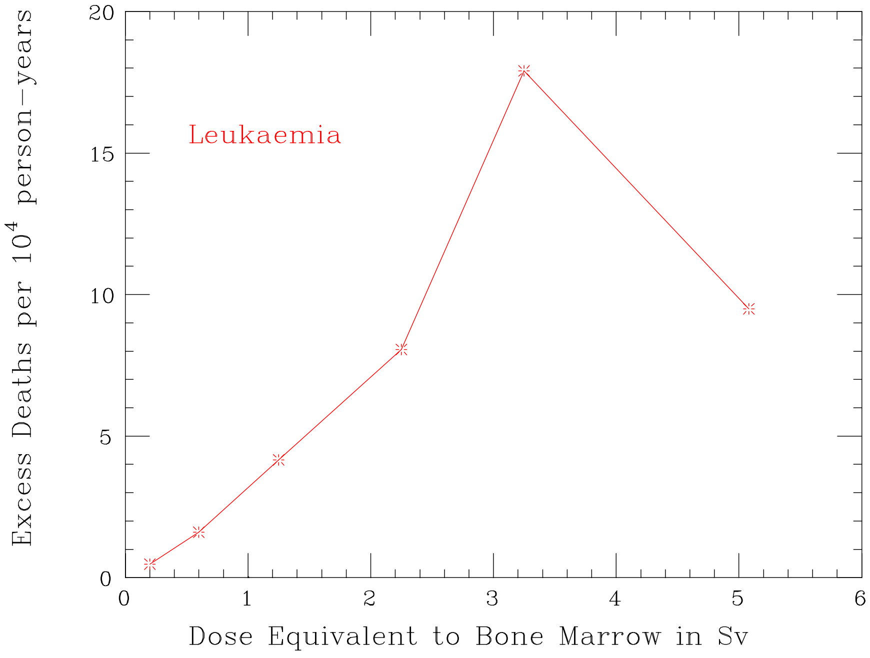
Determining the Risk from Radiation

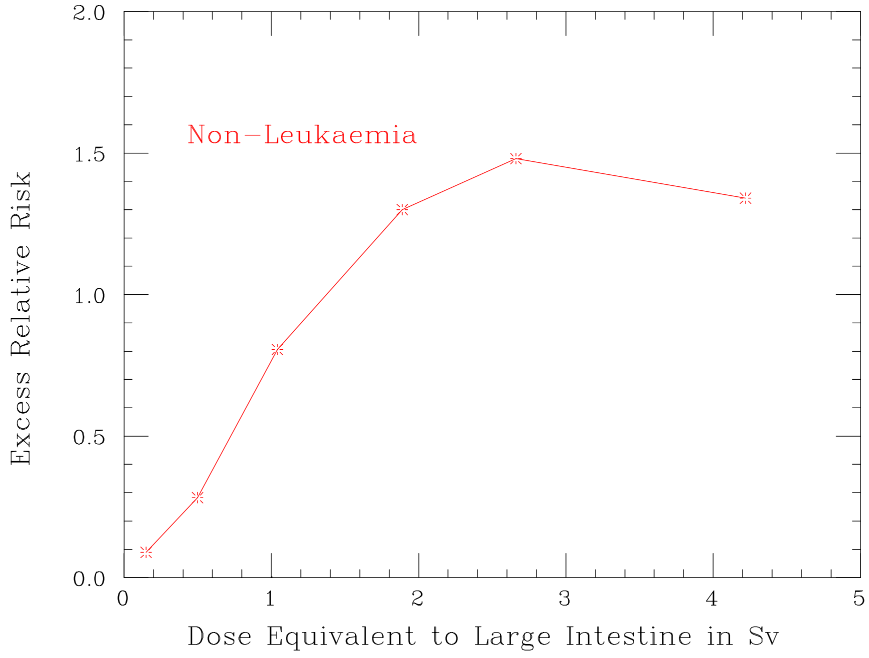
Uncertainties due to MODELS of radiation carcinogenesis

The phases in the formation of a cancer are

1. **INITIATION** – the risk of causing an effect is proportional to the dose and irradiation in this phase *adds* to the existing risk.
2. **MONO-CLONAL GROWTH** – there can be a latent period of up to 40 years.
   Irradiation reduces the latent period in a way roughly inversely proportional to the dose.
3. **PROMOTION** – there is a sudden increase in the growth rate.
   Irradiation leads to a risk which is proportional to the natural incidence and so *multiplies* the existing riak.
   So the risk is extremely age-dependent
4. **PROGRESSION** – the terminal phase.

Determining the Risk from Radiation

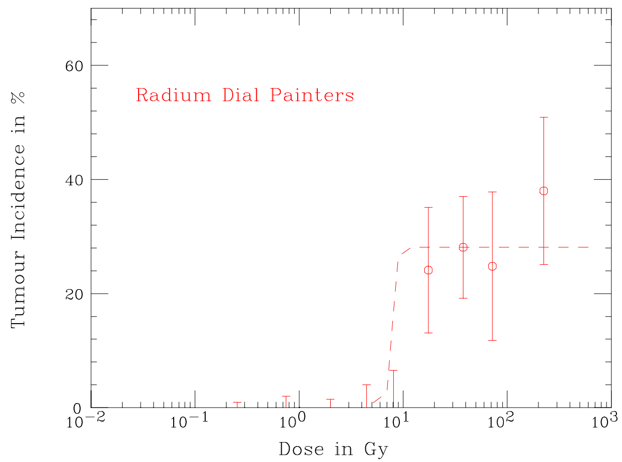




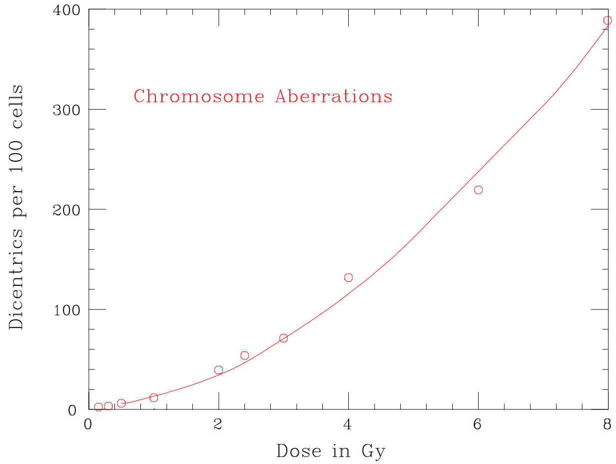
Risks of contracting leukaemia and solid cancers as determined from the Japanese A-bomb survivors. Leukaemia shows an additive risk whereas solid cancers suggest a multiplicative risk

Determining the Risk from Radiation

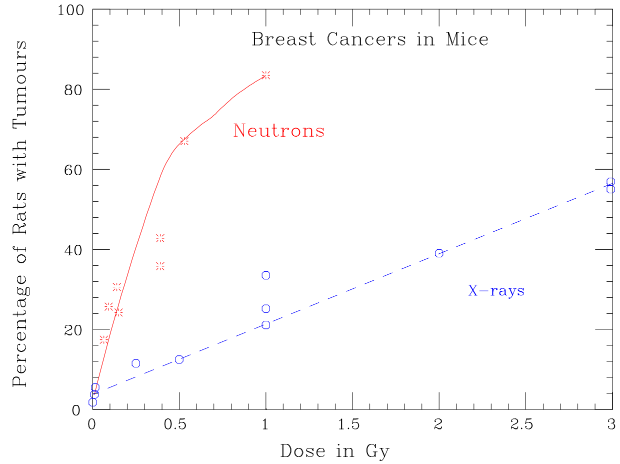
Uncertainties due to EXTRAPOLATION TO LOW DOSES



Bone tumours in radium dial painters indicate a threshold behaviour *i.e.* no tumours below a certain threshold dose



Dicentric chromosome aberrations in human blood indicate the classical linear-quadratic relationship.



Solid breast tumours in rats show a strict linear behaviour.

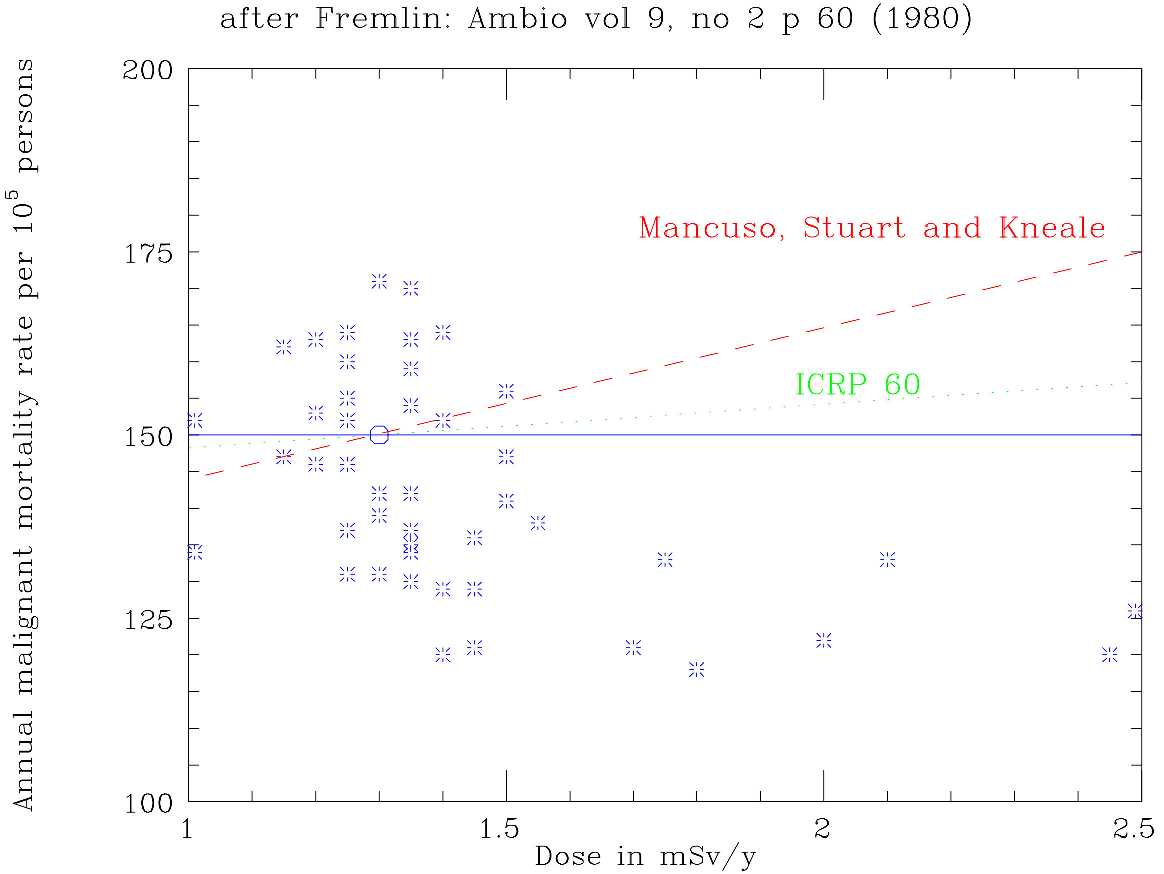
Conventional wisdom assumes a linear extrapolation from observed effects down to zero dose (the LNT, linear no-threshold, hypothesis).

Risk Factors for Protection

Extra deaths for 100 000 people exposed to 1 mSv

Basic Cancer Risk from Hiroshima and Nagasaki	Population (all ages)	12
	Work force (20-65 y)	8
Reduction Factor	for low doses and dose rate	3
Risk Factor	Total cancer	3–4
	Hereditary effects (2nd generation)	0–0.5
	Hereditary effects (all generations)	0-2
	Non-fatal cancers	?
	Total (ICRP 60)	5
The extremists' views	Mancuso, Stewart and Kneale	12
	Gofman and Tamplin	37
The ultimate view	All cancers are due to background radiation 150 deaths per 100 000 per 1.3 mSv	115

Natural Background



Malignant mortality rates for the US white population 1960-1967" by State and natural background radiation including a small constant amount for medical exposure.

The open circle and the horizontal line represent the average for the US as a whole.

The dotted line uses the risk factor of ICRP 60.

The dashed line uses the risk factor of Mancuso, Stewart and Kneale.

Perceived Risks (Part 1)

Deaths per year for the population of the USA (205 million)

	Cause	Actual deaths	Subjects' estimates	Reported deaths (2 local newspapers)
1.	Smallpox	0	57	0
2.	Vitamin poisoning	1	102	0
3.	Botulism	2	183	0
4.	Measles	5	168	0
5.	Fireworks	6	160	0
6.	Smallpox vaccination	8	23	0
7.	Whooping cough	13	93	0
8.	Falls	17	97	0
9.	Bites or stings	43	330	0
10.	Tornado	90	364	61
11.	Lightning	107	91	1
12.	Non-venomous bites	129	174	6
13.	Flood	209	736	14
14.	Excess cold	334	314	0
15.	Syphilis	410	492	0
16.	Pregnancy, birth, abortion	431	1 344	0
17.	Infectious hepatitis	677	1 565	0
18.	Appendicitis	902	605	0
19.	Electrocution	1 023	766	5
20.	Train collisions	1 517	689	1
21.	Asthma	1 886	506	1

Perceived Risks (Part 2)

Deaths per year for the population of the USA (205 million)

	Cause	Actual deaths	Subjects' estimates	Reported deaths (2 local newspapers)
22.	Firearm accidents	2 255	1 343	1
23.	Poisons	2 363	1 013	6
24.	Tuberculosis	3 690	658	0
25.	Fire and flames	7 380	3 336	140
26.	Drowning	7 380	1 684	107
27.	Leukaemia	14 555	2 496	6
28.	Accidental falls	17 425	2 675	22
29.	Homicide	18 360	5 582	486
30.	Emphysema	21 730	2 848	1
31.	Suicide	24 460	4 679	48
32.	Breast cancer	31 160	2 964	0
33.	Diabetes	38 950	1 476	1
34.	Motor vehicle accidents	55 350	41 161	381
35.	Lung cancer	75 850	9 764	5
36.	Stomach cancer	95 120	3 283	1
37.	All accidents	112 750	58 879	1 107
38.	Stroke	209 100	7 109	16
39.	All cancer	328 000	45 609	35
40.	Heart disease	738 000	23 599	79
41.	All disease	1 740 450	88 838	198

Occupational Death Risks

Occupation	Annual Risk of Death
Steeplejack	1.4×10^{-2}
Dam construction	3×10^{-3}
Mining (USA)	1×10^{-3}
Fishing	1×10^{-3}
Aircrew (UK)	6×10^{-4}
Construction	2×10^{-4}
Doctors and Radiologists	1.2×10^{-4}
Light Engineering and Electrical	2×10^{-5}
Clothing and Footwear	5×10^{-6}
All Industries	5×10^{-5}
Radiation at 5 mSv/y in equilibrium	2.5×10^{-4}
Classical Warfare	2×10^{-2}
Smoking (20 cigarettes a day)	5×10^{-3}
President of the USA	1.5×10^{-2}
Accidents in the home	1×10^{-4}

Normal Risks

Common forms of transport

	per 100 h	per 1000 km
Plane	1–2 $\times 10^{-4}$	1–2 $\times 10^{-6}$
Car (automobile)	6×10^{-5}	1×10^{-5}
Train	6×10^{-6}	6×10^{-7}
Bus (autocar)	3×10^{-6}	6×10^{-7}
Bicycle (velo)	1×10^{-4}	5×10^{-5}
Moto	3×10^{-4}	1×10^{-5}
Motor-cycle	7×10^{-4}	1×10^{-5}

Self-imposed Risks

Ski	100 h	7×10^{-5}
Rock-climbing	100 h	4×10^{-3}
Canoeing (kayak)	100 h	1×10^{-3}
Amateur flying	100 h	2×10^{-3}
Smoking	100 cigarettes	7×10^{-5}

Radiation

Orbital space mission or 1 y as a radiation worker	10 mSv	5×10^{-4}
Environmental radiation (no radon) in 1 y	1 mSv	5×10^{-5}
Living by a nuclear power station	0.1 mSv (max.)	5×10^{-6}

Risks that are usually ignored

All at the 10^{-6} level

$\frac{3}{4}$–$1\frac{1}{2}$ cigarettes
$\frac{1}{2}$ a bottle of wine
80 km journey by car
500 km trip by plane
$1\frac{1}{2}$ minutes of rock-climbing
6 minutes canoeing

2 weeks at work
$2\frac{1}{2}$ weeks' contraceptive pills

Being male aged 60 for 20 minutes

Exposure to 20 μSv

Concluding Remarks

- Every activity of man involves some risk.
- Work with ionizing radiation is no exception.
- The risks are:

  1. the certainty of an effect if the dose is high,
     Compare with high-voltage, poisons *etc.*
  2. the possibility of an effect if the dust is low.
     Compare with pollution, gas, dust *etc.*

- Radiation Protection involves

  – AVOIDING risks of Category 1.
  by interlocks, shielding *etc.* and

  – MINIMIZING risks of Category 2.
  by common sense!