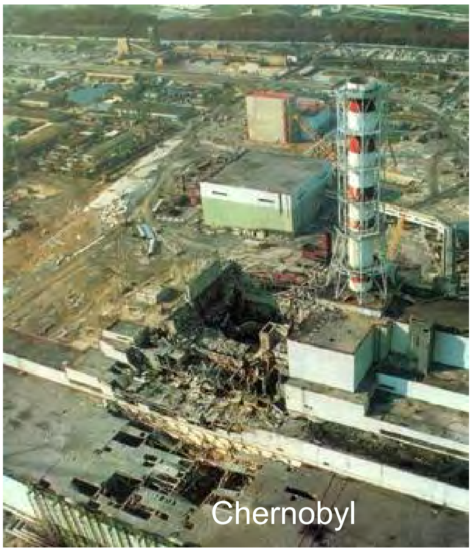


The two main sources for man-made radioactive pollution are:
1. Nuclear bomb tests in the period 1945 to 1999.
2. Reactor accidents – in particular Chernobyl in April 1986.

Chapter 8

Nuclear Weapons – Reactor Accidents and Pollution

This chapter is concerned with radioactive pollution, nuclear weapon tests and reactor accidents that have occurred over the years. The doses to the general public, are mostly small (smaller than those from natural radiation), whereas doses to particular groups may be significant.

In this chapter we shall give a brief review of the physics involved in the development of reactors and atomic bombs – as well as the radioactive pollution from the bomb tests and the reactor accident in Chernobyl.

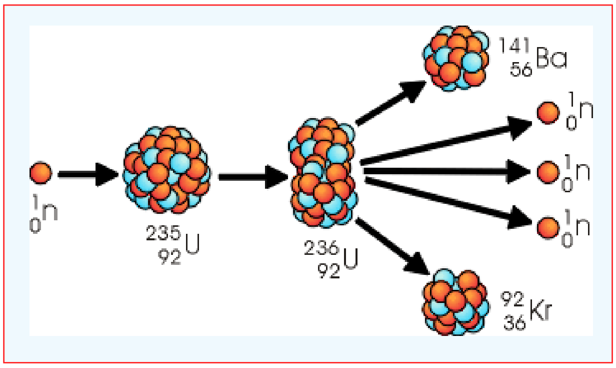
Reactors and Nuclear Bombs

In Chapter 4 we described the research during the 1930th that resulted in the discovery of fission in December 1938. In January 1939 Bohr embarked on a four month stay in the United States as a visiting professor and he brought the exciting news about fission to the U.S. The development from that point was quite rapid. Thus, already in December 1942 the first nuclear reactor was started by Fermi in Chicago – and July 16, 1945 the first atomic bomb exploded near Almagordo in New Mexico.

In the following we shall try to give some of the highlights from this research.

The fission reactor

N. Bohr and J. A. Weeler found that it was U–235 that was the fissile isotope (only 0.71 % of uranium consists of this isotope). The main uranium isotope U–238 is not fissile, but can be fissionable when hit by an energetic neutron with an energy above 1 MeV. Otherwise U–238 is transformed into plutonium Pu–239 which in turn is fissile.



Leo Szilard
(1898 – 1964)

The Hungarian physicist Leo Szilard had the idea about a chain reaction. As you see in the illustration the fission process release neutrons, that in turn can be used to fission other U-235 atoms – and thus give a chain reaction.

The neutrons released in the fission process have an energy of about 1 MeV – and the "*cross section*" (the chance for a reaction) for neutron capture leading to fission is greatest for neutrons with an energy around 1 eV, a million times less (so-called "*thermal neutrons*"). It is therefore necessary to slow down the neutrons for efficient operation of a nuclear reactor, a process called moderation. In a reactor it is necessary to mix in a moderator with the uranium core. A moderator consists of light atoms (preferably close to the weight of the neutron).

In ordinary water, the hydrogen atom has the right weight, but readily absorbs neutrons. Heavy water, containing deuterium is also a useful moderator and is used in certain reactors. On page 14 we have mentioned that the heavy water production at Vemork played a role during the second world war since Norway was the only producer of heavy water.

It was E. Fermi and coworkers that built the very first reactor in a squash court at Stagg stadium in Chicago. They used graphite as moderator and the reactor was constructed by layers of graphite. In the layers they left room for boxes of natural uranium (about 2.5 kg in each box). They had 10 control rods, made of cadmium which could absorb and control the neutrons.

If fission, on average, gave one neutron that could split a new atom, the process would go by itself. This *reproduction factor*, as Fermi called it, must be larger than 1.0. They measured the neutron flux all the time.
The construction had the form of an ellipsoid (like an egg), 7.6 meters wide and about 6 meters high. It had 57 layers of graphite (385 tons) and about 40 tons of uranium oxide.

December 2, 1942 was a cold day with snow in Chicago. It was the day for the first attempt to start a reactor – and the atmosphere at Stagg stadium was intense. Several people were gathered on the balcony where the counters were located (among them Szilard, Wigner and Compton). Fermi gave the order to slowly remove the control rods and the neutron flux (measured by boron-trifluoride counters) increased. Finally he asked to take the last control rod 12 feet out. The clicking of the counters increased to a continuous roar. Fermi raised his hand and said; "*The pile has gone critical*". The reproduction value had been 1.0006. The first day the reactor operated for 4 minutes at an intensity of half a watt.

We can note that Fermi used ordinary uranium (with only 0.71 % of U-235). They noticed that the reactor produced tiny quantities of plutonium Pu-239. The plutonium was formed in the reactor from U-238 in the following way:

$$^{238}_{92}U+^{1}_{0}n\Rightarrow^{239}_{92}U+\beta\Rightarrow^{239}_{93}Np+\beta\Rightarrow^{239}_{94}Pu$$

U-238 absorbs the neutron. U-239 is unstable and emit a β-particle with a half-life of 24 minutes. Np-239 is also unstable, emits another β-particle (half-life 2.3 days) and the fissile isotope Pu-239 is formed. This compound can be used as fuel in a reactor and also as the explosive in a fission bomb. Consequently, a reactor was built in Oak Ridge in 1943 and furthermore three large-scale reactors were built for that purpose at Hanford in Washington, USA in 1945.

After the war a number of reactors have been built – both for power production as well as for research. We can mention that a research reactor was built at Kjeller, Norway which was opened in July 1951.

It is not our purpose to describe the different power reactors used (approximately 450), but we would like to mention a few points. The reactors are based on thermal neutrons, and are divided into two groups; namely gas-cooled/graphite-moderated reactors and water-cooled/water-moderated reactors (light water reactors). In addition, there are reactor types between these categories; for example, the Russian water-cooled/graphite-moderated reactor (the so-called Chernobyl type). There are also heavy water moderated reactors.

The reactors account for 14 % (2011) of the electric power in the world. They do not release greenhouse gases and should therefore represent an excellent alternative for energy production. Two arguments have been raised against nuclear power:

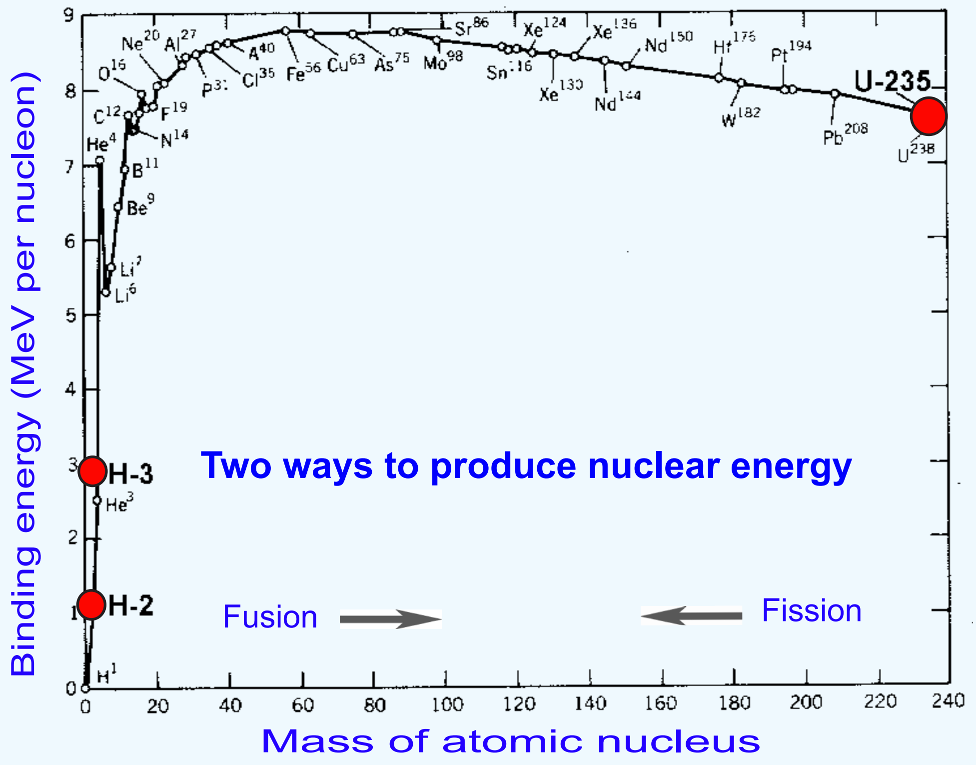
1. Reactor accidents.
2. Radioactive waste

The type of waste that give the problems consists of long-lived radioisotopes and comes from used fuel that is not reprocessed or from components separated in the reprocessing. The waste may be in the liquid or glassified form and the activity is high enough to produce heat. The glassified waste contains more than 99% of the total activity that was present before treatment. The main goal of treatment and storage of radioactive waste is to bring the radioactivity into a form which is suitable for permanent storage.

Reactor accidents has occurred and efforts have been made with regard to design and to make reactors more safe. It is a primary goal to prevent damage to the reactor core. The safety regulations have to be organized as a "*defense in depth*". If an accident should occur, the defense system should be able to reduce the consequences and prevent the release of radioactivity.

The energy involved in fission and fusion

Protons and neutrons are kept together by strong forces in the atomic nucleus. In the figure below we have given the binding energy for the different atoms. This figure is important with regard to the energy involved in both fission and fusion.



The mass (in number of nucleons) of the nucleus is given along the abscissa. Along the vertical axis is given the binding energy per nucleon (mass unit). Deuterium has a binding energy of 1.1 MeV – or 2.2 MeV for the two particles that makes up the deuterium nucleus. The binding energy for He-4 is 7 MeV – i.e. 28 MeV for the 4 nucleons together.

Fission

You see from the figure that it is possible to gain energy by transforming a nucleus with a small binding energy to another with a larger binding energy. Thus, upon a fission of uranium into two almost equal parts the gain is approximately 1 MeV per nucleon (about 235 MeV for one fission). About 25 MeV is in the form of γ-rays and about 5 MeV in kinetic energy of the neutrons released. This implies that in a fission bomb the explosion is followed by a burst of γ-rays and fast neutrons.

Fusion

The other possibility to gain energy is in a fusion process. The requirement is that light atoms with a low binding energy are used. The hydrogen isotopes, deuterium and tritium can be used for fusion and we can give three possible processes.

① $D + D \Rightarrow {}^{3}He + n + 3{,}3\ MeV$

② $D + D \Rightarrow T + p + 4{,}0\ MeV$

③ $D + T \Rightarrow \alpha + n + 17{,}7\ MeV$

D = H-2
T = H-3
α = He-4

Deuterium is a stable isotope and can easily be produced. However, the two first processes requires a start temperature of about 100 million degrees. For reaction 3 the temperature should be about 40 million degrees. If deuterium and tritium can be brought together with such energies a fusion reaction may take place. In a fusion bomb this has been a reality by using a fission bomb to ignite the reaction. Fusion, both for energy production (controlled) and for bombs requires tritium as fuel. Tritium can be formed by bombarding the light Li-isotpe (Li-6) with neutrons in a reactor:

$$\text{Li-6} + n = \text{He-4} + T$$

Lithium consists of two isotopes; Li-6 (7.4 %) and Li-7 (92.6 %). The compound LiD (lithiumdeuteride) has been used for fusion bombs with the assumption that it was only Li-6 that contributed to the tritium production. It came therefore as a surprise when it was discovered that also Li-7 give tritium when bombarded with fast neutrons according the reaction:

$$\text{Li-7} + n = \text{He-4} + T + n$$

The latter process can increase the yield of fusion bombs – which was discovered in the US test bomb "Castle Bravo" in the Bikini atoll in 1954.

Critical mass

An important concept for fission bombs is the critical mass. When the fuel is below critical mass, there aren't quite enough nuclei around to keep the chain reaction going and it gradually dies away.

When the fuel is above critical mass, there are more than enough nuclei around to sustain the chain reactions. In fact, the chain reaction grows exponentially with time – and we have an explosion.

The size of the critical mass depends on shape, density, and even the objects surrounding the nuclear fuel. Anything that makes the nuclear fuel more efficient at using its neutrons to induce fissions helps that fuel approach critical mass. The characteristics of the materials also play a role. For example, fissioning plutonium 239 nuclei release more neutrons on average than fissioning uranium 235 nuclei. As a result, plutonium 239 is better at sustaining a chain reaction than uranium 235 and critical masses of plutonium 239 are typically smaller than for uranium 235. By using a neutron reflector, about 4 – 5 kilograms of Pu-239 or about 15 kilograms of U-235 is needed to achieve critical mass.

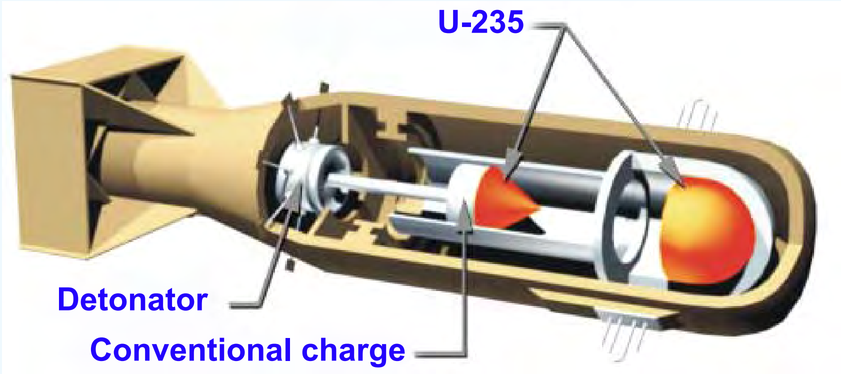
In an atomic bomb, a mass of fissile material, greater than the critical mass, must be assembled instantaneously and held together for about a millionth of a second to permit the chain reaction to propagate before the bomb explodes

During the war the "Manhatten project" included the most competent physicists in the world with the purpose to construct a fission bomb. A laboratory was built in Los Alamos, New Mexico, in late 1944. On the lava flows of an extinct volcano 35 miles north of Santa Fe, Robert Oppenheimer, a brilliant physicist from the University of California, led the development of the first nuclear fission weapons. The fissionable materials, solid uranium tetrafluoride from Oak Ridge and plutonium nitrate paste from Hanford, began to arrive at a Los Alamos, and chemists purified the two metals and metallurgists shaped them into forms suitable for the weapons. Two possible mechanisms were worked out in order to bring the fissile material together and reach critical mass or above. In the "*gun method*" two subcritical masses were brought together and in the "*implosion method*" the fissile material formed in a hollow sphere were forced together.

In July 1945 they had enough fissile materials for three bombs. The first one was a plutonium bomb and the implosion method was used. The test was performed in the desert south of Los Alamos. The test was successful and then the "go signal" was given for the two other bombs that hit Hiroshima and Nagasaki on August 6. and 9. 1945.

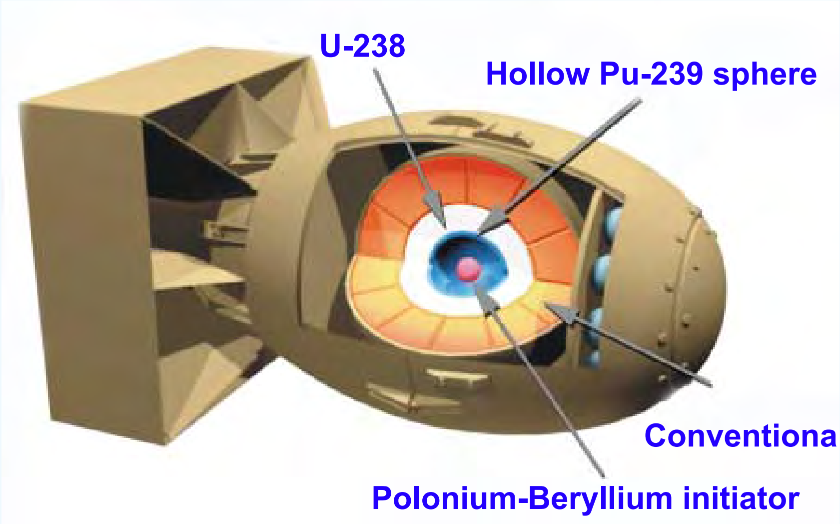
Some of the details for the two bombs in Japan in 1945

The bombs exploded 550 – 600 meters above ground. The explosions released a large amount of energy. The energy takes three forms: 1) Heat, 2). Blast or pressure and 3). Radiation.



Hiroshima bomb
"Little boy"
Gun type

67 kg with 90 % enriched U-235. About 1 kg fissioned Yield equivalent to 15 – 20 kton TNT.
The exposion caused about 100 000 immediate deaths.



Nagasaki bomb
"Fatman"
Implosion type

6.4 kg of Pu-239.
Yield equivalent to 21 kton TNT.
About 40 000 immediate deaths.

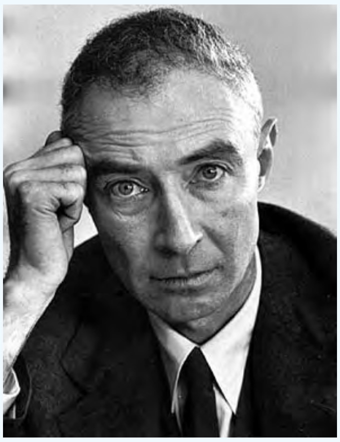
Radiation doses

About 25 MeV of each fission go into γ-radiation – and about 5 MeV into neutrons. Consequently, the explosion is followed by a burst of radiation. Thousands of hours have been spent in order to calculate the doses involved in the burst. The most extensive dosimetry system was carried out in 1986 (DS86). Doses have been calculated – with information about shielding to 86 600 survivors. We shall return to this group in a later section.

"Free in air doses" have been calculated as a function of distance from the hypocenter. The γ-doses are much larger than the neutron doses. For distances within 1000 meter the doses reach values of more than 5 Gy. At such distances the radiation would be lethal. However, all persons within this distance would be killed by the heat and pressure wave. Consequently, radiation is not the most serious threat of the bombs.

The men behind the projects leading to the atomic bombs

A large number of the physicists during world war II and the years after the war contributed to the development of the nuclear bombs. Below we have given the leading scientists in USA and the Soviet Union.



Robert Oppenheimer
(1904 – 1967)

Robert Oppenheimer was the leader of the Los Alamos laboratory – and this group developed the bombs used in Hiroshima and Nagasaki.

In Soviet Union they embarked on a bomb project in 1945 based on valuable information attained via spies (Klaus Fuchs). Igor Kurchatov and his group made the first test in Kazakhstan in August 1949 (plutonium fission).

Igor Kurchatov
(1903 – 1960)

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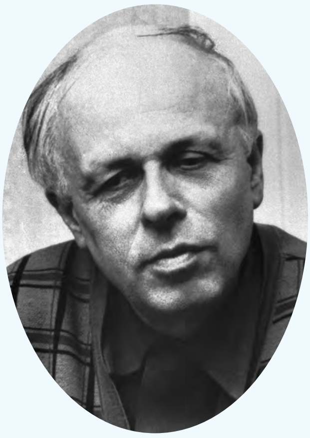
Scientists like Edvard Teller worked for the development of fusion bombs with much higher power. The bombs developed consist of a combination of fission and fusion. A fission was needed to create the high temperatures needed for the fusion. The first man -made fusion explosion took place in November 1952 in the Eniwetok atoll in the Pacific. The bomb or rather the device (because it was so big and heavy – weighing 82 ton) was build up on the small island Elugelap. The explosion which vaporized the island, was estimated to about 10 megaton TNT and resulted in a large fallout. You can see a video of the experiment. Go to the address:
http://www.archive.org/details/OperationIVY1952

Edvard Teller
(1908 –2003)



Andrei Sakharov
(1921 – 1989)

In the Soviet Union Andrei Sakharov developed the hydrogen bomb – and the first one tested in November 1955. The largest bomb ever, called "Tzar Bomba", was of the same type and is estimated to about 50 Mton TNT It exploded October 30, 1961, in Novaya Zemlya.

The fallout from the bomb tests was observed at the University of Oslo. The first wave of radioactive products used 4 days to travel the distance from Novaya Zemlya to Oslo – 2000 km.

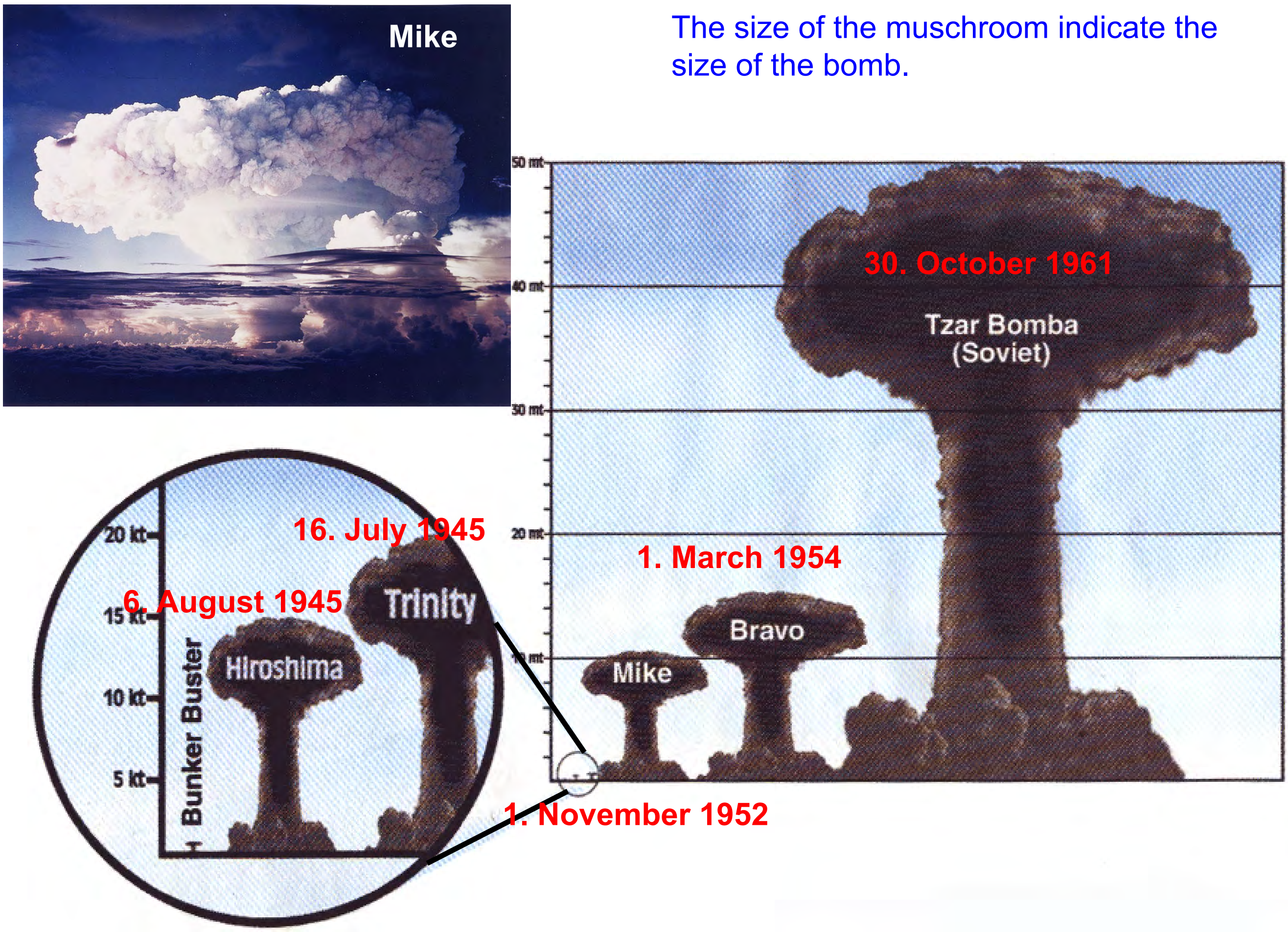
Nuclear bomb tests

During the period from July 1945 up to present, 543 nuclear bombs have exploded in the atmosphere. Furthermore, 1866 underground tests have been performed. The total energy in these tests has been calculated to be equivalent of about 530 megatons of TNT. The nuclear tests were particularly frequent in the two periods from 1954 to 1958 and from 1961 to 1962.

Several nuclear tests were performed in the lower atmosphere. When a blast takes place on the ground or in the atmosphere near the ground, large amounts of activation products are formed from surface materials. The fallout is particularly significant in the neighborhood of the test site. One of the best known tests with significant fallout took place at the Bikini atoll in the Pacific in 1954 (see the "Castle Bravo" test below).

The first fission test was the one in New Mexico on July 16. 1945 – and the first fusion test took place at the Eniwetok atoll in the Marshall Islands on November 1. in 1952 (the Mike test).
The largest nuclear weapon ever tested was the "Tsar Bomba" of the Soviet Union at Novaya Zemlya on October 30, 1961, with an estimated yield of around 57 megatons. The fallout from this explosion as well as the other atmospheric tests at Novaya Zemlya was considerable for Scandinavia. We shall give you some of the fallout measurements carried out in Oslo by Anders Storruste and his students.

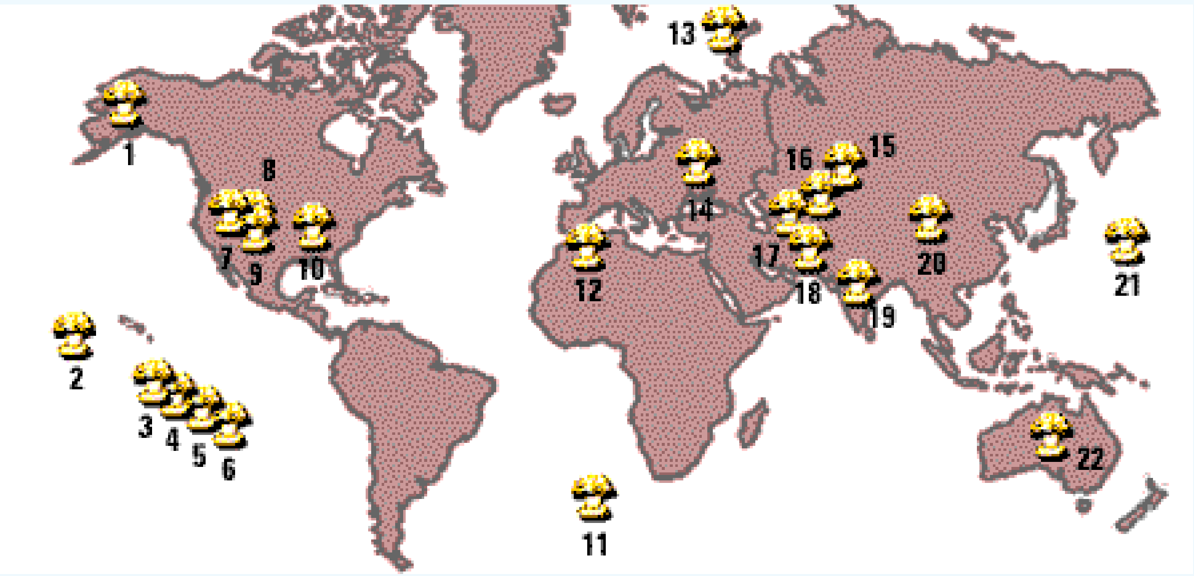
An illustration of the power (energy released)
for some of the best known nuclear bombs and tests



The size of the muschroom indicate the size of the bomb.

Nuclear weapon tests sites

The first nuclear bomb test took place near Almagordo in New Mexico (marked 9 in the map) in July of 1945. Since then, the United States, the Soviet Union, England, France, China, India, Pakistan and Korea have tested the weapons in the air, on the ground and underground. The map below shows most of the places used for these nuclear tests.



The following test sites are marked in the map: 1. Alaska (US) -- 3 Tests, 2. Johnston Island (US) -- 12 tests, 3. Christmas Island (UK & US) -- 30 tests, 4. Malden Island (UK) -- 3 tests, 5. Fangataufa Atoll (France) -- 12 tests, 6. Mururoa Atoll (France) -- 175 tests, 7. Nevada (US) -- 935 tests, 8. Colorado (US) -- 2 tests, 9. New Mexico (US) -- 2 tests, 10. Mississippi (US) -- 2 tests, 11. South Atlantic Ocean (US) -- 12 tests, 12. Algeria (France) -- 17 tests, 13. Russia (USSR) -- 214 tests (many at Novaya Zemlya), 14. Ukraine (USSR) -- 2 tests, 15. Kazakhstan (USSR) -- 496 tests, 16. Uzbekistan (USSR) -- 2 tests, 17. Turkmenistan (USSR) -- 1 test, 18. Pakistan (Pakistan) -- 2 tests, 19. India (India) -- 4 tests, 20. Lop Nur (China) -- 41 tests, 21. Marshall Islands (US) -- 66 tests, 22. Australia (UK) -- 12 tests

The "fallout" of radioactive isotopes from the bomb tests, depends on the type of bomb and, most of all, whether the bomb is detonated in the air, on the ground or underground. The fallout of radioactive isotopes is due to the atmospheric tests.

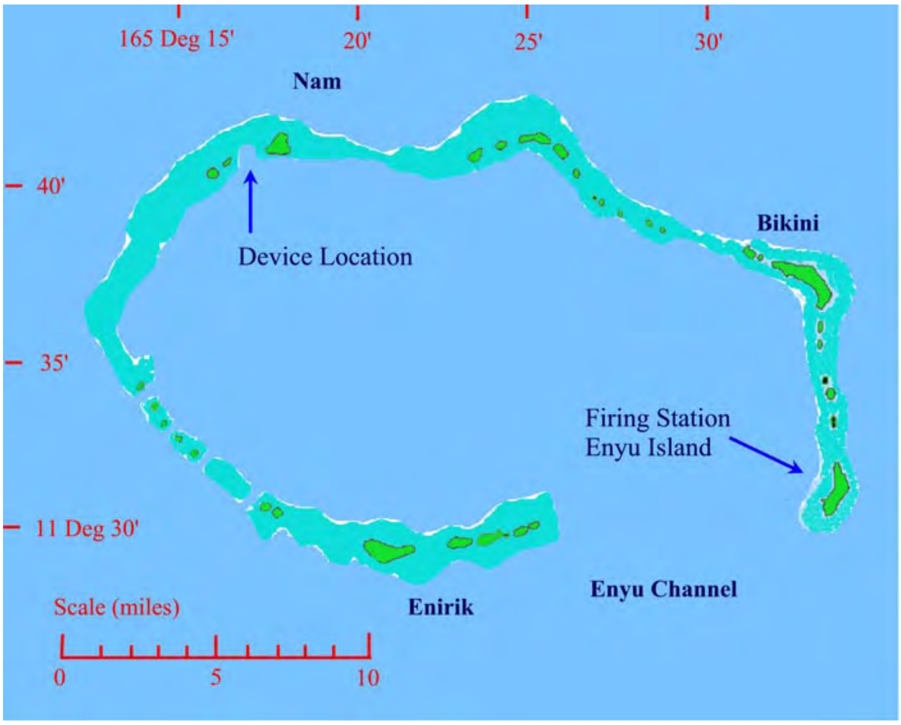
Furthermore, if the explosions take place at altitudes where the so called "fire ball" reach the ground a large amount of radioactive isotopes may be formed.

For the atmospheric nuclear tests a considerable amount of radioactivity reach the stratosphere. Due to the low exchange between the troposphere and stratosphere these isotopes may stay for a long time in the stratosphere.

The radiation doses to the public from all these nuclear tests have been very small. They cannot be measured against the natural background doses. The exceptions are a few atmospheric tests performed in the early years.

A particular US test – Castle Bravo

On March 1, 1954, the United States detonated a hydrogen bomb (with a power of about 15 million tons of TNT) at the Bikini-atoll in the Pacific (see map below). The device was a large cylinder weighing 10.7 tons and measuring 4.56 m in length and 1.37 m in width. It was mounted in a "shot cab" on an artificial island built on a reef off Namu Island, in the Bikini Atoll.



On page 111 this test site is marked as 21. The firing station was about 20 miles (32 km) away. It was a solid bunker and the crew was protected from the blast as well as the radiation.

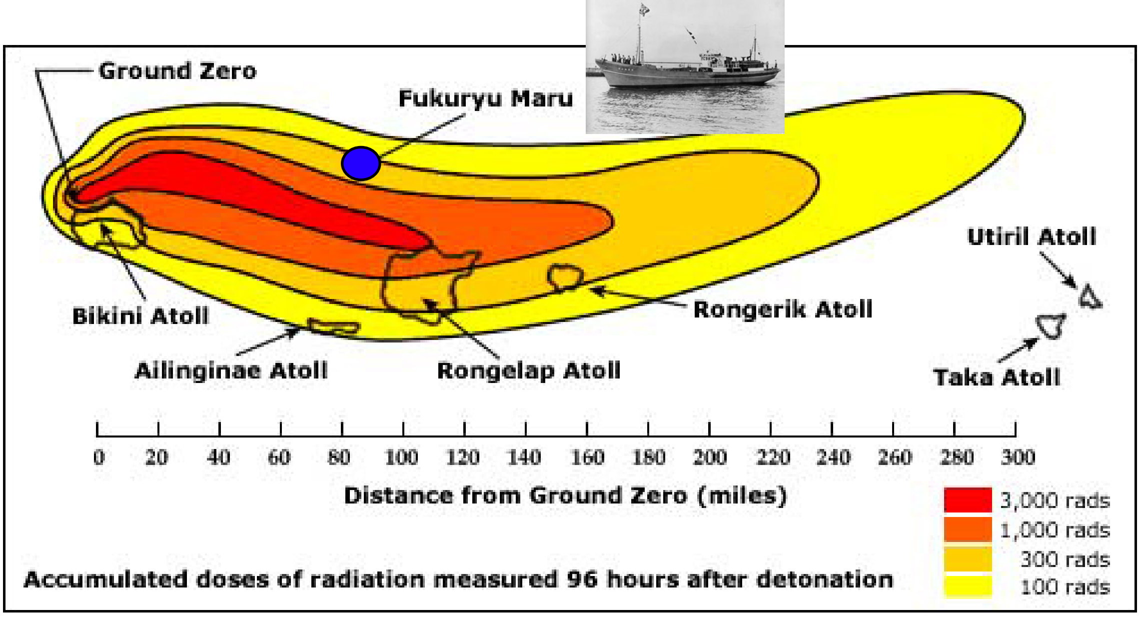
The bomb with the code name "Castle Bravo" was estimated to have a power of about 5 Mton TNT – however, turned out to be about 3 times larger. Let us try to explain this.
The fuel consisted of 37 - 40% enriched lithium-6 deuteride encased in a natural uranium tamper. It was expected that the lithium-6 isotope would absorb a neutron from the fission of plutonium, – emit an alpha particle and tritium in the process. Then tritium would fuse with deuterium (which was already present in the LiD) and consequently increase the yield in a predicted manner.

The designers missed the fact that when the lithium-7 isotope (which was considered basically inert) was bombarded with high-energy neutrons, the reaction outlined on page 107 was possible. This means that much more tritium was produced than expected, and this increased the fusion. The extra neutron from the lithium-7 decomposition resulted in more neutrons than expected, – with the result that more fission was induced in the uranium surroundings. Since both lithium-6 and lithium-7 contributed greatly to the fusion reactions and the neutron production – which in turn resulted in more fission, the yield increased dramatically.

When Bravo was detonated, it formed a muschroom roughly 7 km across within a second. This fireball was visible on the Kwajalein atoll 450 km away. The explosion left a crater of 2,000 m in diameter and 75 m in depth. The mushroom cloud reached a height of 14 km and a diameter of 11 km in about a minute; it then reached a height of 40 km and 100 km in diameter in less than 10 minutes.

Since the explosion took place only 2 meter above ground considerable amounts of material (such as coral) were sucked up into the fireball and large amounts of activation products were formed. Castle Bravo was really a "dirty bomb".

A couple of hours after the blast, the instruments on the American weather station on Rongerik island (about 212 km away) indicated a high radiation level and the crew was evacuated the day after. Evacuations of the 154 Marshallese Islanders only 160 km from the shot did not begin until the morning of 3 March. The islanders received a whole-body radiation doses of about 1.7 Gy on Rongelap, 0.7 Gy on Ailinginae, and 0.14 Gy on Utirik.



Above is a dosemap that gives the accumulated dose 4 days after detonation. If you stayed outside during the 4 days you would attain that dose. The dose is given in rads – and remember that 1 Gy = 100 rads. The position of Fukuru Maru at the blast is indicated.

Because the fallout for these islands was so large, the inhabitants were not allowed to live there for 3 years. A lot of work has been done with cleaning up the islands – and they were declared safe for habitation in 1980.

Fukuryu Maru

This is a picture of Fukuryu Maru which now is on exhibition in Tokyo.

Approximately 130 km from the Bravo test-site was the Japanese fishing boat "Daigo Fukuryū Maru" with 23 fishermen aboard. After the blast they pulled in the fishing equipment and sailed away. Within hours the fallout started in the area where the boat had moved.

Dust, soot and even larger particles came down. The crew lived with this for a number of days and took no special precautions with regard to hygiene, food, and clothing since they had practically no knowledge of radioactivity and its biological effects.

The fishermen received very large doses, calculated to be about 3 Gy. They felt nauseous and received skin burns from β-particles in the fallout. One of the fishermen died of a liver disorder within 6 months. It may be that it was a result of the radiation.
Most of the fishermen were still alive 30 years later. Chromosome analyses showed larger amounts of damage than normal in their lymphocytes.

In general

Because of the extreme temperature of a nuclear explosion, the radioactive material becomes finely distributed in the atmosphere. A certain fraction is kept in the troposphere (the lower 10 km) and is carried by the wind systems almost at the same latitude as the explosion. This part of the radioactive release will gradually fall out, the average time in the atmosphere being about one month.

The main fraction of the radioactive debris from an atmospheric test goes up into the stratosphere (10 to 50 km). This fraction can remain in the stratosphere for years since there is a very slow exchange between the troposphere and the stratosphere. The fallout consists of several hundred radioactive isotopes; however, only a few give significant doses. The most important are the following:

- **Zirconium-95** (Zr-95) has a half-life of 64 days and **iodine-131** (I-131) has a half-life of 8 days. Both of these isotopes, in particular I-131, are of concern for a short period (a few weeks) after being released to the atmosphere. This isotope was important in the Chernobyl accident.

- **Cesium-137** (Cs-137) has a half-life of 30 years. The decay scheme for this isotope (see page 17) shows that both β-particles and γ-rays are emitted. The β-emission has an impact on health when the isotope is in the body or on the skin. The γ-radiation has an impact both as an internal and external radiation source.

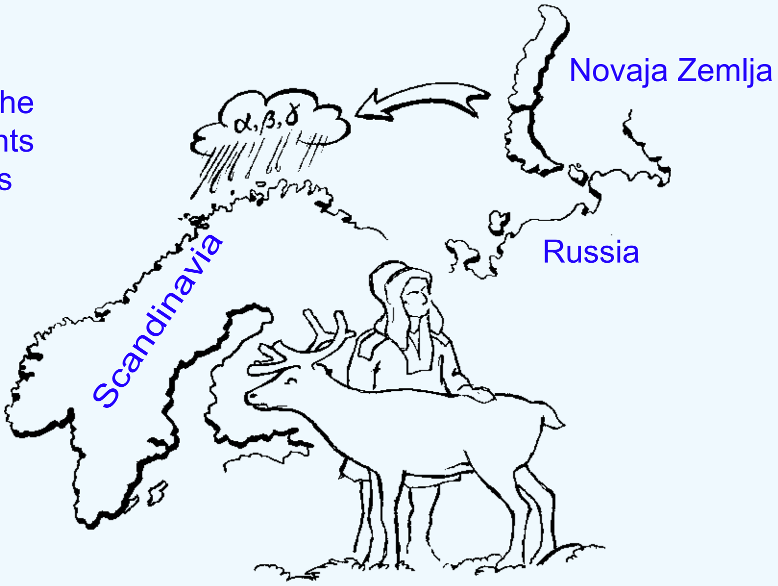
- **Strontium-90** (Sr-90) has a half-life of 29.12 years. This isotope emits only a β-particle and is difficult to observe (maximum energy of 0.54 MeV). This isotope is a bone seeker and is important when the isotope enters the body. It should be noted that Sr-90 has a radioactive decay product, Y-90, which has a half-life of 64 hours and emits β-particles with a maximum energy of 2.27 MeV. With this short half-life, it is likely that this amount of β–energy will be deposited in the same location as that from Sr-90.

- **Carbon-14** (C-14), while not a direct product of fission, is formed in the atmosphere as an indirect product. The fission process releases neutrons that interact with nitrogen in the atmosphere and, under the right conditions, C-14 is formed as an activation product. The individual doses from this isotope are extremely small. However, due to the long half-life of 5730 years, it will persist for many years. When C-14 is used in archeological dating, it is necessary to correct for the contribution from the nuclear tests.

Nuclear tests at Novaja Zemlja in 1961 and 1962

The nuclear tests of most concern for the Northern Hemisphere were performed by the former USSR (Russia) on the island Novaja Zemlja located in the Arctic, approximately 1,000 km from northern Norway. When these islands were chosen as a test site in 1954, more than 100 families lived there. They were all removed from their homes. Altogether 87 atmospheric nuclear tests were performed at this site. The activity was particularly large during 1961 and in the fall of 1962. Most of the tests were performed at high altitudes, thus the "fireball" did not reach the ground. Consequently, the production of activation products was limited.

We shall give some of the results of the measurements carried out in the 1960-ties



The fallout after the tests at Novaja Zemlja was largely determined by precipitation. It was quite large on the western part of Norway. The isotopes Cs-137 and Sr-90 entered the food-chain via grass (in particular reindeer lichen). Consequently, sheep, cows and reindeer ingested radioactive material when feeding on grass and reindeer lichen. People eating the meat or drinking the milk from these animals received some extra radioactivity.

The "Tzar Bomba"

From September 10 to November 4, 1961, the Soviets carried out 20 nuclear tests at Novaja Zemlja. The power of the bombs varied from a few kilotons TNT (equal in power to the Hiroshima bomb) to approximately 57 megatons TNT (the "Tzar Bomba"), which is the largest bomb ever detonated. The "master" of this bomb was Andrei Sakharov. He was given the job by Nikita Khrusjtsjov to construct a 100 Mton bomb. The bomb was considered to be a combination of fusion and fission. A small fission bomb should ignite the fusion which in turn should yield neutrons to produce more fission in an uranium tamper.

It was decided to replace the uranium tamper with lead. This reduced the yield by 50 % and also the fallout. The bomb was delivered with a plane and dropped from 10 000 m with a parachute. This gave the plane time to go 45 km away when the explosion took place at 4000 m above the west coast of Novaja Zemlja. Due to the construction and the height for the explosion the fallout was small and the bomb was rather clean.

Fallout

The radioactive fission products from all the atmospheric tests were released to the atmosphere. Estimations have been made about the release of fission products. The total release of Cs-137 from all the bomb tests is approximately 30 times larger than that released during the Chernobyl accident. The total release of Sr-90 is calculated to be about 75 times larger than the Chernobyl accident.

As mentioned earlier, when a blast takes place in the atmosphere, a large fraction of the radioactivity will go through the troposphere and into the stratosphere. Since the exchange between the two is rather slow the radioactivity will remain in the stratosphere for a long time. Westerly winds on the Northern Hemisphere will bring the activity to the east. The radioactivity from the nuclear tests in the 1960s was distributed over large areas; however, the amount of fallout varied from one region to another according to the variation in rainfall (most of the fallout came down with the rain).

The fallout pattern from the nuclear tests was different from that of the Chernobyl accident. In Chernobyl the radioactive isotopes were restricted to the troposphere, and was then brought around by the wind. The wind direction was very important for the fallout.

The fallout from the tests at Novaya Zemlja was followed and measured in Norway. We would like to give you some examples of the work carried out – mainly by Anders Storruste and his students at the University of Oslo, about 2000 km from the test site.

Measurements in Oslo

A number of measurements were carried out in order to determine the activity in the air – in the rainwater as well as in the food products. To a large extent scintillation counters were used and the observations were concentrated on the γ–radiation from Cs-137. It is far more difficult to observe Sr-90 since it only emits β–particles. Attempts were made in particular experiments to measure the ratio between Cs-137 and Sr-90. This ratio was assumed to be rather constant implying that the Cs-137 observations also yielded information on Sr-90. In some Austrian measurements of milk the ratio Sr-90/Cs-137 increased slowly from about 0.6 to more than 1.0 in the period 1960 to 1997.

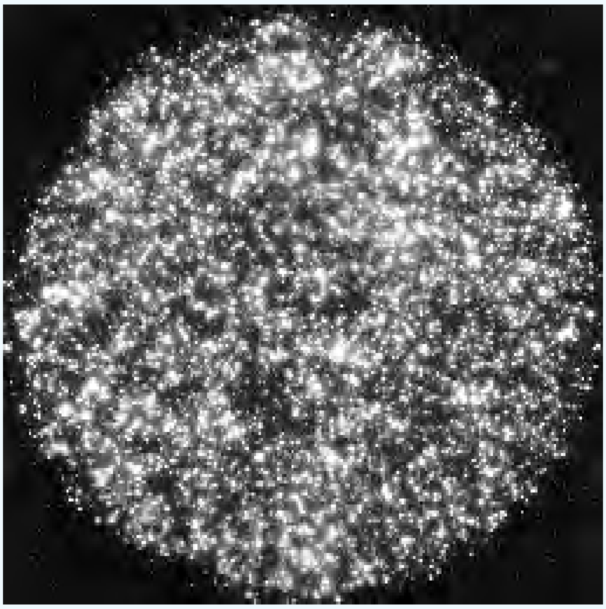
The Cs-137 activity in food products (meat, milk, cheese, etc.) was measured. Furthermore, whole - body measurements were started in order to determine the level of Cs-137. For that purpose particular shielded rooms and equipment were constructed. We shall give you some of the details.

Radioactivity in the air

The radioactive isotopes from the bombs become attached to dust particles in the air and transported with the wind. In order to measure the radioactivity in the air it was used a vacuum cleaner. Thus air containing radioactive dust was sucked through a filter. If the filter was laid directly on an x-ray film and the radioactivity can be observed (see an example below).

The radioactivity on the filter was measured. Since the air volume drawn through the filter was measured, the activity could be calculated in Bq per cubic meter. These experiments were carried out by Ivar Mattingsdal for his master exam in 1963. The data are given in the figure on the next page.

As can be seen from the figure, the activity started to increase on September 14. 1961 (4 days after the first blast at Novaja Zemlja). In October, the air activity 2000 km away from the test site was approximately 30 times larger than normal.



Courtesy of Anders Storruste, Inst. of Physics, Univ. of Oslo

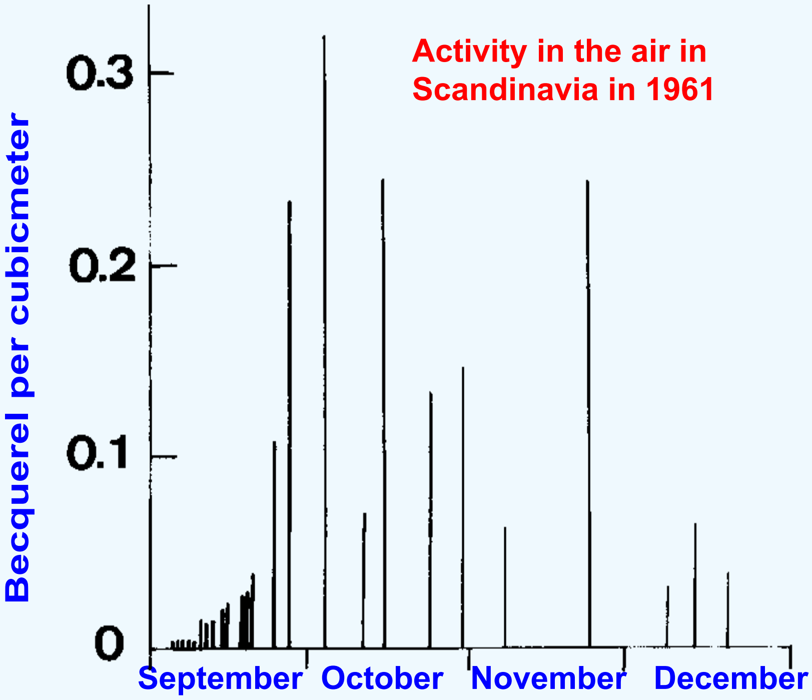
Radioactivity from the bomb tests.

The activity in the air during the nuclear tests at Novaja Zemlja in 1961 was measured by sucking air through filters. The white dots indicate small particles containing radioactive isotopes.

The radioactivity reached Oslo (2000 km away) after 4 days.

The types of isotopes in the filter were measured with a scintillation counter.

The fallout was measured by collecting the rainwater – and then observing the radioactivity.



Ivar Mattingsdal

Courtesy of Anders Storruste and Ivar Mattingsdal, Inst. of Physics, Univ. of Oslo

The measurements presented here serve as an example of airborne radioactivity in combination with nuclear tests in the atmosphere. The observations are made in Oslo – 2000 km from the test site on Novaja Zemlja. The activity is given in Bq per cubic meter air. As can be seen, the "Tzar Bomba" on October 30 did not give any peak value in the beginning of November – which confirm that it was a rather clean bomb.

Similar measurements were performed in 1962. On November 7th, the air activity in Oslo was about 200 times above normal, indicating that one of the bombs (classified as middle power) which exploded on November 3 or 4, produced large quantities of fission products.

Radioactivity in the rain water

The fallout is mainly connected to the precipitation. The rain hitting the roof of the Physics building at the University of Oslo was collected. Samples consisting of 2 liter were damped and the activity measured with Geiger-Mûller counters.

In the period from September 1961 to November 1962 the total fallout in Oslo was 37 kBq/m^2. The average activity in the rain water was 35 Bq per liter. It can be mentioned that the fallout in Norway after the Chernobyl accident was on average 7 kBq/m^2 – however, in certain areas it was about 100 kBq/m^2.

Radioactivity in food and people

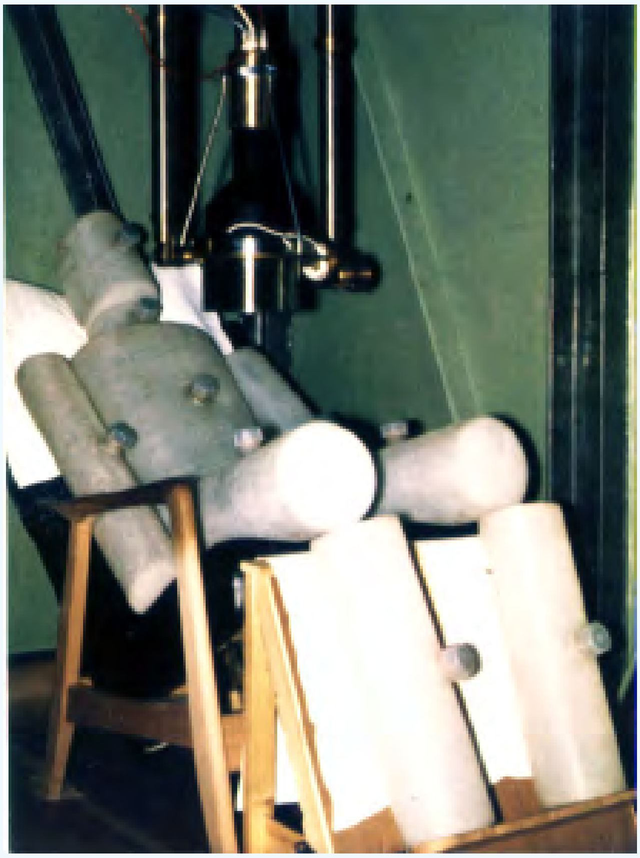
In the years since the bomb tests in the atmosphere were canceled, the amount of radioactive isotopes have continued to diminish. The fallout is dominated by the two isotopes Cs-137 and Sr-90. The fallout has decreased considerably since the mid-1960s but still, more than 40 years later, a small fallout persists from the bomb tests.

The radioactive isotopes hitting the ground become bound to plants, grass and, in particular, reindeer lichen. The activity in this plant decreases more slowly than that for plants withering in the fall.

The radioactive isotopes on the ground slowly diffuse into the soil. Some of them are taken up in plants via the roots. Consequently, a certain fraction of the fallout will find its way into the food chain and finally into humans. The radioactivity in both food products as well as in some humans have been measured and followed for a number of years.

Whole body counting in the 1960-ties

The equipment below was built in connection to the bomtests at Novaya Zemlja. Kjell Madshus built the counter at "The Norwegian Radium Hospital" and measured a number of Laplanders which used a lot of reindeer meet.



In the picture you see a phantom and the scintillation counter.
A large NaI (Tl) crystal (diameter 20 cm and height 10 cm) – coupled to 3 photomultipliers was used. The counter was pointing towards the middle section of the person (phantom in the picture).

The room had concrete walls covered with steel plates to reduce the background radiation. The air was filtered to reduce the effect of radon and daughter products.

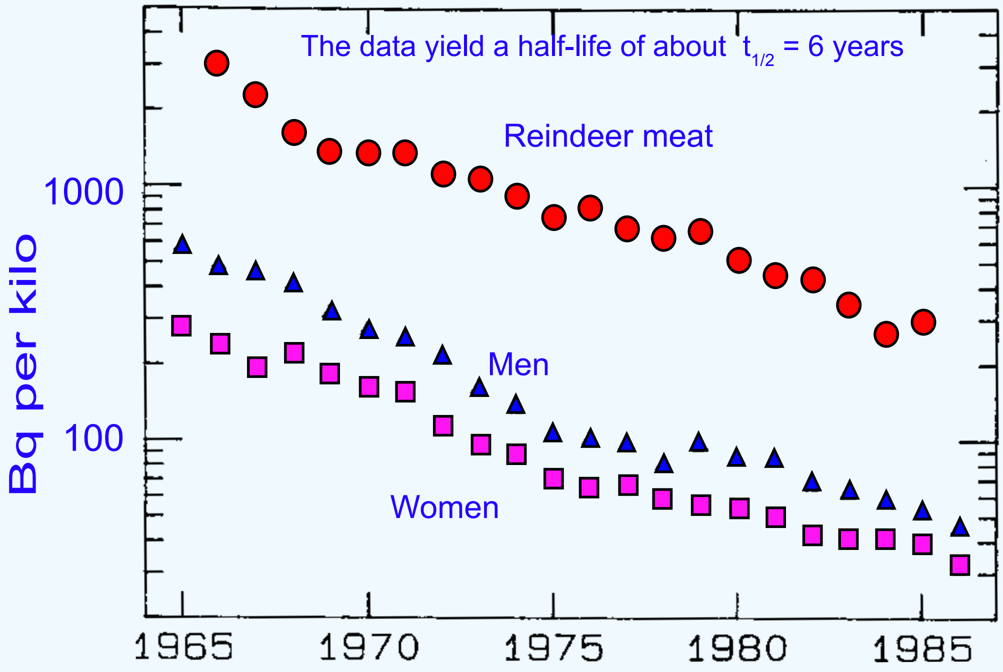
The screening of the room had a weight of 40 ton – the door into the room weighed 3.5 ton!

Calibration was carried out by using the phantom. The short-lived isotopes were used directly. For K-40, the isotope K-42 (half-life 12.5 hours – energy 1.52 MeV) was used.

The phantom in the picture consisted of containers that could be filled with liquids containing radioactive isotopes.

In the figure below, the activity of Cs-137 in reindeer meat was measured from 1965 to 1986. Furthermore, the activity in a group of people living in the area have been measured with the whole body counter. The results for these measurements are given in Bq per kilo.

As can be seen, the activity has decreased slowly since the tests in the atmosphere ceased until the end of the period shown. After the Chernobyl accident in 1986 the activity increased due to new fallout (Swedish results are given on the next page).



The content of Cs-137 in reindeer meat as well as in the people who own the animals. The example is taken from northern Norway. The activity is assumed to be evenly distributed in the body and is therefore given as Bq/kg. The reason for the difference between women and men is presumably the same as that for the content of K-40 (see the figure on page 102). Potassium and cesium are in the same column of the Periodic table and may be distributed in the body in the same way with a higher content when the muscle mass is large relative to the total mass. The ecological half-life calculated from these measurements is about 6 years.

(Data courtesy of A. Westerlund, Norwegian Radiation Protection Authority)

Based on the results in the figure above, it is possible to estimate doses to the people involved – and to calculate the ecological half-life. Nothing was done in order to reduce the fallout.

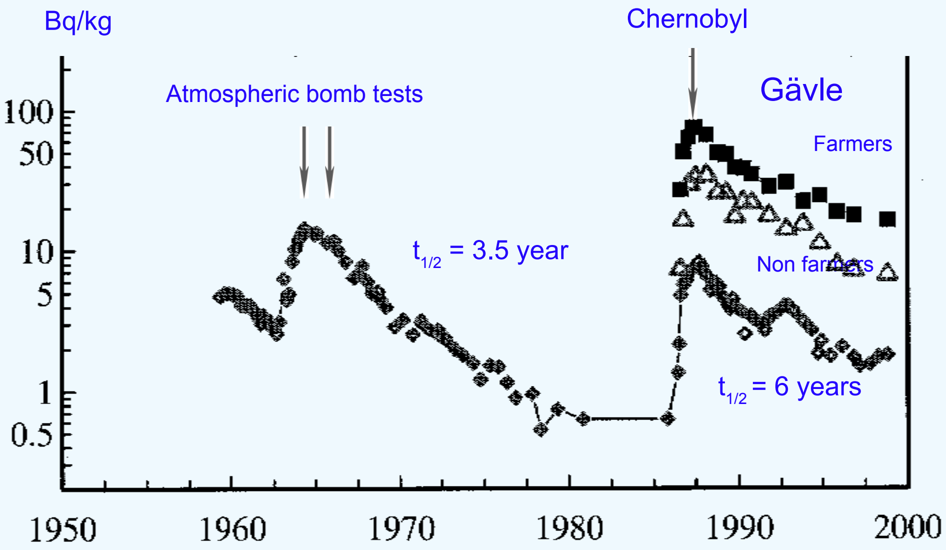
The data in the figure above can be fitted reasonably well to a straight line in the plot, implying that the activity decreases exponentially. The half-life is about 6 years for both the reindeer meat as well as for the people.

Half-life approximately 6 years

Swedish groups 1959 – 2000

Rolf Falk from SSI (Swedish Radiation Protection Institute) have carried out whole body measurements on groups in Sweden. In particular a group from Stockholm has been followed from 1959. The measurements, therefore, include the effect of both the bomb tests of the 1960s and the Chernobyl accident in 1986. The group has a different diet compared to the group of Lapps and the Cs-137 uptake was much smaller.

Furthermore, two groups (farmers and non-farmers respectively) from Gävle have been studied. Gävle is an area, north of Stockholm, which had the highest fallout (approximately 85 kBq/m^2) in Sweden from the Chernobyl accident.



The figure shows the results of total body measurements on different groups of people in Sweden.

(Data courtesy of R. Falk, Swedish Radiation protection Institute, SSI).

As you can see, the total body activity for the Stockholm group reached a peak in 1965 (about 13 Bq/kg), which is a factor of 30 – 50 smaller than that of the Lapplanders (figure on the page above).

The data in the figure can almost be fitted by straight lines and consequently half-lives can be calculated. These half-lives may be considered as ecological half-lives and some values are given directly on the figures.

Doses involved

The data presented in the two figures also yield opportunities to make a rough calculation of the doses involved. Thus, we can estimate the dose obtained for the peak year (1965 for the bomb tests and 1986 for the Chernobyl accident), as well as the accumulated dose for the first 10 years (1965 - 1975 for the bomb tests and 1986 - 1996 for Chernobyl fallout).

These data are given in the table next page.

Cs-137 doses due to the atmospheric bomb tests and the Chernobyl accident

Groups	**Bomb tests**		**Chernobyl**	
	Dose peak year	Dose over 10 years	Dose peak year	Dose over 10 years
Lapps	1.5 mGy	**8.8 mGy**		
Gävle farmers			0.2 mGy	**1.2 mGy**
Stockholm group	0.03 mGy	**0.14 mGy**	0.03 mGy	**0.18 mGy**

The internal doses due to Cs-137 in the Lapps in northern Norway were among the highest to any group of people and very much higher than that to other members of the public. According to the figure on page 141 the Lapps had a whole-body activity in 1965 of approximately 600 Bq/kg for men and 300 for women corresponding to an equivalent dose of 1.5 mGy for men and 0.7 mGy for women that year.

The extra dose in the peak year was approximately half that obtained by commercial air crews every year. From the bomb tests over a 10 year period the dose to the Laplanders was approximately 8.8 mGy, whereas the dose to the Stockholm group was about 0.14 mGy.

For comparison; the dose from the natural background was about 30 mSv for the same period.

How to perform simple calculations of radiation doses ?

It is an important purpose of this project to give information about the nature of radiation and how it is possible to estimate – in fact calculate – doses involved. In the above table some values are given which seem to be interesting for most people. Therefore, we shall describe in more detail how it is possible to calculate radiation doses from radioactive isotopes in the body. The calculations are not exact but give a good overview of the doses and how you yourself can do estimations.

Radiation Doses from Cs-137 in the body

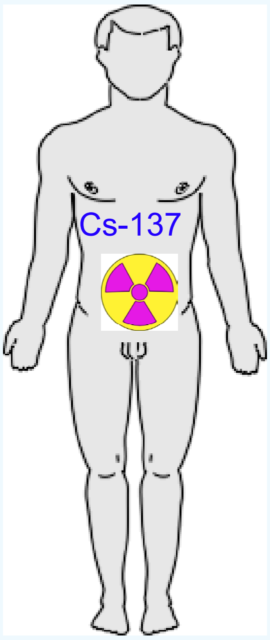
We shall give some details on how to estimate doses. We start with the data presented for the fallout after the bomb tests.

A radiation dose is, by definition, the energy deposited in the body. For radioactive isotopes we can estimate the energy deposited when we use the decay scheme. The decay scheme is a key in these calculations and the scheme for Cs-137 is given on page 23 in Chapter 2. For every disintegration both a β-particle and a γ-photon are emitted. The energy given off into the body consists of the following:

For the β-particle

The β-particles have a very short range in tissue and will consequently be absorbed completely in the body. The average β-energy (E_β) is approximately 1/3 of the maximum energy given in the decay scheme. The following calculation is used (see also the decay scheme):

$$E_\beta = 1/3\ (94.6\ \% \cdot 0.512\ \text{MeV} + 5.4\% \cdot 1.174\ \text{MeV}) = 0.183\ \text{MeV}$$



This means that the β-particles from Cs-137 deposit on average about 0.18 MeV per disintegration.

For the γ-radiation

The γ-radiation will be partly absorbed in the body and partly escape from the body. It is the part of the γ-radiation that escapes from the body that is used in the whole body measurements presented above.

The γ-radiation from Cs-137 has an energy of 0.662 MeV.
We know that x- and γ-rays are absorbed according to an exponential function. This implies that we can define the socalled "*a half-value layer*" – which is the amount of a material that is necessary to reduce the radiation to the half (50 %). With regard to protection it is usual to use concrete or lead. In this case we are interested in the half-value layer in tissue or water. In the present calculations we use a half value layer of 8 cm of soft tissue for the radiation from Cs-137.

Cs-137 is evenly distributed in the body. The γ-photons are emitted in all directions – and a rough estimate is, that approximately half of the γ-radiation is deposited in the body (i.e. E_γ is about 0.33 MeV per disintegration) – whereas half of the radiation escape and can be measured outside the body.

The total energy deposited in the body per disintegration is the sum of the energies from both the β-particle and the γ-radiation, i.e. 0.18 MeV plus 0.33 MeV, giving approximately 0.5 MeV per disintegration.

Cs -137
Energy deposited in the body per disintegation.

$$E = E_\beta + E_\gamma = 0.183\ \text{MeV} + 0.33\ \text{MeV} \approx 0.5\ \text{MeV}$$

Dose

The radiation dose is the energy deposited per unit mass, measured in J/kg. Cs-137 is evenly distributed in the body, and the energy deposited per kg would be the number of disintegrations multiplied by 0.5 MeV. In this calculation we assume that the body burden is *n* Bq/kg and constant throughout a full year (the requirements for this is that the intake of Cs-137 is equal to the excretion). With the above assumption the total number of disintegrations (*N*) would be *n* times the number of seconds in a year:

$$N = n \cdot 60 \cdot 60 \cdot 24 \cdot 365 \text{ Bq/kg} = 3.15 \cdot 10^{7} \cdot n \text{ Bq/kg}$$

The radiation dose is the product of the number of disintegrations and energy deposited per disintegration (remember that $1 \text{ eV} = 1.6 \cdot 10^{-19}$ J):

$$D = 3.15 \cdot 10^{7} \cdot n \cdot 0.5 \cdot 10^{6} \cdot 1.6 \cdot 10^{-19} \text{ J/kg} = n \cdot 2.52 \cdot 10^{-6} \text{ Gy}$$

Since the radiation consists of γ-radiation and β-particles with a radiation weighting factor of 1, the dose would be the same in Sv.

Returning to the figures presented above, we see that the Lapplanders in 1965 had a body burden of 600 Bq/kg. The dose that year was, therefore, 1.5 mGy for men and about half that value for women. The peak year doses for the other groups are given in the table above (page 143).

Accumulated doses

As seen from the curves in the figures on page 141 and 142> the activities, and therefore the doses, decay exponentially. Since we roughly know the half-life, it is possible to estimate the total dose for 10 years. The accumulated dose for 10 years is found by the formula:

$$D_{\text{total}} = \int_{0}^{10} D_0 \cdot e^{-\lambda t} dt = (D_0 / \lambda)(1 - e^{-\lambda t})$$

Here D_0 is the first year dose, λ = ln2/t where t is the half-life in years. Using this formula, the doses presented in the table above are obtained. These are doses in addition to the doses from natural sources.

The background radiation dose from the 4 natural radiation sources is about 3 mSv per year – constant. Thus for a 10 year period the accumulated dose is around 30 mSv. Here we use the unit Sv since we also include radon and α -particles. ICRP use a radiation weight factor 20 for α -particles.

Reactor accidents

During the years with nuclear reactors for making bombs and electricity we have had four major reactor accidents with release of radioactive isotopes. Furthermore, we have to mention the accidents in the Chelyabinsk Region with release of radioactivity. Unfortunately, it is almost impossible to attain knowledge of the amount of radioactive isotopes released – and even more difficult to arrive at extra radiation doses involved and their biological and health effects. However, these accidents have changed most peoples view on radioactivity and in particular nuclear power – which is disastrous in a time with global warming from burning of fossil fuels.

Let us however, briefly mention the following accidents in chronological order:

1. **Kyshtym** – September 29, 1957 (and in 1967).
2. **Windscale** – October 10, 1957.
3. **Three Mile Island –** March 28, 1979.
4. **Chernobyl** – April 26, 1986.
5. **Fukushima** – March 11. 2011

The Chernobyl accident is the most serious one. We shall in the following give some information about these accidents as known in 2011.

Kyshtym

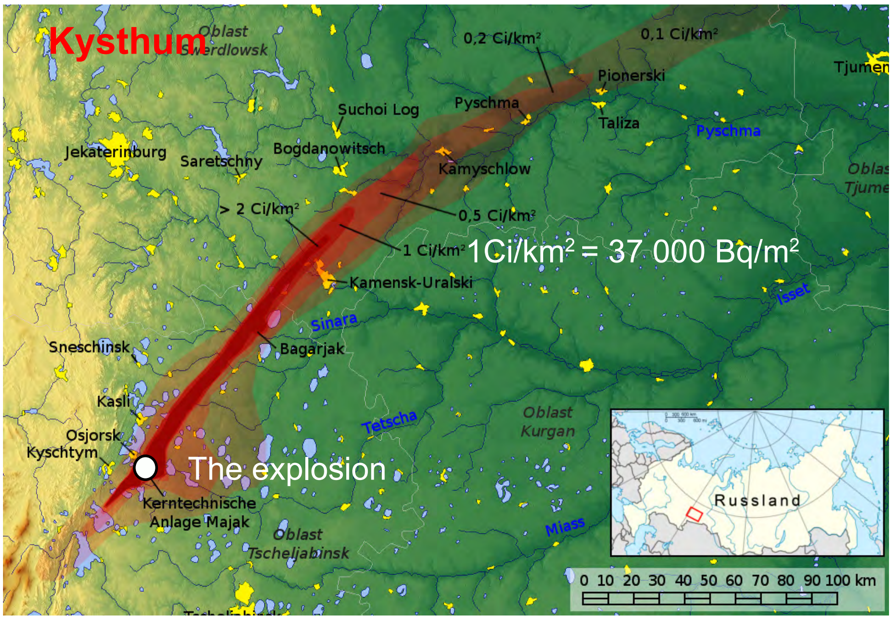
It was in the Chelyabinsk province, about 15 kilometers east of the city of Kyshtym on the east side of the southern Urals that Igor Kurchatov built the first plutonium production reactor for the bomb program. The first reactor was built in 18 months and several more reactors were built – mainly for the production of plutonium. The area is now polluted by radioactivity, due to accidents and bad handling of radioactive waste.

In the first years they dumped radioactive waste in the Techa River. The amount and type of isotopes are uncertain (about 100 PBq is mentioned) mainly in the years 1950 and 1951.

In September 1957, the cooling system of a radioactive waste containment unit malfunctioned and exploded – and released a large amount of isotopes. The radioactive cloud moved towards the northeast, reaching 300–350 kilometers from the accident. The fallout of the cloud resulted in a long-term contamination of an area of more than 800 square kilometers with Cs-137, Sr-90 (a β-emitter with half-life 29.2 years), Zr-95 (65 days), Ce-144 (284 days) and others. Cs-137 and Sr-90 are of importance with regard to extra doses to the people in the region. A region of 23 000 km^2 was contaminated to a level of more than 1 Ci/km^2 (equal to 37 000 Bq/m$^{2)}$. In 1957 this region had 273 000 inhabitants. About 2000 lived in an area with 3700 kBq/m^2.

This area is usually referred to as the East-Ural Radioactive Trace (shown in the map next page).

The last event in this region happened in 1967. A small lake (Lake Karachy) that was used for waste disposals and during the long hot summer of 1967 the lake dried up and wind resuspended the sediments. About 22 $\cdot$ 10^9 Bq of Cs-137, Sr-90 and Ce-144 was released to the nearby region.



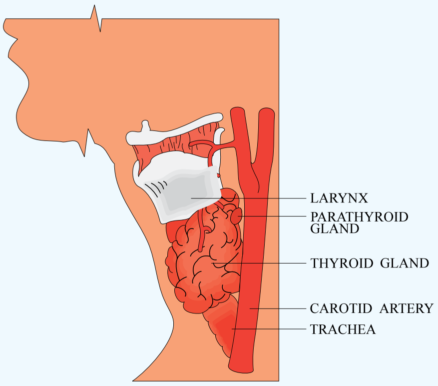
Here is a map of the area for the atomic accident in Kyshtym. The fallout area is shown and marked by red color. It is stretched out more than 100 km.
Some values for the total fallout is given on the map. All these values, as well as the doses to the people involved are mainly estimates. Extra annual doses via the food of 0.1 mGy have been mentioned.

Windscale

The Windscale reactors in Cumberland, England were built in order to produce plutonium for a fission bomb. The work started in 1947 and the first bomb was tested in Australia in October 1952. The two reactors in Windscale (today Sellafield) used graphite as moderator. It was known that when graphite was bombarded by neutrons, dislocations in the crystalline structure would cause a build up of potential energy (so-called "*Wigner energy*"). If this energy was allowed to accumulate, it could escape spontaneously in a powerful rush of heat. Therefore they used to release the energy by annealing – and it was during such an annealing process the fire started on October 10, 1957. It was just a fight in order to stop the fire. The core was burning for about one day and they managed to stop it by water.

The fire resulted in the release of radioactive isotopes such as I-131, Cs-137, Ru-106, Xe-133 and even Po-210. Altogether about 700 TBq was released. I-131 was considered to be the main problem – and it was found in the milk the day after. As a result the milk from a region of 500 km^2 was dumped into the Irish Sea for a month. The highest activity of 50,000 Bq/l was found in milk from a farm about 15 km from the reactor. Furthermore, as a result of this accident it was decided that milk with an activity of more than 0.1 µCi per liter (3700 Bq per liter) could not be sold. It was calculated that the thyroid dose to the people in the area was 5 – 20 mGy for adults and 10 – 60 mGy for children.

Estimation of thyroid doses



It would be of great value if we could calculate the dose to the thyroid after intake of I-131 With the knowledge we have it is possible to carry out rough estimates of the doses involved after intake of I-131 in milk and other food products.

Let us use the Windscale accident and the following scenario:

1. You drink 10 liter of milk containing 3700 Bq/l. This is an intake of 37 000 Bq.

2. All I-131 ends up in the thyroid gland – weighing 10 – 20 gram (lets use an average of 15 gram). For maximum dose we assume that all I-131 atoms disintegrate within the thyroid.

3. The half-life of I-131 is 8 days.

4. I-131 emits a β-particle with maxim um energy 0.6 MeV and γ-radiation with an energy of 0.36 MeV.

All β-particles, with an average energy of 1/3 of the maximum energy, are absorbed in the thyroid. Only a small fraction of the γ-energy is deposited in the thyroid (lets assume 25 %), whereas a larger fraction escapes from the body (this is why this isotope can be used for diagnostic purposes). Consequently, a reasonable estimate is that each disintegration deposits approximately 0.3 MeV in the thyroid gland.

In the present scenario we assume a total intake of I-131 (A_0) to be 37 000 Bq. The total number of disintegrations (X) is found from the equation:

$$X = A_o/\lambda = 37{,}000/\lambda = 3.7 \cdot 10^{10}$$

In this calculation $\lambda = \ln 2/t$. For t we use the physical half-life of 8 days (the effective half-life is 7.6 days).
The energy deposition in the thyroid is then:

$$\text{Energy} = 0.3 \cdot 10^{6}\ \text{eV} \cdot 3.7 \cdot 10^{10} = 1.1 \cdot 10^{16}\ \text{eV}$$

The energy deposited in the thyroid can be given in Gy if we assume that the weight of the thyroid is 15 gram

$$D = \frac{1.1 \cdot 10^{16} \cdot 1.6 \cdot 10^{-19}}{0.015} \approx 117 \cdot 10^{-3}\ \text{J/kg} \approx 117\ \text{mGy}$$

The most sensitive parameter in this calculation is the weight of the thyroid. For children the weight is smaller and consequently the dose is larger using the same assumptions.

In this and other similar calculations we use the equations given in Chapter 3. The calculations give a reasonable idea of doses to the thyroid and can be used in scenarios in connections to accidents like Windscale and Chernobyl. The main pathway for I-131 to reach the thyroid is via milk.

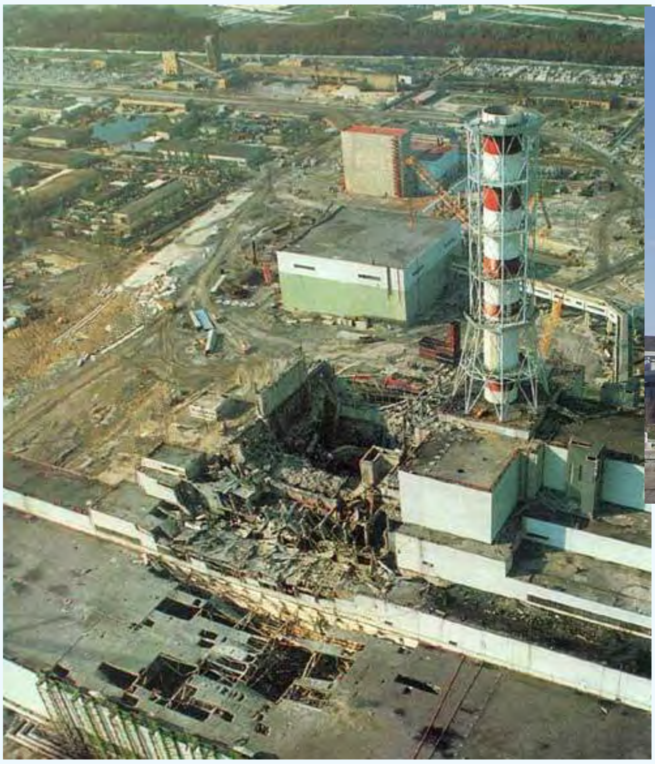
Three Mile Island

A well-publicized accident happened on Three Mile Island near Harrisburg, Pennsylvania, March 28, 1979.

The cooling on a pressurized water reactor (PWR) was lost, and parts of the reactor core melted down in the course of 6 to 7 hours before the reactor was covered with water. The reactor had a safety container and only minor amounts of radioactivity were released. In fact, the activity released was smaller than that normally released every year from the natural radioactive sources in Badgastein, Austria, a source that some years ago was considered to be healthy (and may be it is).

Because of some misunderstanding between the Nuclear Regulatory Commission and the authorities, it was recommended that children and pregnant women, living within 8 km from the reactor be evacuated. This recommendation, which was quite unnecessary, had the unfortunate consequence of raising anxiety and fear among the public.

The Chernobyl accident – April 1986



Two pictures of the Chernobyl reactor

Left: A picture from 1986, just after the accident.
Above: A new picture which shows that the reactor is buried in its sarcophagus.

The Chernobyl accident was the most severe ever to have occurred in the nuclear industry. The accident occurred during a low-power engineering test of the Unit 4 reactor. The safety systems had been switched off, and improper, unstable operation of the reactor allowed an uncontrollable power surge to occur, resulting in successive steam explosions that severely damaged the reactor building and completely destroyed the reactor

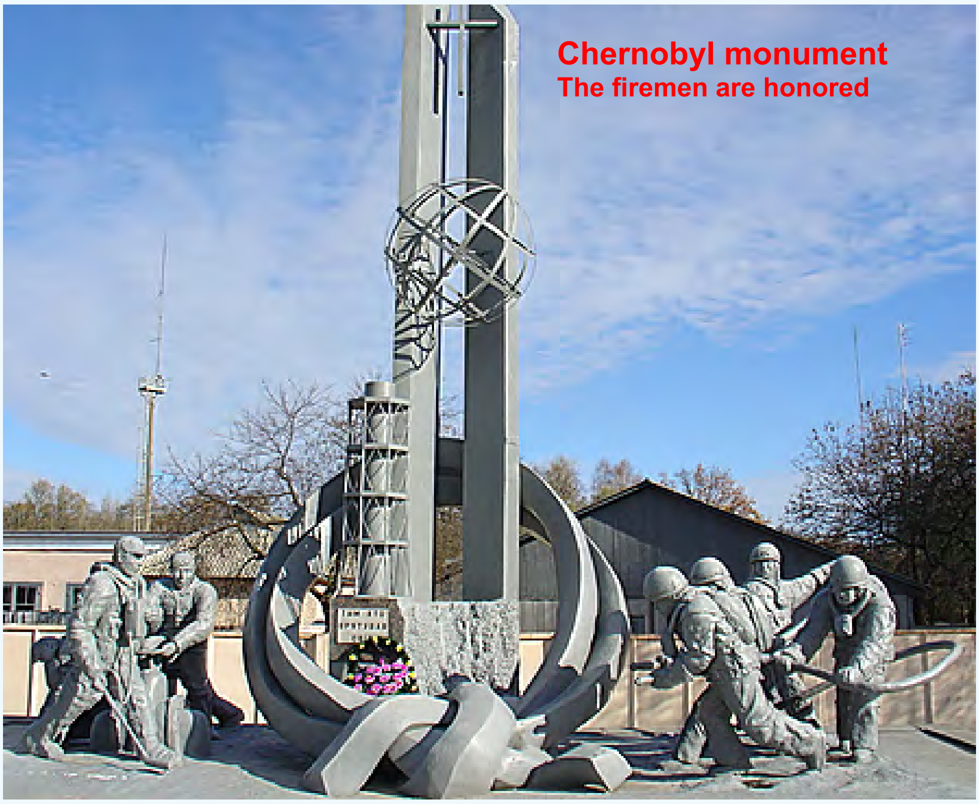
The steam explosion, might have lifted the reactor core and all water left the reactor core. This resulted in an extremely rapid increase in reactivity, which led to vaporization of part of the fuel at the centre of some fuel assemblies and which was terminated by a large explosion attributable to rapid expansion of the fuel vapor disassembling the core. The explosion blew the core apart and destroyed most of the building. The dramatic accident which happened at 1.24 on April 26 was known to the world a couple of days later when the released radioactivity reached Poland and Sweden.

Today several detailed reports are available. We suggest the following web page with reports from UNSCEAR, WHO and IAEA up to 2008:

http://www.unscear.org/unscear/en/chernobyl.html

Let us start with the conclusion made by UNSCEAR based on the 2000 report of the Chernobyl forum.

The accident at the Chernobyl nuclear power plant in 1986 was a tragic event for its victims, and those most affected suffered major hardship. Some of the people who dealt with the emergency lost their lives. Although those exposed as children and the emergency and recovery workers are at increased risk of radiation-induced effects, the vast majority of the population need not live in fear of serious health consequences due to the radiation from the Chernobyl accident. For the most part, they were exposed to radiation levels comparable to or a few times higher than the natural background levels, and future exposures continue to slowly diminish as the radionuclides decay. Lives have been seriously disrupted by the Chernobyl accident, but from the radiological point of view, generally positive prospects for the future health of most individuals should prevail



Chernobyl monument
The firemen are honored

Release of radioactivity

Several data exist with regard to the release of radioactivity from Chernobyl. Let us first conclude that the most important isotopes are I-131 (half-life 8 days) and Cs-137 (half-life 30 years). All effects from I-131 occurred during the first weeks after the accident. Thus, by the end of 1986 almost 40 half-lives had passed and the activity reduced by a factor 10^{12}.

Cs-137 on the other hand will reach 50 % of its start value in 2016.

Radioactivity was released for 10 days – it stopped rapidly on May 5. The amount released has been calculated – based on an estimation of the amount of radionuclides present in the core at the time of the accident. According to the last UNCEAR report the release of Cs– 137 is estimated to be 85 PBq, about 30% of the core inventory and that of I-131 is estimated to be 1,760 PBq, about 50% of the core inventory. If you use the equations in chapter 3 you can calculate the weight of the release. Thus, about 26.4 kg Cs-137 and about 382 gram of I-131 was released.

The released isotopes can be divided in classes according to the form and possibility to be transported over long distances. Thus UNSCEAR use the groups; noble gas, volatile, intermediate and refractory. It is the volatile elements such as I-131 and the Cs-isotopes that are of most concern to areas outside the vicinity of the reactor. As shown in the figure on page 68 the volatile isotopes reached Oslo and was measured on May 9. 1986.

In the table below we give some of the most important data for the release of isotopes. It is the UNSCEAR values from 1996.

Isotope	Half-life	Type	Amount (PBq)
Xe-133	5.3 days	Noble gas	6500
Cs-134	2.06 years	Volatile	~54
Cs-137	30.0 years	Volatile	~85
I-131	8.04 days	Volatile	~1760
Te-132	77 hours	Volatile	~1150
Sr-89	50.5 days	Intermediate	~115
Sr-90	29.2 years	Intermediate	~10
Ru-103	39 days	Intermediate	120
Ru-106	368 days	Intermediate	73
Ba-140	12.7 days	Intermediate	240
Zr-95	64 days	Refractory	196
Ce-141	32.5 days	Refractory	196
Ce-144	284 days	Refractory	~116
Pu-241	13 years	Refractory	~6

Fallout

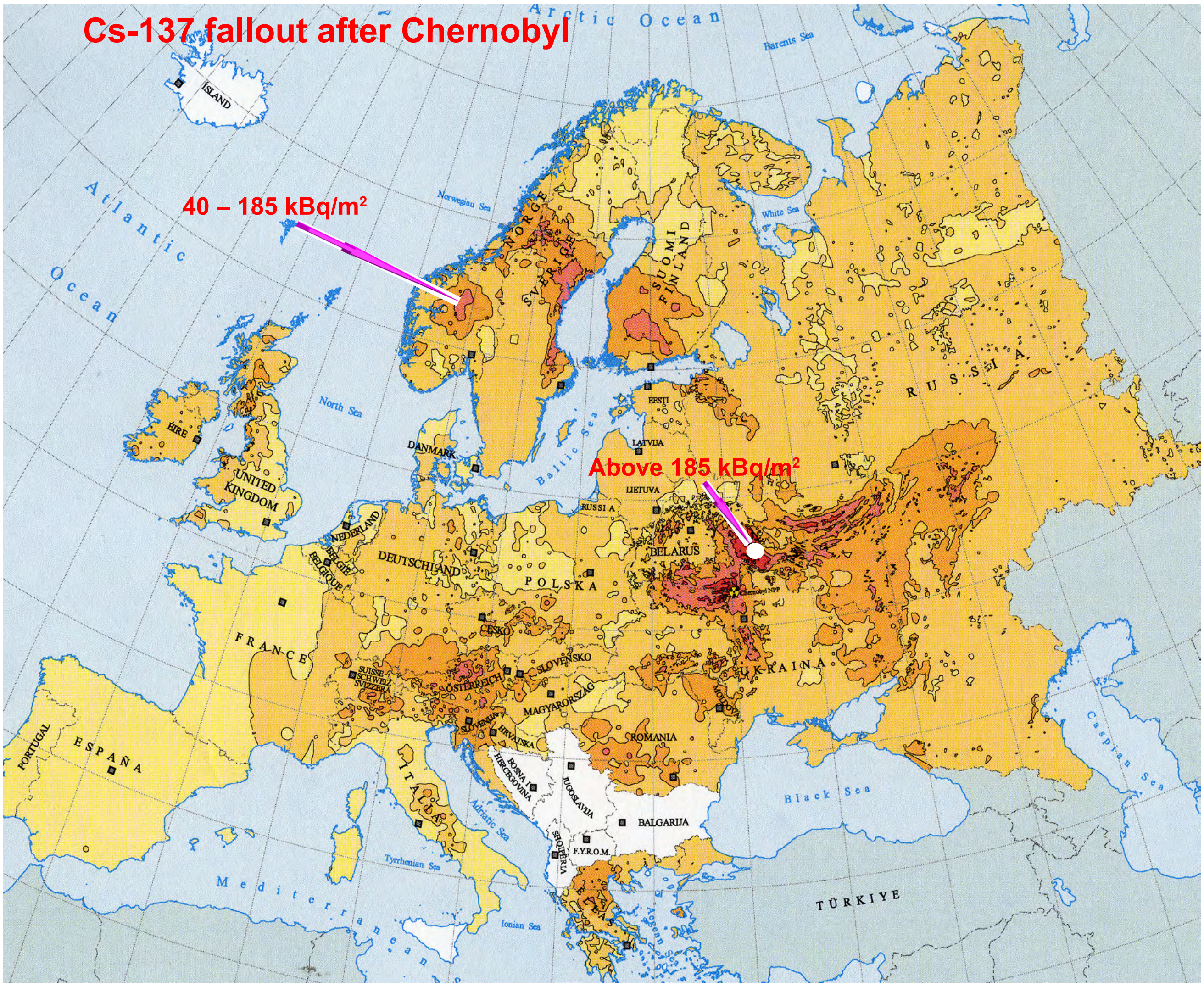
Approximately half of the released activity fell out in the area around the reactor. All of the plutonium and most of the strontium (Sr-89 and Sr-90) fallout was restricted to a region within 30 km of the reactor. However, for the volatile isotopes (Cs-134, Cs-137 and I-131), the distribution was extensive. Belarus and the western parts of Russia received most of the cesium fallout, but considerable amounts were transported by the wind to western Europe.

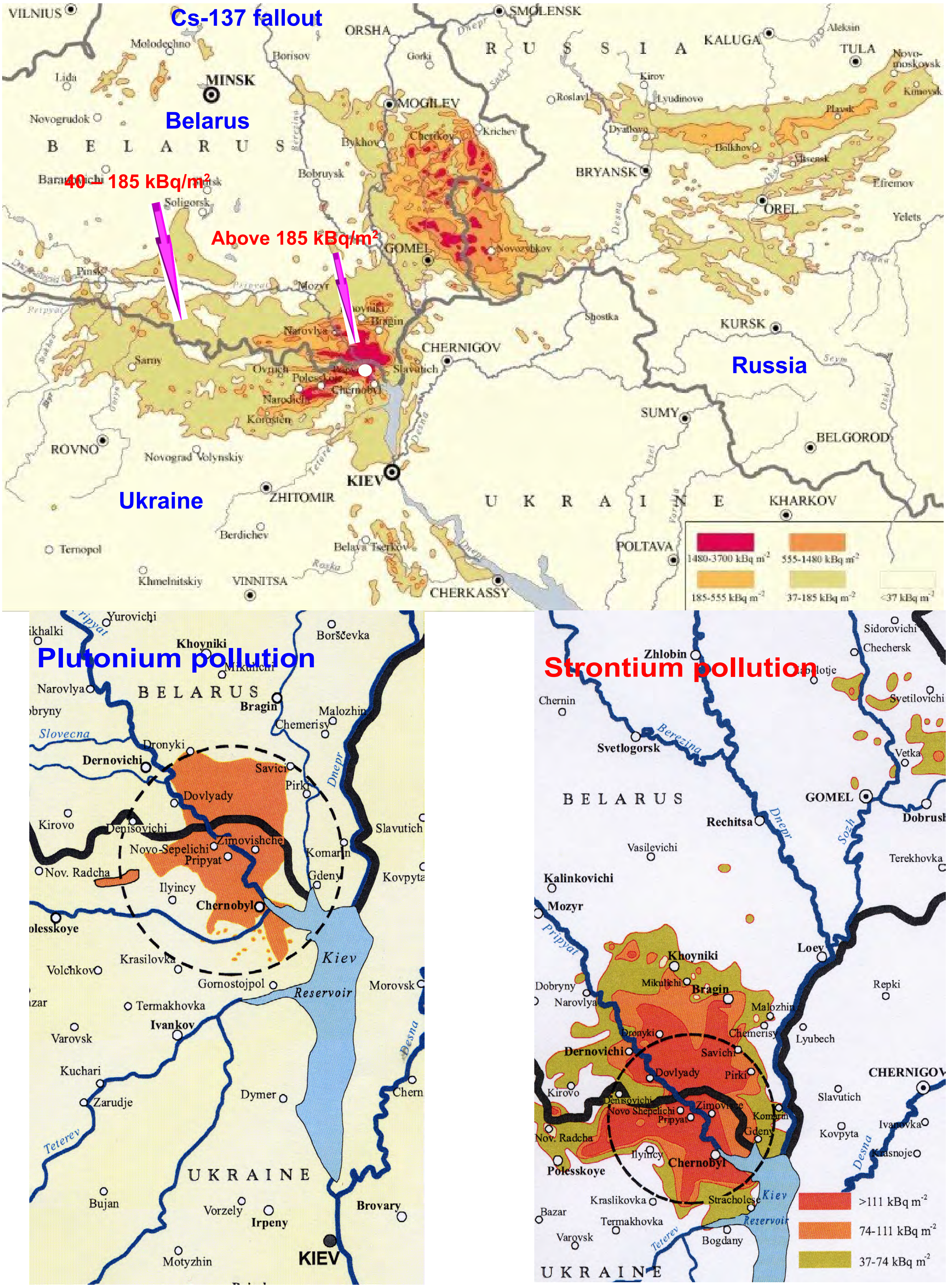
During the first days after the accident, the wind direction was to the northwest (towards Scandinavia). Considerable amounts of fission products were transported to the middle regions of Sweden and Norway. Unfortunately, it was raining in some of these areas and the fallout was consequently large. Thus, in parts of Sweden (the area around Gävle, north of Stockholm) and in Norway the fallout of Cs-137 reached up to 100 kBq/m^2 (about 3 Ci/km^2). The average value, however, was much smaller and on the order of 5 to 10 kBq/m^2.

The fallout is presented in the maps on the two next pages.

Cs-137 is given in the two maps on the next page. The amount is given by colors. Red yields the highest values. Regions with more than 37 kBq/m^2 are considered as polluted areas. This definition is rather low and implies that large areas in Scandinavia had a fallout above this limit. Furthermore, the maps indicate that the fallout in Scandinavia reached values like those quite near Chernobyl (compare the two maps).

No similar maps can be given for I-131 – due to the fact that the half-life is too short. However, it is reasonable to assume that the fallout of I-131 followed the same pattern as that for Cs-137. This may be of interest with regard to thyroid doses to people in western Europe.





Here is given the fallout of Cs-137 (top), plutonium (Pu-239 and Pu-240) and Sr-90. The color indicate the total deposition. In the case of plutonium the colored area indicate levels above 3700 Bq/m². For Sr-90 the darkest colored area indicates a deposition above 111 kBq/m². The dashed circle indicate 30 km from the reactor.

The maps show that the fallout of strontium and plutonium is limited to the regions near the reactor. The reactor is in the middle of the circle, which marks the 30 km zone.

In the Nordic countries more than 20 laboratories become involved in measurements of the fallout from Chernobyl. During the first days Cs-137 and I-131 activity in the air was observed as well as the deposition on the ground. Later a large amount of measurements were carried out for different food products in an attempt to arrive at doses to the public.

On page 76 we have given an example how the different isotopes can be observed and measured for a sample with a mixture of different isotopes. The easiest way to identify the isotopes is by γ-spectroscopy.

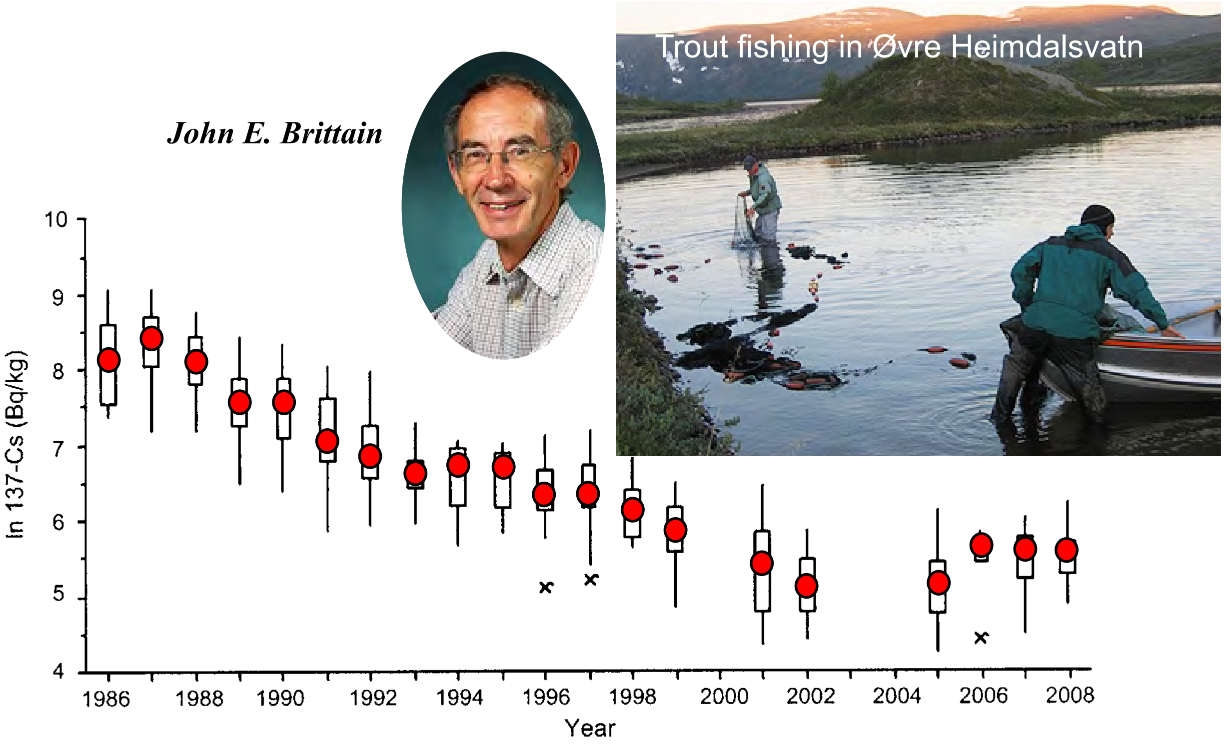
The doses attained after accidents like Chernobyl can be estimated from the activity in the food products. We know quite a lot about the Cs-137 doses and almost nothing about the I-131 doses to the thyroid for young and old people outside the region around the reactor.

Cs-137 content in trout in a Norwegian lake

J. E. Brittain and coworkers have measured the content of Cs-137 in brown trout from Øvre Heimdalsvatn for a period of 22 years from 1986. The Cs-137 deposition in this area was the highest in Norway (on average 130 $kBqm^{-2}$). The activity in brown trout increased during the summer of 1986 and reached a maximum activity of 7200 Bq/kg in late August. The lake is ice covered from late October to the beginning of June. The Cs-137 concentration in trout (200 to 300 gram) has been measured all years after 1986. Today the activity is about 150 Bq/kg. The observed values are given in the figure below.

From this figure it can be found that the ecological half-life was 3.6 years for the first 6 years after Chernobyl. Then the value increased and approaches now the physical half-life for Cs-137 (30 years).

It would of course be of interest to obtain similar data for other areas and other ecosystems.



In this figure is shown the Cs-137 activity in brown trout from Øvre Heimdalsvatn for the period 1986 to 2008. The red dots show the average value. The activity is given in a logaritmic scale as ln(Bq/kg).

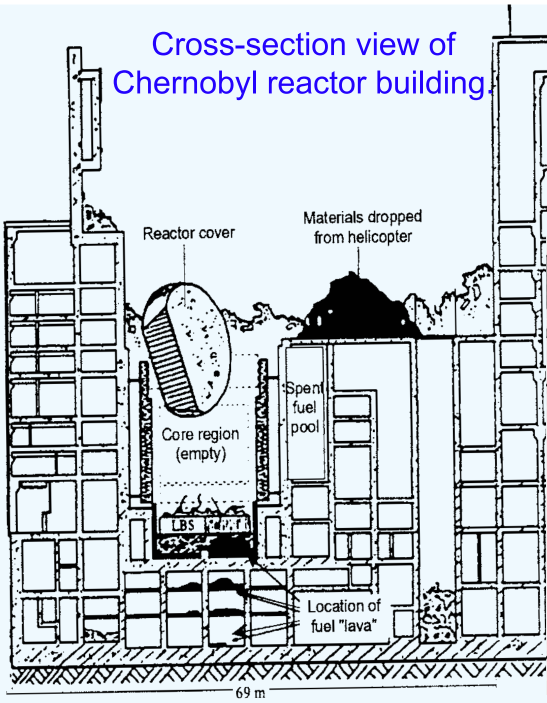
Doses and health effects

It is evident that the doses to the general public in most areas are small. However, some brave workers made a heroic work with extinguishing the fire and covering the reactor. We shall give some details about those that received the largest doses and carried the burden of the Chernobyl disaster. The section is divided into:

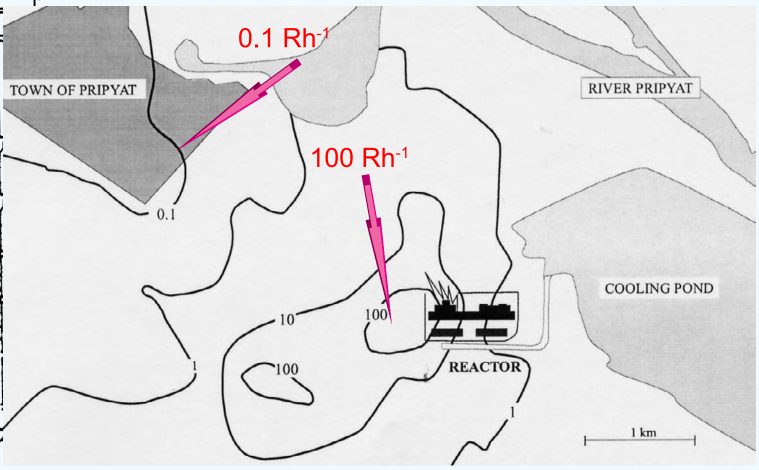
1. Emergency workers involved in the accident the first days.
2. Decontamination workers in the period 1986 – 1990.
3. The groups evacuated.
4. Public in general.

1. Emergency workers

About 600 workers were on the site on the morning of 26 April. The workers were faced with a situation with several fires in an open very strong γ-source. It was the γ-radiation that was the real treat. Furthermore, the released radionuclides in the air could be inhaled and dust particles could be deposited on the skin and in the cloths. The power plant workers carried film badges that could register doses up to about 20 mGy – the firemen carried no dosimeters. The situation can best be explained by the two figures below.



Cross-section view of Chernobyl reactor building.



Measured exposure rates in air on 26 April 1986 in the local area of the Chernobyl reactor. The exposure is given in roentgen per hour Rh^{-1}. If you are exposed to 100 R, the dose would be approximately 1 Gy

The dose rates on the roof and in the rooms of the reactor block reached hundreds of gray per hour. It is reasonable to assume that most of the workers were well aware of the radiation. These people – firemen and others, helicopter pilots – those working with extinguishing the fire and covering the damaged reactor are the real heroes of this accident.

The number of heavily exposed workers present at the reactor site in the early hours of 26 April 1986 was 203. Of these, 115 were treated for acute radiation syndrome, beginning on day 2, at the specialized treatment centre in Moscow (the leader of the department was A.K. Guskova). In Kiev 12 more patients with acute radiation sickness were hospitalized.

More than 140 workers got whole body γ-radiation doses of about 2 Gy – and more. The doses were not measured directly – but have been assumed based on ESR-measurements on dental enamel. These measurements agreed within ± 20% with the dose estimates based on clinical and biological criteria i.e. the number of chromosome aberrations (dicentrics) in a blood-lymphocyte culture.
The doses calculated to those treated in Moscow is given in the following table.

Number	Dose range (Gy)	Number of deaths	Days to death
31	0.8 – 2.1	0	
43	2.2 – 4.1	1	96
21	4.2 – 6.4	7	16 – 48
20	6.1 – 16	20	10 – 91
115		28	

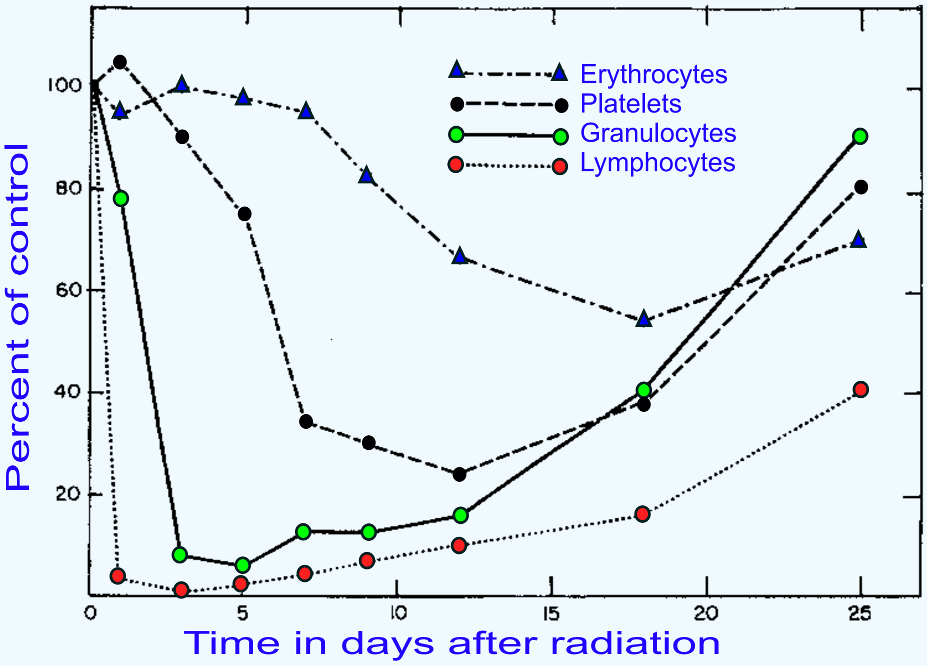
The internal radioactivity was measured – even whole body counting was performed. The thyroid doses were rather low, mainly below 1.2 Gy. The internal Cs-doses were much smaller than the external doses (mainly 1 – 3 %).

The medical unit evacuated people from the reactor vicinity – starting only 30 minutes after the accident. They also distributed potassium iodide in order to minimize the thyroid dose. A large number of people were examined and the diagnosis of "*acute radiation sickness*" was given to 106 workers. Let us briefly mention the bone marrow syndrome and the observations that are involved.

Bone marrow syndrome

Failure of the bone marrow is the cause of death for whole-body doses in the range of 3 to 10 Gy. Experiments with whole body irradiation of mice (see figure below) show a significant decrease in white and red blood-cells. This situation was also observed for the accident in Norway (see the figure on page 80). A dose of 5 Gy will kill about 99% of the hematopoietic stem cells in mice The stem cells are necessary for the production of circulating blood cells (erythrocytes, granulocytes and platelets). A reduction of these cells will result in anemia, bleeding and infections.

The first sign of such radiation sickness is nausea, vomiting and diarrhea. This situation may disappear after a couple of days. Then, the consequences of lost blood cells become evident. Again, significant diarrhea may take place, often bloody, and a fluid imbalance may occur. This, together with bleeding, occurs in all organs. In addition, if infections occur, death may take place in the course of a few weeks.



All patients with bone marrow syndrome were treated separately. With the onset of fever, intravenous administration of two or three broad-spectrum antibiotics was prescribed.

A total of 13 allogeneic bone marrow transplantations and six embryonic liver cell transplantations were performed.
Seven of 13 patients died as a result of skin and intestinal injuries before bone marrow engraftment could be expected.
Three patients died of "graft-versus-host disease" and two survived.
It must be concluded that we in 1986 did not have enough knowledge to perform bone marrow transplants with success.

The average dose to those 28 that died in Chernobyl was 8.5 Gy. The first one died after 10 days and the last one lived for 96 days. The Norwegian worker with a whole body dose of 22.5 Gy lived for 13 days (see page 79).

Altogether 820 persons were so-called "emergency workers" and witnesses to the accident. 87 percent of them got a whole body dose of more than 0.5 Gy.

2. Recovery operation workers

About 600,000 persons (civilian and military) have received special certificates confirming their status as liquidators. Of those, about 240,000 were military servicemen. The principal tasks carried out by the recovery operation workers (liquidators) included decontamination of the reactor block, reactor site, and roads (1986 – 1990) and construction of the sarcophagus. With regard to dosimetry, several groups have been considered separately – sometimes with physical dosimeters and sometimes without. After the first days, the workers carried dosimeters. No one was treated for acute radiation syndrome.

Of particular interest are the 226,000 recovery operation workers who were employed in the 30-km zone in 1986 – 1987, as it is in this period that the highest doses were received. The external radiation doses have been estimated in one of three ways: (a) individual dosimetry, (b) group dosimetry (an individual dosimeter was assigned to one member of a group that should perform a particular task) or (c) time-and-motion studies (measurements of gamma-radiation levels were made at various points of the reactor site, and an individual's dose was estimated as a function of the points where he or she worked and the time spent in these places).

Let us mention some groups.

Helicopter pilots

A number of helicopter pilots (1125) worked the first days with covering the damaged reactor. They were exposed to γ-radiation during this work. The doses to pilots were estimated using either personal dosimeters or, less reliably, calculations in which the damaged reactor was treated as a collimated point source of radiation. The doses obtained by calculation were checked against the results derived from the personal dosimeters for about 200 pilots.

The average dose estimates are 260 mGy for the pilots who took part in the mitigation activities from the end of April to the beginning of May, and 140 mGy for the pilots who were exposed after the beginning of May.

Workers making the sarcophagus

In order to build the sarcophagus a group of 626 workers from the Kurchatov Institute was used. They worked both outside and inside the damaged reactor. The doses involved have been estimated on both ESR and by biological dosimetry (see inset next page). The recorded and calculated doses show that more than 20% received doses between 50 and 250 mGy, and that about 5% of them received doses between 250 mGy and 1.5 Gy. Using the FISH technique for three nuclear research specialists resulted in doses of 0.9, 2.0 and 2.7 Gy.

Average doses to recovery workers

The doses to the recovery workers during the first two months are not known with much certainty since the dosimetry was inadequate until the middle of June. From July 1986 onwards, individual dose monitoring was performed for all non-military workers, using either TLDs or film dosimeters.

The maximum dose allowed during the year 1986 was 250 mGy. The average effective dose from external gamma irradiation to recovery operation workers (approximately 200 000) in the years 1986 – 1987 was about 100 mGy, with individual effective doses ranging from less than 10 mGy to more than 500 mGy.

The remainder of the recovery operation workers (about 400,000), received lower doses. This group includes those who worked inside the 30-km zone in 1988 – 1990, and those who decontaminated areas outside the 30-km zone.

Internal doses – thyroid doses

"*In vivo*" thyroid measurements were carried out on more than 600 recovery operation workers. The thyroid doses were estimated based on these measurements. The average value was 210 mGy – individual doses up to 3 Gy. The main entrance of I-131 to the body was via food in particular milk. Both the measurements and the estimations of thyroid doses are very rough and uncertain.

Stable iodine prophylaxis was used by some of the recovery operation workers, but it was not mandatory nor was it proposed to everybody.

The internal doses resulting from intakes of radionuclides such as Sr-90, Cs-134, Cs-137, Pu 239 and 240 have been assessed for about 300 recovery operation workers who were monitored by whole body measurements from April 1986 to April 1987. The average value of the effective dose committed was estimated to be 85 mSv.

Biological dosimetry

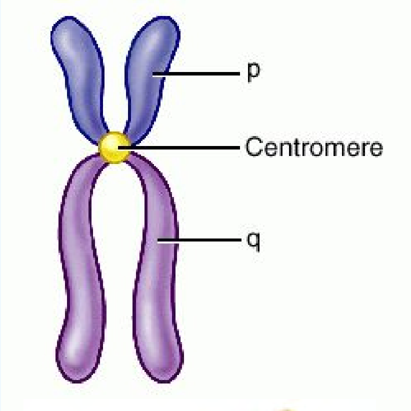
The γ-doses to several groups of workers involved in the Chernobyl accident, have been estimated by two types of dosimeters. 1) ESR measurements on induced stable radicals and 2) chromosome aberrations.

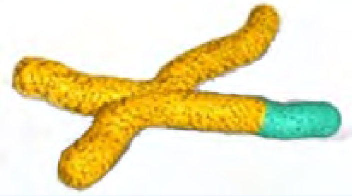
In chapter 6 (pages 82 – 83) we described the ESR-dosimetry which was used for the first time in an accident at Kjeller, Norway in 1982. Furthermore, the recent development have made this technique useful for doses in the mGy-region. However, it must be concluded that the doses determined in the Chernobyl accident are very uncertain.

Biological dosimetry, i.e. observations of chromosome aberrations is based on changes induced in the chromosomes – such as *dicentrics* and *translocations*.

The frequency of aberrations (such as dicentrics, rings and fragments) as measured in peripheral lymphocytes has been used for dosimetry since the 1960s. In this method lymphocytes, which mainly are in the G_0 phase of the cell cycle, have been stimulated to go into the cell cycle – they are cultivated for 48 hours at 37 C° and harvested when they are in metaphase. The chromosomes are stained and one can search for aberrations. It is quite easy to observe dicentrics and the frequency is related to the dose – an example is given in the figure below. The dose-effect curve is found to be linear-quadratic. The method was used in Chernobyl and the doses correlated with those from ESR.

A drawing of a normal chromosome with one centromere.
Dicentric is when two centromeres are observed.
Below is a translocation.

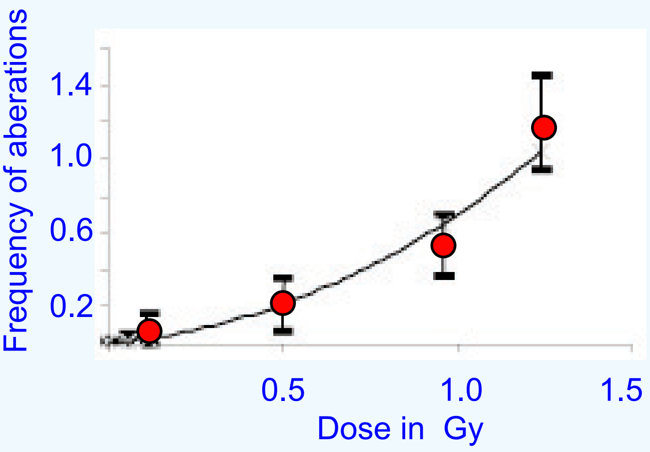




The chromosome aberrations like dicentrics are unstable with time after exposure which make the dose reconstruction uncertain. Other more stable chromosome aberrations are "translocations". A fraction or part of one chromosome become attached to another. An "inversion" is a chromosome rearrangement in which a segment of a chromosome is reversed end to end.

The translocations can be observed by the so called "chromosome painting", a method based on the FISH technique (Fluorescence in situ Hybridization). The technique is useful to estimate cumulative radiation exposure and have been used since the mid 1990-ties.

The FISH-technique has been used in some retrospective studies on some Chernobyl workers. However, the technique is not sufficiently sensitive to allow estimation of individual doses in the low dose range received by the majority of recovery operation workers.



3. Evacuated groups

In the evening of April 26 the exposure rate in Pripyat, about 3 km from the damaged reactor, reached 1 – 10 mR (roentgenunit) per hour (approximately 0.01 – 0.1 mGy). This level was not too alarming, but they considered the situation to be serious. They considered the possibility that the burning reactor core might melt the concrete floor and fall into cellars below which may be filled with water. This could have given a vapor explosion with more release of radioactivity (later it became known that there was no water in the cellars). Late evening it was decided to evacuate the people (about 50 000) the next day. The first evacuation of more than 40 000 took place on April 27 by 1200 buses and was done in 3 hours.

More people were evacuated during the first days up to May 7. Later more people were evacuated – and altogether 116 000 people was evacuated the first year.

Dose level and evacuation

You can probably evaluate the dose level measured in Pripyat. Assuming an exposure rate of 1 mRh^{-1} constant throughout a full year would give you a dose of about 8 mGy per year.

For the people living around the reactor, an exposure level of 5 – 20 mRh^{-1} was used as a criterion for evacuation. If such an exposure level is kept constant for a full year the effective dose would be from 40 – 160 mGy.

The exposure rate after this accident would certainly not be constant. The short-lived isotopes – which are the most important during the first weeks, would disappear and only the Cs-isotopes would be back. Consequently, one would assume that the evacuated groups would return to their homes when the exposure rate went down.

As we know today this evacuation caused a lot of psychological and social problems. Consequently, it can be concluded that the evacuation of most of the people created more serious health problems than the extra radiation (which they tried to avoid) could ever do.

It is an extremely difficult task to evaluate the doses to the groups living in the neighborhood of the reactor and elsewhere with fallout from the accident. A large number of measurements have been carried out – and even more estimations have been done. For those interested, it is worthwhile to go to the UNSCEAR report from 2000 which can be found on internet with the address:

http://www.unscear.org/docs/reports/annexj.pdf

Let us give a short summary and some comments based on the UNSCEAR report.

Efforts have been made to estimate the doses during and through the first weeks after the accident. Furthermore, external doses due to the fallout during the first year have been calculated for groups in Belarus, Russia and Ukraine.

The conclusion is that the doses to the evacuees from external irradiation were mainly due to the isotopes deposited on the ground – and that the irradiation during the passage of the radioactive cloud played a minor role.

External doses

The external γ-dose is mainly due to the volatile isotopes Te-132, I-131 and the Cs-isotopes. Measurements like that given on page 68 for Oslo was carried out in May and June. Based on the measurements it is possible to reconstruct the situation immediately after the accident. The largest contribution to the external dose is from the short lived isotopes. However, after a couple of months, i.e. in July 1986 these isotopes had already been reduced by a factor more than 10^3 – and by the end of the year by a factor more than 10^6.

The estimation showed that the effective dose to about 30,000 evacuees from the city of Pripyat and other settlements in the 30-km zone was about 17 mGy on average. Overall, it is estimated that about 86% were exposed to doses lower than 50 mGy, and only about 4% were exposed to doses greater than 100 mGy.
In the case of the evacuees from the Belorussian territory the estimated average dose was 31 mGy.

It can be noted that estimations indicate that the doses to those evacuated from Pripyat (27 April) were lower than would have been experienced if there had been no evacuation. For examples, the evacuation reduced the number of people from about 1,200 to 28 persons for those who obtained doses above 400 mGy. The health gain (if any) must be valuated against all the health problems the evacuation created.

External doses during the first years

Since 1991, methods for average dose estimation have been introduced based on TLD measurements and Cs-137 whole-body counting. Average effective doses from external irradiation received during the first 10 years after the accident are estimated to range from 5 mGy in the urban areas of the Russian Federation to 11 mGy in the rural areas of Ukraine.

Internal doses

The doses from internal exposure came essentially from the intake of I-131 and other short-lived isotopes during the first days or weeks following the accident, and subsequently, from the intake of Cs-134 and Cs-137.
The doses from the Cs-isotopes have been estimated based on the dietary intake from measured concentrations in foods. In addition whole-body counting have given some data. On pages 123 – 124 you can see how doses from Cs-137 can be calculated.
The calculations resulted in an average internal effective dose during the first 10 years after the accident to range from 4 – 13 mGy. This is much lower than the dose received from natural radiation.

It can be of interest to mention the results from a large number of whole-body measurements on Cs-137 for those living in the polluted areas of Belarus, Ukraine and Russia. The overall concentration is given as 50 Bq per kg body weight. However, no information is given about the time for the observations. In order to judge the value given (50 Bq/kg), you can go to the figures on page 141 and 142. You see that the Lapps living to a large extent on reindeer meat, in 1965 had a body burden of 600 Bq/kg (men) and 300 Bq/kg (women). The Gävle farmers after Chernobyl (about 70 Bq/kg). It must be remembered that for all areas we must take into account an ecological half-life – which according to previous experience probably is in the range 3 – 6 years in the first years afterwards. According to J. Brittains observations for trouts in Øvre Heimdalsvatn (page 154) the ecological half-life increases and may probably be more equal to the physical half-life.

Summing up

As a rule of thumb for estimating accumulated doses to people living in areas with Cs-137 pollution UNSCEAR indicate that a pollution of 1 kBq/m^2 will give an accumulated extra lifetime dose of 0.16 mSv. However, we know that all fallout products slowly will both die out and more important be buried into the ground.

If we use the above value for the people living in the most polluted areas (above 185 kBq/m^2) they may expect an extra lifetime dose of about 30 mSv. It is necessary to mention that the accumulated dose from the natural radiation yield a dose of more than 5 times this value.

Thyroid doses

Because of the thyroid cancers observed for children exposed by the Chernobyl accident, it has been considerable interest to arrive at estimate for the thyroid doses. The main route of exposure for the thyroid dose was the pasture-cow-milk pathway, with a secondary component from inhalation. A large number of measurements of radio iodine contents in the thyroids of people were conducted in Belarus, the Russian Federation and Ukraine to assess the importance of the thyroid doses.

The average thyroid dose to those evacuated (116 000) has been estimated to 0.47 Gy. Doses to the children was in general found to be larger. Thus, the doses to children (up to 15 years) in Ukraine (Pripyat and others in the 30 km zone) were in the range 0.1 – 2.1 Gy. For Belarus the doses were in the range 1.0 – 4.3 Gy.

Another scenario with I-131 and thyroid dose

On page 148 we have presented a scenario in connection to the Windscale accident. We can make another scenario based on Chernobyl.

1. You drink 1/2 liter of milk every day for 160 days – or 20 half-lives for I-131.
2. The start value for I-131 can be set to 100 000 Bq per liter.

As given in the scenario on page 148 each disintegration deposit 0.3 MeV in the thyroid gland. We assume natural decay of I-131 with half-life of 8 days.

During the 160 days after the accident you drink 80 liter of milk – containing 50 000 Bq the first day – and then successively smaller and smaller amount. The total amount of I-131 (N) can be found as follows;

$$N = \int_0^{160} N_0 \cdot e^{-\lambda t} = \frac{N_0}{\lambda}(1 - e^{-160}) = \frac{N_0 \cdot 8}{\ln 2}(1 - e^{-160}) \approx 577 \text{ kBq}$$

The rest of the calculation would be equal to that on page 148. The dose to the thyroid gland (15 gram) would be 1.82 Gy.

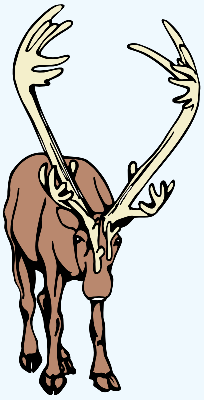
Doses to people in Scandinavia

It is evident from the maps on page 152 that the fallout was rather large in Scandinavia. In the most polluted areas more than 100 kBq/m^2 Cs-137 was measured. Consequently, food products (mainly meat from sheep and reindeer) contained Cs-isotopes to a level of more than 100 000 Bq/kg. Due to the short half-life of Cs-134 of 2 years, the activity decreased rapidly during the first years. Shortly after the accident, the activity ratio between Cs-134 and Cs-137 was approximately 1 : 2.

Calculations indicated that the average equivalent dose to people in Scandinavia was approximately 0.2 mGy the first year after the accident. About 2/3 of the dose was due to food products, and about 1/3 was due to external γ-radiation.

The authorities in Norway and other countries introduced maximum values for Cs-137 in food products. However, no guidelines had been worked out and consequently the maximum level changed from one country to another. In Norway the maximum level for Cs in food products was set at 600 Bq/kg – a value that probably would have ruined the reindeer business. This conclusion is based on the experience from the fallout after the bomb tests on Novaja Zemlja (see the results on page 141), which indicated a half-life of about 6 years for reindeer meat. Consequently, the maximum level was increased for reindeer meat to 5000 Bq/kg. The official argument for this was that we eat very little reindeer meat.

Comment on Cs-137 doses



With the knowledge we have it would be of interest to give a rough estimation of the doses in combination with Cs-137 content in food products.
Let us assume a dinner with reindeer meat containing 100 000 Bq/kg (about the maximum ever measured). We assume that you eat 200 gram and your weight is 70 kg.
Cs-137 has a physical half life of 30 years, but is rapidly excreted from the body. The biological half-life is approximately 3 months – which gives an effective half-life of about 90 days.

The total number of disintegrations (x) in your body by eating 20 000 Bq of Cs-137 is given by:

$$x = \int_0^\infty A_0 \cdot e^{-\lambda t} dt = \frac{A_0}{\lambda} = 2.24 \cdot 10^{11}$$

Here A_o = 20 000 Bq.
$\lambda = \ln 2/t_{1/2}$ and the effective half-life of 90 days is used.

The integration time goes to infinity, but during the first year more than 93% of the dose is given.

On page 144 we see that each disintegration yields an energy absorption of about 0.5 MeV. Furthermore, cesium is distributed evenly throughout the body.
The total energy deposition in the body (weighing 70 kg) is therefore $1.12 \cdot 10^{17}$ eV.
Since 1 eV = $1.6 \cdot 10^{-19}$ joule the following dose is obtained:

$$D = \frac{1.12 \cdot 10^{17} \cdot 1.6 \cdot 10^{-19}}{70} = 2.56 \cdot 10^{-4} \text{ J/kg}$$

This calculation shows that the total dose after intake of food with 20 000 Bq of Cs-137 is:

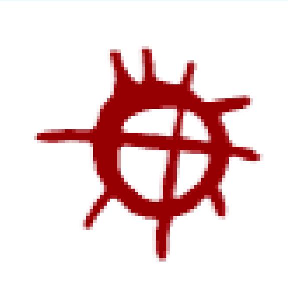
D = 0.256 mGy = 0.256 mSv

Radiation weight factor is 1

If you have such a meal every month through a year the dose would be 3 mSv – or approximately equal to that from the natural radiation (see chapter 7).

Considerations with regard to max-values in food products

With background in the above considerations it can safely be concluded that the dose to the general public in combination with the Chernobyl accident would have been lower than the dose from natural radiation whether food restrictions had been introduced or not the first year after the accident. In the following years the dose would have been smaller and smaller.



With basis in radiobiology we can conclude that introduction of maximum values was unnecessary and that we paid a heavy load in the efforts to reduce the radiation dose.
(However, if we assume that the LNT-hypothesis is valid, it is possible to calculate the collective dose which was saved – and from this dose the number of fatal cancers avoided. According to the LNT-hypothesis all radiation – also the natural radiation is deleterious and should be avoided if possible.)

The radiation authorities use the LNT-hypothesis in their work and was forced to implement maximum values in connection with the Chernobyl disaster. Since the zero-level was not attainable, the value was set as low as possible within reasonable limits.

An important effect, so far not mentioned, is that these maximum values resulted in an irrational fear for radiation which have had large psychological effects. It would have been nice if the radiation authorities could work out examples like that above – rather than using the LNT-hypothesis.
If maximum levels should be introduced, a rule of thumb would be that the extra dose from a pollution should not exceed the dose from natural radiation. In connection to the Chernobyl accident the limit could have been set at for example 0.01 mCi in a year. The curie unit would not scare people whereas 370 000 Bq is a very large number.

Thyroid and other cancers after Chernobyl

Cancer is the only late effect after radiation that has been observed and where we know parts of the mechanism. It starts with a DNA-damage to a cell that is not repaired (or misrepaired). The damaged cell must be trigged to go into the cell cycle and is not stopped on the way. This results in two damaged cells.
Previously, we have discussed lung cancer for underground miners due to radon doses (page 110). Cancers have also been observed for the survivors of the bombs in Japan in 1945. The radiation dose in Japan was due to a burst of γ-rays and neutrons, whereas the dose from radon is due to α-particles from the radon daughters and given in the course of several years. The lung doses that may give lung cancer seems to be above 1 Gy (page 110).

In combination with the Chernobyl accident a number of rescue workers received extra doses of 100 mGy and more. Another group is all the children exposed to I-131 during the first days after the accident. For both rescue workers and the children exposed to I-131 the dose represents a problem. Let us look into the two groups and see what we know today.

Thyroid cancers

About 4000 thyroid cancer cases have been diagnosed in the period 1992–2002 in persons who were children at the time of the Chernobyl accident and lived in the polluted areas. Only a few cases (15) have resulted in death. Furthermore, it is reasonable to assume that a large fraction of the cases would have been unobserved since thyroid cancer is in general quite benign. However, a large screening project has been performed in the polluted regions.

The main pathway of the thyroid doses in Chernobyl was through ingestion of foodstuffs, especially milk, containing high levels of radio iodine. We have previously (see page 148 and 162) made scenarios with I-131 and thyroid doses. In the Chernobyl scenario we used a start value of 100 000 Bq per liter. The child should drink 1/2 liter every day for 160 days. The resulting dose was 1.82 Gy. Larger values would be obtained assuming a smaller thyroid gland and otherwise similar conditions. The uncertainties in the dose determinations after Chernobyl is the following:

1. The determination of I-131 to milk was based on measurements of all the activity in milk. No good γ-spectroscopy with germanium detectors was carried out. See the Oslo-measurements on page 76.

2. The measurements of the I-131 concentrations in the thyroid was based on measurements to the neck of a number of people. Again no γ-spectroscopy was performed.

3. The size of the thyroid gland for these childern is not known. This parameter is very important in the estimations of the dose.

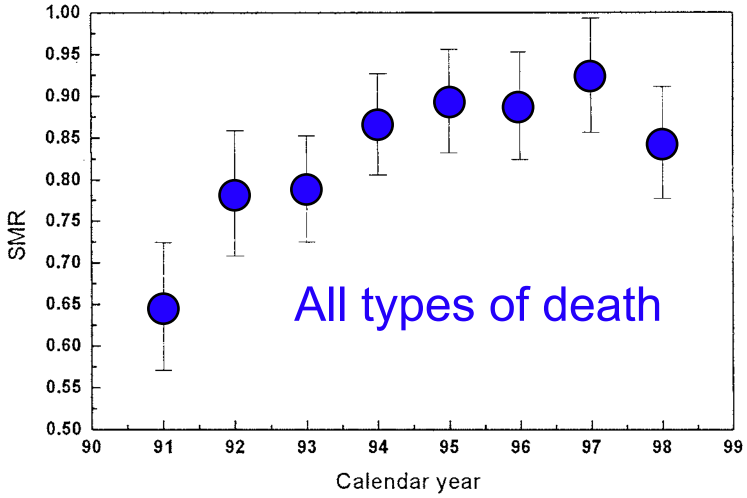
A lot of research have been carried out in recent years to attain more information on thyroid cancer. This research include the following groups: 1) The survivors of atomic bombing in Japan, 2) Marshall Islanders exposed to nuclear test fall-out, 3) Children exposed during therapeutic external radiation therapy.

The conclusions are as follows: Thyroid nodules of all types and sizes, including small ones detected by screening methods, are increased by radiation exposure. Furthermore, the thyroid is among the most radiation-sensitive tissues in the body, with excess cancers occurring at doses as low as 100 mGy. It was found that both iodine deficiency and iodine supplementation seems to modify the risk. The appearance of childhood thyroid cancer was larger in iodine-deficient populations, and it can be noted that all the areas involved in the Chernobyl accident had some level of iodine insufficiency in 1986.

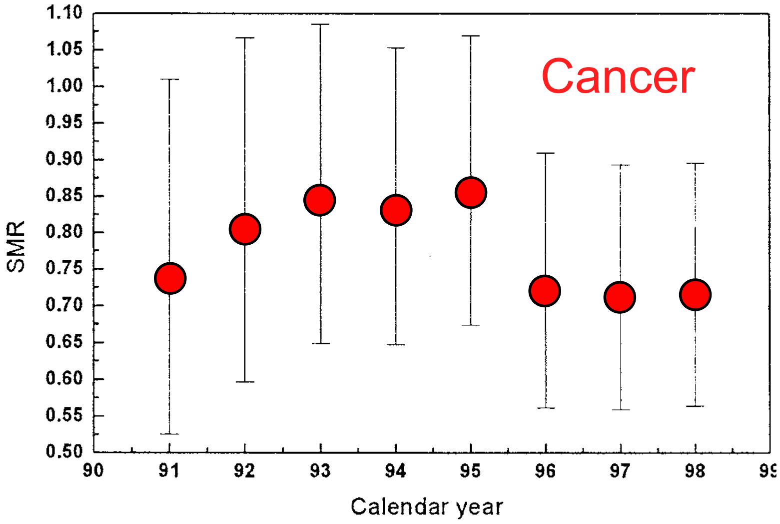
Russian emergency workers

V.K. Ivanov and coworkers have studied the health effects on 65 905 Russian emergency workers. They got an extra dose of from 5 mGy to 300 mGy (average 100 mGy). The number of deaths in this group, up to 1998 was 4995. Four different classes of death are considered. They are based on WHO and are; 1. Malignant neoplasms. 2. Cardiovascular diseases. 3. Injuries and poisoning. 4. Causes from diseases other than those above.

The control was the mortality rate for the corresponding ages (males) in Russia. The results show that the mortality for the emergency workers is ***lower*** (only 82 %) than the general Russian rate. Also the incidence of cancer was lower for the emergency workers.



In the figure above is given the deaths of Russian emergency workers in the period 1991 to 1998. The death rate is compared to the general Russian rate with SMR = 1.0 "Standard Mortality Ratio". Below is given the data for cancer.



Chernobyl – Summery

Approximately 25 years after the accident we can sum up as follows.

1. The Chernobyl accident was the largest and most severe reactor accident ever. The accident itself resulted in 31 acute casualties – 28 due to the acute radiation syndrome.

2. Large areas were contaminated. People in the regions must live with Cs-137 and Sr-90 contamination for hundreds of years to come.

3. An increase of childhood thyroid cancer has been observed in the most contaminated areas in Belarus, Ukraine and Russia.

4. There is no evidence of other radiation-induced cancers in the three most contaminated countries at this time. Interesting data for Russian emergency workers indicate a positive effect of radiation. The reports and statements up to now are based on the LNT-hypothesis.

5. The most severe effect of the Chernobyl reactor accident is the psychological effects and mental disorders. It is a fact that a large amount of Post-Traumatic Stress Disorders (PTSD) have appeared with symptoms such as depression, hypochondrias, headache, dizziness, fatigue or chronic tiredness, poor concentration, anxiety, physical and mental exhaustion, feeling of hopelessness, and lack of libido. ***The main reason for this is the LNT-hypothesis which give a rather dark future for all involved which have attained an extra radiation dose.***

It has also been observed that there is an increased incidence of high blood pressure, alcohol abuse and even suicide. None of these syndromes are caused directly by radiation.

6. One important factor to the psychological effects was the evacuation of large groups of people. It would have been wise to evacuate those near the reactor (Pripyat) – but they should have been brought back. The radiation level is lower than for many high radiation areas around the world.

A consequence of the Chernobyl accident is that millions of people now suffer from psychological effects. The accident has resulted in an increase of "*radio-phobia*". This needs to be taken seriously. An understanding of radiation and radioactivity combined with the dissemination of properly acquired data will help reduce radio-phobia. An important objective of this book is to increase understanding and provide some of the relevant data.

We are of the opinion that knowledge about radioactivity, how to calculate radiation doses, and how to compare doses from accidents with doses from natural radiation, medical use and air-travel is of considerable value to the public. Those who exaggerate the fear of radiation need to take responsibility for increasing radio-phobia and the damage spawned by radio-phobia.

For a summary see: http://chernobyl.undp.org/english/docs/chernobyl.pdf

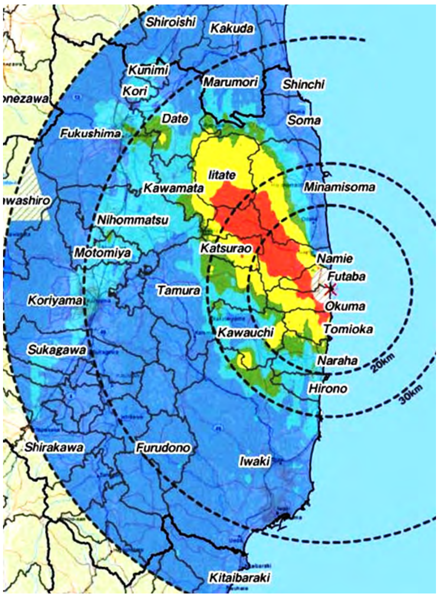
Fukushima Japan 2011

On March 11, 2011 an earthquake, of the order 9.0 on the Richter scale, occurred off the northeast coast of Japan and the tsunami that followed killed about 19 000. The height of the tsunami varied considerably and maximum has been calculated to 127 feet.

The Japanese reactors, including the Fukushima Daiichi reactors were automatically shut down by the earth quake. The reactor site in Fukushima included 6 reactors (built in the period 1967 – 1973). Units 4, 5 and 6 had been shut down prior to the earthquake for planned maintenance. The heat of the fuel was cooled with power from emergency generators. The subsequent destructive tsunami with waves of up to 15 meters (the reactors were designed to handle up to 6 meters) disabled the emergency generators that should cool the reactors. Over the following three weeks there was evidence of meltdowns in units 1, 2 and 3. Visible explosions, suspected to be caused by hydrogen gas, in units 1 and 3 may have damaged the primary containment vessel with an uncovering of the spent fuel pools.

Radioactivity was released (mainly I-131 and the cesium isotopes (Cs-137 and CS-134) to the environment. We do not know the total release of isotopes, but it has been suggested to be about 10 % of the release from Chernobyl. In August 2011, the Nuclear Safety Commission (NSC) of Japan published the following results for the total amount of radioactive materials released into the air during the accident at Fukushima. The total amounts released between March 11 and April 5 were $130 \cdot 10^{15}$ Bq (130 pBq) I-131 and $11 \cdot 10^{15}$ Bq Cs-137. This is approximately 10 % of the Chernobyl release.

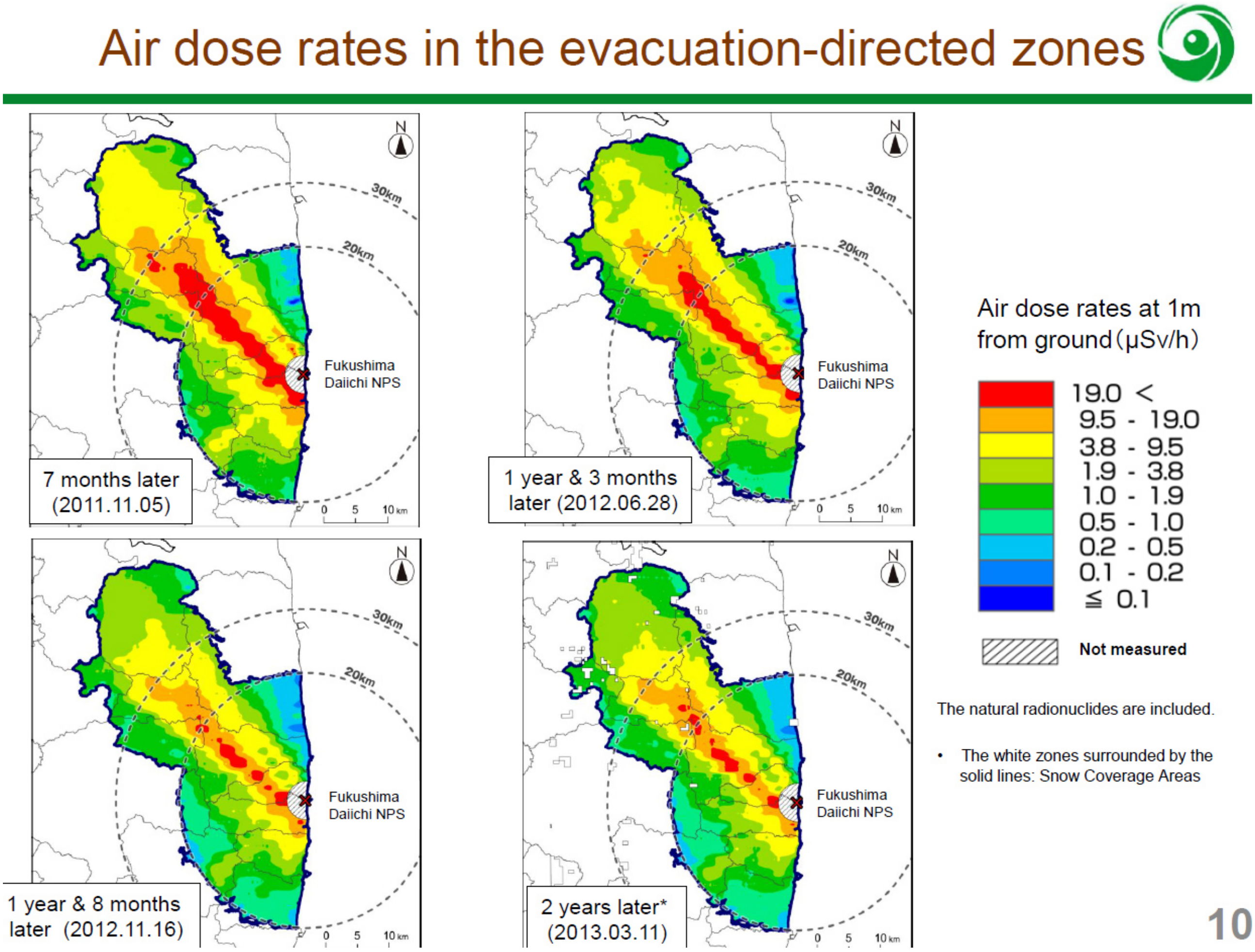
Falloutmap



The release to air resulted in fallout to regions near the reactor. An attempt to give the fallout for the Cs-isotopes is given in the map to the left. The yellow and red colors indicate areas with the largest fallout. It is mainly in a narrow region up to about 40 km to the northeast. The exposure level in these areas resulted in evacuation of about 150 000 people.
A large amount of activity was also released to the sea. This activity, which is diluted in the ocean is of minor effect. Some restrictions was introduced for the local fishermen.

A large amount of measurements has been carried out with the purpose to determine doses. Unfortunately all measurements are given as μ Sv/h which is meaningless as a measure of the radiation level. Since it is γ -radiation (low LET) the measurements are numerically equal to μ Gy/h exposure dose.

Both ionization chambers and scintillation dosimeters have been used. Most measurements yield the exposure rate 1 meter above ground. We shall give some maps and follow the decay of radiation during the first two years after the accident.



Air dose rates in the evacuation-directed zones

Air dose rates at 1m from ground (μSv/h)

🟥 19.0 <
🟧 9.5 - 19.0
🟨 3.8 - 9.5
🟩 1.9 - 3.8
🟩 1.0 - 1.9
🟩 0.5 - 1.0
🟦 0.2 - 0.5
🟦 0.1 - 0.2
🟦 ≦ 0.1
▨ Not measured

The natural radionuclides are included.

- The white zones surrounded by the solid lines: Snow Coverage Areas

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Japan's Nuclear Regulation Authority (NRA) has revealed the most contaminated areas in the Fukushima evacuation zone by these maps. The radiation intensity is given by colors with red as the most intense. The measurements are made 1 m above ground and only the external γ -radiation is measured. It is the natural γ -irradiation and the γ -radiation from the Cs-isotopes. As you remember this radiation has an energy of 0.66 MeV.
The measurements are in this original figure expressed in μ Sv/h (see the color codes). which is rather confusing and impossible. Here we are concerned with low LET γ -radiation (radiation weight factor is 1.0) and Gy is equal to Sv values.
The exposure dose rate during the first year decayed by about 40 %. The decay is quite rapid in the beginning due to the fact that Cs-134 has a halflife of 2 years. However, the Cs-137 will be in the area for decades.

Whole body doses

An interesting question is the whole body dose to a person living in the contaminated area. The average whole body dose would be smaller than the skin exposure dose. The γ -radiation from Cs has a half value layer in tissue of about 9 cm. The Cs-radiation is coming from the ground and the dose to the upper part of the body would be smaller.
If a person lived in the area, a large part of the time he/her would be inside buildings with a reduced exposure level. It is very difficult to give a value for the annual dose. Let us assume a person is living in the yellow area for a year (exposure rate 3.8 – 9.5 μ Gy/h). The maximum dose in open air would be 30 – 83 mSv. A normal life, being indoor and may be out of the zone for some time, would reduce the annual dose by about 50 %. This dose, which is far above the Japanese average can be compared to some of the high dose areas discussed on pages 97 – 99.

Radioactivity in the food products

Food monitoring data were reported from 19 to 31 May by the Ministry of Health, Labour and Welfare for a total of 818 samples collected in 18 different prefectures. Most of the monitoring continues to be concentrated in Fukushima prefecture, where 328 out of the 818 samples (over 40%) were collected.

Analytical results for 766 samples (over 93%) of the 818 samples indicated that Cs-134 and Cs-137 or I-131 were either *no*t detected or were *below* the regulation values set by the Japanese authorities (500 Bqkg^{-1}). However, 52 samples were above the regulation values for radioactive cesium and/or iodine. In Fukushima prefecture, five samples of fishery products collected on 16 and 17 May; one sample of unprocessed tea leaves collected on 17 May; three samples of shiitake mushrooms and nine samples of bamboo shoots collected on 19 May; five samples of seafood collected on 20, 21 and 23 May, and; one sample of Japanese apricot, two samples of shiitake mushrooms and seven samples of bamboo shoots collected on 26 May were above the regulation values for Cs-134/Cs-137. One sample of algae collected on 21 May was also above the regulation values for Cs-134/Cs-137 and I-131.
These measurements have continued and in the end of July 2013 the activity has dropped by a factor of 5. The food products contained below 25 Bqkg^{-1}

Conclusion

The above results are surprising. After Chernobyl we measured up to 100 000 Bqkg^{-1} in meat in Norway, and if the release of isotopes was about 10 % of the Chernobyl release we would expect much lager values. One reason may be that the majority of the release went to the sea.

Ecological half lives – mainly Cs-137

In connection with fallouts from reactor accidents it is important to gain information about the ecological half lives in order to live and work in a fallout area. In combination with the fallout from atomic bomb experiments in the atmosphere we found an ecological half-life of about 6 years for Cs-137 in reindeer meat (page 140). The same half life was found for the Laplanders eating the reindeer meet. For a Stockholm group the ecological half life was only 3.5 years (page 141).

The work by J.E. Brittain and coworkers (page 154) with the fallout from Chernobyl is very interesting in this connection. They found that the ecological half life for Cs-137 in brown trout in a fallout region (130 kBqm^{-2}) was about 3.5 years for the first 5 – 6 years, and then increased and seems now to be close to the physical half life (30 years). However, during the first 25 years after the Chernobyl accident (almost 1 half life for Cs-137) the activity has decreased by a factor of about 18.

Information about ecological half lives is important with regard to use and live in fallout areas.

Summing up

The tsunami in March 2011 killed about 19 000 people and destroyed 120 000 buildings and damaged more than 200 000. However, it was the Fukushima reactors that very soon overshadowed all news. The nuclear accident was eventually classified at Level 7, the highest on the International Nuclear and Radiological Event Scale (INES).
No radiation-related deaths or acute effects have been observed among nearly 25,000 workers involved. The thyroid doses from iodine-131 ranged up to several tens of milligray and were received within a few weeks after the accident. The whole-body (or effective) doses mainly from caesium-134 and caesium-137 ranged up to ten or so milligray. The additional exposures received by most Japanese people in the first year and subsequent years due to the radioactive releases from the accident are less than the doses received from natural background radiation (which is about 2.1 mSv per year).
Approximately 150 000 people were removed from the fallout area. If the LNT-theory is used it can be calculated how many mansievert this group have avoided – and consequently avoided some cancers. On the other side this removement introduces mental health problems.

Conclusions for Fukushima

Environment: Since the earthquake, a powerful movement gained momentum to halt Japan's use of nuclear energy, which provided 30 percent of the country's electricity. Japan has therefore had to increase its imports of natural gas, low-sulfur crude oil and fuel oil at a substantial economic and environmental cost. Seventy-five percent of the country's electricity now comes from fossil fuels.

Health: The reactor accident after the earthquake and tsunami scared the people far more than the tusnami itself. The main reason for this is again the LNT-theory. The theory with its ALARA principle neglect all other effects of radiation – in particular the positive effects discovered during the last 30 years.

WHO still assume the LNT-theory, whereas UNSCEAR reflects a view that is more doubtful to LNT. Thus in May 2013 they state; "Radiation exposure following the nuclear accident at Fukushima-Daiichi did not cause any immediate health effects. It is unlikely to be able to attribute any health effects in the future among the general public and the vast majority of workers,"
Furthermore; ***the Scientific Committee does not recommend multiplying very low doses by large numbers of individuals to estimate numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels.***

Last comment: It is a pity that all dose measurements – in partiular exposure doses are given in the Sv-system. Even WHO use this system.