IAEA
International Atomic Energy Agency
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# Occupational Radiation Protection during High Exposure Operations

Lessons Learnt from Occupational Radiation Protection in Past Accidents

Nuclear Accidents – Chernobyl Accident –

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# 1. General information of the Chernobyl accident

- The Chernobyl NPP consisted of 4 operational power units. Units 5 and 6 were under construction.
- Commissioning of the first 4 units took place from 1977 to 1984.

http://www.rt.com/news/155072-chernobyl-images-now-then/

# 1. General information of the Chernobyl accident

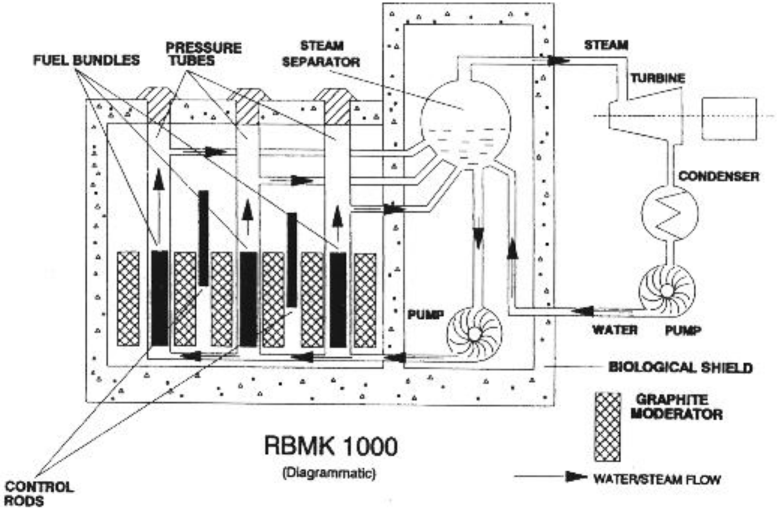
- The accident occurred on 26 April 1986 in the night from Friday to Saturday during a low-power engineering test of the Unit 4.

- Improper, unstable operation of the reactor, which had design flaws, allowed an uncontrollable power surge to occur, resulting in successive steam explosions, which severely damaged the reactor building and completely destroyed the reactor.

( A photo of the destroyed fourth reactor of the Chernobyl nuclear power plant taken by the plant's official photographer Anatoliy Rasskazov in the first hours after the deadly explosion , The Telegraph, http://www.telegraph.co.uk/news/picturegalleries/worldnews/8461299/Chernobyl-power-plant-in-pictures-25-years-since-the-worlds-worst-nuclear-accident.html)

# 1. General information of the Chernobyl accident

- RBKM reactor diagram (3200 MWth)




Operator actions triggered such excessive increase of power in the fuel that it most probably disintegrated in one part of the core. The first steam explosion moved 2000 tons reactor cover and then it was triggered combustion of the graphite moderator.

# 1. General information of the Chernobyl accident

Chernobyl accident has occurred as a result of several factors, which can be summed up and described briefly as:

- The design of RBKM had not ensured nuclear safety inherently, which is a prerequisite for a modern nuclear power plant. Within this type of reactor, power is not slowed down with rise of water coolant temperature (positive void coefficient of reactivity), and
- The control rods had a design flaw (after the first moment of their insertion the power increases). All these operators didn‘t know.
- They were not enough prepared for the test due to other priority of prolong operation and their actions were unsatisfactory. For this style of testing they did not have any written instructions. They didn‘t stop and think, but on the spot they modified reactor test conditions.

# 1. General information of the Chernobyl accident

Chernobyl accident has occurred as a result of several factors, which can be summed up and described briefly as (cont'd):

- In former Soviet society a questionable oversight over nuclear safety existed. A lack of independent checks and inspections was obviously
- Some operational experiences were already existing but not proceeded
- Nuclear safety in operation was not in the first place. Accident management procedures were not available
- Independant safety reviews of the design and analysis of potential accidents were not performed.

# 1. RKBM reactor safety after Chernobyl accident

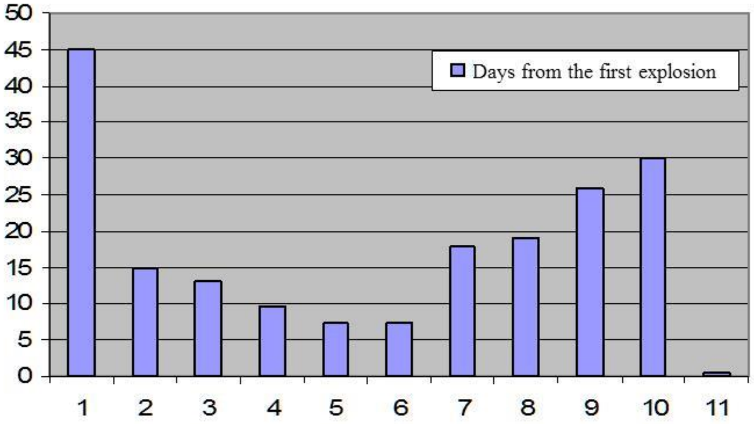
The safety level of RBMK reactors has been significantly enhanced by a series of organizational and technical measures. These include:

- modification of the physical characteristics of the reactor by installing additional absorbers and conversion to fuel with a 2.4% enrichment level;
- installation of a fast acting emergency protection system;
- updating of operational documentation and improvement of staff qualifications;
- tightening up of the operating procedure requirements.

# 1. General information of the Chernobyl accident

## Uncontrollable radioactive release

- The accident released a mixture of radionuclides into the air over a period of about 10 days.



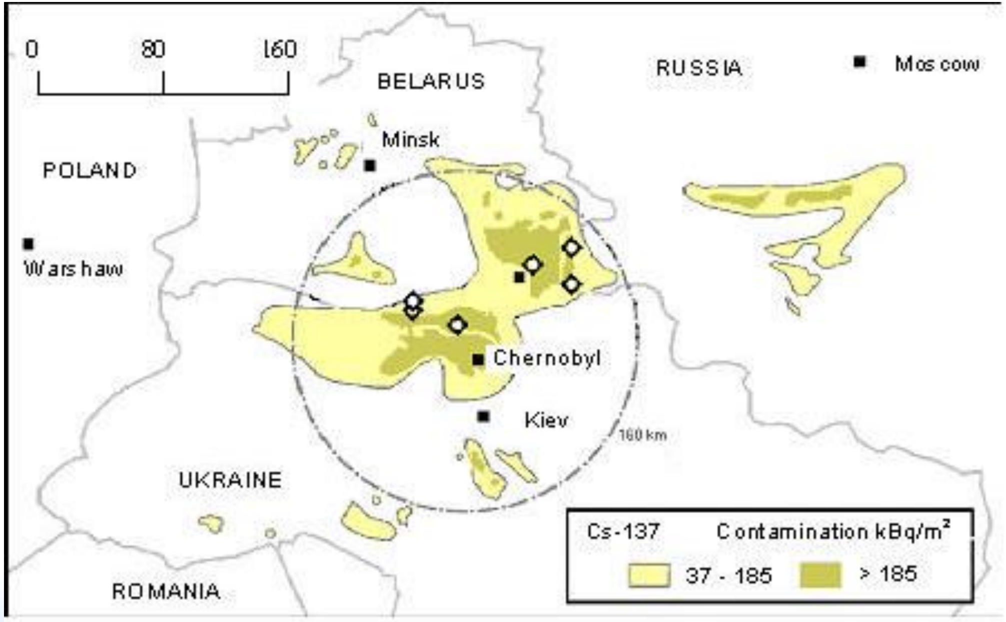

- Total radioactive release amounted to more than 12,000 PBq, including 6,500 PBq of inert gases, 1,800 PBq of $^{131}I$ and 85 PBq of $^{137}Cs$.

# The first three phases of the release

- The explosions introduced to the environment disintegrated radioactive fuel in the form of the particles (actinides: alpha and beta emitters) together with the fission products.  Such explosions with the release of fuel particles are not possible in PWR or BWR reactor core. These heavy elements are otherwise non-volatile.
- The second stage of the release of some amounts of volatile fission products (such as iodine, caesium, and tellurium from the core debris) accompanied with the graphite burning. Volatile fission product release is characteristic for all types of nuclear accident scenarios, also PWR and BWR, but graphite burning triggered additional way for the dispersion of fine particles and an uncertainty for the termination of the release.
- Since the decay heat was not removed efficiently from the rest of the fuel, the third stage of the release was due to additional fuel overheating which accelerated the release of volatiles and due to very high temperature also semi-volatile fission products.

# 1. General information of the Chernobyl accident

## Caesium deposition




Heavier radioactive elements from the fuel were found in the fallout more locally around the plant, while volatile radioactive elements were dispersed in the atmosphere and also washed down with the rain in the region countries and across Europe.

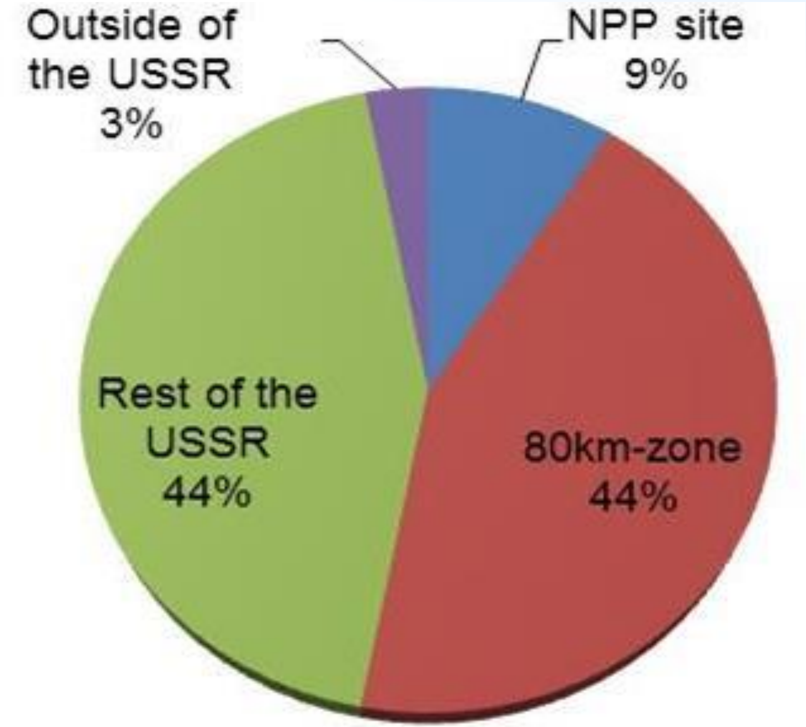
# Fallout and dispersion of nuclear fuel

About 4 % of the core in the form of small fuel particles was reported to be widely dispersed due to the release as follows:

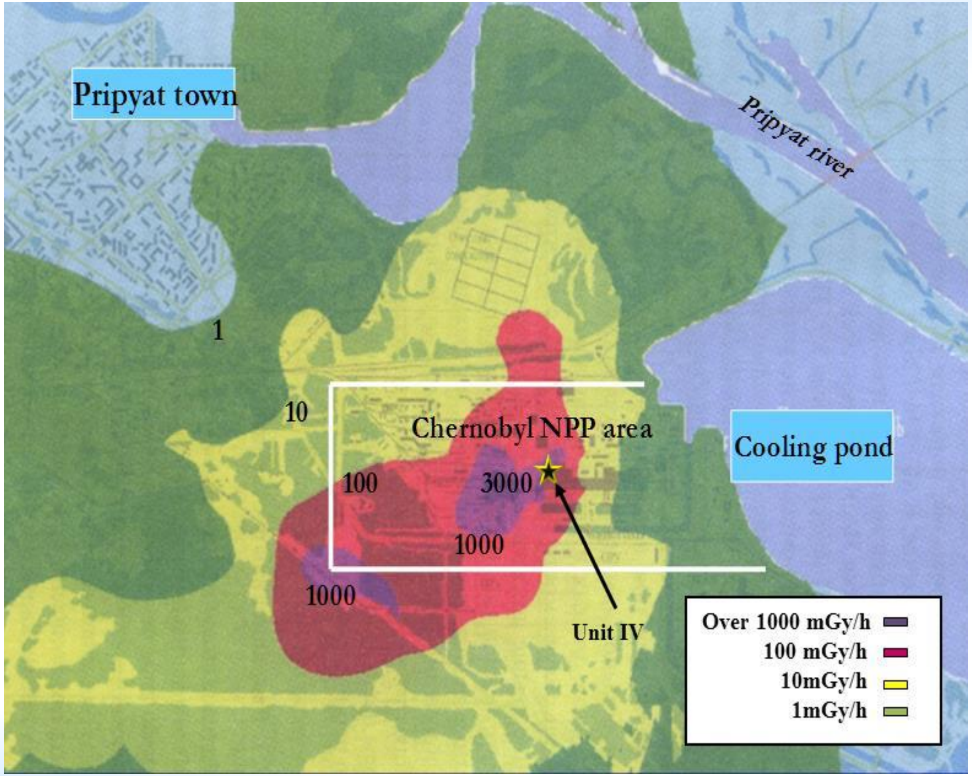
| | |
|---|---|
| • At the Chernobyl site | 0.3 – 0.5 % |
| • Distance 0 to 20 km | 1.5 – 2 % |
| • Distance over 20 km | 1 – 1.5 % |

Less than 96% of the radioactive fuel remained inside the Unit IV

# Released fission products dispersion



# The first radiation data

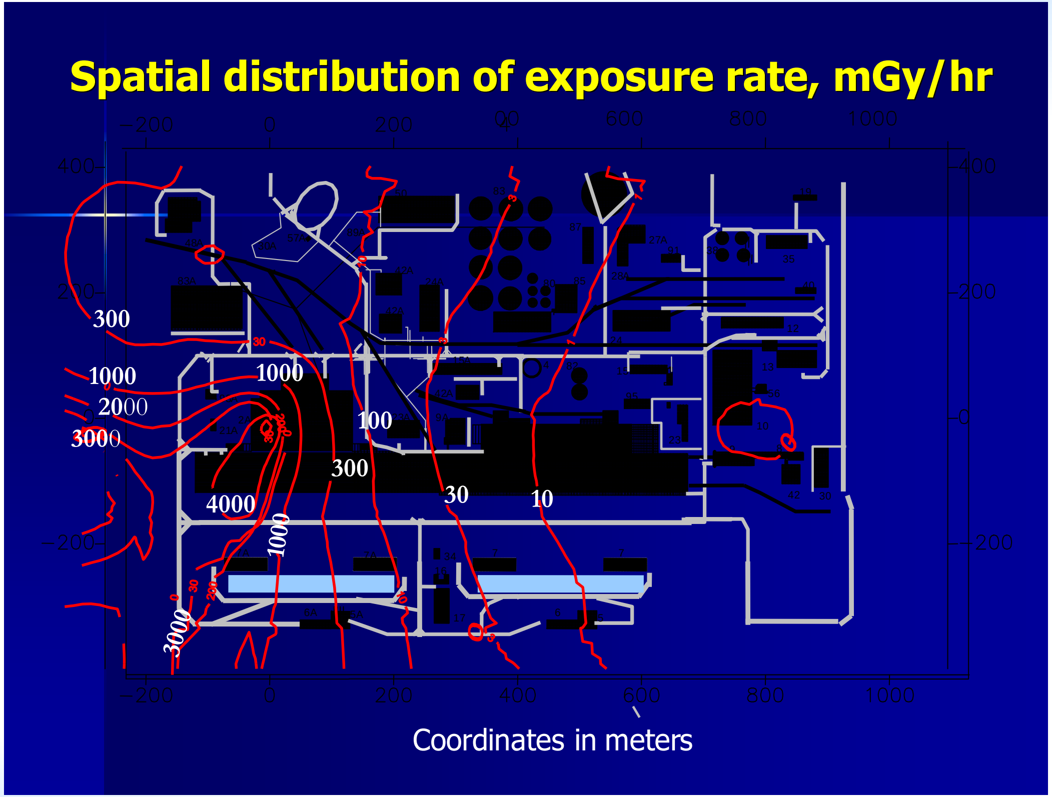



The first radiation data were reported after 1 - 3.5 hours later from the explosion:

The level of radiation or ambient dose rate was very high in the NPP site - several thousand mGy/h

Dangerous situation also occurred outside the NPP. Dose of 1 Gy which corresponded to threshold of deterministic health effects was formed in the 4-km zone during 2 days

# Exposure rates on…….



# 2. What first responders knew?

https://en.wikipedia.org/wiki/Chernobyl_disaster NOTE: find reference

- The driver of one of the fire engines, later described what happened:

We arrived there at 10 or 15 minutes to two in the morning.... We saw graphite scattered about. Our colleague asked: "Is that graphite?" I kicked it away. But one of the fighters on the other truck picked it up. "It's hot," he said. The pieces of graphite were of different sizes, some big, some small, enough to pick them up...

We didn't know much about radiation. Even those who worked there had no idea. There was no water left in the trucks. He filled a cistern and we aimed the water at the top. Then those boys who died went up to the roof – three of them.... They went up the ladder ... and I never saw them again.[49]:54

- Anatoli Zakharov, a fireman stationed in Chernobyl since 1980, offers a different description in 2008:

I remember joking to the others, "There must be an incredible amount of radiation here. We'll be lucky if we're all still alive in the morning."[50]

He also said: Of course we knew! If we'd followed regulations, we would never have gone near the reactor. But it was a moral obligation – our duty. We were like kamikaze.[50]

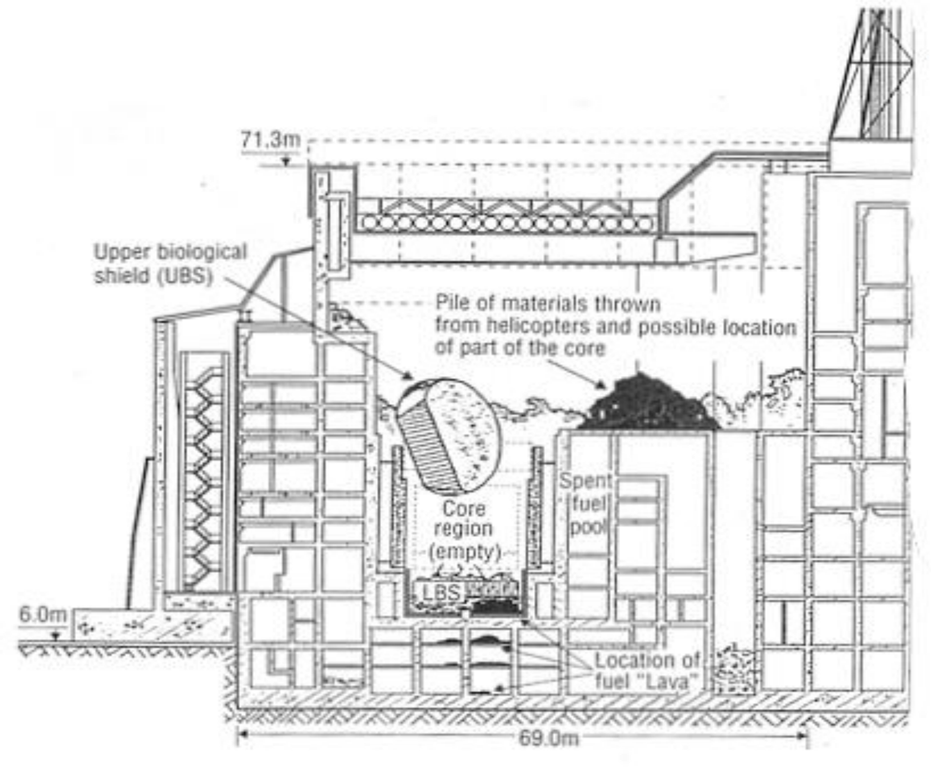
# Exposure rates of first responders

Just after the accident, the dose rates on the site were of this order of magnitude:

- At the site boundary: 10 – 1 000 mGy/h
- On the site: 30 – 3 000 mGy/h

- Turbine hall: 10 – 1 000 mGy/h
- Premises: 1 – 4 000 mGy/h

# Unit IV Diagram



# 2. Emergency and preparedness regulation in the USSR to the Chernobyl accident

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## The basic regulation requirement of emergency situation

- Emergency plan shall be prepared in any authorized facility.
- All practicable measures shall be intended for minimize external exposure and radionuclide intake for emergency workers.
- Overexposure of emergency workers above dose limit must be justified.
- Elevated planned exposure shall be below twice the annual dose limit for single undertaken action and below 5 times above the annual dose limit for the whole emergency period (i.e. 100 mSv and 250 mSv).
- Written permission of administration and personal consent of emergency worker for elevated planned exposure is required.
- The emergency work orders shall include detailed list of actions, their time limitation and safety tips.

# 2. Emergency and preparedness regulation in the USSR to the Chernobyl accident

## EP management system to the accident

- Plan of emergency management of the Chernobyl NPP.
- Plans of radiation protection of the NPP personnel and public.
- Procedure of emergency notification.
- Emergency system of the national operator “Suozatomenergy”.
- Special medical provisions.
- General procedure for official inquiry and liquidation of major accidents in industry.

# Emergency work

The main actions undertaken by the emergency workers were:

- Fire control,
- Saving life,
- Cut-off ventilation / electricity, switching of cooling system,
- Examination of equipment,
- Radiation survey, and
- Water supply.

# Recovery operations

**The principal tasks carried out by the recovery operation workers included:**

- Decontamination of the reactor block, reactor site, and roads (1986-1990),
- Construction of the sarcophagus (May- November 1986),
- Construction of a settlement for reactor personnel (May-October 1986),
- Building of Slavutich town (1986-1990),
- Construction of waste repositories (1986-1988),
- Construction of dams (July-September 1986) and water filtration systems (1987),
- Radiation monitoring and security operations (1986-1990).

# Emergency and recovery workers

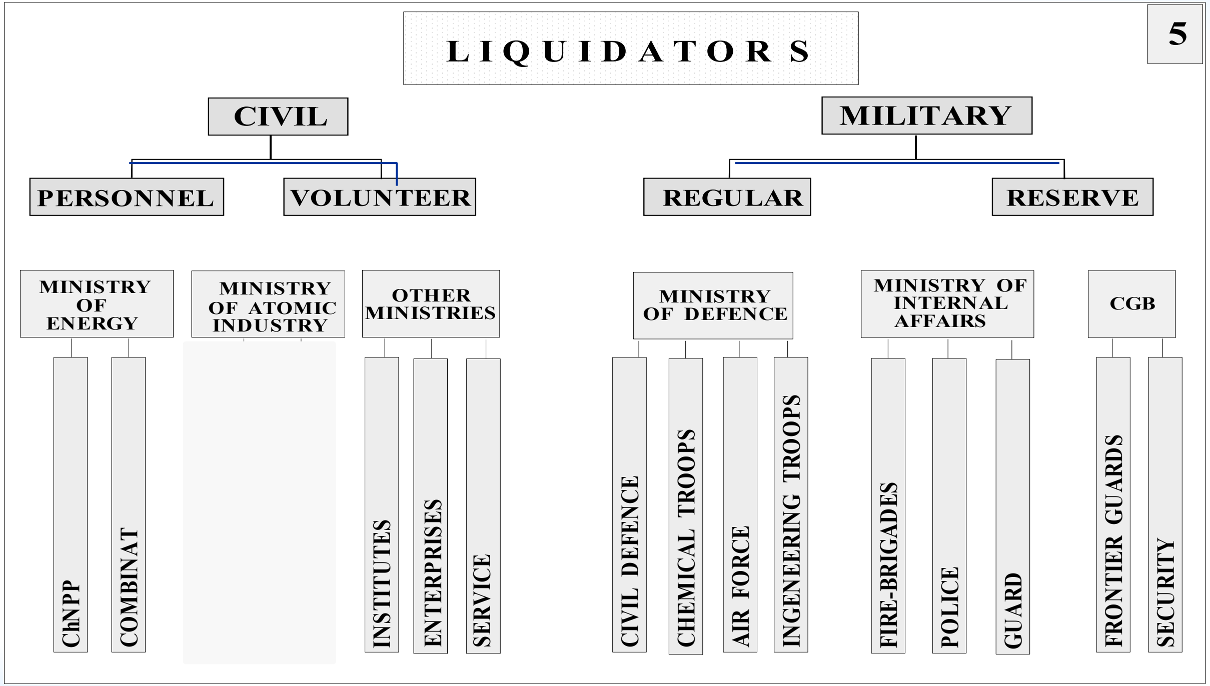
Workers involved in the Chernobyl accident emergency and recovery phases can be divided in two groups:

- Those involved in emergency measures during the first day of the accident (26 April 1986), who are usually referred to as “emergency workers”.
- Those active in 1986-1990 at the power station or in the zone surrounding it for the decontamination work, sarcophagus construction and other clean-up operations. This second group of workers is usually referred to as “recovery operation worker” (although the term “liquidator” gained common usage in the former Soviet Union).

The total number of emergency and recovery operation workers was 530,000 including 150,000 liquidators who worked at the NPP site area. The duration of emergency exposure situation was assumed to be 7 months.

# 3. Categories of emergency workers

## Governmental categories of liquidators



# 3. Categories of emergency workers

## Cohorts of liquidators (emergency workers) in 1986

| Cohort | | Number |
|---|---|---|
| 1986-04-26 | | |
| | Witnesses and first responders | 1,000 |
| 1986-04-27 to 1986-05-20 | | |
| | Urgent response teams | 35,000 |
| | Military | 13,000 |
| | Civil | 22,000 |
| 1986-05-21 to 1986-11-30 | | |
| | Emergency and recovery workers | 89,000 |
| | Military | 49,000 |
| | Civil | 40,000 |
| Total | | 125,000 |

# 3. Categories of emergency workers

## General activities

| Measure | Object | Dates |
|---|---|---|
| Reducing release | Ruined Unit 4 | 1986-04-26 to 05-10 |
| Evacuation | Pripyat town<br>Chernobyl town, Rural settlements | 1986-04-27<br>1986-05-03 to 05-07 |
| Decontamination | Units 1 to 3, industrial area<br>Settlements, roads<br>“Red” forest | 1986 to 1990<br>1987 |
| Construction | Shelter<br>West depository<br>Damps<br>Filter screen | 1986-05-21 to 10-31<br>1986 to 1988<br>1986-07-11 to 09-25<br>1987 |
| Building | Shift industrial community<br>Slavutich town | 1986-05-15 to 10-31<br>1986-05-25 to 1988 |
| Physical protection | Scala-1M (10 km), 30 km zone | Permanently |
| Radiation Monitoring | Contaminated territories | Permanently |

# Dose limits of emergency workers

## Dose restrictions after the accident

| Date | Dose limit | |
|---|---|---|
| 1986-04-26 | Not established | Personnel of the Chernobyl NPP |
| 1986-04-27 to 1986-05-20 | 500 mSv<br>250 mSv | Military liquidators<br>Civil liquidators |
| 1986-05-21 to 1986 -12-31 | 250 mSv | All categories of liquidators |
| 1987-01-01 to 1987-12-31 | 250 mSv | The permission of the USSR Ministry of Public Health for special work |
| | 100 mSv | Works at the Unit 3 and the NPP site |
| | 50 mSv | Everywhere except for above |

# Exposure of emergency workers

Emergency dose monitoring was absent during *reflex* phase:

- The first radiation data were reported 1 to 3.5 hours after explosion.
- Individual dose monitoring was not carried out on 26 April. Only film badges were present. Routine individual dose monitoring was carried out for 4,750 workers and attracted personnel before the accident.
- Actual doses for witnesses were in the range of 40 – 15,000 mGy.
- Dose of 40 mGy was received only during one trip from Pripyat town to the NPP.

| Category | Number | Dose [mGy] | | Collective dose [ man Gy] |
|---|---|---|---|---|
| | | Mean | Median | |
| Witnesses | 1,057 | 550 | 450 | 581 |
| Medical patients | 134 | 3,400 | 2,400 | 455 |

# 3. Categories of emergency workers

## Management at the *reflex* phase

- In general, chaos and uncertainty are common features of major nuclear accident which are characterized the following attributes:
  - ✓ prevalence of disorder over order
  - ✓ Blocked information channels
  - ✓ total uncertainty concerning the radiation situation, exact personnel location and severity of the plant status and operational parameters

- These uncertainties create risks for decision making
  1. Decision maker under a great stress
  2. The more uncertainty the greater risk of making wrong decisions
  3. Range of alternative decision options: to do any acceptable actions or to do actions allowing a reduction of uncertainties

# 4. *Reflex* phase: 26 April 1986

Key issues in *reflex* phase were as follows:

- To clarify the situation and identify immediate and future threats

  >> Collection and comprehensive analysis of witness evidence
- To put the emergency plan into action

  >> Emergency management and urgent actions directed on maintenance of the operationality of the object
- To limit the number of involved emergency workers

  >> Evacuation of unnecessary witnesses, establish security check-points
- To measure exposure rates and surface radioactivity contamination

  >> Establish the emergency zoning
- To prevent radionuclide carry over (surface contamination spread)

  >> Functionality of radiation protection check-points

# 5. Early phase: 27 April – 20 May 1986

## Chemical factors during emergency response

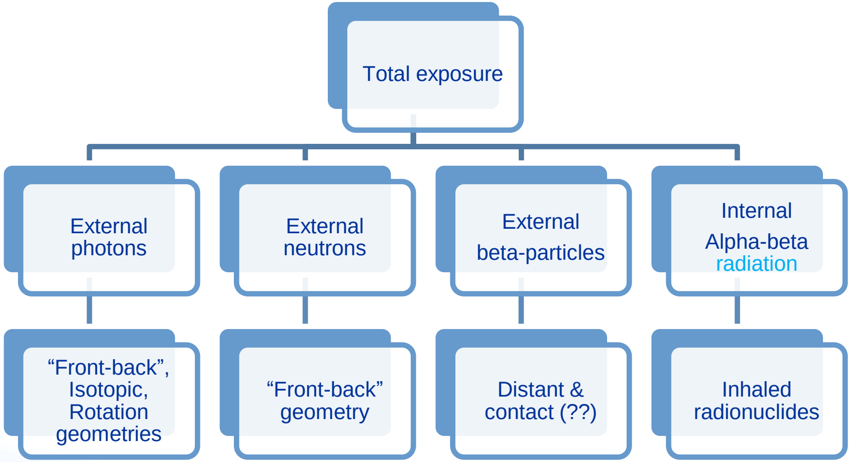
| Origin | Initial materials | Pollutants |
|---|---|---|
| Fire at Unit 4 | Graphite, building and materials containing organics, bitumen | CO, $NO_2$, hydrogen cyanide (??), phosgene, smoke, superfine aerosols |
| Sublimation of materials dumped on the reactor | Sand, clay, lead, dolomite, boron compounds | Lead in air |
| Dust catching for building, roof, industrial site and roads of 30 km zone | For example: oxalic and hydrochloric acids, formalin; resins, oil-slime | Superfine acid aerosols, sulphur/organic containing vapours |

# Radiological and other factors during the early phase: 27 April – 20 May 1986

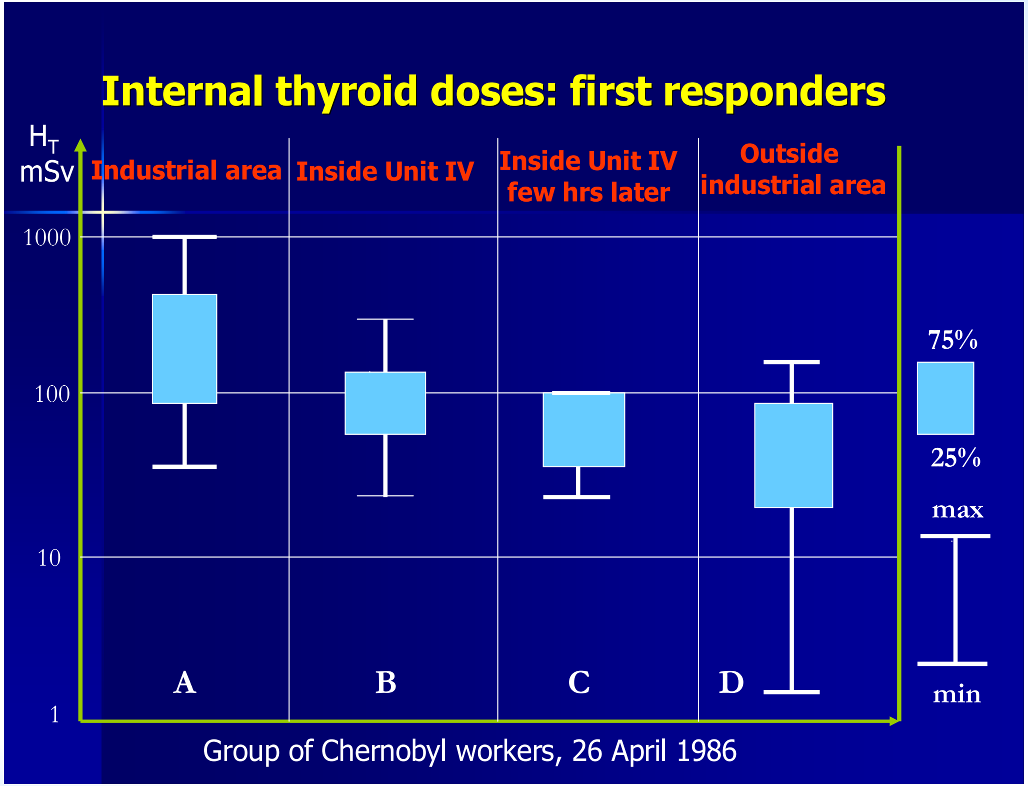
## Physical factors during emergency response

- The main physical factor was ionizing of air. Ion levels exceeded the permissible level by orders of magnitude ($10^3$ – $10^5$ higher near Unit 4). This factor led to the oropharyngeal syndrome, seen in around 60% of the liquidators in 1986.

## Radiological factor



# Internal thyroïd doses



# 5. Early phase: 27 April – 20 May 1986

- Neutron exposure:
  - ✓ The first measurement of neutron fluence showed evidence of a continuing nuclear chain reaction. This suggestion became start point in the set of early countermeasures directed to nuclear safety.
  - ✓ Neutron exposure was a minor contributor to the total dose (up to 1 – 2% of gamma exposure near Unit 4, June - July 1986)
- Gamma exposure
  - ✓ Energy dependence of different individual dosimeters was in the range of 0.8 – 1.7 compared with reference dosimeters. This uncertainty should be taken into account when analysing dosimetry data.

# 5. Early phase: 27 April – 20 May 1986

Key issues in the early phase were as follows:

- To establish a  list of urgent actions, available means and man power according to the radiation situation and predictable threats
- To use the graded approach for operational planning
- To estimate resources for urgent measures
- To apply the system of emergency management in a proper manner

# 5. Early phase: 27 April – 20 May 1986

## Dose monitoring of the workers

- 1986-04-27 Regional civil defence unit handed condenser dosimeters DKP-50 to the Chernobyl NPP safety engineering department.
- 1986-04-28 TLD devices were deployed at the dosimeter point of industrial camp “Skazochniy”.
- 1986-04-28 WBC was deployed at the dosimetry point.
- 1986-05-10 Occupational individual monitoring of the Chernobyl personnel was satisfactory established.
- 1986-06 Results of individual monitoring were reported daily to the governmental commission.

# 6. Intermediate phase: 21 May – 30 November 1986

## Special health regulation

- Special health regulations covered all objects and aspects of emergency works. Firstly, radiation zones were established.

| Zone | Description | Dose rate criteria [μGy/h] |
|---|---|---|
| 1 | Zone of strict control | 30-50 |
| 2 | Including 30-km zone and excluding 10-km zone | 50-200 |
| 3 | Prohibited 10-km zone excluding industrial site of NPP and Pripyat town | >200 |
| 3-A | Site of NPP and Pripyat town | |

# 6. Intermediate phase: 21 May – 30 November 1986

## Surface contamination

- Temporary permissible levels of surface contamination adopted on 1986-05-07.

| Surface | β [cpm per $cm^2$] | Exposure rate [μGy/h] |
| --- | --- | --- |
| Skin, underwear, towel, bed, linen, footwear, protective device & clothes | 1,000 | 1 |
| dwellings, internal surface of transport facility | 2,000 | 2 |
| External surface of transport facility | 3,000 | 3 |

# 6. Intermediate phase: 21 May – 30 November 1986

## Individual and collective doses (1986-04-26 to 12-31-1986)

| Category | Number | Dose [mGy] | | Collective dose [man Sv] |
|---|---|---|---|---|
| | | Mean | Median | |
| Hospital patients | 134 | 3,400 | 2,400 | 455 |
| Witnesses | 1,057 | 550 | 450 | 581 |
| Early civil liquidators | 21,600 | 115 | 56 | 2,484 |
| NPP personnel | 2,358 | 87 | 48 | 205 |
| US-605 personnel | 21,500 | 82 | 50 | 1,763 |
| Military liquidators | 61,762 | 204 | 220 | 12,600 |
| Attached 30 km zone | 31,021 | 20 | 6.3 | 620 |
| Total | 139,432 | 134 | | 18,708 |

# 7. Conclusions

Both positive and negative lessons of the Chernobyl accident concerning radiation protection of emergency workers are still valid for the international community.

1. Two issues are considered extremely important, i.e.

    (1) Management and exposure control for the first responders and,
    (2) Involvement of a great number of people in the recovery operation.

2. Even at high stress levels, most of the emergency workers carried out their duties in spite of their own personal safety, including radiation safety.

3. The Chernobyl experience demonstrated changing priorities and key issues in different phases of mitigation.

# 7. Conclusions

4. Negative lessons are:

(1) Absence of adequate personal dose monitoring means and dosimeters for measurements of high levels of dose rate;
(2) Working assumption that reactor was not destroyed for water supply operation;
(3) Working assumption that active core was placed inside reactor;
(4) Political decision on Unit III restoration without economic justification;
(5) There was a 11 to 15 hour delay in decisions taking due to great uncertainties;
(6) Absence of appropriate workplace and individual monitoring led to serious radiological consequences among emergency workers and witnesses

# 7. Conclusions

5. Positive lessons are as follows:

(1) Reliable system of security check-points and sanitary check points;
(2) The ranking of the harmful factors: external gamma → external beta→ internal exposure;
(3) Development of retrospective dosimetry techniques;
(4) Timely triage of victims and system for three-stage medical treatment;
(5) Managing stable iodine prophylaxis;
(6) Dose management based on the Dose Order Form;
.

# 7. Conclusions

5. Positive lessons are as follows:

(7) Change of routine managers to the emergency managers in the field of radiation protection;
(8) Dual personal dose monitoring of external exposure: daily and cumulative;
(9) Application of “Choice of main source”, “Step-by step recapture of territory” approaches, “Optimal impact on radiation situation” concept;
(10) Application of unmanned techniques for the reduction of operational duration;
(11) Dose distribution analysis in ALARA procedure;
(12) Application of suitable and adequate personal protective equipment (including protective clothing, respiratory equipment, protective aprons and gloves). It was proved that lead protective equipment was not optimum in the limited time conditions for intensive manual operations.

# LESSONS LEARNT

**Brief RP guidelines corresponding to Chernobyl negativee RP issues (emergency workers and organization)**

- Be informed in advance about all probable risks and remember what are radiation deterministic effects
- Have electronic dosimeter with an alarm level and an easily audible alarm
- Participate in pre-job briefing about necessary actions and communicate your opinion
- Entrance a high dose rate area only after receiving information on dose rate and on expected dose. Support personnel should control your dose on distance or periodically and provide time measurements. Short radio link communications, for example, could be available and used between the workers on distance.

# LESSONS LEARNT (cont'd)

**Brief RP guidelines corresponding to Chernobyl negativee RP issues (emergency workers and organization)**

- Use respiratory protection equipment if required to avoid your internal contamination. Use the glasses or full face mask to protect yourself.
- Start, stop and think if the procedures or planned actions are not clear. Avoid heroic decisions in the field and do not expose yourself if not planned or necessary. Perform the actions in a quick manner. The priority is helping to save the lives
- Respect the requirements for contamination control set by the RP personnel.
- Take care about your dosimeters to provide the received dose data to the RP service

# LESSONS LEARNT(cont'd)

**Brief RP guidelines corresponding to Chernobyl RP issues (emergency organization)**

- Be informed about release source term of those probabilistic safety analysis accident scenarios having a higher probability
- Understand behavior of volatile fission products release, associated risk, and protection measures
- Use information from dose rate analysis at the site in case of accident and instruct the radiation protection unit about safe access to the rooms
- Prepare and use electronic and passive dosimeters of high quality and reliability and a channel for supply of additional dosimeters for a high number of workers
- Establish backup for dosimetry recording system
- Prepare Radiation/Dosimetric Work Permit System

# LESSONS LEARNT(cont'd)

**Brief RP guidelines corresponding to Chernobyl RP issues (emergency organization)**

- Prepare exposure control procedures for the personnel with brief information on radiation stochastic and deterministic effects. Assure information in case of emergency regarding the doses above 100 mSv and for the volunteers for higher exposures over 250 mSv. Prepared dose authorization forms and a justification protocols for any exposures above 100 mSv and any exposures above 250 mSv. Prohibit any exposures near or above the threshold of 1 Gy whole body dose.
- Prepare a strategy and modules for RP training of a higher number of emergency workers
- Prepare strategy of information notices and regular communication of the accident facts and risks to the emergency workers
- Prepare a strategy for pre-job briefings for a high number of emergency workers

# LESSONS LEARNT(cont'd)

- Prepare a set of necessary personal protection equipment/air supplied and dosimeters with a safe alarm function for fire fighters and emergency workers
- Prepare stable iodine administration strategy and respiratory protection equipment
- Assure the means for air contamination measurement and a quick determination of the release source term
- Prepare the instruments to detect gamma, beta and alpha radiation and emergency gamma spectrometry devices. Use gamma dose rate telemetric probes, and high range switched-on when entering a potentially high dose rate area. Prepare mapping system of radiological conditions.
- Assure activation of usual RP management with the experts and RP engineers in the decision making in emergency management system

# LESSONS LEARNT(cont'd)

- Obtain a justification for planned actions from emergency management and a signature from the volunteers that they understand high dose effects and agree with the planned exposure.