FROM CHERNOBYL TO FUKUSHIMA
EXPERIENCES OF A YOUNG SCIENTIST

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CAPACITY BUILDING

RPI

CONTENTS

INTRODUCTION

CAPACITY BUILDING

CAPACITY BUILDING (1)

- The **capacity building for radiation protection** is a process through which the government, regulatory body, operators, and other relevant parties achieve **an optimized and sustainable level of protection and safety**.
- This keynote presentation gives a personal perspective on this process focusing on the 25+ years after the Chernobyl accident (1986) and on several important challenges addressed during this time.

CAPACITY BUILDING (2)

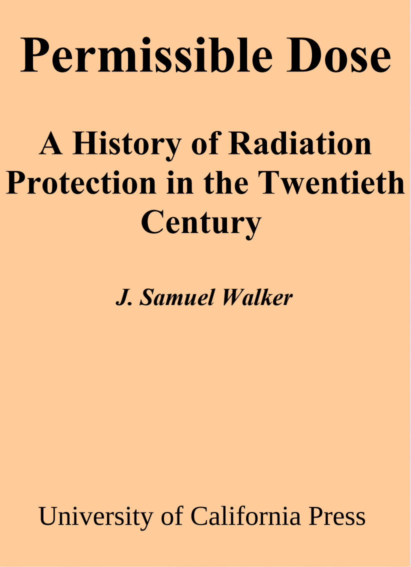
- The capacity building is usually defined as an overarching process, which includes four essential elements:
  - **education and training,**
  - **human resource development,**
  - **knowledge management, and**
  - **knowledge networks.**
- **Research and technological development**, should also be regarded as essential.

PRE-CHERNOBYL ERA

1895 - 1986

EARLY DEVELOPMENTS

- During several decades after the discovery of Röntgen in1895, **the phenomenon of ionizing radiation evolved from a source of public fascination to an origin of widespread public fear and scientific controversy**.
- The lack of understanding of the effects of ionizing radiation led to the **uncontrolled use of sources** of ionizing radiation and caused a range of serious consequences.
- Thomas A. Edison, one of early x-ray enthusiasts, became thoroughly disillusioned with the new technology when his assistant, Clarence Dally suffered radiation damage to his hands and face and died from mediastinal cancer in 1904.

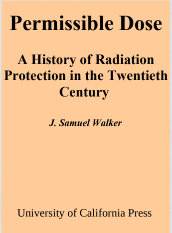


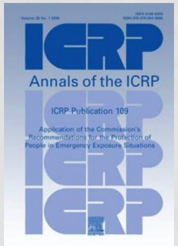
CREATION OF THE RADIATION PROTECTION REGULATIONS AND ICRP

- During the 1920s, the growing knowledge prompted the establishment of **the first radiation protection regulations**.
- The Second International Congress of Radiology (1928) established the International X-Ray and Radium Protection Committee, which in 1950 obtained its present name: the **International Commission on Radiological Protection** (ICRP).

Recommended reading:

- *Permissible Dose: A History of Radiation Protection in the Twentieth Century*. J. Samuel Walker. Berkeley, CA: University of California Press, 2000.
- *The History of ICRP and the Evolution of its Policies*. R.H. Clarke and J.Valentin. A part of the ICRP Publication 109. 2009.
- http://www.icrp.org/docs/The%20History%20of%20ICRP%20and%20the%20Evolution%20of%20its%20Policies.pdf





BEGINNING OF THE NUCLEAR ERA

- After the World War II the research has been stimulated **by the broad spectrum of medical and industrial applications**.
- To a large extent, the **research works have also been supported by the massive military funds** of superpowers, which were engaged in the nuclear arms race.
- The **military nuclear programmes** had caused a number of **long-standing problems**, such as the contamination of the environment around military sites, global fallouts and the excessive exposure of nuclear workers and members of general public.

UNSCEAR

The **United Nations Scientific Committee on the Effects of Atomic Radiation** (UNSCEAR) was created in 1955 by the **UN** General Assembly resolution in response to widespread concerns about the potential dangers of worldwide radioactive fall-outs.

Recommended reading:

- *The birth of UNSCEAR—the midwife's tale.* Ray Appleyard. 2010 *J. Radiol. Prot.* **30** 621.
- *Some recollections of UNSCEAR.* David Sowby. 2008. *J. Radiol. Prot.* **28** 271.

IAEA

- The establishment of an "international atomic energy agency" that should promote the peaceful uses of nuclear energy was proposed in 1953 by US President Eisenhower in his **Atoms for Peace** address to the UN General Assembly.

- In 1957, the IAEA's Statute came into force and the **first *IAEA General Conference*** took place in Vienna.

Recommended reading:

- A Short History of the IAEA. http://www.iaea.org/About/history.html
- *History of the International Atomic Energy Agency : the first forty years / by David Fischer. — Vienna : IAEA, 1997.* http://www-pub.iaea.org/mtcd/publications/pdf/pub1032_web.pdf

RADIATION PROTECTION CAPACITY BEFORE THE CHERNOBYL ACCIDENT

- **By the mid-1980s**, radiation protection has had a half-century history of development and has incorporated a substantial volume of fundamental scientific knowledge in radiobiology, biokinetics of radionuclides and dosimetry of ionising radiation.
- Additionally to the issues related to the military programmes, several accidents on civil facilities have also contributed to a pre-Chernobyl pool of challenges in radiation protection.
- Nevertheless, in general, **radiation protection has been regarded as a well-established field with an adequate capacity for all types of situations, including nuclear incidents**.

THE PALOMARES ACCIDENT

THE IAEA'S REVIEW MISSION, 2009

ACCIDENT

- On January 17, 1966 a United States Air Force B-52 bomber, carrying four nuclear weapons, collided with a KC-135 tanker during refuelling.
- The accident happened over the Palomares village (Almeria province, Spain).
- Both of the aircrafts crashed and of the four hydrogen bombs the B-52 carried, three were found on land.

ENVIRONMENTAL CONTAMINATION

- The **non-nuclear explosives in two of the weapons detonated** upon impacting the ground, resulting in the dispersion of radioactive fragments and radioactive contamination of the environment in and near the Palomares village.
- The fourth bomb, which fell into the Mediterranean Sea, was recovered intact in April 1966.

Pu CONTAMINATION IN 1966

Source: BBC, 2012 http://www.bbc.co.uk/news/magazine-18689132

PALOMARES, 1966: SURVEYING FOR PLUTONIUM CONTAMINATION

Photo credits: Sandia National Laboratories

RESIDUAL CONTAMINATION

- A series of recent studies, conducted by CIEMAT and supported by US, have revealed that despite of the the large-scale remediation efforts, **the area needs a further attention**.
- Some of lands, which in 1966 were released for the unconditional use, are contaminated above regulatory criteria established by the Spanish regulatory body.
- The criteria relate to the concentrations of $^{239+240}Pu$ in soil down to a 15 cm depth and indicate a partial use restriction for land above 5 Bq g^{-1} and a total use restriction for land above 25 Bq g^{-1}.
- In practice the levels of ^{241}Am were used to represent these criteria assuming that a level of 1 Bq g^{-1} of ^{241}Am is equivalent to 5 Bq g^{-1} of $^{239+240}Pu$.
- **As the social and economic activities of the region are rapidly developing, the Spanish government expropriated these lands.**

IAEA'S REVIEW MISSION, 2009

LESSON FOR THE CAPACITY BUILDING: CONSIDERATION OF FUTURE GENERATIONS

- The radiological criteria for environmental remediation should be derived with the use of the **safety assessments** and **optimization**.

- The optimization should consider **the protection of future generations** with account taken of the **social and economic circumstances anticipated in the future**.

1966: BACKBREAKING SURVEY

- Surveying for plutonium contamination required the surveyor to hold the detector at the distance of few centimetres from the surface.

- The rocks and the dry vegetation often damaged thin film windows of **detectors** and caused an **unusually high failure rate**.

NEW INSTRUMENTS

- The experience of the Palomares accident stimulated the development of new plutonium survey systems, which detect the low-energy photon emissions.
- The prototype of a new system was available in in January 1968, when the similar nuclear weapon accident occurred near the Thule US Air Force Base, Greenland.
- This type of detectors nowadays is known now as **FIDLER - Field Instrument for Detection of Low Energy Radiation**. It is based on the scintillation detector optimized for low-energy X-ray and gamma radiation detection.

LESSON FOR THE THE CAPACITY BUILDING: WE NEED A STOCK OF SPECIALIZED EQUIPMENT

- Accidents can led to the contamination of the environment by **“non-typical” radionuclides**.
  e.g. pure beta-/alpha- or low-energy photon emitters can dominate in transport accidents, malevolent acts, etc.
- The emergency response teams should be equipped with the appropriate instruments and many countries may lack the specialized systems or expertize in their use.
- The IAEA can establish **a stock of specialized mobile equipment**, such as FIDLER or calibrated *in situ* gamma spectrometry systems, which can be provided on request of a Member State together with the expertize of the IAEA staff.

FROM CHERNOBYL TO FUKUSHIMA

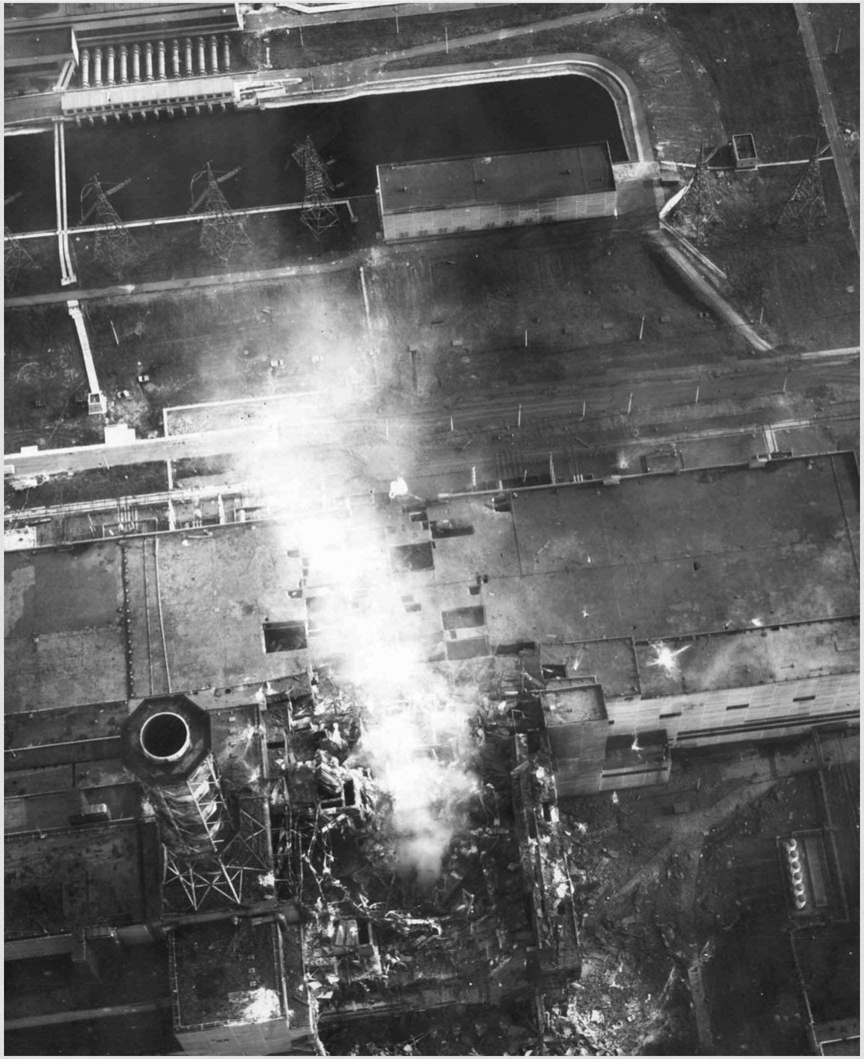
1986 - 2014

SCENE OF THE CHERNOBYL ACCIDENT

The Chernobyl Nuclear Power Plant is located in the Kiev region in the north of Ukraine, 7 km south of the Ukrainian-Belarusian border in an area of forest and meadows near the point where the Pripyat river joins the Dnieper.

APRIL & MAY 1986

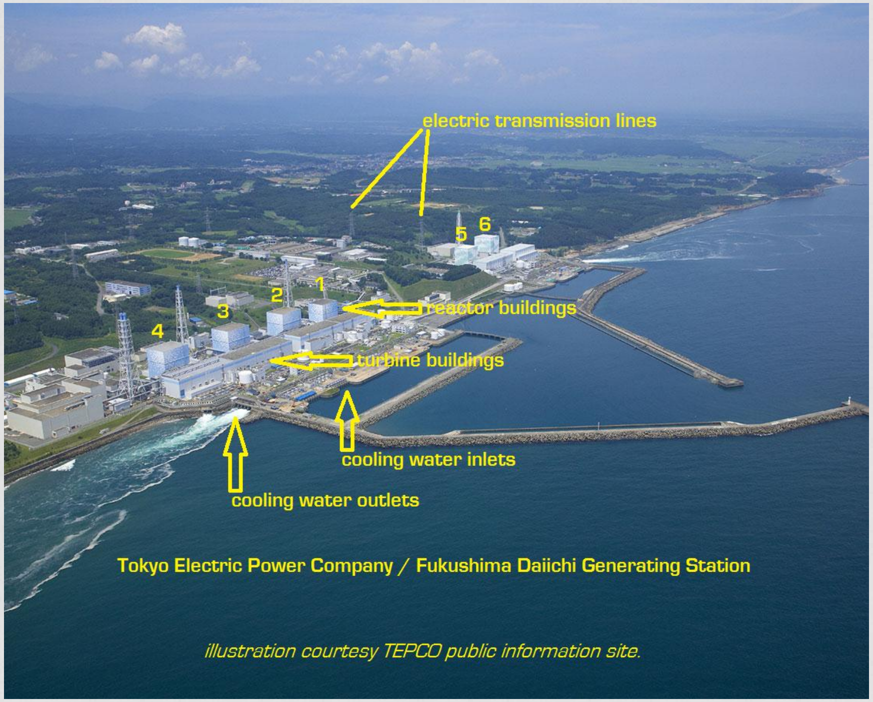
- Between 1 and 2 am on the 26th of April 1986, an accidental explosion during a safety test destroyed the core of Unit 4 and started a powerful fire, which lasted for about 10 days.
- A massive amount of radioactivity was released into the environment during the explosion and the fire.
- The radioactive cloud dispersed over the entire northern hemisphere and deposited substantial amounts of radioactive material.



DESTROYED REACTOR BUILDING

SCENE OF THE ACCIDENT AT THE FUKUSHIMA-DAIICHI NPP

The Fukushima-Daiichi NPP is located on the Pacific coast of Japan in area with the complex topography. The western part of Fukushima Prefecture is mountainous and it has many lakes and forests. NPP is located about 180 km from Greater Tokyo Area with the total population of more than 35 mln.

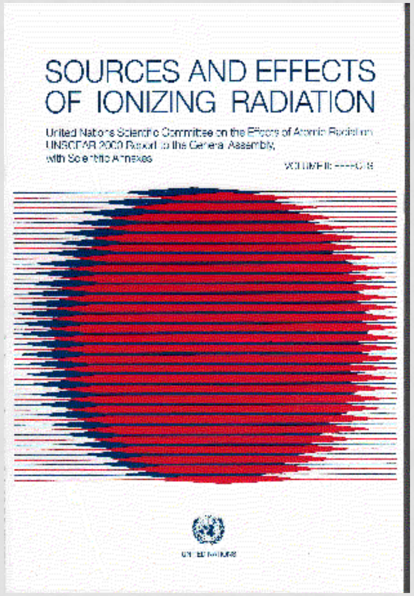


SOURCE TERMS

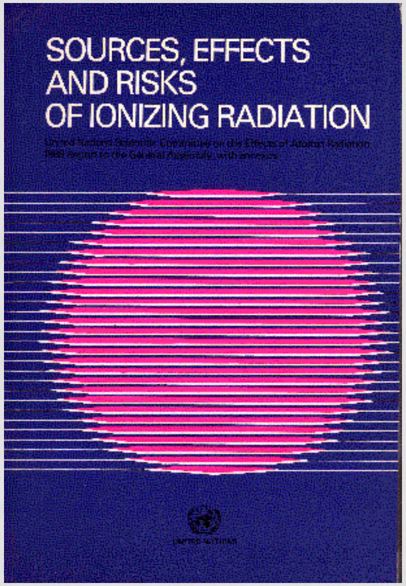
Category	Chernobyl Unit 4 USSR, 1986	Fukushima Daiichi Japan, 2011	
Atmospheric release[1,2], PBq	Chernobyl Forum (IAEA, 2006) and UNSCEAR (2008)	TEPCO (2012) http://www.tepco.co.jp/en/press/corp-com/release/2012/1204659_1870.html	(a)Stohl et al. (2012) (b)Steinhauser et al. (2014) (c)Chino et al. (2011) (d)Zheng et al. (2011)
^{133}Xe	6 500	Noble gases:500	12 200 - 18 300[a]
^{132}Te	1 150	n/a	~180[b]
^{131}I	1 760	500	150[c]
^{133}I	910	n/a	146[b]
^{134}Cs	~47	10	20 − 53[a]
^{137}Cs	~85	10	20 − 53[a]
^{89}Sr	~115	n/a	~0.2[b]
^{90}Sr	~10	n/a	~0.02[b]
^{241}Pu	~2.6	n/a	$1.1\times10^{-4} - 2.6\times10^{-4}$ [d]
$^{239+240}Pu$	0.03	n/a	n/a

CHERNOBYL ACCIDENT: RECOMMENDED READING

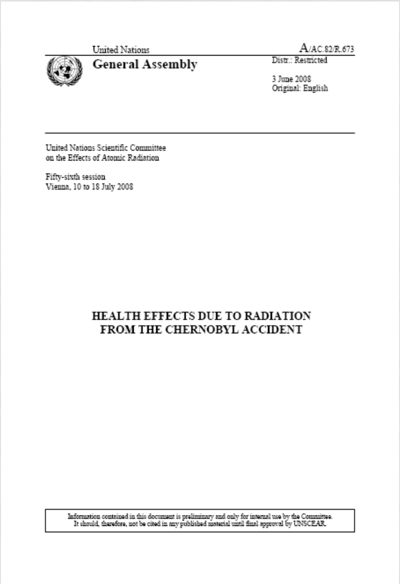
UNSCEAR, 1988



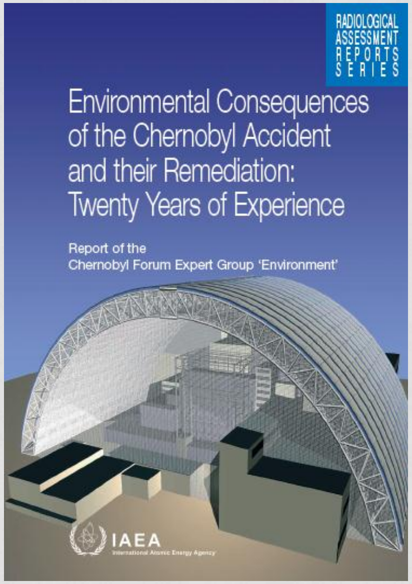
UNSCEAR, 2000



UNSCEAR, 2008



IAEA, 2006



1986: LIMITED CAPACITY

- The unprecedented scale of the Chernobyl accident has revealed that the practical and theoretical **capacity of radiation protection was far from the ideal.**

- After the accident the **radiation protection practitioners have experienced a variety of problems**, ranging from a lack of appropriate instruments and dose assessment techniques to conceptual problems related to establishing of radiological criteria, optimization of protection and safety, development of the remediation strategy and management of the enormous volume of radioactive waste.

1986: OPEN ISSUES

- The Chernobyl accident has **necessitated** further research and **modernization of the protection system and dose assessment methodology**.
- For example, after the accident the **concept of the collective effective dose** was over-exploited and **misused** for epidemiological assessments and projection of the number of cancer deaths from trivial individual doses.
- A number of **methodological issues in dose assessment** and dosimetry became important.

1986: LACK OR UNCLARITY OF IMPORTANT COMPONENTS OF THE PROTECTION SYSTEM

- Additional difficulties were associated with the lack or unclarity of important components of the protection system, namely:
  - concept of the "individual dose" to the representative person; reference person; reference biokinetic and dosimetric models and their globally-averaged parameter values; age-dependent dose coefficients and bioassay interpretation data, etc.;
  - Approaches to the optimization of protection and limitation of doses to the emergency responders and members of the public in normal and emergency situations;
  - Monetary equivalent of the unit collective dose;
  - Control of radionuclides in commodities and foodstuffs;
  - Approaches to the management of large volumes of radioactively contaminated material and radioactive waste.

1986: SPECIFIC TECHNICAL PROBLEMS

The absence of the following key dose assessment tools:

- **Dose coefficients** "dose per unit activity intake" **for members of general public and specifically for children, embryo and foetus**;
- Advanced human **respiratory and alimentary tracts models**;
- Recycling **biokinetic models**, which can be used **for the interpretation of bioassay data**;
- "**Environmental dose coefficients**" for the assessment of the external exposure from radionuclides in environmental media.

ASSESSMENT OF DOSES TO THE THYROID GLAND

SHORT-LIVED RADIOISOTOPES OF IODINE.
DOSES TO THE EMBRYO AND FOETUS.

CHALLENGES AND SOLUTIONS

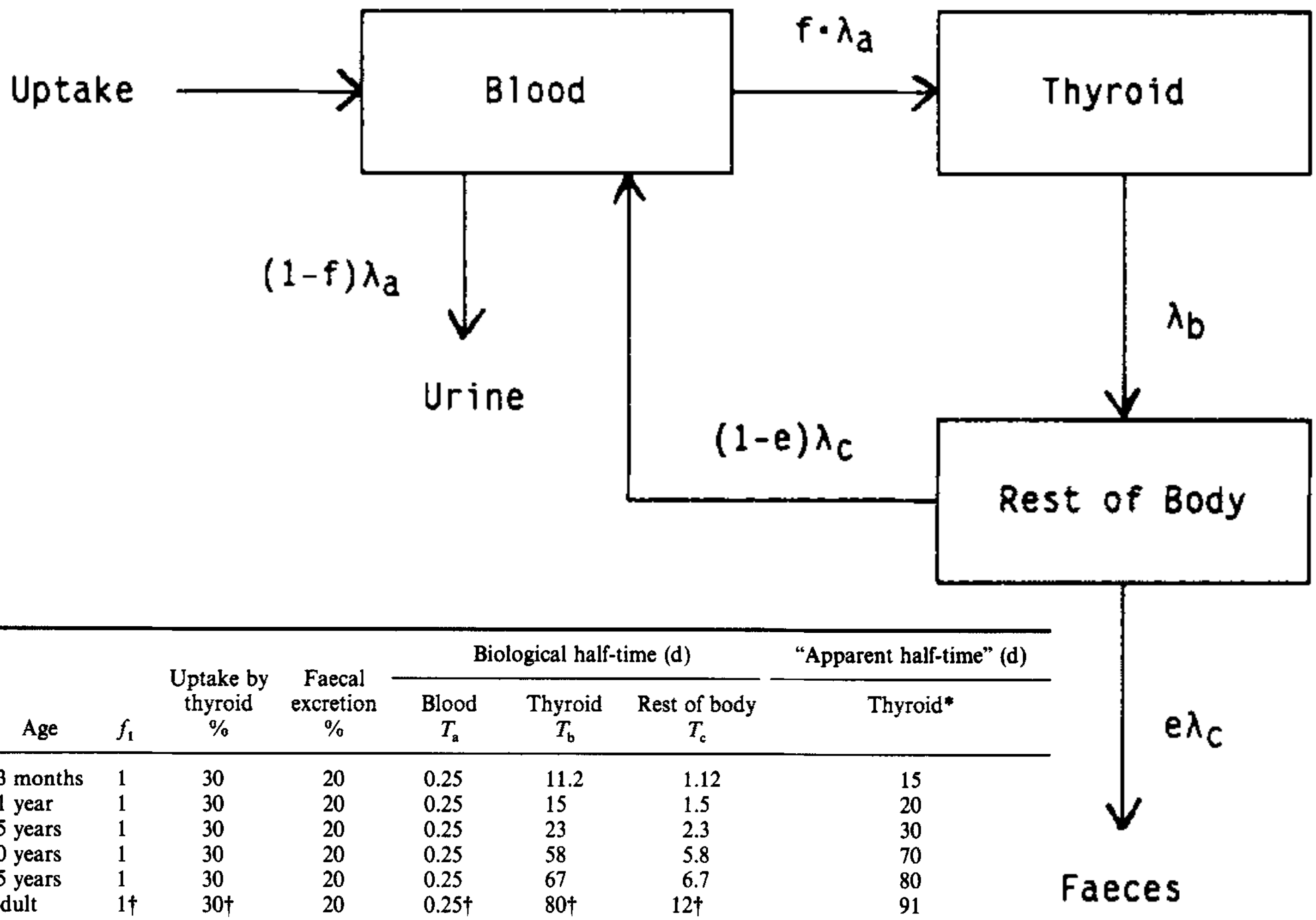
EXPOSURE TO IODINE

- In Belarus, Russia, and Ukraine, the assessments of the thyroid doses from intakes of ^{131}I were based on 400 000 direct thyroid measurements with the use of detectors placed against the neck.

- **Challenges**:
  - Doses from short-lived isotopes of radioiodine;
  - Doses to the embryo and fetus;
  - Doses to the offspring from radioiodine in the breast milk.

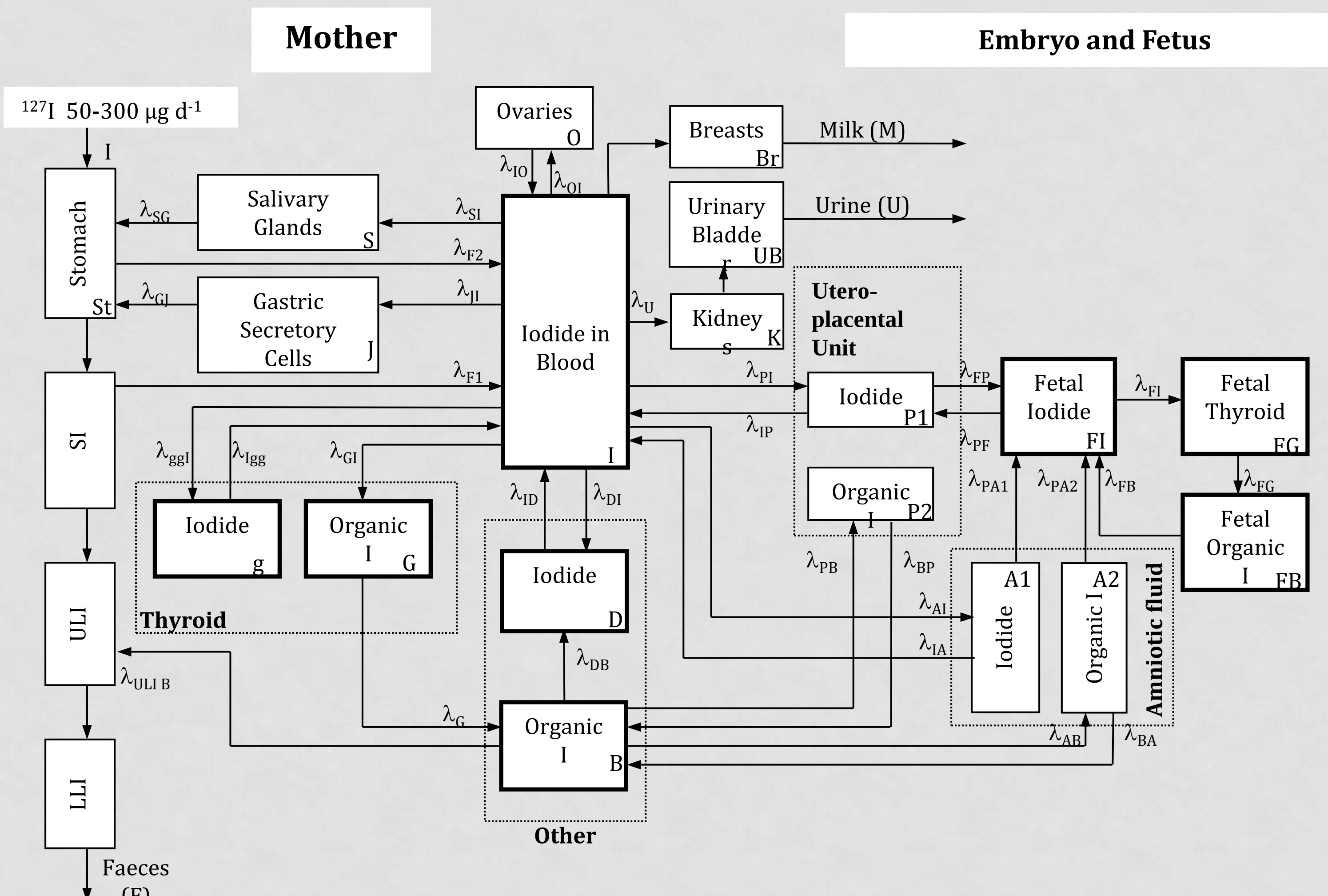
CLASSICAL IODINE BIOKINETIC MODEL

RIGGS (1952), ICRP-30 (1979) AND ICRP-56 (1990)



Age	f_1	Uptake by thyroid %	Faecal excretion %	Biological half-time (d): Blood T_a	Biological half-time (d): Thyroid T_b	Biological half-time (d): Rest of body T_c	"Apparent half-time" (d): Thyroid*
3 months	1	30	20	0.25	11.2	1.12	15
1 year	1	30	20	0.25	15	1.5	20
5 years	1	30	20	0.25	23	2.3	30
10 years	1	30	20	0.25	58	5.8	70
15 years	1	30	20	0.25	67	6.7	80
Adult	1†	30†	20	0.25†	80†	12†	91

NEW IODINE BIOKINETIC MODEL FOR PREGNANCY
BERKOVSKI (1999, 2002), ICRP-88 (2001) AND ICRP-95 (2004)



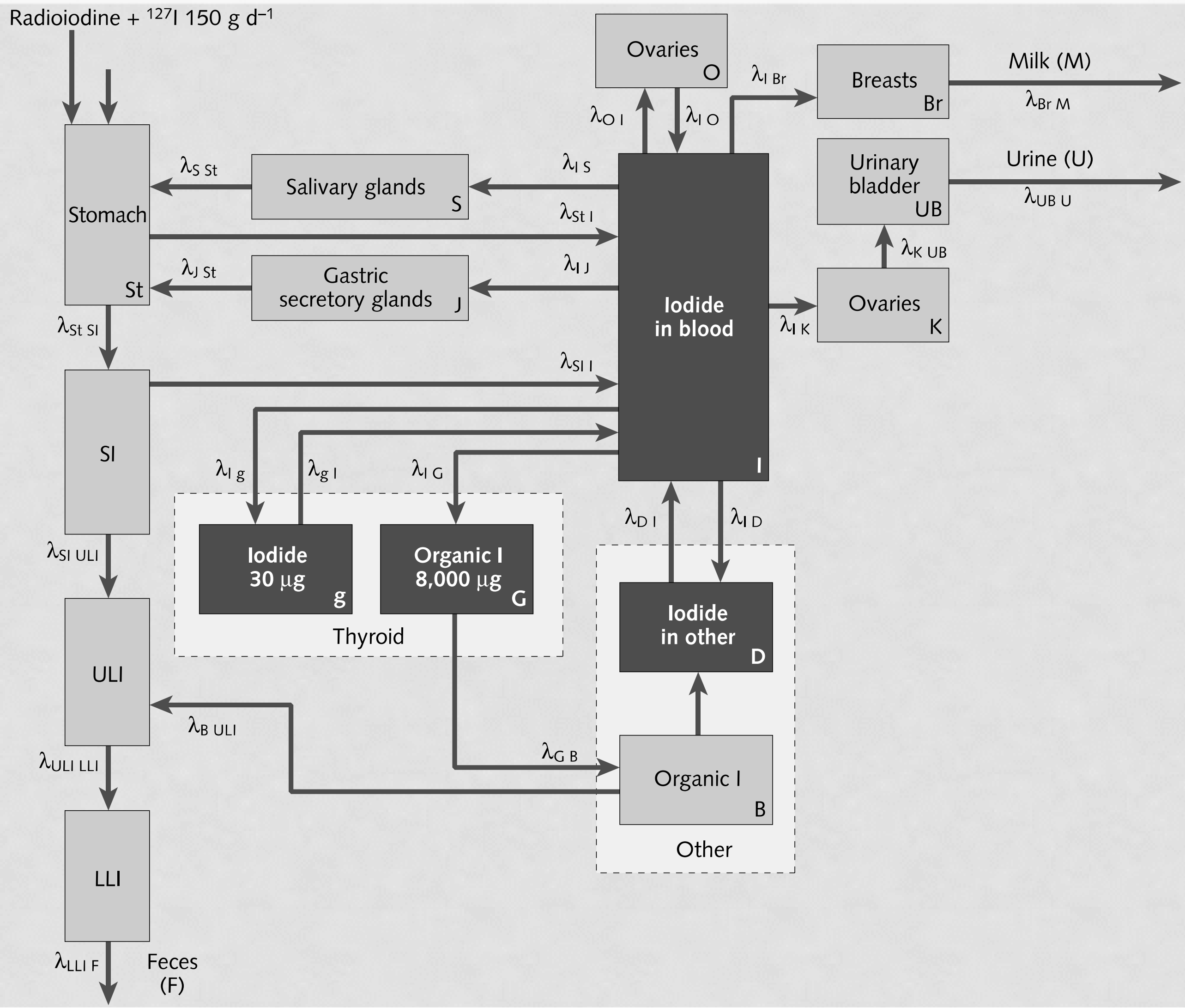
BASIS OF THE NEW BIOKINETIC MODEL FOR THE MATERNAL IODINE

- **Experimental data on** iodine **kinetics in the gastrointestinal tract**, including the salivary gland and gastric secretory cells. The secretion of iodide into saliva and gastric juice and its subsequent re-absorption represents the **gastroenteric iodide cycle** in the model.
- **Clinical data on** radioiodine **uptake** by the maternal thyroid **during the first hours after intake**, which has been used for setting the short-term kinetic parameters of the model.
- **Clinical data on** changes in maternal iodine **kinetics during pregnancy and breastfeeding**.

TABLE 2. Average values of ^{131}I thyroidal uptake (ingestion) reported for persons living in iodine replete areas [22]

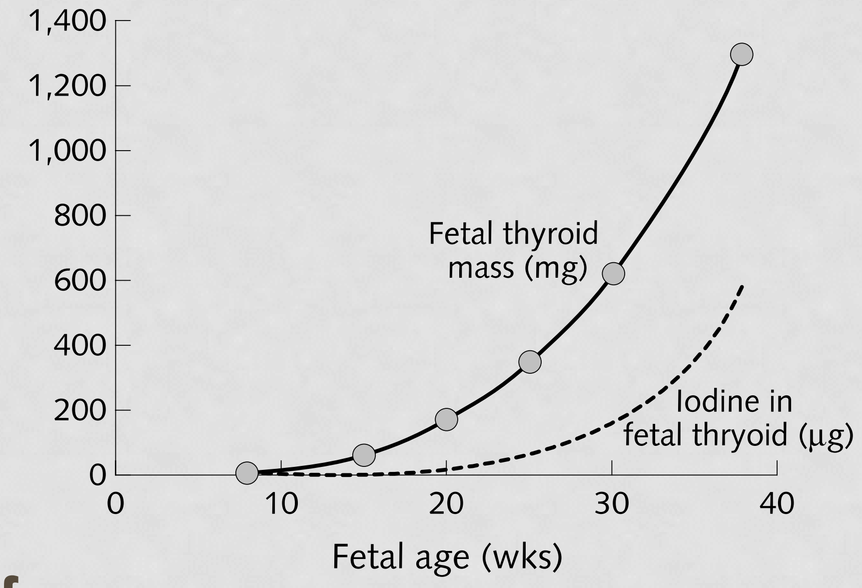
Thyroid status	Time after intake	
	2 hours	24 hours
Hypothyroidism	3%	5%
Euthyroidal	10%	25%
Diffuse goiter	41%	64%

IODINE BIOKINETIC MODEL FOR THE SHORT-TERM PROCESSES AND LACTATION

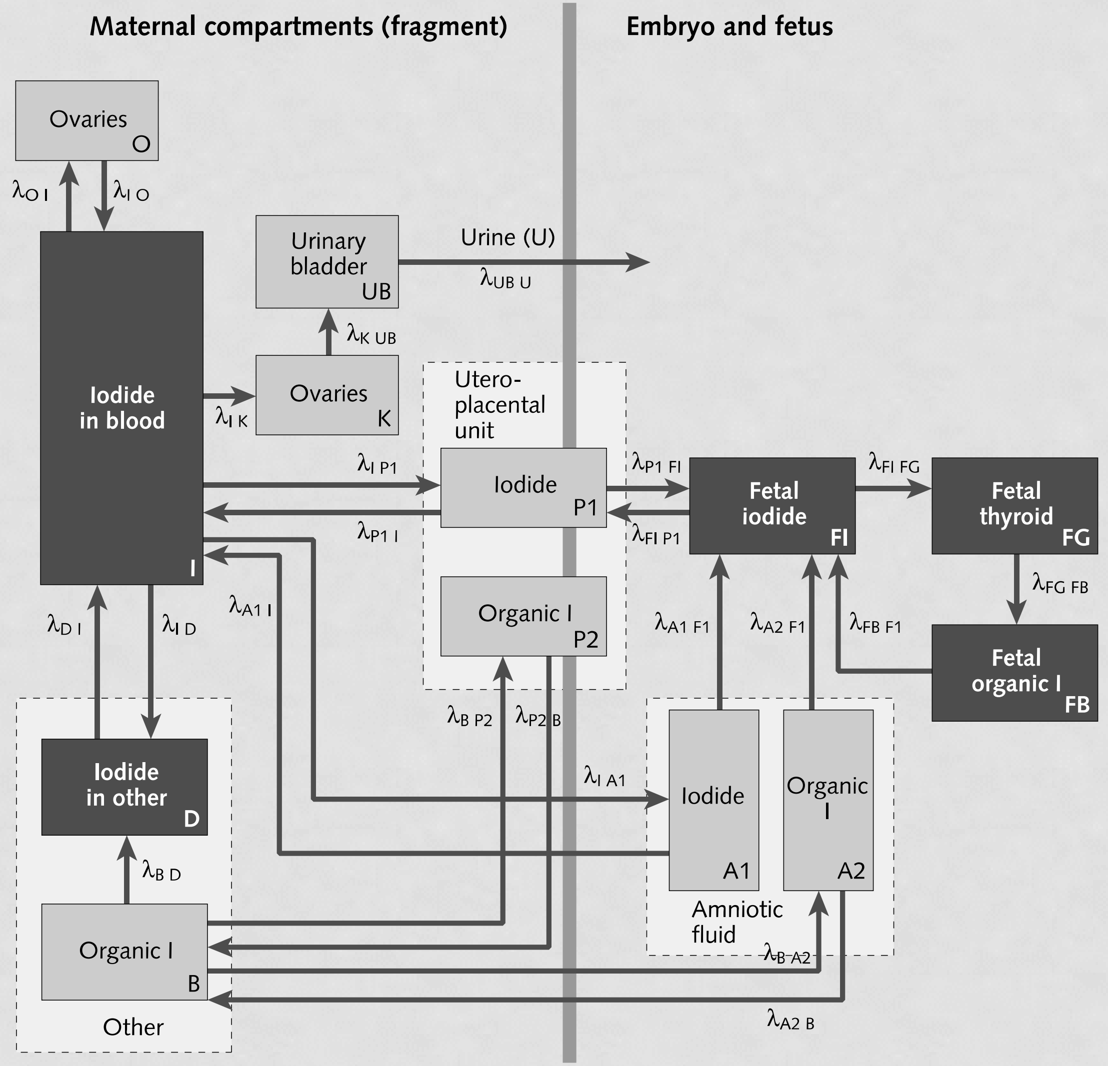


BASIS OF THE BIOKINETIC MODEL FOR THE FETAL IODINE (1)

- **Anatomical data on** the time course of the **mass of the thyroid of the human fetus**.
- **Clinical data on the transplacental kinetics** of radioiodine and its **accumulation in amniotic fluids**.
- **Anatomical data on the mass and blood content of the placenta** at different gestation stages.

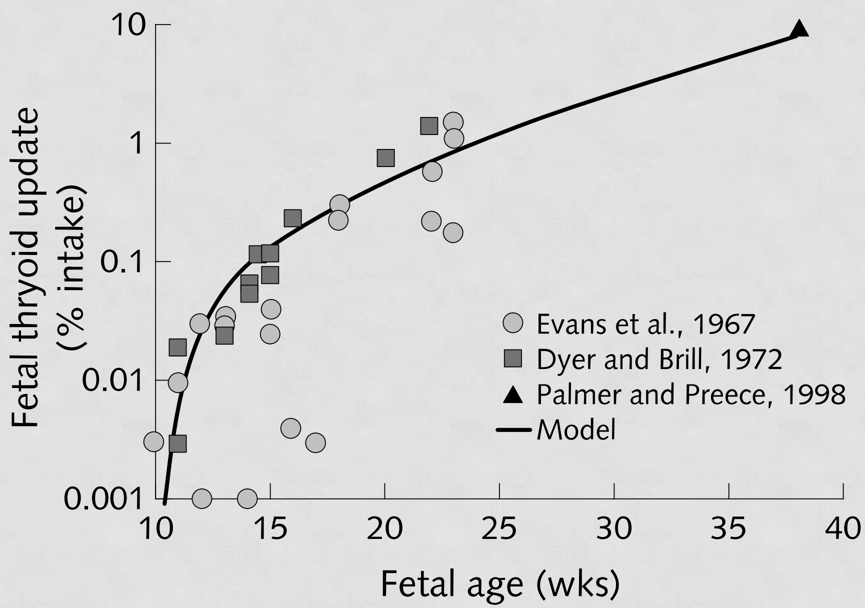


IODINE BIOKINETIC MODEL OF THE TRANSFER OF IODINE TO THE FETUS



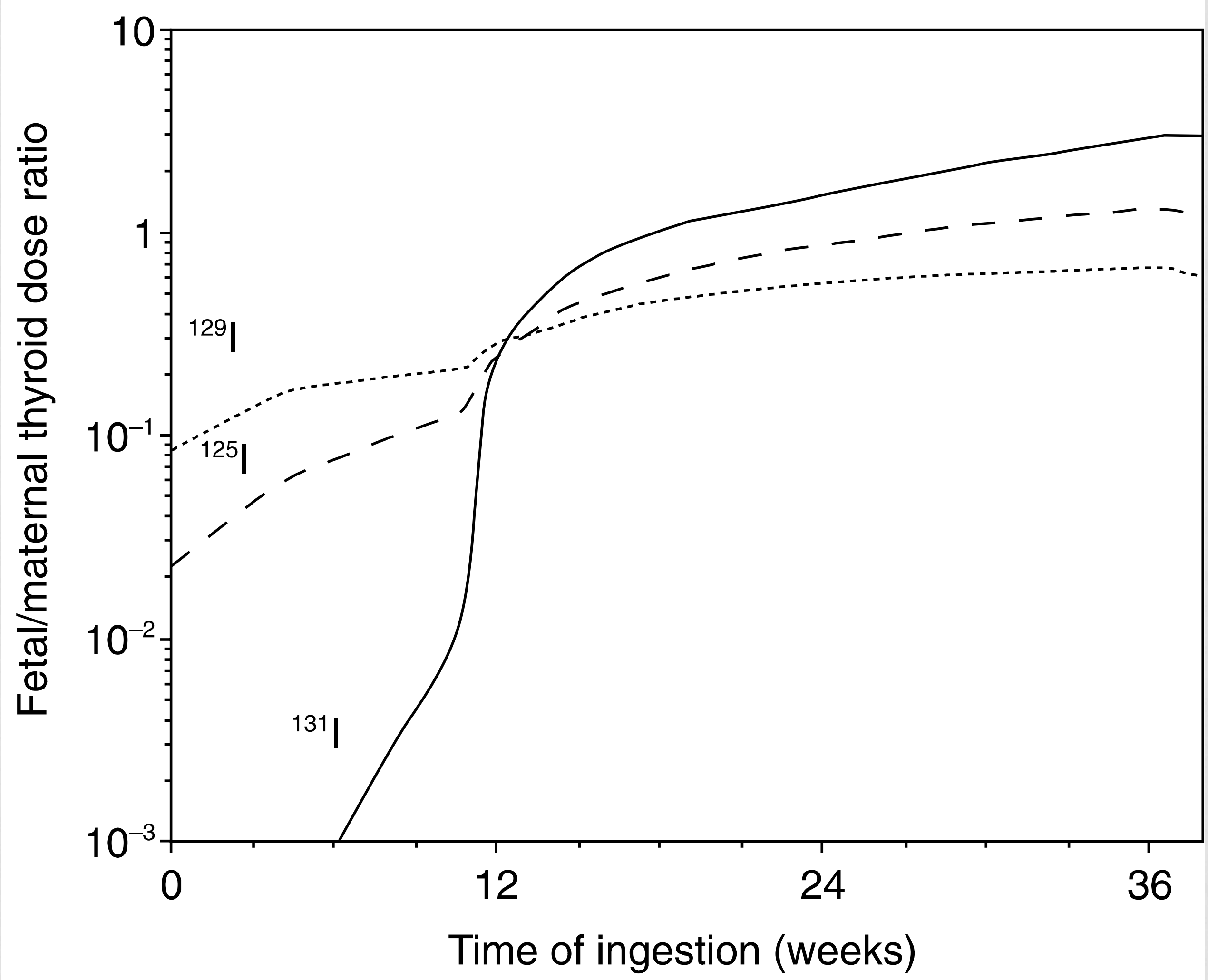
BASIS OF THE BIOKINETIC MODEL FOR THE FETAL IODINE (2)

- **Clinical data on** levels of radioiodine **uptake by the fetal thyroid** of human and animals at different gestational stages and at different times after iodine injection into maternal blood.
- **Clinical data on** the time course of fetal **thyroid functional activity**. The onset of the activity from the 11th week.



THE RATIO OF COMMITTED EQUIVALENT DOSES TO THYROID GLANDS OF THE FETUS AND MOTHER

ACUTE INGESTION AT DIFFERENT GESTATION STAGES



DOSIMETRIC CHARACTERISTICS OF RADIOIODINES

Radioiodine and daughter radio-nuclides[4] (yield for daughters)	Half-life	Energy per nuclear transformation (MeV)		Equivalent dose to the thyroid of offspring[a,b] (Sv)	Postnatal thyroid dose[a,c]	Reference dose to the maternal thyroid[b][2] (Sv)	Thyroid dose ratio: offspring/ mother[a,b]
		Electrons	Photons				
^{125}I	60.14 d	0.0194	0.042	1.9×10^{-7}	48%	1.5×10^{-7}	1.2
^{129}I	1.6×10^{7}y	0.0638	0.0246	6.7×10^{-7}	56%	1.0×10^{-6}	0.7
^{131}I	8.04 d	0.1917	0.3816	6.1×10^{-7}	19%	2.1×10^{-7}	2.9
^{131}Xe (1.11%)	11.9 d	0.1439	0.02				
^{132}I	2.3 h	0.4954	2.2804	6.1×10^{-9}	–	1.9×10^{-9}	3.2
^{133}I	20.8 h	0.4107	0.6072	1.3×10^{-7}	–	4.0×10^{-8}	3.3
^{133}Xe (97.1%)	5.245 d	0.1357	0.0461				
^{133m}Xe (2.9%)	2.188 d	0.1924	0.0408				
^{135}I	6.61 h	0.3671	1.5763	2.7×10^{-8}	–	8.1×10^{-9}	3.3
^{135}Xe (84.6%)	9.09 h	0.3172	0.2486				
^{135m}Xe (15.4%)	15.29 min	0.0976	0.429				

[a]Acute inhalation of 1 Bq at 36th week of gestation.

[b]Worker, inhalation of Aerosols Type F, 5 μm AMAD.

[c]Contribution to the full dose to thyroid of offspring.

[d]Daughter radionuclides are not taken into account in dosimetric calculations.

DOSES TO THYROID AMONG GENERAL PUBLIC

- Reported individual thyroid doses varied up to approximately **40 Gy**, with **average doses of a few to 1 Gy**, depending on the area where people were exposed (Bouville A, et al. 2007).
- For the more than **6 million residents** who were not evacuated, the **average thyroid dose was about 0.1 Gy**, while for about **40 000** of them, the thyroid doses were more than **1 Gy** (UNSCEAR, 2008).
- The average thyroid dose to **pre-school children** was some **2 to 4 times greater** than the population average.

IN UTERO THYROID DOSE

- Participants were **2,582 mother-child pairs** in which the mother had been pregnant at the time of the Chernobyl accident on 26 April 1986 or in the 2-3 mo following when ^{131}I in fallout was still present.
- Individual **in utero thyroid dose** estimates were found to **range** from less than **1 mGy to 3.2 Gy**, with an **arithmetic mean** of **72 mGy**.

Recommended reading:

- Radioiodine biokinetics in the mother and fetus. Part 1. Pregnant Women. Proc. of Int. Seminar on Radiation and Thyroid Cancer. Berkovski, V. World Scientific. pp. 319-325. 1999.
- Radioiodine biokinetics in the mother and fetus. Part 2. Fetus. Proc. of Int. Seminar on Radiation and Thyroid Cancer. Berkovski, V. World Scientific. pp. 327-332. 1999.
- New iodine models family for simulation of short-term biokinetics processes, pregnancy and lactation. Berkovski, V. Food Nutr. Bull. 23 (Suppl): 87-94, 2002.
- *Estimation of the thyroid doses for Ukrainian children exposed in utero after the Chernobyl accident*. Likhtarov I. et al., Health Phys. 2011 Jun;100(6):583-93.

UNSCEAR-2008: A MAJOR PUBLIC HEALTH IMPACT

- Among the residents of Belarus, the Russian Federation and Ukraine, there had been **up to the year 2005 more than 6,000 cases of thyroid cancer reported in children and adolescents** who were exposed at the time of the accident, and more cases can be expected during the next decades.

- Apart from this increase, there is no evidence of a major public health impact attributable to radiation exposure two decades after the accident.

DOSE PER UNIT MEASURED QUANTITY

CHALLENGES AND SOLUTIONS

PROSPECTIVE DOSE ASSESSMENTS OF INDIVIDUAL DOSE VS. ASSESSMENTS BASED ON THE MONITORING DATA

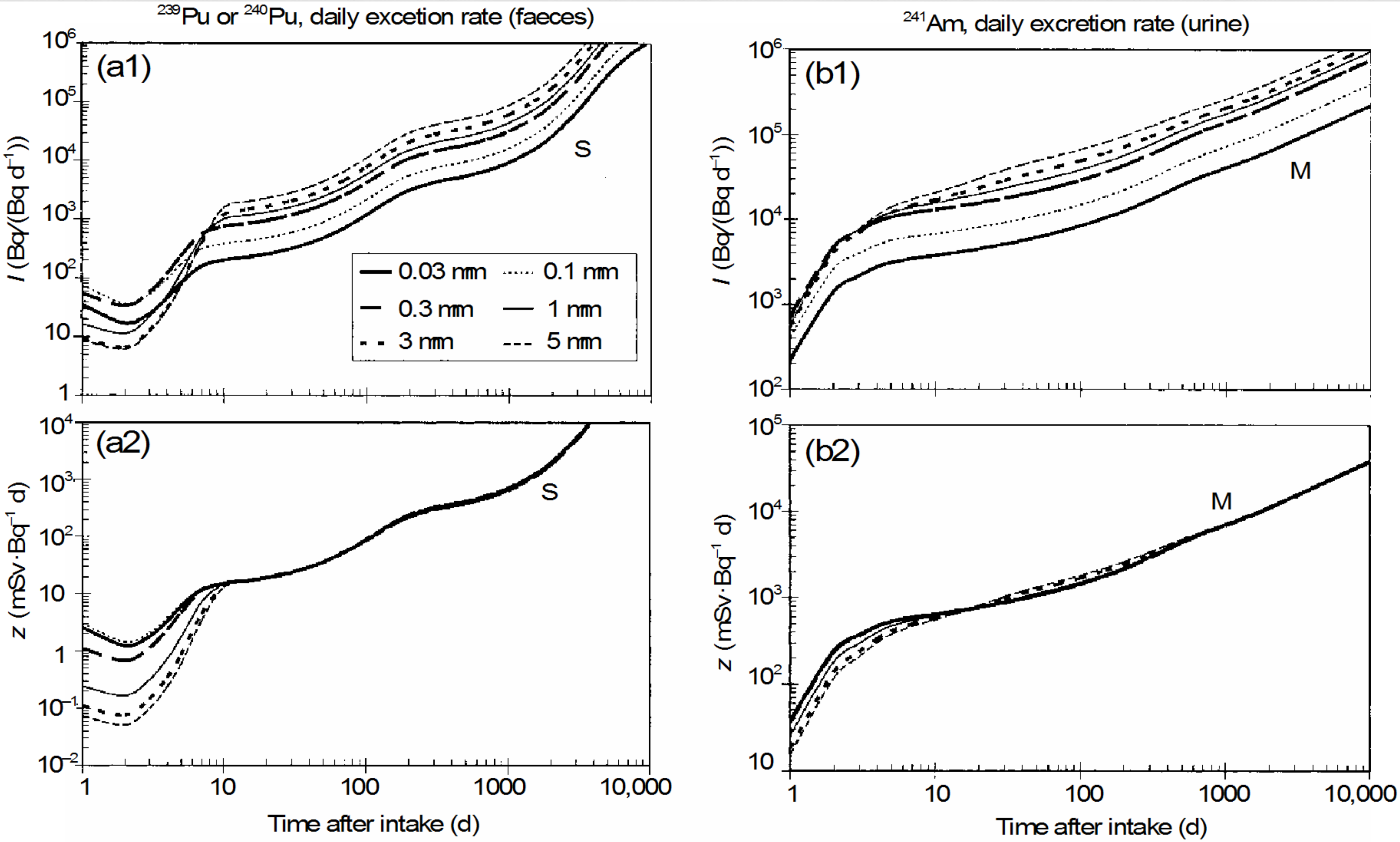
- In the prospective dosimetry, the intake of the radionuclide is the main input information for dose assessments.
- '**Dose per unit intake**' coefficients (denoted as **e**) are the natural instrument in such problems.
- In assessments based on monitoring data, the primary input information is the bioassay or workplace monitoring data.
- In the case of inhalation, **e** is substantially depend on the **activity median aerodynamic/thermodynamic diameter (AMAD/AMTD)** and the **Type of material (TM)**, which describe the solubility of aerosols in lungs.

DOSE PER UNIT MEASURED QUANTITY

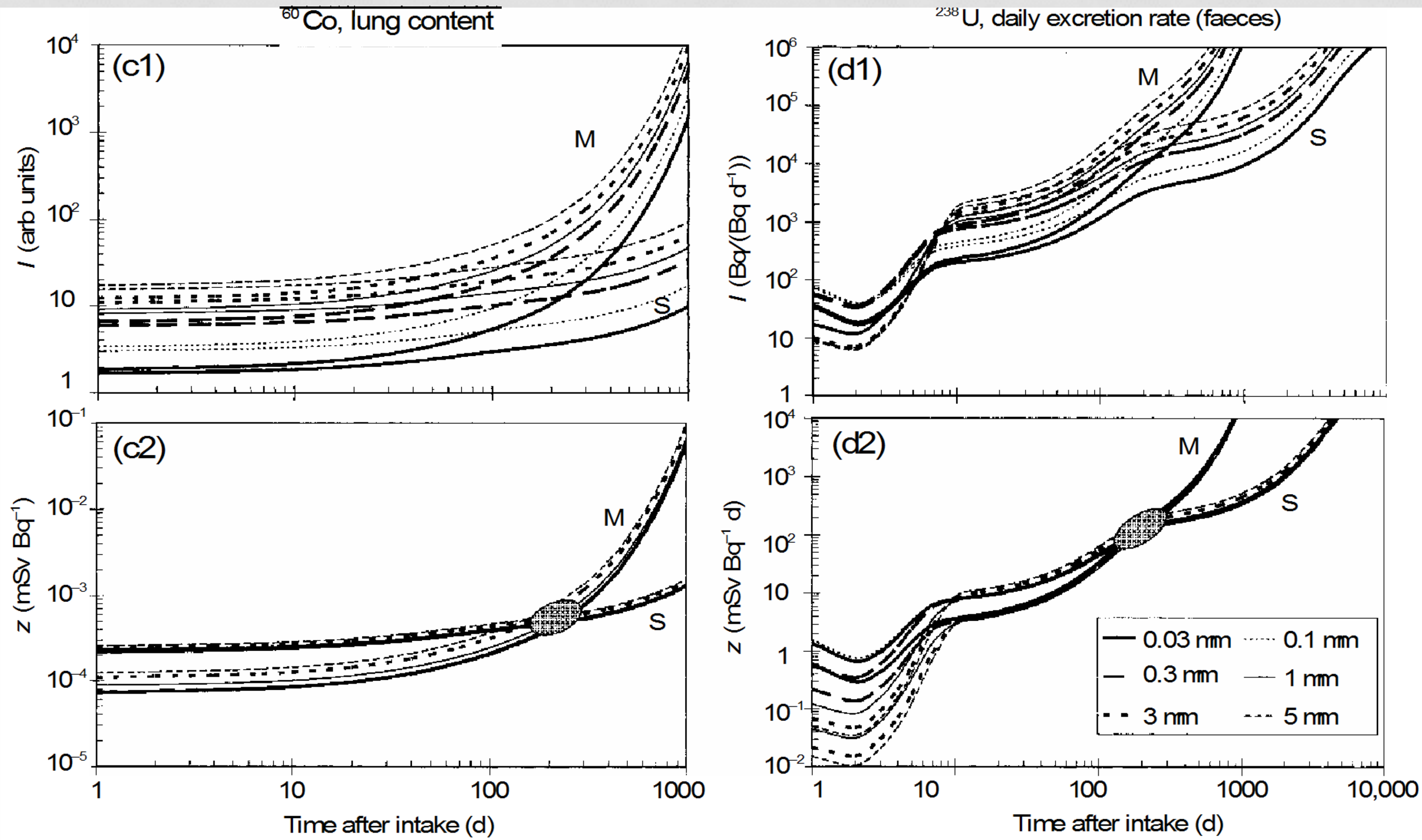
- The **assessment of the activity intake after inhalation from the bioassay data** can be difficult due to the lack of information about the time of intake, chemical form and AMAD of the aerosols.
- Aggregated time-dependent functions '**dose per unit measured quantity**' ***z*(*t, AMAD, Type of Material*),** -- e.g. 'dose per daily excretion rate' -- have been proposed as a convenient and reliable tool for bioassay.
- The analysis of the variation of **z** with changes of AMAD has demonstrated the areas of the relative invariance, which permits the application of a single reference **z-function** in the wide range of AMAD.
- **The proposed approach has been used by the ICRP in the preparation of the new series of publications "Occupational Intakes of Radionuclides"**, which should replace ICRP Publications 30, 68 and 78.

- Recommended reading: "Dose per unit content" functions: a robust tool for the bioassay. Berkovski, V.; Bonchuk, Y.; and Ratia, G. Rad. Prot. Dosim. 105 (1-4) 2003.

THE VARIATION OF FUNCTIONS *I(T)* (*ACTIVITY INTAKE PER UNIT EXCRETION RATE*) AND *Z(T)* (*COMMITTED EFFECTIVE DOSE PER UNIT EXCRETION RATE*) WITH AMAD AND TYPE OF MATERIAL



THE VARIATION OF FUNCTIONS *I*(*T*) AND *Z*(*T*) WITH AMAD AND TYPE OF MATERIAL



CURRENT AND FUTURE WORKS

CHALLENGES AND SOLUTIONS

NEW SAFE CONFINEMENT AT THE CHERNOBYL SITE

POWER REACTORS IN UKRAINE

Reactor	Type V=PWR	MWe net	Commercial operation	Scheduled close, likely close
Khmelnitski-1	V-320	950	Aug 1988	2018, 2032
Khmelnitski-2	V-320	950	Aug 2005	2035, 2050
Rivne/ Rovno-1	V-213	402	Sep 1981	2030
Rivne/ Rovno-2	V-213	416	Jul 1982	2031
Rivne/ Rovno-3	V-320	950	May 1987	2017, 2032
Rivne/ Rovno-4	V-320	950	late 2005	2035, 2050
South Ukraine-1	V-302	950	Oct 1983	***2023***
South Ukraine-2	V-338	950	Apr 1985	2015, 2030
South Ukraine-3	V-320	950	Dec 1989	2019, 2034
Zaporozhe-1	V-320	950	Dec 1985	2015, 2030
Zaporozhe-2	V-320	950	Feb 1986	2016, 2031
Zaporozhe-3	V-320	950	Mar 1987	2017, 2032
Zaporozhe-4	V-320	950	Apr 1988	2018, 2033
Zaporozhe-5	V-320	950	Oct 1989	2019, 2034
Zaporozhe-6	V-320	950	Sep 1996	2026, 2041
Total (15)		**13,168 MWe net (13,835 MWe gross - Energoatom May 2010)**		

CONCLUSIONS

CAPACITY BUILDING

CONCLUSIONS

- The **experience** of the Chernobyl accident **has been broadly used for the modernization of the ICRP protection system** and upgrading of the international safety standards and national regulations.
- **The intensive work of the radiation protection community** during the quarter of a century between two accidents at the Chernobyl and Fukushima Daiichi power plants has substantially **reinforced and expanded the capacity of radiation protection**.
- Particularly, the **UNSCEAR, ICRP and the IAEA have published a series of reports**, which addressed the discussed issues and the **new international safety standards** now included the up-to-dated scientific approaches.

CONCLUSIONS

- A decline in the research funding is a dangerous tendency in the capacity building and it should be compensated by the better coordination of research projects and by the “intervention” of international organizations.
- The author believes that the IAEA, as well as other international organizations, should play a more active role in the capacity building for radiation protection.
- Particularly, the **IAEA can take the leadership in the strategic planning, coordination and support of research programmes and in scientific exchanges** related to the capacity building.